Desk study

Resilient WASH systems in Drought prone areas

CARE Nederland

In collaboration with The Netherlands Red Cross

Techniques to improve the resilience of community WASH systems in drought-prone areas

Commissioned by:
CARE Nederland

In collaboration with:
The Netherlands Red Cross

With support of:
PSO

October 2010

This study has been commissioned by CARE Nederland, to explore the current body of knowledge with regards to resilient techniques in water supply where water availability is limited – in particular drought-prone areas – and to prepare the technical basis for the evaluation of WASH projects developed in areas that are (potentially) exposed to drought

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Impact of drought on WASH systems

There are uncertainties with projected impacts of climate change, but reliability of projection depends on the area. For some regions projections of future precipitation change are more robust, while outside of these areas the predictions vary between models. Predictions also become less consistent between models as scale decreases.[1] One robust finding is that there will be changes in the seasonality of river flows in areas where much of the winter precipitation falls as snow.[2] Projections also indicate that not everywhere will be affected by reduced cumulative water availability – in fact, some areas will start to receive more annual rainfall, while other areas will receive less. Even so, the variability is likely to increase, with more intense rainfall over short periods of time or longer periods with little or no rainfall, with the increased likelihood of extreme water-related events such as floods or droughts.[3]

The focus of this study is methods of increasing resilience of water systems in particular. The rationale for focusing on water is to do with its critical role in people's ability to negotiate a drought – this seems to be particularly the case with access to water supply during drought emergencies. Some examples:

- After 1992-3 drought in Southern Africa, people became aware that drought was inextricably linked with management & conservation of surface and ground water sources – questions were asked then about how to make water supply systems more able to resist drought periods.[4]
- Access to water was the main concern during drought of 2000 in Afghanistan, even above food supply.[5]

While water supply is important, it is clear that it is only one part of reducing vulnerability. Studies have shown that people's ability to adapt to drought depends on specific livelihood characteristics, and that the poor and landless are not automatically the most vulnerable.[6] A real reduction in vulnerability must go further than only looking at the aspect of water availability and should encompass how people's livelihoods are also made less vulnerable or more viable in the context of drought. Increasing the resilience of WASH activities as a stand-alone activity will have limited impact unless other non-WASH sectors are engaged in reducing people's vulnerability to drought – things such as access to markets, access to finance, levels of infrastructure and diversity of livelihood options can all affect people's livelihoods and dictate vulnerability.

Regarding water systems, the overall aim is to study what techniques can be used to <u>improve water availability over space and time</u> in areas not only prone to drought and changing climate variability, but also those areas with deteriorating water availability due to increasing water demands and human influences (see "Definitions of drought" section). Resilience is a concept used to describe how to make water systems more robust in terms of water availability, thereby reducing the vulnerability of people that rely on them. Both resilience and vulnerability are concepts related to the capacity to anticipate / cope with / resist / recover from a hazard, and both are determined by physical, environmental, social, economic, political, cultural and institutional factors:[7]

- Vulnerability = potential to suffer harm or loss
- Resilience = potential to cope with harm or loss
- Increased resilience = reduced vulnerability

Techniques covered in this study include both groundwater and rainwater sources, but in general emphasis has been placed on systems that allow the more efficient capture and storage of rainwater and recharge of this rainwater to groundwater, rather than emphasizing an expanding use of groundwater in itself. Improving water availability will not only be about improving existing techniques, but may also be about introducing new techniques to an area. Many of the rainwater harvesting techniques (especially floodwater harvesting and storage techniques) are not only sometimes uncommon, but also at times unknown and not practiced at all[8] – in other words, there is huge potential to pick and choose potentially relevant techniques for specific sites in order to improve water availability. Why the techniques are not more widespread remains an unanswered question but will have to do with lack of understanding of adoption criteria which include biophysical preconditions, socio-economic conditions, market issues, land tenure issues and human capacity.[9]

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[1] Batchelor, C.; Schouten, T.; Smits, S.; Moriarty, P.; Butterworth, J. (2009) *14. Climate change and WASH services delivery – Is improved WASH governance the key to effective mitigation and adaptation?* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands. p.2.
[2] Wilk, J.; Wittgren, H.B. (eds). (2009) *Adapting Water Management to Climate Change*. Swedish Water House Policy Brief Nr. 7. SIWI, 2009. p.5.
[3] UNEP / GRID, IPCC. Quoted in: USAID (2010) *Summary of the World Water Crisis and USG Investments in the Water Sector*, *May 15, 2010.* See also: Batchelor, C.; Schouten, T.; Smits, S.; Moriarty, P.; Butterworth, J. (2009) *14. Climate change and WASH services delivery – Is improved WASH governance the key to effective mitigation and adaptation?* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands.
[4] Holloway, A. (1995) Southern Africa: Drought Relief, Drought Rehabilitation...What about Drought Mitigation? *Newsletter, Relief and Rehabilitation Network*, ODI, London, UK.
[5] Matheou, A. (2001) Natural disasters and complex political emergencies: responding to drought in Afghanistan. *Humanitarian Exchange* No.19, HPN, ODI, London, UK.
[6] Moberg, F.; Galaz, V. (2005) *Resilience: Going from Conventional to Adaptive Freshwater Management for Human and Ecosystem Compatibility*. Swedish Water House Policy Brief Nr. 3. SIWI, 2005. p.9.
[7] Benson, C.; Twigg, J. (2007) *Tools for Mainstreaming Disaster Risk Reduction: Guidance Notes for Development Organisations*. Provention Consortium, Geneva, Switzerland. p.12.
[8] Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.
[9] Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.

Yet it is clear that the potential for increasing water availability is there, especially in terms of rainwater harvesting. If we consider that all the rain that fell on the land could be harvested, there would be fewer water and food security problems as water demand could be met – the fact is that much of this rain falls in short periods of time with high intensity, and that a large part of it runs off the land,[10] while that which is collected is not collected nor stored efficiently.[11] Improved methods are therefore needed in areas of high runoff to collect this rainwater over the large surface area on which the rain falls. This is in order to collect it efficiently as both "blue flow" (the liquid component that recharges aquifers, lakes and rivers) as well as "green flow" (the component that supports plant/crop production through rain-fed irrigation). It is the efficient use of "green flow" that has huge consequences for food security since an estimated 60% of the world's staple food production relies on this water (and in Sub-Saharan Africa it is almost 100%).[12]

It would be convenient to have some multiplication factor for WASH project managers to know how much to increase water availability to be able to adapt to a changing climate. While climate change predictions give some idea of decrease in water availability globally due to climate (see map under "Definitions of drought"), this will depend on the area in question and the scale as to how robust the predictions are. There is a need to improve understanding and modelling of climate changes related to the hydrological cycle at scales relevant to decision making by WASH managers since uncertainty of predictions increase at such scales – this is currently a gap in ability to plan.[13] Perhaps while not perfect, planning could be related initially to projected changes in precipitation volumes on larger scales (see map under "Definitions of drought"). However, while planning WASH interventions in this way might be a step in the right direction, basing planning only on changes in precipitation would be too simplistic, as water availability is not solely affected by climate change – population growth and changing water demand also play major roles in water availability. For example in an area where a WASH project would be planned for an area based on a predicted decrease in rainfall, water could remain scarce due to an increased population and surging water demand, especially for irrigation which is predicted as likely to increase under lower rainfall conditions. Supply-side strategies therefore need to be planned together with a demand-side strategies in water programmes which seek to adapt to water scarcity and climate change.[14] Any planning factor for WASH managers should then take into account rainfall decreases, current water resources available to the population, population growth and projected increased demand. An additional complication is that water availability is not the only aspect of concern when planning WASH interventions, since intensity of rainfall events should also be factored in. Greater intensity events may require some structures to be reduced (e.g. embankments, bunds) rather than increased.

This table below shows an overview of climatic drought on water systems in rural and urban settings – however it is incomplete insofar that climatic drought is not the only factor affecting water availability, and there are many techniques outlined in other sections that discuss how to increase water availability in general. While this table looks at both urban and rural settings, the main report only goes into rural water/irrigation systems in detail. Areas for further study include techniques to increase resilience of sanitation, hygiene, drainage, solid waste management and larger irrigation programmes in rural areas, plus all aspects of WASH programming in urban areas, which will become increasingly important – it is estimated that by 2030, 2/3[rd] of the world population will live in cities or large towns.[15]

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[10] Runoff accounts for 10 – 30% of annual rainfall in dryland areas. See: Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.

[11] Steenbergen, F.V.; Tuinhof, A. (2009) *Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retention, Reuse and Rainwater Storage*. BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), the Co-operative Programme on Water and Climate (CPWC) and the Netherlands National Committee IHP-HWRP. p.64.

[12] Moberg, F.; Galaz, V. (2005) *Resilience: Going from Conventional to Adaptive Freshwater Management for Human and Ecosystem Compatibility*. Swedish Water House Policy Brief Nr. 3. SIWI, 2005. p.4.

[13] Batchelor, C.; Schouten, T.; Smits, S.; Moriarty, P.; Butterworth, J. (2009) *14. Climate change and WASH services delivery – Is improved WASH governance the key to effective mitigation and adaptation?* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands. p.3.

[14] Batchelor, C.; Schouten, T.; Smits, S.; Moriarty, P.; Butterworth, J. (2009) *14. Climate change and WASH services delivery – Is improved WASH governance the key to effective mitigation and adaptation?* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands. p.3.

[15] Wilk, J.; Wittgren, H.B. (eds). (2009) *Adapting Water Management to Climate Change*. Swedish Water House Policy Brief Nr. 7. SIWI, 2009. p.8.

	Effects of drought	Underlying causes of effects	Overall techniques to increase resiliency of WASH system
Construction techniques			
Making concrete	• Badly made concrete and cracked linings (e.g. in tanks)	• Less water used for curing • Impure water used for mixing	• Ensure adequate mixing, ratios, purity of ingredients • Minimize water content in mixture • Ensure adequate curing
Water quality issues			
Saline water	• Salinity increases • Corrosion of equipment/pipes	• Less recharge = less dilution of naturally-occurring minerals • More demand = more extraction = saline intrusion • Higher population = pollution from anthropogenic sources	• Diversify water sources • Household & communal level solar distillation • Managed Aquifer Recharge (MAR) • Reduce water-logging in irrigated areas
Mechanical water extraction			
Handpumps	• Handpumps not repaired (weak effect?)	• Lack of household finance to contribute to repairs due to suffering household economy	• Choose simple technologies • Consider handpumps where a viable sustainable handpump option has to be shown to work in an area • Promote increased levels of ownership & responsibility
Surface water including rainwater			
Managed Aquifer Recharge			
• Infiltration ponds	• Water quality deteriorates • Water levels in wells & boreholes reduce	• Water levels reduce = excessive algae and water plant growth due to water being too shallow • Less recharge to aquifers	
• Contour trenches	• Lower crop yields	• Water levels reduce • Less recharge to aquifers & crops	• Diversify livelihoods of farmers
• Bunds	• Lower crop yields	• Less water to crops from flooding	• Drought-resistant & fast-growing crops • Diversify livelihoods of farmers
• Gully plugs / check dams	• Lower crop yields	• Less water to crops	• Drought-resistant & fast-growing crops • Diversify livelihoods of farmers
• Leaky dams	• Less water stored behind dam	• Less recharge	• Reduce water loss behind by using adjustable sheets filled with small size gravel on the upstream side of the dam.
• Controlled flooding	• Lower crop yields	• Less water to crops from flooding	• Drought-resistant & fast-growing crops • Diversify livelihoods of farmers
• Drip irrigation	• Less impact		
• Well shafts & boreholes	• Water levels reduce in wells & boreholes that are being recharged	• Less recharge	
Ground catchment & storage			
• Natural rock catchment & open water reservoirs	• Tend to dry up quickly	• Lack of rainfall	• Site on rock that is bare and free of vegetation/soil with no fractures

	• Conflict over water for animals	• High evaporation rates • Seepage through dam • Storage not sufficient for demand	• Maximize the natural topography = deeper • Follow proper construction methods • Gutters and break walls to slow down and direct runoff • Improve access to micro-finance • Phased construction until capacity is sufficient for water demand
• Natural or artificial ground catchment & lined sub-surface tanks	• Water storage used up	• Lack of rainfall • High evaporation rates • Leaking linings due to bad construction • Storage not sufficient for demand – tanks are too expensive for volumes of water to outlast extended dry periods	• Build smaller tank structures but more of them over longer time = less reinforcement per tank, more manageable to construct and cover & more affordable. • Reduce evaporation & seepage due to poor construction & siting • Follow proper concreting guidelines • Make tanks from cheaper materials and repair more often • Improve access to micro-finance • Support the capacity of the government or private sector to be able to provide (for payment) a tankering scheme
• Natural ground catchment & open water reservoirs	• Tend to dry up quickly, especially if unlined • Conflict over water for animals	• Lack of rainfall • High evaporation rates • High seepage rates through base of pond and through dam • Storage not sufficient for demand – silting up of ponds due to high silt load, high level of work in constructing ponds	• Reduce evaporation & seepage • Follow proper construction methods • Reduce siltation = more volume • Promote private ownership of ponds = de-silting process more likely • Improve access to low-cost loans with long-time repayment conditions so that farmers can replicate technology. • Phased construction until capacity is sufficient for water demand
Roof catchments & storage	• Water storage used up	• Lack of rainfall • Leaking linings due to bad construction • Storage not sufficient for demand – tanks are too expensive for volumes of water to outlast extended dry periods	• Promote smaller tank structures = more manageable to construct and cover, while being more affordable to families. • Reduce seepage due to poor construction & siting • Follow proper concreting guidelines • Make tanks from cheaper lower quality materials and repair more often • Design the outlet of the tank so that there is no dead storage • Ensure the catchment itself is efficient (e.g. gutters). • Improve access to micro-finance

			• Support the capacity of the government or private sector to be able to provide (for payment) a tankering scheme
Fog collection & storage	• Not affected		
Dew collection & storage	• Not affected		
Shallow groundwater			
Hand-dug, jetted & driven wells			
• Traditional hand-dug wells	• Can dry up • Groundwater levels dropping in perched aquifers	• Less recharge of aquifer due to less rainfall • Increasing population & water demand • Size of aquifers – e.g. perched aquifers will be used up faster • Wells not sunk deep enough into water table	• Avoid perched aquifers • Sink wells deeper – de-water well during caissoning within the water table • Allow for subsequent deepening by using telescopic lining • Dig wells during the latter half of the dry season • Recharge aquifer through Managed Aquifer Recharge (MAR) boreholes • Jet in the bottom of the well to provide a means of faster recharge • Increase flow by use of porous concrete or perforated pointed steel pipes driven horizontally into the aquifer
• Riverbed hand-dug wells, Riverbed infiltration galleries, Riverbed jetted & driven wells, Infiltration wells	• Can dry up	• Less recharge of aquifer due to less rainfall • Increasing population & water demand • Size of aquifers – e.g. limited sand volume • Wells not sunk deep enough into water table • Incorrect siting • Graded gravel around pipe not correctly done	• Increase volume through construction of groundwater dam • Sink wells/pipes deeper • De-water wells during caissoning within the water table • Construct during the latter half of the dry season • Site in riverbeds that are dry for part of the year, where water remains in the riverbed throughout the dry season. • Increase flow by use of porous concrete & perforated pointed steel pipes driven horizontally into the aquifer (riverbed wells) and graded gravel (infiltration galleries & jetted wells) • Site in a degrading river section where there is no deposition (infiltration galleries) • Graded gravel needs around pipes to minimize clogging and increase flow
Groundwater dams	• Can dry up • Water yields low	• Less recharge of aquifer due to less rainfall	• Competent siting & construction • Build sand dam in stages to reduce silt

		• Increasing population & water demand • Size of aquifers – e.g. limited sand volume • Too much silt accumulates behind dam • Wells not sunk deep enough into water table • Incorrect siting = leaking dams	• Soil & water conservation techniques in upper part of catchment • Sink abstraction wells/pipes deeper
Spring protections	• Can dry up	• Less recharge of aquifer due to less rainfall • Size of aquifers limited • Increasing population & water demand	• Improve flow by excavating carefully at spring eyes • A holding reservoir can be constructed to bridge peak demand, or a lined pond provides a way to store larger quantities during all the hours of flow • Design for dry season flow rates
Medium to deep groundwater			
Boreholes	• Groundwater levels dropping • Subsidence & damage to infrastructure • Pumping systems need lots of maintenance = expensive = sometimes not repaired • Pumps & handpumps break down Increased salinization due to seawater intrusion • Environmental degradation around waterpoints due to livestock	• Less recharge of aquifer due to less rainfall • Increasing population & water demand • Size of aquifers limited • Mining causing subsidence • Overuse of pump at congested points • Lack of cash to repair at communal level • Communal system of maintenance & issue of spare parts (see paper)	• Correct borehole siting • Water level monitoring • Stop drilling in areas where saline groundwater is a problem & concentrate on rainwater-groundwater dilution using MAR techniques • Drill deep enough to start with • Deepen existing boreholes • Reduce water demand • Find alternative sources • Achieve greater regional coordination between water providers • Avoid boreholes in pastoralist & agropastoralist areas • Link problem into Integrated Water Resource Management (IWRM)
Water trucking & water vendors			
Water trucking & water vendors	• More business generated for vendors • More money spent by users	• More water tankering required by NGOs, governments & individuals	• Support the capacity of the government or private sector to be able to provide (for payment) a water trucking scheme to during the driest parts of the year. • Continue to improve access to alternative water sources for users to reduce reliance on water trucking
Urban piped water[16]			
General	• Insufficient water = water rationing	• Less recharge of aquifer due to less rainfall • Increasing population & water demand	• Improve efficiency of water use in domestic & industries • Introduce metering

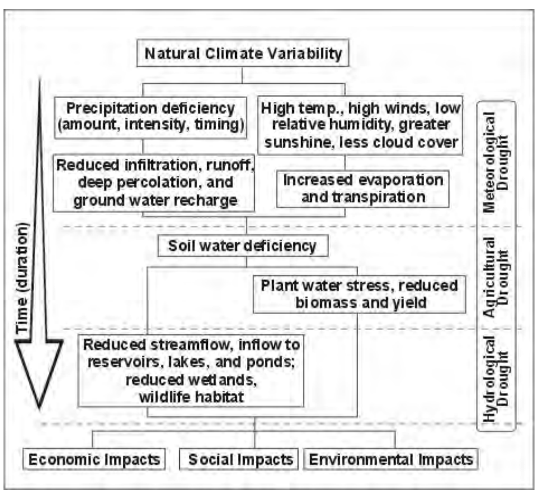
[16] Ideas taken from: Charles, K.; Pond, K.; Pedley, S. (2009) *Vision 2030 The resilience of water supply and sanitation in the face of climate change. Technology fact sheets*. University of Surrey, UK.

			• Investigate alternative water harvesting methods • Investigate regional MAR techniques (e.g. recharge aquifer like a tank, to be used in times of drought)[17] • Improve reuse of wastewater for non-potable uses • Investigate reuse of wastewater for artificial groundwater recharge together with Soil Aquifer Treatment (SAT).[18]
Water intake & treatment system	• Dams weakened by prolonged low storage levels • Deterioration in water quality of stored water	• Less rain & water intake = lack of pressure on dam walls • Water not diluted, also high intensity runoff events = more turbid	• Adapt intake infrastructure to handle low flows • Redesign water treatment plant & improve filtration systems
Water distribution system	• Low pressure in system = ingress of contamination • Insufficient water to meet demand • Public health risk from inappropriate water saving in the home • Infrastructure damage	• Not enough water in pipes during peak demand • Reduced moisture in soils = movement = damage	• Improve water storage to supply dry periods • Pipe maintenance improved to reduce leaks • Research low-water usage appliances for non-critical domestic use • Design for movement – e.g. shorter lengths of pipes • Adapt maintenance programme to identify breakages

[17] As in the case of Windhoek. See: Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.27.
[18] Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.7.

Definitions of drought

1. A temporary reduction in water or moisture availability to significantly below the normal or expected amount for a specified period.[19] Note that:
   - The terms "temporary" and "normal" in this definition vary in absolute terms according to location, so no figures can be put here to define drought. Rather drought has to do with a diversion from the average or expected pattern in an area.
   - How much variation is allowable before being defined as drought conditions also will no doubt vary from place to place and is often arbitrarily decided, rather than on the basis of its precise relationship to specific impacts[20] – for example, drought was considered to have occurred when rainfall during the monsoon season was less than 80% of the long-term average in Asia.[21]
   - Even though drought is a chronic problem in arid and semi-arid lands (ASALs), it is not only something that occurs in low rainfall areas but also affects humid areas. For example the average annual rainfall in Orissa, India is 1,300mm but it experiences droughts[22]; in Kitui District, Kenya, drought is well documented but annual rainfall is 1,000mm.[23]
   - The "specified period" can also vary from seasons or years to much shorter periods, as is the case with agriculture. Research in East and West Africa shows that short dry spells lasting 2-4 weeks occur almost every rainy season and cause crop water stress, negatively affecting crop growth and potential crop productivity. This means that poor rainfall distribution over time is a more common cause of crop failure than low cumulative annual rainfall.[24]
2. Research by Wilhite and Glantz (1985)[25] of the National Center for Atmospheric Research, in the early 1980s uncovered more than 150 published definitions of drought, reflecting differences in regions, needs, and disciplinary approaches. They categorized the definitions in terms of four basic approaches to measuring drought (see diagram below):[26]
   a. Meteorological: an expression of precipitation's departure from normal over some period of time. These definitions are usually region-specific and are the first indicators of drought.
   b. Hydrological: refers to deficiencies in surface and subsurface water supplies, measured as streamflow and as lake, reservoir, and groundwater levels. There is a time lag between lack of rain and less water in streams, rivers, lakes, and reservoirs, so hydrological measurements are not the earliest indicators of drought. When precipitation is reduced or deficient over an extended period of time, this shortage will be reflected in declining surface and subsurface water levels.



National Drought Mitigation Center (NDMC), University of Nebraska-Lincoln, USA.

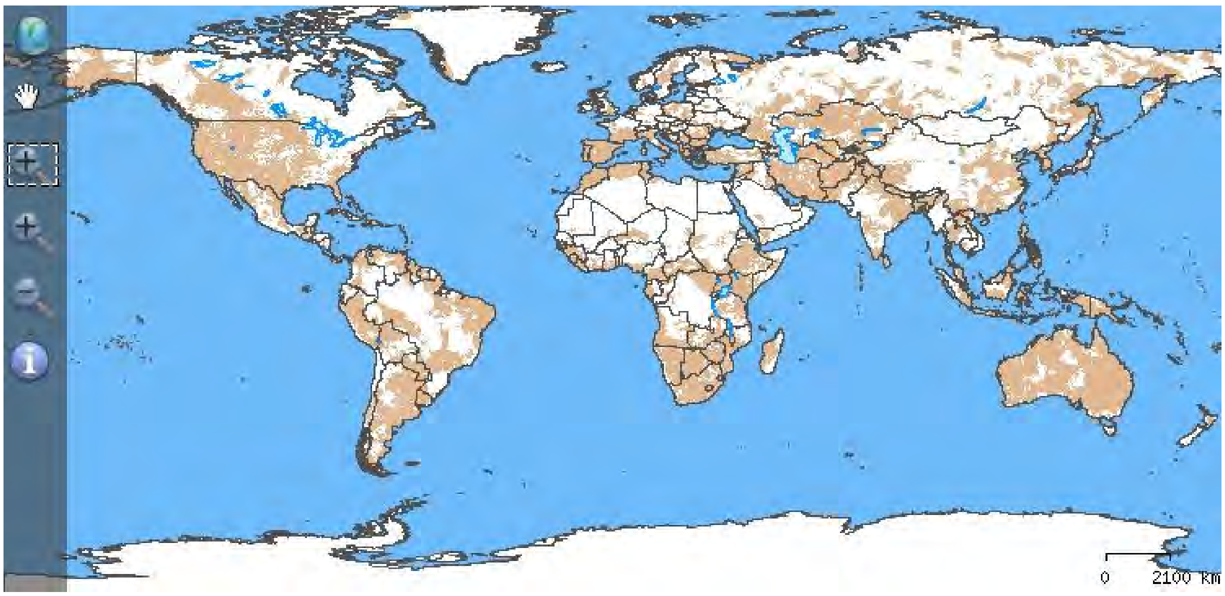
   c. Agricultural: refers to when there is not enough soil moisture to meet the needs of a particular crop at a particular time. Agricultural drought happens after meteorological drought but before hydrological drought. Agriculture is usually the first economic sector to be affected by drought.
   d. Socioeconomic: refers to physical water shortage starts to affect people, individually and collectively. Or, in more abstract terms, most socioeconomic definitions of drought associate it with the supply and demand of an economic good.

[19] IIRR, ACACIA & CordAid (2004) *Drought Cycle Management: A toolkit for the drylands of the Greater Horn.* p.6.
[20] http://www.drought.unl.edu/whatis/concept.htm
[21] Pandey, S.; Bhandari, H. (2009) *Drought, coping mechanisms and poverty: Insights from rainfed rice farming in Asia*. Occasional Papers No.7, IFAD, Rome, Italy. p.14.
[22] Pandey, S.; Bhandari, H. (2009) *Drought, coping mechanisms and poverty: Insights from rainfed rice farming in Asia*. Occasional Papers No.7, IFAD, Rome, Italy.
[23] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. SASOL / Maji Na Ufanisi, Nairobi, Kenya.
[24] In Sub-Saharan Africa, crop yields are around 1 tonne/ha or less, which is <20% of potential yields even in water scarce savannah environments – the key issue is inadequate soil water in the root zone at the right time of crop growth. See: Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.
[25] Wilhite, D.A.; Glantz, M.H. (1985) Understanding the drought phenomenon: The role of definitions. *Water International* 10:111–120.
[26] Summary available from NDMC at: http://www.drought.unl.edu/whatis/define.htm. More details available at: http://www.drought.unl.edu/whatis/concept.htm.

In addition to definitions of reduced moisture availability over time, drought seems to be also more readily occurring where the following "normal" non-drought conditions exist which could catalyze and aggravate the severity of drought when it happens (see diagram) – such conditions are characteristic of ASALs,[27] which is probably why much drought literature has focused on these areas in particular:

- High potential evapotranspiration (PET) rates in comparison to rainfall. In ASALs for example, annual PET rates are usually more than twice the annual rainfall.[28] These occur due to a mix of high temperatures, greater amounts of sunshine, less cloud cover, high winds and low relative humidity.
- High spatial and temporal variability of rainfall. In ASALs for example, precipitation varies greatly over space and time – erratic rainfall events means that number and timing of rainfall events is never certain.
- Short but high rainfall intensity with consequent high run-off volume (rather than infiltration). Again, in ASALs this is a common feature.

In geographical terms, those areas experiencing less water moisture than normal covers quite a wide area. The map below from the Global Risk Data Platform shows the regions with droughts recorded between 1979 and 2008, where drought events are identified as three consecutive months with less than 50% of precipitation as compared with the average.



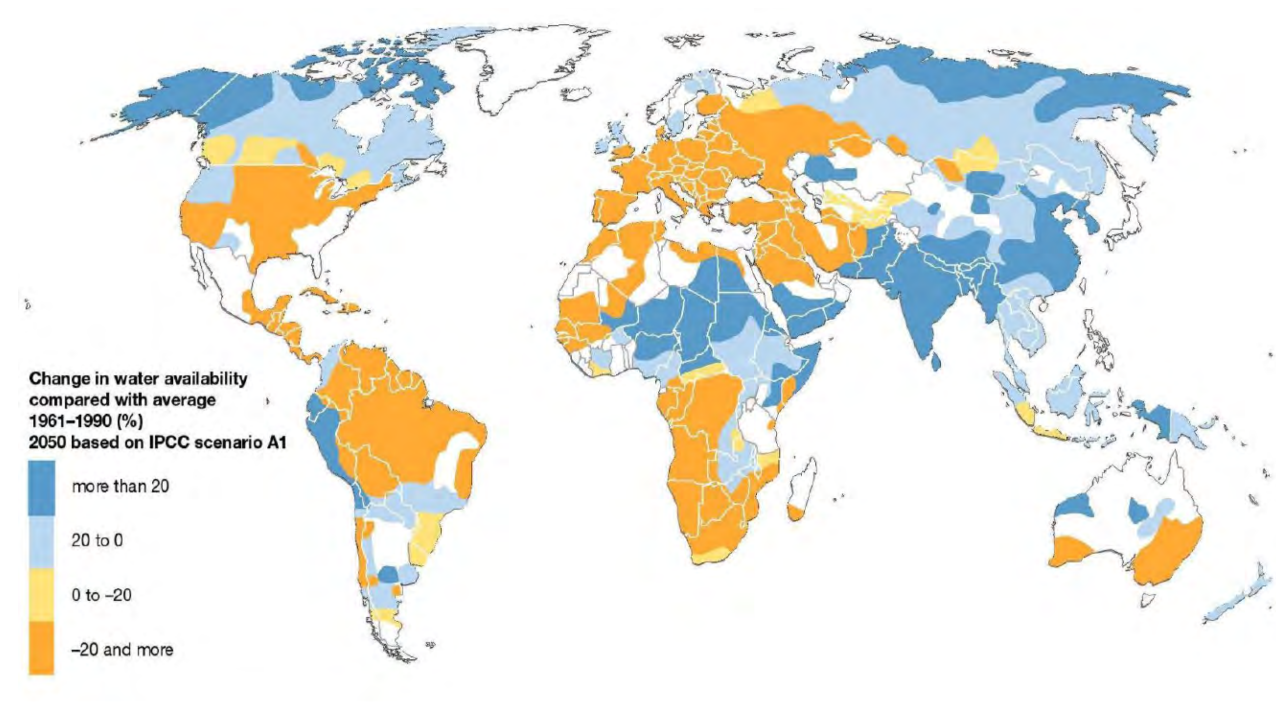
Source: Global Risk Data Platform: http://preview.grid.unep.ch/index3.php?preview=map

In terms of the effect of climate change on drought-prone areas, it is clear from projections that not everywhere will be affected by reduced cumulative water availability due to changing weather patterns. In fact, some areas will start to receive more annual rainfall, while other areas will receive less. Even so, the variability is likely to increase, with more intense rainfall over short periods of time or longer periods with little or no rainfall, with the increased likelihood of extreme water-related events such as floods or droughts.[29]

[27] Definition of ASALs is: (a) Arid Lands: high ambient temperatures with a wide diurnal range; evapotranspiration rates are more than twice the annual rainfall (in most districts); low and erratic bimodal rainfall that is highly variable in space and time; often rain falls as short high intensity with high runoff and soil erosion; approximate rainfall of 150-450 mm / year. Pastoralists and agro-pastoralists inhabit these districts. (b) Semi-Arid Lands: receive between 500 – 850 mm of rainfall annually. Areas include those with rain fed and irrigation agriculture; areas are being encroached by marginalized small holders, areas which are mainly pastoralist and areas which are protected. See: Government of Kenya (2007) *National Policy for the Sustainable Development of Arid and Semi Arid Lands of Kenya*.

[28] Government of Kenya (2007) *National Policy for the Sustainable Development of Arid and Semi Arid Lands of Kenya*. E.g. In Somaliland, PET ranges from 1,750 – 2,250 mm per year, whereas annual rainfall is between 300 – 500 mm per year.

[29] UNEP / GRID, IPCC. Quoted in: USAID (2010) *Summary of the World Water Crisis and USG Investments in the Water Sector, May 15, 2010.* See also: Batchelor, C.; Schouten, T.; Smits, S.; Moriarty, P.; Butterworth, J. (2009) *14. Climate change and WASH services delivery – Is improved WASH governance the key to effective mitigation and adaptation?* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands.



Source: UNEP / GRID, IPCC. Quoted in: USAID (2010) *Summary of the World Water Crisis and USG Investments in the Water Sector, May 15, 2010.*

So it is clear that decreased water availability is causing water stress and scarcity in many areas, and that some of this is a result of supply issues – i.e. available resources, drought and its aggravating climatic conditions or climate change and variability. However, demand is the other side of the coin – huge population growth and increasing water demand is an increasing factor in affecting decreasing water availability, since water has to be shared by more people who want to use more of this resource. In geographical terms, water stress and water scarcity can be shown spatially – see Annexes 1 & 2. The case of groundwater in Balochistan demonstrates this – groundwater use has increased hugely due to expansion in agriculture, rapid population and industrial growth in the last 20 years, resulting in the drying up of water sources like dug wells and springs. This situation was then aggravated by the drought between 1998-2002.[30]

It seems for this research that a useful definition of "drought-prone areas" might therefore include:

- ✓ Areas experiencing temporary reduction in precipitation to significantly below the normal/expected amount for a specified period.
- ✓ A variety of climatic zones, from ASALs to humid regions, but perhaps especially areas with high PET rates, where precipitation varies greatly over time & space, and where precipitation falls intensely over short periods.
- ✓ Predicted areas of future water availability decrease due to climate change.
- ✓ Areas with current and future predicted water stress and scarcity as a result of increasing population and water demand.

[30] Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.23.

Drought & resilient WASH resources overview

Reference	Read	Content
Drought, DCM, climate change, pastoralism, IWRM, DRR, participatory approaches		
ACF-IN (2008) '*How to Make WASH Projects Sustainable and Successfully Disengage in Vulnerable Contexts: a practical manual of recommendations and good practices based on a case study of five ACF-IN water, sanitation & hygiene projects*.	✓	Review of sustainability issues and WASH projects.
Arab Water Council (2009) *9. Vulnerability of arid and semi-arid regions to climate change – Impacts and adaptive strategies.* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands. Available at: http://www.worldwatercouncil.org/index.php?id=32	✓	Discusses potential impact of climate change in ASALs
Batchelor, C.; Schouten, T.; Smits, S.; Moriarty, P.; Butterworth, J. (2009) *14. Climate change and WASH services delivery – Is improved WASH governance the key to effective mitigation and adaptation?* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands. Available at: http://www.worldwatercouncil.org/index.php?id=32	✓	Discusses potential impact of climate change on WASH service delivery
Charles, K.; Pond, K.; Pedley, S. (2009) *Vision 2030 The resilience of water supply and sanitation in the face of climate change. Technology fact sheets*. University of Surrey, UK.	✓	Overview of adaptation methods to various climate change scenarios including drought.
Day, S. (2009) Community Based Water Resource Management. *Waterlines* Vol.28, No.1., pp.47-62.		
Dominic Mazvimavi, Zvikomborero Hoko, Lewis Jonker, Innocent Nhapi and Aidan Senzanje. Integrated Water Resources Management (IWRM) – From Concept to Practice. *Physics and Chemistry of the Earth, Parts A/B/C*. Volume 33, Issues 8-13, 2008, Pages 609-613.		
Eldridge, C. (2002) Protecting livelihoods during drought: some market-related approaches. *Humanitarian Exchange* No.22, HPN, ODI, London, UK.	✓	Argues for the importance of market-related approaches to drought risk reduction.
Grey, D.; Sadoff, C. (2006) *Thematic document framework theme 1. Water for growth and development.* 4th World Water Forum, Mexico City, March 2006. World Bank, Washington, USA.	✓	Discusses how to promote sustainable management of water resources to alleviate poverty.
Hedlund, K. (2007) *Slow-onset disasters: drought and food and livelihoods insecurity. Learning from previous relief and recovery responses.* ALNAP / Provention Consortium.	✓	Overview of droughts and previous humanitarian interventions.
Holloway, A. (1995) Southern Africa: Drought Relief, Drought Rehabilitation...What about Drought Mitigation? *Newsletter, Relief and Rehabilitation Network*, No.4, ODI, London, UK.	✓	Initial awareness of need to make water systems more resilient to drought.
IIRR, ACACIA & CordAid (2004) *Drought Cycle Management: A toolkit for the drylands of the Greater Horn.*	✓	Provides a simplified and clear overview of the complex subjects relating to drought cycle management and the drylands including a range of issues which are relevant to sustainability. Although it has been written for East African ASALs, many of the issues included will be relevant to other dryland areas, even if specific cultural norms and practices may be different.
Johan Rockström. Resilience building and water demand management for drought mitigation. *Physics and Chemistry of the Earth, Parts A/B/C*. Volume 28, Issues 20-27, 2003, Pages 869-877.		
Kashyap, A. (2004) Water governance: learning by developing adaptive capacity to incorporate climate variability and change. *Water Science and Technology* 29 (7), 141–146.		
Lenton, R. (2004) Water and climate variability: development impacts and coping strategies. *Water Sci Technol.* 2004;49(7):17-24.		Overview of the relationship between climate variability, integrated water resources management, and the achievement of the Millennium Development Goals
Matheou, A. (2001) Natural disasters and complex political emergencies: responding to drought in Afghanistan. *Humanitarian Exchange* No.19, HPN, ODI, London, UK.	✓	Role of water in Afghan drought 2000-01
Moberg, F.; Galaz, V. (2005) *Resilience: Going from Conventional to Adaptive Freshwater Management for Human and Ecosystem Compatibility*. Swedish	✓	Emphasizes the need to shift from conventional to ecosystem-oriented adaptive management.

Water House Policy Brief Nr. 3. SIWI, 2005.		
Oxfam (2000) *Integrating drought cycle management in programming: a series of briefs for practitioners.*		Overview of introducing pastoralism and Drought Cycle Management model and how it should be integrated into NGO programming.
Oxfam (2010) *Introduction to Community-Based Water Resources Management: A Learning Companion*. Oxfam Disaster Risk Reduction and Climate Change Adaptation Resources.	✓	Oxfam document to support staff to implement community based water resource management in dryland areas.
Pandey, S.; Bhandari, H. (2009) *Drought, coping mechanisms and poverty: Insights from rainfed rice farming in Asia*. Occasional Papers No.7, IFAD, Rome, Italy.	✓	Synthesizes major findings of farmers' coping mechanisms to drought from a cross-country comparative research study.
USAID (2010) *Summary of the World Water Crisis and USG Investments in the Water Sector*, *May 15, 2010.*	✓	Overview of water availability in terms of supply & demand, in relation to the future and climate change.
WHO/DFID (2009) *The resilience of water supply and sanitation in the face of climate change. Summary and policy implications. Vision 2030.*	✓	Summarizes understanding on how climate change will affect drinking water and sanitation.
Wijk-Sijbesma, C, van (2001): The best of two worlds. Methodology for participatory assessment of community water services. Delft: *IRC International Water and Sanitation Center Technical Paper Series* 38. p156, p.220.		Tested whether participatory approaches that are more demand-responsive & gender- and poverty-sensitive result in water services that are better sustained and used.
Wilhite, D.A.; Glantz, M.H. (1985) Understanding the drought phenomenon: The role of definitions. *Water International* 10:111–120.		150 definitions of drought
Wilk, J.; Wittgren, H.B. (eds). (2009) *Adapting Water Management to Climate Change*. Swedish Water House Policy Brief Nr. 7. SIWI, 2009.	✓	Presents a general overview of observed & projected impacts of climate change on water resources, concepts of adaptation including specific examples of strategies in practice.
Groundwater dams		
Arnold, E.; Dool, C.A.van den; Joosse, J.F. (2002) *Retaining water in the Black Cotton Soil Area near Ikanga, Kenya. A study carried out by SaSol. Final report*. TU Delft, The Netherlands.	✓	Carried out research into alternative dam options including using plastic sheeting for sub-surface dams.
Beimers, P.B.; Eijk, A.J. van; Lam, K.S.; Roos, B. (2001) *Improved design sand-storage dams, Kitui District, Kenya. Project Report*. June 2001. TU Delft, The Netherlands.	✓	A detailed project that evaluated 50 sand dams and then tried to optimize the design based on observations & engineering in order that a manual could be produced.
Borst, L., Haas, S.A. (2006), *Hydrology of Sand Storage Dams, A case study in the Kiindu catchment, Kituï District, Kenya*. Master thesis, Vrije Universiteit, Amsterdam, The Netherlands.		
Brandsma, J.; Hofstra, F.; Lous, B.; Masharubu, B.; Mailu, D. (2009) *Impact evaluation on Sand Storage Dams: Evaluation on the Technical and Socio-economic aspects, Kitui, Kenya*. Wageningen UR, The Netherlands.	✓	Evaluated technical & socio-economic impact of increased water from sand dams.
Ertsen, M.; Hut, R. (2009) Two waterfalls do not hear each other. Sand-storage dams, science and sustainable development in Kenya. *Physics and Chemistry of the Earth, Parts A/B/C*. Volume 34, Issues 1-2, 2009, Pages 14-22.	✓	Discusses experiences in Kitui with sand storage dam development.
Ertsen, M.W.; Biesbrouck, B.; Postma, L.; Westerop, M.V. *Community organisation and participatory design of sand-storage dams in Kenya.*	✓	A review of the SASOL sand dam project in Kitui. Found that institutions set up to manage sand dams ceased to function after construction finished.
Fewster, E. (1999) *The Feasibility of Sand Dams in Turkana District, Kenya*. MSc thesis. WEDC, Loughborough University, UK	✓	Looked at feasibility of groundwater dams for Turkana District, Kenya. Based on fieldwork in Turkana.
Gicheruh, C.M. (2008). *Advisory for technical and managing staff on technical and administrative procedure: water supply project, Mutomo District, Kenya*. Report No. 2008/14 undertaken for GAA. Earth Water Ltd, Nairobi, Kenya.	✓	Technical review of what worked and didn't work with various GAA outputs including shallow wells, rock catchments & sand dams.
Gijsbertsen C. (2007) *A study to upscaling of the principle and sediment (transport) processes behind sand storage dams, Kitui District, Kenya*. Vrije Universiteit, Amsterdam, The Netherlands.	✓	Investigated sediment type behind various sand dams – found dams with both coarse

		sand and silt. Concludes that rivers with existing sandy sediments are most suited to being used for sand dams.
Hanson, G. (1987). *Groundwater dam research and development in the Hararghe region, Ethiopia*. National Water Resources Commission, Addis Ababa, Ethiopia.	✓	Review of implementation of groundwater dams in Ethiopia.
Hoogmoed, M. (2007). *Analyses of impacts of a sand storage dam on groundwater flow and storage: groundwater flow modelling in Kitui District, Kenya.* Vrije Universiteit, Amsterdam, The Netherlands.	✓	Looked at groundwater levels in riverbed and riverbanks.
Hut, R.; Ertsen, M.; Joeman, N,; Vergeer, N.; Winsemius, H.; Giesen, N.van de (2008) Effects of sand storage dams on groundwater levels with examples from Kenya *Physics and Chemistry of the Earth, Parts A/B/C*. Volume 33, Issues 1-2, 2008, Pages 56-66	✓	Not so relevant: modeled groundwater levels upstream of 2 dam sites.
Jansen, J. (2007). *The influence of sand dams on rainfall-runoff response and water availability in the semi-arid Kiindu catchment, Kitui District, Kenya*. Master of Science Thesis, Vrije Universiteit, Amsterdam, The Netherlands.	✓	Not so relevant: measured run-off in sand dam area.
Lasage, R. Aerts, J.; Mutiso, G.-C.M.; 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*, Volume 33, Issues 1-2, 2008, Pages 67-73.	✓	Based on various indicators, they found that sand dams were a successful adaptation to drought and reduced vulnerability.
Munyao, J.N.; Munywoki, J.M.; Kitema, M.I.; Kithuku, D.N.; Munguti, J.M.; Mutiso, S. (2004) *Kitui sand dams: Construction and operation.* Sasol Foundation, Nairobi, Kenya.	✓	An overview of sand dam construction, but not clearly set out. Contains lots of information indirectly relevant to field implementers, with too many calculations that are not clear to understand or replicate.
Nilsson, Å. (1988). Groundwater Dams for Small-scale Water Supply. IT, London.	✓	Overview of groundwater dam technology.
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, Nairobi, Kenya.	✓	Manual for construction of groundwater dams. Fairly simple overview.
Nissen-Petersen, E. (2006) *Water from Dry Riverbeds*. Danish International Development Assistance (DANIDA).	✓	Manual for construction of groundwater dams.
Orient Quilis, R. (2007) *Modelling sand storage dams systems in seasonal rivers in arid regions. Application to Kitui district (Kenya).* Master of Science thesis, TU Delft, The Netherlands.	✓	Not so relevant: looked at groundwater dynamics around sand storage dams in the long term and large scale, plus effect on water level of series of dams rather than single structures.
Orient Quilis, R.; Hoogmoed, M.; Ertsen, M.; Foppen, J.W.; 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*; Volume 34, Issues 4-5, 2009, Pages 289-298.	✓	Explains the overlapping effect of having sand dams in series on water level & quantity.
RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.*	✓	Overall guidance manual and what to look out for when building sand storage dams. Based on field experience.
SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. SASOL / Maji Na Ufanisi, Nairobi, Kenya.	✓	Experience on groundwater dam implementation in drought-prone area of Kenya.
Vanrompay, L. (2003) *Report on the Technical Evaluation and Impact Assessment of Sub-surface Dams (SSDs)*. VSF-B Turkana Livestock Development Project (TLDP), Kenya.	✓	Evaluated the VSF-B sub-surface dams constructed between 2000 & 2002.
VSF (2006). *SubSurface Dams : a simple, safe and affordable technology for pastoralists. A manual on SubSurface Dams construction based on an experience of Vétérinaires Sans Frontières in Turkana District (Kenya), September 2006.*	✓	A manual based on VSF's practical field implementation in Turkana. Dams were sited according to dry season pasture & cost reduced to allow replicability.
Wipplinger, O. (1958). *The Storage of Water in Sand*. Water Affairs Section, South-West Africa Administration.		
Managed Aquifer Recharge (MAR), rain-fed irrigation		
Rathore, M.S. (2005) *Groundwater exploration and augmentation efforts in Rajasthan – a review*. Institute of Development Studies, Jaipur, India.	✓	Report that evaluates other technical studies to show that it is difficult to prove groundwater recharge occurs due to MAR.
Arnold Pacey and Adrian Cullis (1986) *Rainwater Harvesting: The Collection of rainfall and run-off in rural areas*. IT Publications, London.		
Bouwer, H. (2002) Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal* 10:121-142.		

Critchley, W.; Siegert, K.; Chapman, C. Finkel, M. (1991) *Water Harvesting, A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production*. FAO publication AGL/MSC/17/91. Available on line at: http://www.fao.org/docrep/U3160E/U3160E00.htm	✓	Manual on soil & water conservation measures (e.g. bunds)
Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK.	✓	Useful insight into evolution of bund design in Turkana projects – what worked, what didn't.
Dijk, J. A. van (1995) *Taking the Waters. Soil and water conservation among settling Beja nomads in Eastern Sudan*. African Studies Centre Research Series No.4. Aldershot: Avebury (Ph.D. thesis).	✓	Study of water conservation measures in Sudan including bunds
Ertsen, M. (2009) *Re-hydrating the Earth by Contour Trenching in Vietnam: Summary of the Hydrological Research within the Partners for Water project "Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam"*. TU Delft, The Netherlands.	✓	Summarizes main report
Esfandiari, M.; Rahbar, G. (2006) Monitoring of inflow and outflow rate from Kaftari artificial recharge of groundwater system in Dorz-Sayban Region in Southeastern Iran. Section 9, pp. 149-158. In: B. Neupane, R. Jayakumar, A. Salamat and A. Salih, (eds.), *Management of Aquifer Recharge and Water Harvesting in Arid and Semi-arid Regions of Asia*. UNESCO and IHP, Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi, India.		Information about controlled flooding system in Iran for groundwater recharge purposes.
Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.	✓	Useful overview of rainwater harvesting techniques and adaptation to increase water availability.
Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP.	✓	A document that draws together experience of MAR in semi-arid areas in order to provide examples of good practice.
Gale, I.; Neumann, I.; Calow, R.; Moench, M. (2002) *The effectiveness of Artificial Recharge of groundwater: a review*. Groundwater Systems and Water Quality Programme, Phase 1 Final Report CR/02/108N. British Geological Society, Keyworth, UK.	✓	A document that draws looks at physical & socio-economic factors determining success of MAR.
Gale, I.N.; Macdonald, D.M.J.; Calow, R.C.; Neumann, I.; Moench, M.; Kulkarni, H.; Mudrakartha, S.; Palanisami, K. (2006) *Managed Aquifer Recharge: an assessment of its role and effectiveness in watershed management*. British Geological Survey Commissioned Report, CR/06/107N. 80pp.	✓	Summarizes how to effectively conduct MAR based on field experiences.
Gale, I.N.; Macdonald, D.M.J.; Calow, R.C.; Neumann, I.; Moench, M.; Kulkarni, H.; Mudrakartha, S.; Palanisami, K. (2006) *Managed Aquifer Recharge: an assessment of its role and effectiveness in watershed management*. Final report for DFID KAR project R8169, Augmenting Groundwater Resources by Artificial Recharge – AGRAR. British Geological Society, Keyworth, UK.	✓	Final report from the AGRAR research project.
Grove, J. (2009) *Report on recharge system and drip irrigation*. DAPP, Zimbabwe.	✓	Field report on success of recharge tubewells.
Holtslag, H.; Wolf, J. de (2009) *The tube recharge*. Connect International.	✓	Data on field trials of borehole recharge near hand dug wells.
Hoyer, M. von; Junker, M.; Centurion, C.; Irrazabal-Soza, D.; Larroza, F.A.; Farina-Larroza, S.; Paredes-Rolon, J.L. (2000) *Sustained Water Supply by Artificial Groundwater Recharge in the Chaco of Paraguay*. SH1 (2000), Sonderheft ZAG p. 207-215.		Data on MAR of saline shallow aquifers in Paraguay.
Kahlown, M.A.; Abdullah, M. (2004) Leaky Dam to Rejuvenate Depleting Aquifers in Balochistan. *Pakistan Journal of Water Resources*, Vol.8 (2) July-December, 2004.	✓	Reviews leaky dam trial in Pakistan.
Kulkarni, H.; Badarayani, U.; Phadnis, V.; Robb, R. (2005) *Detailed case study of Kolwan valley, Mulshitaluka, Pune district, India. AGRAR Project Case Study Research Report: Kolwan valley site, Pune District, Maharashtra, India*.	✓	Looks at the impact on groundwater of an artificial recharge project – it definitely has an impact (especially on base flows recharging streams) but at times hard to quantify.
Kundu, N.; Soppe, G. (2002). *Water resources assessment: Terai region of West Bengal*. Jawahar Publishers, New Delhi, India.		Information on gully plugs & bunds.
Li, F.R.; Cook, S.; Geballe, G.T.; Burch, W.R. (2000) Rainwater harvesting agriculture: an integrated system for water management on rainfed land in China's semiarid areas. *AMBIO*, 2000, 29, 477-483.		
Merz, J.; Nakarmi, G.; Weingartner, R. (2004) Potential Solutions to Water Scarcity in the Rural Watersheds of Nepal's Middle Mountains. *Mountain Research and Development* Vol 23 No 1 Feb 2003: 14–18.	✓	Review of various water harvesting techniques.
Naik, M.S.; Momin, G.A.; Rao, P.S.P.; Sarai, P.D.; Ali, K. (2002) Chemical composition of rainwater around an industrial region in Mumbai. *Current science*, 2002, 82, 1602-1606.		Looks at rainwater contamination in industrial runoff area.
Negassi, A., Bein, E., Ghebru, K., Tengnäs, B. (2002), *Soil and water conservation manual for Eritrea*. Regional Land Management Unit (RELMA), Swedish International Development Coorperation Agency (SIDA).		

Niemeijer, D. (1998) Soil nutrient harvesting in indigenous teras water harvesting in Eastern Sudan. *Land Degrad. Dev.*, 1998, 9, 323-330.		
NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions*. Netherlands Water Partnership.	✓	Review of various water harvesting techniques.
Pandey, D.N.; Gupta, A.K.; Anderson, D.M. (2003) Rainwater harvesting as an adaptation to climate change. *Current science*, vol.85, no.1, pp.46-59.	✓	Reviews history of rainwater collection over millennia, advocates for RWH as effective means to adapt to climate change.
Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam*. Final Report Executive Summary. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands.	✓	Summarizes main report, but also has data on groundwater level changes following trenches.
Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam*. Final Report. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands.	✓	Report on contour trenches in Vietnam to improve soil moisture availability & recharge shallow groundwater levels.
Pramana, K.E.R. (2007) *The Effectiveness of Contour Trenches in Vietnam*. MSc thesis, TU Delft, The Netherlands.	✓	Original thesis that provided basis for future trials.
Steenbergen, F.V.; Tuinhof, A. (2009) *Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retention, Reuse and Rainwater Storage*. BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), the Co-operative Programme on Water and Climate (CPWC) and the Netherlands National Committee IHP-HWRP.	✓	Gives various case studies of techniques to recharge, retain & reuse rainwater to increase and use available water in the "water buffer" as a way to adapt to climate change.
Tabor, J.A. (1995) Improving crop yields in the Sahel by means of water harvesting. *Journal of Arid Environments*, vol.30, no.1, pp.83-106.		
UNESCO-IHP and Central Ground Water Board, Govt. of India, New Delhi. (2000) *Rainwater harvesting and Artificial Recharge to Groundwater: a guide to follow.*		
Unicef / Ara Centro. (2009) *Qualidade de agua na recarga de aquifero: experiencia em curso na vila de Nhamatanda, Provincia de Sofala.*	✓	Diagrams & photos of borehole recharge from roof catchments.
Vohland, K.; Barry, B. (2009) A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. *Agriculture, Ecosystems & Environment*, vol.131, no.3-4, pp.119-127.		
Controlled flooding / spate irrigation / drip irrigation		
European Union (2008) *Design manual volume 1: Technical design criteria*. The European Union's Food Security Programme for Yemen Technical Assistance to the Tihama Development Authority. Available at www.spate-irrigation.org	✓	Technical guidelines for spate irrigation structures.
IDE - International Development Enterprises / CGIAR (2007) *Technical manual for IDEal micro irrigation systems*. IDE/CGIAR, Lakewood, USA.	✓	Manual on low-cost drip irrigation for small plots.
Mikhail, M.; Yoder, R. (2008) *Multiple use water service implementation in Nepal and India: experience and Lessons for scale-up*. IDE, CPWF and IWMI.	✓	Looks at IDE project experience with implementation of water systems in Nepal and India, including drip irrigation.
Ratsey, J. (2008). *Design manual volume 2: guidelines for wadi diversion and protection works*. The European Union's Food Security Programme for Yemen Technical Assistance to the Tihama Development Authority. Available at www.spate-irrigation.org	✓	Technical guidelines for spate irrigation structures.
Steenbergen, F. van; Lawrence, P.; Mehari Haile, A.; Salman, M.; Faurès, J.-M. (2010) *Guidelines on spate irrigation*. FAO irrigation and drainage paper 65. FAO, Rome, Italy. Available at www.spate-irrigation.org	✓	Summarizing 10 years of experience, the guidelines bring together ideas and practices on improving different aspects of spate irrigation.
Summary report. Proceedings of the Subregional Expert Consultation on Wadi Development for Agriculture in the Yemen 1987. Available at www.spate-irrigation.org	✓	Summarizes problems & recommendations from various countries.
Open reservoirs		
Cecchi, P. ; Berger, C.; Couté, A.; Gugger, M.; Zongo, F. (2009) *Cyanobacteria, cyanotoxins and potential health hazards in small tropical reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org.	✓	Explains risks of cyanobacterial blooms in open reservoirs.
Cecchi, P. ; Leboulanger, C.; Bouvy, M.; Pagano, M.; Nemy, V. (2009) *Agricultural intensification and ecological threats around small reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org.	✓	Overview of effect of fertilizers, pesticides etc on water quality
Dekker, T. (2007) *Modeling the Buriti Vermelho Catchment: In Search of the Best Model with Low Data Availability*. MSc thesis, TU Delft, The Netherlands.		How to measure seepage rates in reservoirs.
Dekker, T.; Rodrigues, L. N.; Olsthoorn, T.; Giesen, N. van de (2009) *Deep Seepage Assessment in Small Reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org.	✓	How to measure seepage rates in reservoirs.
Giesen, N. van de.; Liebe, J. (2009) *Hydrological Impact Assessment of Ensembles of Small Reservoirs*. Small reservoirs toolkit. Available from	✓	How to assess hydrological impact of numerous reservoirs.

www.smallreservoirs.org		
Greaves, F. (2009) *WASH Assessment trip to CCSMKE, Kenya: 9th - 18th March 2009.*	✓	Field report to Northern Kenya which investigated how to improve traditional ponds.
HR Wallingford (2004) *Guidelines for Predicting and Minimizing Sedimentation in Small Dams.* HR Wallingford.		
Kangalawe, R.Y.M. (2005) *Local Participation in the Design Process for Water Retention in Tanzania: Challenges and Opportunities*. Institute of Resource Assessment, University of Dar es Salaam, Tanzania.	✓	Highlights the need for participation in construction of small dams in Tanzania.
Kinderen, I. van (2006) *Social capital in rural dry season farming communities and its effect on the use and implementation of small water reservoirs*. MSc thesis, TU Delft, The Netherlands.	✓	Suggests to look at social aspects in dam construction, not only technical issues.
Kumar, P.; Kandpal, B.M. (2003) *Project on reviving and constructing small water harvesting systems in Rajasthan. SIDA evaluation 03/40*. SIDA Dept for Asia, Stockholm, Sweden.		
Liebe, J.; Andreini, M.; Van de Giesen, N., Steenhuis, T. (2007) The small reservoirs project: research to improve water availability and economic development in rural semi-arid areas. In: Kittisou, M.; Ndulo, M.; Nagel, M.; Grieco, M. (Eds.) *The Hydropolitics of Africa: A Contemporary Challenge*. Cambridge Scholars Publishing.		
Liebe, J.; Giesen, N. van de. ; Steenhuis, T. (2009) *Evaporation Losses from Small Reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org.	✓	Looks at evaporation rates in reservoirs vs land-based tests
Mufute, N.L. (2007) *The development of a risk-of-failure evaluation tool for small dams in Mzingwane catchment*. MSc thesis. University of Zimbabwe, Harare, Zimbabwe.	✓	Analyzed risks of failure in small dams in Zimbabwe.
Nelson, K. D. (1985) *Design and Construction of Small Earth Dams*. Inkata, Melbourne, Australia.		Construction guidelines on earth dams over 3m height.
Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA.	✓	Overview of types of open reservoirs & their construction.
Poolman, M.I. (2005) *Developing small reservoirs: A participatory approach can help.* MSc thesis, TU Delft, The Netherlands.	✓	Investigates participatory approaches in dam construction in Ghana.
Shaw, R. (ed) (1999). *Running Water: more technical briefs on health, water and sanitation*. Practical Action Publishing, London.	✓	Construction guidelines on earth dams under 3m height (Technical Brief 48). Info about floating intakes & bank infiltration methods Technical Brief 47). Info on desalination (Technical Brief 40).
Stone, L. (2003) *Earthen dams for small catchments: a compilation of design, analysis and construction techniques suitable for the developing world*. Michigan Technological University, USA.	✓	Design criteria for small dams.
Sub-surface tanks		
Aqua4all (2008) *Final Report for Aqua4All supported Projects for implementation of 10 RWH system in Borena Zone South Ethiopia.*	✓	Final report for project implementing sub-surface runoff tanks in Ethiopia.
Kantor, H. (2008) *The story of GRAVIS: observing 25 years of community empowerment*. Gramin Vikas Vigyan Samiti (GRAVIS), Jodhpur, India.	✓	Details the implementation of rainwater harvesting structures in the Thar Desert, India.
Malik, D. (2008) Sustainable water security in the Thar Desert, India: Blending traditional wisdom with modern techniques. *33rd WEDC International Conference, Accra, Ghana, 2008: Access to sanitation and safe water: Global partnerships and local actions*. WEDC, Loughborough, UK.	✓	Review of rainwater harvesting techniques in the Thar desert.
Ngigi, S.N.; Savenije, H.H.G.; Thome, J.N.; Rockström, J.; de Vries, F.W.T.P. (2005) Agro-hydrological evaluation of on-farm rainwater storage systems for supplemental irrigation in Laikipia district, Kenya. *Agricultural Water Management*, vol. 73, no.1, pp. 21-41.		
Nissen-Petersen, E. (2006) *Water from Roads: A handbook for technicians and farmers on harvesting rainwater from roads.* DANIDA.	✓	Overview of types of open reservoirs but also some information about tank types.
Groundwater, wells, infiltration galleries, boreholes		
Carter, R.; Chilton, J.; Danert, K.; Olschewski, A. (2010) *Siting of drilled water wells: a guide for project managers*. DRAFT version. RWSN, St. Gallen, Switzerland.	✓	Code of practice for siting boreholes.
Danert, K.; Armstrong, T.; Adekile, D.; Duffau, B.; Ouedraogo, I.; Kwei, C. (2010) *Code of Practice for Cost Effective Boreholes*. RWSN, St. Gallen, Switzerland. Available at http://www.rwsn.ch/documentation/skatdocumentation.2010-08-23.4523209156/file	✓	Code of practice for effective borehole drilling.
Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK.	✓	Good overview of sand abstraction and offset pump options.

Lawrence, A.R.; McDonald, D.M.J.; Howard, A.G.; Barrett, M.H.; Pedley, S.; Ahmed, K.M.; Nalubega, M. (2001). *Guidelines for assessing the risk to groundwater from on-site sanitation*. British Geological Society, Keyworth, UK.	✓	Guidelines for distance from boreholes to latrines.
Peters, e.; van Lanen, H.A.J.; Torfs, P.J.J.F.; Bier, G. (2005) Drought in groundwater - drought distribution and performance indicators. *Journal of Hydrology*, Volume 306, Issues 1-4, 9 May 2005, Pages 302-317.		
Pickford, J. (ed) (1991). *The Worth of Water: technical briefs on health, water and sanitation*. Practical Action Publishing, London.	✓	Construction guidelines on infiltration galleries (Technical Brief 22).
Roscoe Moss Company (1990) *Handbook of ground water development*. John Wiley & Sons, USA. Available at: http://books.google.co.uk	✓	Has a part about how to deepen existing boreholes.
Watt, S.B.; Wood, W.E. (1979) *Hand Dug Wells and their Construction*. IT, London, UK.	✓	Excellent book on hand dug well construction.
Springs		
Frangi, B.; Romagny, L.; Chancel, N. (2004) Building of spring-fed gravity-flow water supply systems in remote mountain villages of Lao PDR. *People-centred approaches to water and environmental sanitation. 30th WEDC International Conference, Vientiane, Lao PDR, 2004.*	✓	Reducing cost of remote spring construction.
Rolf, H. (2008) *Chamavita spring water schemes, Usambara Mountains, Tanzania. Mission report 01-11-2008 – 17-11-2008*. Aqua4All, Nieuwegein.		
Roof rainwater harvesting		
DTU (2002) *Very-low-cost roofwater harvesting in the humid tropics: existing practice.* DFID KAR Contract R7833 Report R1, January 2002. Development Technology Unit, School of Engineering, University of Warwick, UK.	✓	Looks into lowering costs & increasing performance of RWH systems.
Gould, J.; Nissen-Petersen, E. (1999). *Rainwater Catchment Systems for Domestic Supply.* IT, London, UK.	✓	Overview of all rainwater collection systems.
Nijhof, S,; Jantowski, B.; Meerman, R.; Schoemaker, A. (2010). Rainwater harvesting in challenging environments: Towards institutional frameworks for sustainable domestic water supply. *Waterlines*, Vol.29 no.3, pp.209-219.	✓	Lessons learned in RWH in remote areas.
Nijhof, S.; Shrestha, B.R. (2010). *Micro-credit and Rainwater Harvesting*. DRAFT document.	✓	Draft review of alternative finance models & low-cost technologies for roof rainwater harvesting.
Nissen-Petersen, E. (2006) *Water from Roofs: A handbook for technicians and builders on survey, design, construction and maintenance of roof catchments.* DANIDA.	✓	Design manual on rainwater harvesting systems.
Rees, D. (2000) *Partially Below Ground (PBG) tank for rainwater storage: Instructions for Manufacture*. DTU Technical Release Series TR-RWH 01. Warwick University, UK.	✓	Manufacturing instructions for ferrocement partial below ground tanks.
Rees, D.; Whitehead, V. (2000) *Brick Jars: Instructions for manufacture*. DTU Technical Release Series TR-RWH07. Warwick University, UK.	✓	Manufacturing instructions for brick jars
Rees, D.; Whitehead, V. (2000) *Ferro-Cement Jar: Instructions for manufacture.* DTU Technical Release Series TR-RWH06. Warwick University, UK.	✓	Manufacturing instructions for ferrocement jars
Rees, D.G.; Nyakaana, S.; Thomas, T.H. (2000) *Very-low-cost roofwater harvesting in East Africa: (Based on a Feasibility Study performed in the Great Lakes Region during May – July 2000)*. Working Paper No. 55, September 2000. Development Technology Unit, School of Engineering, University of Warwick, UK.	✓	Results of research looking into lowering costs & increasing performance of RWH systems.
Thomas, T.; Rees, D. (1999) Affordable roofwater harvesting in the humid tropics. "Rainwater Catchment: An Answer to the Water Scarcity of the Next Millennium." *9th International Rainwater Catchment Systems Conference*. Petrolina, Brazil, July 1999.	✓	Investigates cost-benefit of rainwater tanks and how to reduce first cost and make tanks more affordable.
Worm, J.; Hattum, T. van (2006) *Rainwater harvesting for domestic use*. Agrodok 43. Agromisa Foundation and CTA, Wageningen, The Netherlands.	✓	
Fog & dew collection		
Abualhamayel, H.I.; Gandhidasan, P. (2010) Design and testing of large fog collectors for water harvesting in Asir region, Kingdom of Saudi Arabia. *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010*. pp.116-119.	✓	Data from trials in Saudi Arabia
Beysens D.; Milimouk I.; Nikolayev, V.S.; Muselli, M.; Marcillat J. (2003) Using radiative cooling to condense atmospheric vapour:a study to improve water yield. *J of Hydrology*, Vol. 276, pp. 1–11, 2003.		
Clus, O.; Lekouch, I.; Durand, M.; Lanfourmi, M.; Muselli, M.; Milimouk-Melnytchouk, I.; Beysens, D. (2010) Large Dew water collectors in a village of S-Morocco (Idouasskssou). *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010*. pp.243-245.	✓	Data from a community-level dew collector system in Morocco.
Jacobs, A.F.G.; Heusinkveld, B.G.; Berkowicz, S.M. (2002) A simple model for potential dewfall in an arid region. *Atmospheric Research* Vol. 64, pp. 285–295.		
Lastra, C.d.l. (2002) *Report on the Fog-Collecting Project in Chungungo: Assessment of the Feasibility of Assuring its Sustainability.*	✓	Evaluation of Chilean project of fog collection.
Lekouch I.; Kabbachi, B.; Milimouk-Melnytchouk I.; Muselli M.; Beysens D. (2010)		

Dew, fog, and rain as supplementary sources of water in south-western Morocco. *Energy*, doi:10.1016/j.energy.2010.03.017.		
Lekouch, I.; Kabbachi, B.; Milimouk-Melnytchouk, I.; Muselli, M.; Beysens, D. (2010) Influence of temporal variations and climatic conditions on the physical and chemical characteristics of dew and rain in South-West Morocco. *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010*. pp.43-46.	✓	Results from dew trials in Morocco.
Muselli M.; Beysens D.; Milimouk I. (2006) A comparative study of two large radiative dew water condensers. *Journal of Arid Environments*, Vol. 64, pp. 54–76, 2006		
Nilsson T. (1996) Initial experiments on dew collection in Sweden and Tanzania. *Sol Energy Materials and Solar Cells*;Vol.40, pp. 23-32, 1996		
Sarsour, J.; Stegmaier, T; Linke, M.; Planck, H. (2010) Bionic development of textile materials for harvesting water from fog. *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010.*	✓	Data about more efficient nets.
Ucles, O.M.; Moro, M.J.; Villagarcia, L.; Morillas, L.; Canton, Y.; Domingo, F. (2010) Is dewfall an important source of water in semiarid coastal steppe ecosystems in SE Spain? *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010*. pp.172.	✓	Review of dew collection rates in Spain.
Van Heerden, J.; Olivier, J.; Van Schalkwyk, L. (2010) Fog Water Systems in South Africa: An Update. *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010*. p.160	✓	Review of fog collection in South Africa.
Rock catchments, artificial catchments		
Nissen-Petersen, E. (2006) *Water from Rock Outcrops: A handbook for engineers and technicians on site investigations, designs, construction and maintenance of rock catchment tanks and dams*. DANIDA.	✓	Basic overview of water from rock outcrops.
Water re-use		
Godfrey, S.; Labhasetwar, P.; Wate, S. (2009) Greywater reuse in residential schools in Madhya Pradesh, India—A case study of cost–benefit analysis. *Resources, Conservation and Recycling*, 53 (2009) 287–293.	✓	Greywater re-use cost benefit analysis to show that using greywater makes economic sense.
Godfrey, S.; Labhasetwar, P.; Wate, S.; Jimenez, B. (2010) Safe greywater reuse to augment water supply and provide sanitation in semi-arid areas of rural India. *Water Science & Technology* 62.6, pp.1296-1303.	✓	Greywater re-use to increase water availability in semi-arid areas of India.
Water quality, bulk & household treatment		
Aadan, A.I. (1982) *Final report on solar water distillation project. Warbixin iyo gunaanud ee mashruuca kudha sannadka1981ka*. Jamhuuriyadda Dimoqraadiga Soomaaliya.	✓	Experience from building larger scale solar distillation plant.
Alward, R. (1970) *Installation of a solar distillation plant on Ile de la Gonave, Haiti. Internal report No. I.67.* Brace Research Institute, McGill University, Canada.	✓	Experience from building larger scale solar distillation plant.
Bojcevska, H.; Jergil, E. (2002) *Removal of cyanobacterial toxins (LPS endotoxin and microcystin) in drinking-water using the Bio-Sand household water filter*. Minor field study in Mozambique, September – November 2002. Uppsala University, Uppsala, Sweden.	✓	Looks at efficiency of biosand filters in removal of cyanobacterial toxins.
CARE Yemen (2004). *East of Aden Watercones Pilot Project Report.*	✓	Reviews the effectiveness of Watercone distillation units for coastal communities in Yemen.
Grützmacher, G.; Böttcher, G.; Chorus, I.; Bartel, H. (2002) *Removal of Microcystins by Slow Sand Filtration*. Wiley Periodicals.	✓	Looks at efficiency of biosand filters in removal of cyanobacterial toxins.
Koninga, J. de; Thiesen, S. (2005) Aqua solaris – an optimized small scale desalination system with 40 litres output per square meter based upon solar-thermal distillation. *Desalination.*	✓	Trials on a solar still producing 40 litres/m^2/day.
Practical Action. *Solar distillation technical brief.*	✓	Overview of household solar distillation.
Weert, F. van; Gun, J. van der; Reckman, J. (2009) *Global Overview of Saline Groundwater Occurrence and Genesis*. International Groundwater Resources Assessment Centre (IGRAC), Utrecht, The Netherlands.	✓	Comprehensive overview of salinity in groundwater.
Construction		
Constantine, T. (2001) *Cracking in Waterproof Mortars*. DTU, Warwick University, UK.	✓	Research done on how to reduce cracking in mortar in rainwater tanks.
Davis, J.; Lambert, R. (1995). *Engineering in Emergencies*. IT, London, UK.	✓	Overview of many different construction practices.
Harvey, P.; Baghri, S.; Reed, B. (2002) *Emergency Sanitation: Assessment and Programme Design*. WEDC, Loughborough, UK.	✓	Information on rebar spacing.
Neville, A.M. (1981) *Properties of Concrete*. Pitman.		All things to do with concrete.

Drought actors overview

Below is a selection of actors that were encountered during this research. It is by no means anywhere near exhaustive.

Actor	Name	Contact details	Relation to WASH in drought context
NGOs			
Aquaforall	Dick Bouman	Groningenhaven 7, 3433 PE Nieuwegein, The Netherlands Tel: +31 70 3519 726 Email: d.bouman@aquaforall.nl Web: www.aqua4all.nl	Funded studies in MAR techniques & water conservation, involved in funding other rainwater harvesting research and publications. Aims to create a link between the Dutch public & private water sector and actors in water and sanitation projects in developing countries.
Connect International	Henk Holtslag	Jan van Houtkade 50, 2311 PE Leiden, The Netherlands Tel: +31 71 5141333 Email: holtslag.dapper@kpnmail.nl Web: www.connectinternational.nl	Involved in tubewell MAR recharge trials.
Ecole Supérieure de Physique et Chimie Industrielle	Daniel Beysens	10 rue Vauquelin, 75231 Paris, France Email : beysens@pmmh.espci.fr	One of the researchers of dew collection.
FogQuest	Dr. Robert Schemenauer, Executive Director	448 Monarch Place Kamloops, BC V2E 2B2 Canada Tel. +1 250 374-1745 Email: robert.schemenauer@fogquest.org Web: www.fogquest.org	Provides information, training and consultancy about fog collection systems.
IDE		10403 W Colfax Ave. #500 Lakewood, CO 80215, USA Tel: +1 303 232 4336 Web: www.ideorg.org	Uses a market-oriented development model to increase the income of the rural poor by improving market access, increasing agricultural production, and creating sustainable local businesses. Has brought cost of drip irrigation systems down and adapted them for small-scale farmers.
Oxfam GB	St. John Day, IWRM Advisor	Oxfam GB Niger Niger Mob: +227 96536626 UK Mob: +44 7805 787534 Email: sday@oxfam.org.uk	Has a history of working in drought-prone pastoralist areas.
Practical Action		The Schumacher Centre for Technology & Development, Bourton on Dunsmore, Rugby CV23 9QZ, UK Tel: +44 1926 634400 Email: practicalaction@practicalaction.org.uk Web: www.practicalaction.org	Has a history of working in drought-prone areas.
SASOL (Sahelian Solutions Foundation)	G-C.M Mutiso	Nairobi: Box 14333, Westlands 00800 Nairobi, Kenya Tel. +254 2 860772 E-mail: muticon@wananchi.com Field: Box 85, Kitui, Kenya Tel. +254 141 22873 E-mail: sasol@kenyaweb.com	Well known for its sand dams in Kitui, Kenya. The area they work in has the highest concentration of sand dams in the world.
Tearfund	Frank Greaves, Water & Sanitation Adviser	100 Church Road, Teddington, Middlesex TW11 8QE, UK Tel: +44 20 8943 7757 Email: Frank.Greaves@tearfund.org Web: www.tearfund.org	Involved in funding various rainwater harvesting initiatives in several countries.
UN agencies & related organizations			
FAO (Food & Agricultural Organization)		Viale delle Terme di Caracalla 00153 Rome, Italy	Brings knowledge of water harvesting for improving food

		Tel: (+39) 06 57051 Email: FAO-HQ@fao.org Web : www.fao.org	security.
IFAD (International Fund for Agricultural Development)		Via Paolo di Dono, 44 00142 Rome, Italy Tel: +39 654591 E-mail: ifad@ifad.org Web: www.ifad.org	International financial institution & specialized agency of the UN dedicated to eradicating poverty and hunger in rural areas of developing countries through low-interest loans and grants.
Intergovernmental Panel on Climate Change (IPCC)		C/O World Meteorological Organization 7bis Avenue de la Paix CH- 1211 Geneva 2, Switzerland Phone : +41-22-730-8208 / 54 / 84 Email: IPCC-Sec@wmo.int	A scientific body to provide the world with a clear scientific view on the current state of climate change and its potential environmental and socio-economic consequences.
UNEP (United Nations Environment Programme)		P.O. Box 30552 Nairobi 00100, Kenya Tel: +254 20 7621 234 E-mail: unepinfo@unep.org Web: www.unep.org	Focuses on environmental challenges including climate change. Together with WMO, established the Intergovernmental Panel on Climate Change (IPCC).
UNESCO (UN Educational, Scientific and Cultural Organization) and IHP (International Hydrological Programme)		UNESCO/Division of Water Sciences 1 rue Miollis, 75732 Paris Cedex 15, France Tel : +33 1 45 68 40 01 Email: ihp@unesco.org Web: www.typo38.unesco.org/index.php?id=240	IHP has supported the IAH-MAR research since 2000. IHP is an international scientific cooperative programme in water research, water resources management, education and capacity-building.
UNICEF (UN Children's Fund)	Dr Sam Godfrey, WASH Section Chief	UNICEF Mozambique Tel: +258 21 481 127 Email: sgodfrey@unicef.org www.unicef.org/mozambique	Has been involved in MAR techniques in India and Mozambique.
Donors			
DANIDA – Ministry of Foreign Affairs of Denmark		2, Asiatisk Plads, DK-1448 Copenhagen K, Denmark Tel: +45 33920000 Email: devforum@um.dk	Has funded rainwater harvesting research.
DFID (Department for International Development)		1 Palace Street, London SW1E 5HE, UK Tel: +44 20 7023 0000 www.dfid.gov.uk	Has funded research into MAR techniques.
SIDA (Swedish International Development Cooperation Agency)		Valhallavägen 199, 105 25 Stockholm, Sweden Tel: +46 8 698 50 00 E-mail: sida@sida.se Web: www.sida.se	Has funded rainwater harvesting projects and research including sand dams.
Academia, institutes and networks			
Agromisa Foundation		Duivendaal 8, Building 401, 6701 AR Wageningen, The Netherlands Tel: +31 317 412217 Email: agromisa@agromisa.org	Involved in rainwater harvesting publications. Agromisa is linked to Wageningen University and Research Centre and specializes in exchanging information on small-scale sustainable agriculture and related topics.
British Geological Society (BGS)		Keyworth, Nottingham NG12 5GG Tel: +44 115 936 3241 Email: sales@bgs.ac.uk Web: www.bgs.ac.uk	Involved in research into MAR techniques
Gansu Research Institute for Water Conservation	Prof. Qiang Zhu	13 Guangchang South Road, 730000 Lanzhou, China Tel. + 86 510 85880170 Email: gzhuhz@yahoo.com.cn	Key researcher in rainwater harvesting and dryland farming in arid areas.
International Association of Hydrogeologists (IAH)	Ian Gale (works for British Geological Society)	Email: i.gale@bgs.ac.uk Web: www.iah.org/recharge	Involved in research into MAR techniques. IAH is an organisation for scientists, engineers and other professionals working in the

			fields of groundwater resource planning, management and protection.
International Groundwater Resources Assessment Centre (IGRAC)		P.O. Box 85467, 3508 AL Utrecht, The Netherlands Tel: +31 88 335 7700 Email: info@igrac.net Web: www.igrac.net	Promotes sharing of groundwater information and experience on a worldwide scale. Collects data on areas where MAR techniques used, also maps salinity issues.
International Water Management Institute (IWMI)		127, Sunil Mawatha, Pelawatte, Battaramulla, Sri Lanka. Tel: +94 11 2880000 Email: iwmi@cgiar.org Web: www.iwmi.org	Is one of 15 research centres sponsored by CGIAR. Aim is to improve the management of land and water resources for food, livelihoods and the environment.
IRC International Water & Sanitation Centre		Bezuidenhoutseweg 2 2594 AV The Hague The Netherlands Tel : +31 70 3044000	IRC facilitates sharing, promotion and use of knowledge about water and sanitation.
Netherlands Water Partnership (NWP)		Bezuidenhoutseweg 2, 2594 AV Den Haag, The Netherlands Tel: +31 70 304 3700 Email: info@nwp.nl Web: www.nwp.nl	Collaborates in diseminating information on rainwater harvesting solutions among other things. NWP is a network that unites Dutch water expertise, consisting of members from private companies, government, knowledge institutes. Acts as a centre of information on water expertise, policy developments and market opportunities.
Partners voor Water		Bezuidenhoutseweg 2, 2594 EH Den Haag, The Netherlands Tel: +31 70 778 80 58 Email: info@partnersvoorwater.nl Web: www.partnersvoorwater.nl	Has funded contour trenches in Vietnam. Organization aims to strengthen the international position of the Dutch water sector by encouraging interaction of private, public and non-profit sectors, and knowledge institutes.
RAIN Foundation	Robert Meerman, Programme Officer	Donker Curtiusstraat 7-523 1051 JL Amsterdam, The Netherlands Tel. +31 20 58 18 294 Email: meerman@rainfoundation.org Web: www.rainfoundation.org	An international network that aims to increase access to water for vulnerable people through collecting and storing rainwater.
RWSN (Rural Water Supply Network)	Dr. Kerstin Danert, Coordinator for Cost-Effective Boreholes	c/o SKAT Swiss Resource Centre and Consultancies for Development Vadianstrasse 42, CH-9000 St.Gallen, Switzerland Phone: +41 71 228 54 33 Fax: +41 71 228 54 55 Email: kerstin.danert@skat.ch Web: www.rwsn.ch	A global knowledge network that helps practitioners to make informed decisions on how to better improve access to safe water for rural people. Involved in low-cost borehole research.
Small reservoirs project	Dr. Marc Andreini, IWMI Ghana	c/o CSIR Campus, Odei Block, Airport Residential Area, Accra, Ghana Tel: +233 21 784752 Email: m.andreini@cgiar.org Web: www.smallreservoirs.org	Project looking at researching how to improve functionality of small reservoirs. Website used for distribution of findings.
Spate irrigation network		Web: www.spate-irrigation.org	A network of professionals and practitioners to exchange experiences and good practice in spate irrigation.
Stockholm International Water Institute (SIWI)		Drottninggatan 33 SE - 111 51 Stockholm, Sweden Tel. +46 8 522 139 60 Email: siwi@siwi.org	SIWI is a policy institute that seeks sustainable solutions to the world's escalating water crisis. It manages projects, synthesises research and publishes findings and recommendations on current and future water, environment, governance and human development issues.

Technical University-Delft – Department of Civil Engineering	Dr. Maurits Ertsen	Building 23, ,Stevinweg 1 / PO-box 5048 2628 CN Delft / 2600 GA Delft, The Netherlands Tel: +31 15 2785440 Email: M.W.Ertsen@tudelft.nl Web: www.tudelft.nl	Various pieces of research on the geohydrological functioning of sand storage dams and their technical design. Were involved in implementing contour trench trials in Vietnam.
UNESCO-IHE, Delft		Westvest 7, 2611 AX Delft, The Netherlands Tel: +31 (0)15 215 1715 Email: info@unesco-ihe.org Web : www.unesco-ihe.org	Were involved in implementing contour trench trials in Vietnam.
VU University – Institute for Environmental Studies		De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands Tel. +31 20 59 89898 Email: international@dienst.vu.nl Web: www.vu.nl	Have conducted several socio-economic studies on the subject of sand storage dams.
Warwick University – Development Technology Unit (DTU)	Dr. Terry Thomas	School of Engineering, Warwick University, Coventry CV4 7AL, UK Tel. +44 24 7652 3122 Email: T.H.Thomas@warwick.ac.uk Web: www.www2.warwick.ac.uk/fac/sci/eng/research/civil/crg/dtu	
Private sector			
Acacia Water	Merel Hoogmoed	Jan van Beaumontstraat 1, 2805 RN Gouda, The Netherlands Tel. +31 612143599 Email: merel.hoogmoed@acaciawater.com Web: www.acaciawater.com	Established in 2003 at the Vrije Universiteit Amsterdam (Faculty of Earth and Life Sciences). Their strength is the specialization in the field of groundwater
ASAL Consultants	Erik Nissen-Petersen	P O Box 739, Sarit 00606, Nairobi, Kenya Tel : +254 733 619066 Email: info@waterforaridland.com Web: www.waterforaridland.com	Lots of experience in East Africa in implementation of rainwater harvesting technologies such as sand dams & rock catchments.
Royal Haskoning	Marieke Nieuwaal	Barbarossastraat 35, P.O. Box 151, Nijmegen 6500 AD, The Netherlands Tel: +31 24 328 42 84 Email: m.nieuwaal@royalhaskoning.com Web: www.royalhaskoning.com	Were involved in implementing contour trench trials in Vietnam.

Drought scenarios & links to other disasters

Droughts occur in different settings, the response to which may vary according to the setting. Various drought scenarios are outlined below.

Drought scenarios by geographical location – response to drought can vary according to global location (e.g. certain techniques will be more suitable in hilly areas, others in the plains) which will also have a different climate regime (e.g. techniques might vary according to the amount of rain or PET in the area):

- Mountainous areas
- Flat lowlands
- Arid & Semi-Arid Lands (ASALs)
- Humid and sub-humid areas

Drought scenarios by source of water scarcity – response to drought can vary according to the nature of what is limiting water availability (e.g. improve water capture and storage, or reduce water demand and use water-saving technologies):

- Natural climate variability & climate change = reducing cumulative rainfall quantity, decreased snow/glacier melt and increased rainfall intensity
- Population increase = increasing water demand, deteriorating surface and groundwater quality

Drought scenarios by livelihood – response to drought can vary according to what people do and where they live (e.g. pastoralists need water for livestock and relation to pasture is important, whereas farmers need water for agriculture and relation to their fields is important): [31]

- Pastoralist
- Agropastoralist
- Farmer
- Hunter-gatherer
- Urban

Drought has a potential effect to cause other disasters. Some effects are summarized below:[32]

- Drought causes increased poverty and food insecurity. Where drought events often occur with such frequency that people have no time to recover before another drought hits, their usual coping strategies for normal cyclical drought become inadequate. This results in increasing poverty and chronic food insecurity.
- Drought causes decreased agricultural productivity. Increased temperatures cause increased water demand for crops, which may be less available. Recent research into the effects of climate change indicates that even if basic adaptive measures are taken, global agricultural production will decline 3% by 2080 due to increased temperatures. In Kenya, the 1998 – 2000 droughts caused a 15% reduction in agricultural production (5% of which was livestock).
- Drought negatively impacts wellbeing of women and girls who will spend more time collecting firewood, collecting water from increasingly distant sources, attending to sick family members and cultivating land (most agricultural activities undertaken by women).
- Drought can increase conflict. Although complex to link as cause and effect, in some areas (e.g. Darfur) drought has resulted in differing interpretations of rights to access water and land among nomadic and sedentary groups, contributing to the escalation of ethnic tensions.
- Drought impacts power generation, industrial production and investment. In Kenya, 26% of all the economic losses during the 1998 – 2000 drought was due to reduction in hydropower generation, while 58% was due to reduction in industrial production, which was the largest sector affected.

[31] Livelihoods defined in: IIRR, ACACIA & CordAid (2004) *Drought Cycle Management: A toolkit for the drylands of the Greater Horn*. p.13.

[32] Information taken from: Arab Water Council (2009) *9. Vulnerability of arid and semi-arid regions to climate change – Impacts and adaptive strategies.* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands. Also: Grey, D.; Sadoff, C. (2006) *Thematic document framework theme 1. Water for growth and development.* 4th World Water Forum, Mexico City, March 2006. World Bank, Washington, USA. Also: Hedlund, K. (2007) *Slow-onset disasters: drought and food and livelihoods insecurity. Learning from previous relief and recovery responses.* ALNAP / Provention Consortium.

Overview of drought-resilient WASH techniques: focus on water supply & non-motorized irrigation

Introduction

The Vision 2030 study recently looked into the resilience of WASH systems in the face of climate change. It concluded that simple guidance and support tools are needed to facilitate rapid and widespread assessment of WASH programmes with regards to allowing progressive adaptation to increase resilience, but that such tools are not yet available. It seems that progress is hindered by limited experience and insufficient access to lessons learned. Yet the development of planning tools based on credible outcomes from predicted climate change would be an important contribution.[33] This is what this study attempts to begin to address, by looking at what techniques can be applied to make water systems more resilient to the drought component of climate change.

While there are interesting innovations in technologies, in general the techniques and recommendations for WASH managers planning drought-resilient WASH should be based on lessons learnt through past and ongoing attempts to meet existing WASH challenges. Review of climate change literature suggests that most of the proposed solutions to climate change are just the usual ones (e.g. increase storage, managing demand), only better implemented in more robust fashion. This can increase the likelihood of new initiatives being successful and reduce the risk of mistakes being repeated.[34]

This section will focus on water supply and non-motorized irrigation in rural areas for populations of up to 5,000 people. Both technical and non-technical components are important in discussing how to make water systems resilient. On the one hand, software is only as good as the technology it promotes – technological innovation and improvement of techniques are necessary, especially with regards to new and emerging problems related to drought.[35] On the other hand, it is known that about 80% of projects become unsustainable not because of technical issues but because of non-technical issues such as management, social relationships and community dynamics.[36] The various measures for improving water availability are outlined below:

Technical measures include:

- Improvement of the availability of water over space (e.g. more points of water in an area = better access for people & livestock):
  - Local recharge, retention/storage and re-use of water, which are increasingly being seen as the most important adaptations for ensuring water availability and food security to rural and urban populations, especially in developing countries in the face of climate change.[37]
  - Various methods for gaining more water from rainwater and groundwater sources, some of which are innovative and need further research.
  - Methods on how to limit impact on existing saline groundwater and how to recharge/dilute it.
  - Methods to increase available water to communities through treatment of non-potable saline water.
  - Ways to improve handpump sustainability since this affects water availability in many areas.
- Improvement of the availability of water over time (e.g. more water available to span increasing length of dry seasons, or even short dry spells when considering agriculture):
  - Methods to improve the siting and construction of physical structures in order to make them less prone to failure and more efficiently used. Such techniques may also apply in general (e.g. key methods to prevent sub-surface tanks from leaking will also apply in areas not prone to drought) – however, they are included insofar that they help to improve reliability of water availability.
  - Suitable storage methods that take into account the high rain intensity that falls for short time periods in many areas – such storage needs to be able to not only store enough volume of water to last through many months of dry season and/or drought, but also needs to be able to conserve evaporation given the high PET rates in many areas.

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[33] WHO/DFID (2009) *The resilience of water supply and sanitation in the face of climate change. Summary and policy implications. Vision 2030*. p.38.
[34] Batchelor, C.; Schouten, T.; Smits, S.; Moriarty, P.; Butterworth, J. (2009) *14. Climate change and WASH services delivery – Is improved WASH governance the key to effective mitigation and adaptation?* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands. p.6.
[35] Godfrey, S.; Gonzalez, L. (2010) Crossfire: the key focus on challenging environments should be technological, paying special attention to physical design and construction. *Waterlines*, Vol.29 no.3, pp.181-185.
[36] ACF-IN (2008) '*How to Make WASH Projects Sustainable and Successfully Disengage in Vulnerable Contexts: a practical manual of recommendations and good practices based on a case study of five ACF-IN water, sanitation & hygiene projects*. p.166.
[37] See: Kashyap, A. (2004) Water governance: learning by developing adaptive capacity to incorporate climate variability and change. *Water Science and Technology* 29 (7), 141–146. Also see: Steenbergen, F.V.; Tuinhof, A. (2009) *Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retention, Reuse and Rainwater Storage*. BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), the Co-operative Programme on Water and Climate (CPWC) and the Netherlands National Committee IHP-HWRP. p.4. See also: Wilk, J.; Wittgren, H.B. (eds). (2009) *Adapting Water Management to Climate Change*. Swedish Water House Policy Brief Nr. 7. SIWI, 2009. pp.6-7.

    - Suitable management of a variety of water sources, where for example open water sources are used first so that most is used rather than evaporated, leaving other stored water for later.
- Improvement of techniques that influence water demand:
    - Water-saving technologies and irrigation practices
    - Re-use techniques
    - Drought-resistant crops

Non-technical measures include:
- Institutional solutions (e.g. establishment of effective water user associations to manage communal facilities)
- Financial & economic solutions (e.g. availability of micro-finance to users to replicate technology)
- Environmental solutions (e.g. siting of seasonal water points in relation to pasture availability in pastoral areas)

Implementing such techniques falls within the idea of Drought Cycle Management (DCM) planning. Droughts occur regularly and should not be seen as one-off occurrences – rather they should be planned for in order to reduce negative effects. Drought Cycle Management (DCM) therefore describes in a general way how to reduce vulnerability (& increase resilience) of populations to drought through proper planning. The aim is also to use funds more effectively: making existing systems more resilient during the normal and alert stages means that less money should have to be spent during the emergency phase. Oxfam for example found that in drought-prone ASAL areas, development work is increasingly disrupted and/or undermined by the shift to emergency response.[38] A diagram illustrating Drought Cycle Management is shown in Annex 3.

[38] Oxfam (2000) *Integrating drought cycle management in programming: a series of briefs for practitioners.*

Techniques to increase resilience and reduce vulnerability

Overall issues to consider

	Technical	Institutional	Financial & economic	Environmental
Drought Cycle Management & project cycle		• Introduce DCM into all NGO programming in drought-prone areas so that money is invested where it should be, rather than being diverted for emergencies • Access donor funding that supports longer project durations for drought contexts = the technical side of implementation not rushed.[39]		
Adopt and implement Integrated Water Resources Management (IWRM)		• Align plans across the whole water sector and other sectors that have an influence on water supply (e.g. the power sector) and demand for WASH services (e.g. planning departments).[40]		
Adopt principles of adaptive management in planning WASH approaches		• In a complex and rapidly changing situation there can never be sufficient information to reach a settled 'optimum' decision. Hence, the WASH sector should put effort into planning approaches that are and supported by strong monitoring and information management systems, which allow for constant adaptation and the upgrading of plans and activities.		
Strategy specific to pastoralist & agropastoralist areas	• Increase number and size of appropriate dryland water sources (ponds, pans, berkeds, hafirs, rock catchments etc) for			• Concentrate efforts on seasonal water points rather than perennial (e.g. those more directly varying with rainfall) and

[39] In Turkana, pressure for results from project timetables or donor requirements was seen as a risk to project success, since it took longer than the average project cycle to prove that bunds worked (due to erratic nature of rainfall, coupled with an ongoing learning process & adjustment in design, and initial scepticism/reluctance of beneficiaries). See: Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. pp.31, 119.

[40] Batchelor, C.; Schouten, T.; Smits, S.; Moriarty, P.; Butterworth, J. (2009) *14. Climate change and WASH services delivery – Is improved WASH governance the key to effective mitigation and adaptation?* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands. p.6.

[41] Oxfam found in Wajir, Kenya, that permanent boreholes created for livestock resulted in a shift in traditional herding patterns = overgrazing of pastures normally used only at end of dry season. See: Oxfam (2000) *Integrating drought cycle management in programming: a series of briefs for practitioners.* See also: IIRR, ACACIA & CordAid (2004) *Drought Cycle Management: A toolkit for the drylands of the Greater Horn*. See also: Government of Kenya (2007) *National Policy for the Sustainable Development of Arid and Semi Arid Lands of Kenya.*

	communities to phase their use through the year. • Result = less distance to walk in dry season (normally increases as DS prolongs) • Result = water stays for longer per site • Result = cost of water might reduce • Result = fewer animals die = less cattle raiding = more stability • Avoid installation of permanent water sources – give priority to water harvesting structures.[41]			vary according to pasture spatial needs.[42] • Reduce pressure on existing pastureland & water sources, and improve animal production through lower travel times by creating new seasonal water points in under-utilized areas of pasture, with maximum distance between sources of 30km, yet in areas of guaranteed peace.[43] • Water points for pastoralists should be at least 5km out of towns = avoid conflict & waiting times.
Operation & maintenance		• Concentrate on technologies that need less community management and less operation and maintenance. (See "Promote economic use" part of this table.) • Where communal management is required, time is needed that goes beyond the average NGO project cycle (e.g. 33 months).[44] In such situations, devote enough time to community mobilization and user group formation as these tend to be more sustainable.[45]	• For communal managed systems, a good system of regulation or a clear audit process needs to be in place that the whole community is aware of.[46]	
Maximize & build on existing knowledge & resources		• Plan WASH activities with (not for) local people. Listen to local people & consider their ability to sustain interventions.[47]	• Use local artisans and local materials = increased morale that local people can do it on their own without too much	• Heed local ownership & regulation traditions for use of water & pasture

[42] VSF (2006). *SubSurface Dams : a simple, safe and affordable technology for pastoralists. A manual on SubSurface Dams construction based on an experience of Vétérinaires Sans Frontières in Turkana District (Kenya), September 2006.* p.48.
[43] Distance to be confirmed, but estimated from: Fewster, E. (1999) *The Feasibility of Sand Dams in Turkana District, Kenya.* MSc thesis. WEDC, Loughborough University, UK. p.74. Also: VSF (2006). *SubSurface Dams : a simple, safe and affordable technology for pastoralists. A manual on SubSurface Dams construction based on an experience of Vétérinaires Sans Frontières in Turkana District (Kenya), September 2006.* pp.10, 45.
[44] Wijk-Sijbesma, C, van (2001): The best of two worlds. Methodology for participatory assessment of community water services. Delft: *IRC International Water and Sanitation Center Technical Paper Series 38.*
[45] Experience in India showed that projects that devoted time to community mobilization and user group formation where rights & responsibilities were clearly defined were likely to be more sustainable. See: Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.20.
[46] Financial mismanagement is one of the key risks to community solidarity with water committees - see: ACF-IN (2008) '*How to Make WASH Projects Sustainable and Successfully Disengage in Vulnerable Contexts: a practical manual of recommendations and good practices based on a case study of five ACF-IN water, sanitation & hygiene projects.* p.168.
[47] IIRR, ACACIA & CordAid (2004) *Drought Cycle Management: A toolkit for the drylands of the Greater Horn.* p.37.

		• Build on existing community drought coping mechanisms and local knowledge systems.[48, 49]	outside help = replicable	• Incorporate local understanding of environmental capacity before planning new water sources.
Promote a demand-responsive approach & participation[50] and ownership of technology & structures.	• Men & women should decide what technology & service levels they need, and location of facilities.[51] PRA can help identify perceived needs and can result in better performing projects.[52] Women should be actively involved. • Encourage flexibility in design depending on PRA results. During technical design, the true participatory process allows continual learning and adjustment to go both ways – in this view, participation is not a concession by powerful outsiders but an essential process for project success.[53]	• Men & women should decide on management arrangements = better able to cope with problems in times of stress. Women should be actively involved as they have a vested interest to make the system work (due to lower water collection times for example).	• Men & women should decide on financing arrangements. Women should be actively involved. • Beneficiaries in non-destitute communities with livelihoods (e.g. pastoralists with animals) need to feel they own the WASH facility (that they firstly perceived they needed via PRA). Ownership can be generated through (a) contribution towards the project costs, but this can/should be more than just stones, water, labour but rather hard cash as well; (b) clear idea by beneficiaries on who will own the final facility; (c) clear spatial separation of pastoral & town water supplies.[54] • Reasonably secured ownership of land resources appears to be a necessary prerequisite for promotion/adoption of rainwater harvesting techniques – farmers find it difficult to invest in storage systems on land they do not control.[55]	
Improve involvement of women	• Involve women in design of facilities.	• Women are traditional domestic water managers and are usually those who are involved in	•	

[48] IIRR, ACACIA & CordAid (2004) *Drought Cycle Management: A toolkit for the drylands of the Greater Horn*. p.101.
[49] Wilk, J.; Wittgren, H.B. (eds). (2009) *Adapting Water Management to Climate Change*. Swedish Water House Policy Brief Nr. 7. SIWI, 2009. p.17.
[50] Research shows that services are better sustained with demand-responsive approaches and is the reason why it was one of the guiding Dublin Principles in 1992. Also see: Wijk-Sijbesma, C, van (2001): The best of two worlds. Methodology for participatory assessment of community water services. Delft: *IRC International Water and Sanitation Center Technical Paper Series 38.* p156, p.220. Also this was one of quoted success factors in rainwater harvesting experience in various countries – see: Nijhof, S,; Jantowski, B.; Meerman, R.; Schoemaker, A. (2010). Rainwater harvesting in challenging environments: Towards institutional frameworks for sustainable domestic water supply. *Waterlines*, Vol.29 no.3, pp.211.
[51] See: www.fao.org/docrep/W7314E/w7314e0g.htm - experience in India showed that water conservation projects that involve people in all stages from planning through to execution had higher success rates, while those that did not involve them tended to fail.
[52] Experience in India showed that better performing projects engaged local people in discussion of problems & priorities, where concerns and interests of different groups were addressed. See: Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.18.
[53] Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana.* IT Publications, London, UK. pp.116.
[54] Cash was suggested by local organization during fieldwork in Turkana. Interviews with nomadic Turkana about willingness to pay indicated that there was very high WTP when beneficiaries knew that they would be the only owners of the facility. See: Fewster, E. (1999) *The Feasibility of Sand Dams in Turkana District, Kenya.* MSc thesis. WEDC, Loughborough University, UK. pp.87, 98-100, 115.
[55] Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.

		agriculture, yet involvement is still weak[56] – continue to advocate involvement in decision making, design and O&M.[57]		
Promote economic use of water,[58] allow for different management options of water systems, consider private sector	• There may be a role for the private sector in providing critical technical expertise in both design and construction phases of techniques to individual users/farmers.	• There are certain opportunities for non-communal water supply (e.g. privately owned, self-supply, household treatment) that could be explored. Such methods can be more resilient just by the fact that they are not communally-owned & managed.[59]	• Promote economic use of water – e.g. vegetables, trees, fruits = cash available which is a buffer to reduce vulnerability, and health impact of better diet	
Give preference to decentralized rainwater harvesting systems	• Decentralized rainwater catchments are known to be more efficient than larger area catchments – for the sake of efficiency (to gather more water quantity) therefore, preference should therefore be given to smaller scale decentralized systems.[60] In addition, in terms of decision making and control, decentralization is argued as important in success of rainwater harvesting.[61]			
Technical expertise & piloting new techniques	• Successful water projects require relevant technical expertise from beginning to end of project. Short-term hiring of technical consultants is not enough to guarantee quality work and success.[62] Expertise is essential for certain design and			

[56] See: Nijhof, S,; Jantowski, B.; Meerman, R.; Schoemaker, A. (2010). Rainwater harvesting in challenging environments: Towards institutional frameworks for sustainable domestic water supply. *Waterlines*, Vol.29 no.3, pp.209-219. See also: Arab Water Council (2009) *9. Vulnerability of arid and semi-arid regions to climate change – Impacts and adaptive strategies.* Perspectives on water and climate change adaptation. IRC, The Hague, The Netherlands.

[57] The guiding Dublin Principles in 1992 stated that women should play a central part in provision, management and safeguarding of water.

[58] The guiding Dublin Principles in 1992 stated that water has an economic value in all its competing uses and should be recognized as an economic good.

[59] One of the general recommendations to improve sustainability is to not take the community voluntary committee management model as the default model. It is recommended that NGOs & donors are more open to different approaches, including the private sector and self-supply, particularly in dryland contexts where community management is more challenging – see: ACF-IN (2008) '*How to Make WASH Projects Sustainable and Successfully Disengage in Vulnerable Contexts: a practical manual of recommendations and good practices based on a case study of five ACF-IN water, sanitation & hygiene projects*. p.168. It appears that there is evidence that privately-owned supply is more sustainable. A review of WASH systems in Somalia showed that privately-owned supplies worked very well and people were willing to invest in them, due to mistrust about communally-operated systems – see: Muthusi *et al* (2007). *Rural Water Supply Assessment*, FAO-SWALIM.

[60] Experience from Negev: rain falling over 1 ha yielded 95,000 litres, compared to 24,000 litres per hectare from a 345 ha catchment = 75% less water collected due to longer distance of runoff. See: Pandey, D.N.; Gupta, A.K.; Anderson, D.M. (2003) Rainwater harvesting as an adaptation to climate change. *Current science*, vol.85, no.1, p.55.

[61] Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.

[62] Hedlund, K. (2007) *Slow-onset disasters: drought and food and livelihoods insecurity. Learning from previous relief and recovery responses*. ALNAP / Provention Consortium. p.8

	construction phases and we should not assume that indigenous knowledge will contain everything to solve local problems – rather it is a balance between the two.[63] • Each system needs to be designed and constructed so as to be site-specific. A successful technology at one site should be transferred to another area with different physical and/or social settings only after great care and some modification.[64] This is to say that a certain amount of experimentation and failure may be needed in this process. It is therefore recommended to start small, learn as you go and expand as needed.[65]			
Mix & match	• There is no one solution for drought-prone areas – best is to mix and match according to: o Time of water use (e.g. open dams for use directly after rains = more used and less evaporated, sand dams used in areas where livestock go in dry season) o Technical constraints (certain techniques suitable only certain places – e.g. sand dams built in riverbed, berkeds built away from riverbed)			

[63] Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.
[64] Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.
[65] NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions*. Netherlands Water Partnership.

Concrete techniques

SUMMARY	**Technical**	**Institutional**	**Financial & economic**	**Environmental**
Concrete techniques	• Mix dry ingredients before adding water • Use the correct ratios for different applications – check contractors mixes on site • Minimize water in concrete mix – consider plasticizer as an admixture • Use clean water for mixing • Use clean aggregate • Do not use weathered rock as aggregate • For slabs, reinforcement should be correctly specified (thickness of bar, spacing, location in slab, adequate cover) • Use poker vibrator if possible, especially when making tank foundations • Ensure adequate curing	•		

Overview:
Poor construction techniques are to blame for many leaking water structures, which in turn affects water availability. Key construction issues such as the making of concrete, correct construction of stone masonry, as well as the issue of pipes passing through water-bearing structures. This section focuses on concrete making. Proper techniques are often bypassed or shortened, which increases the risk of failure and reduces the life of the structures. This is especially true in many drought-prone areas that have dry climates and where water is at a premium, since it affects the essential curing process.

Key techniques for construction: [66]

- All dry ingredients should be mixed first before adding water.
- Use the correct ratios for different applications – refer to relevant tables.[67] A field method to check if contractors have used the correct ratio is to take some of the wet mix, put it into a transparent bottle and shake up with some water – the cement fraction should settle out on top when it is left to stand, giving an indication of the cement fraction.[68]
- Add only the very minimum amount of water for workability – this is one of the most important aspects to making strong concrete. The amount of water needed for the hydration process when mixing concrete is a lot less than what is normally added to mixtures in the field, where additional water is needed to increase workability of the concrete. The point is that the less water used, the better, since if too much water is used, the concrete will become weaker. This is because any excess water not used in hydration will remain in the pores – when this water evaporates, the pores remain – the more water added, the bigger the pores and the weaker the final product. Admixtures can be added to the concrete mix in order to reduce the amount of water needed. Research has shown that superplasticizers work best by reducing the amount of water that needs to be added when mixing concrete, which results in 35% less shrinkage. The resulting end material is stronger and can reduce the amount of micro cracks in mortar by half compared to normal mortar while resulting in 76% fewer leaks. In general, the amount of plasticizer to be added should not be greater than 2% of the dry material weight.[69] A plasticizer that can be used that is possibly available is household washing up liquid.

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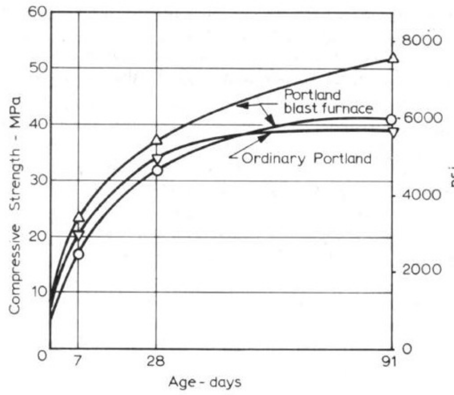
[66] Unless otherwise stated, taken from: Constantine, T. (2001) *Cracking in Waterproof Mortars*. DTU, Warwick University, UK.
[67] For example see: Davis, J.; Lambert, R. (1995). *Engineering in Emergencies*. IT, London, UK. p.571
[68] Author's experience of a technique used by engineers in Somaliland.
[69] http://en.wikipedia.org/wiki/Plasticizer

In hot climates though, more research is needed in the field application of plasticizers, since the reduction of water used (and increased strength of product) may not be that great due to more water needed to prevent drying out between mixing and application.[70]

- Type of water used should be as pure as possible.
- Don't use weathered rock for concrete aggregate. For the best concrete it is best to use a fresh rock aggregate such as crushed granite of gneiss or well-washed river gravel. With the latter the river has removed the weak pieces.[71]
- Use clean gravel – impurities will weaken the concrete.
- Use aggregate (gravel) of 5-20mm for non-porous concrete[72] and 5-10mm for porous concrete.[73] Aggregate can be graded using 2 locally-made sieves of 5mm and 20mm – discard any aggregate that remains on the 20mm sieve or that falls through the 5mm sieve. The reasons for having a maximum size is to do with workability, but also that the maximum size is not greater than the "cover" of concrete over a reinforcing bar – if a stone would span the distance from outer edge to reinforcement, this can become a zone of weathering where water can get in to corrode the reinforcement.[74]
- Reinforce lower side of flat slabs as concrete does not work well under tension. Reinforcement can be avoided if making dome shape structures (e.g. cover to rainwater tank, or dome latrine slab).
- Spacing of reinforcement bars depends on the slab span, thickness and type of reinforcement used – refer to relevant tables.[75]
- Place reinforcement bars with a 30mm "cover" from the edge.
- If possible use a poker vibrator to eliminate air bubbles, especially when casting foundations. This should be placed vertically to the full depth of the concrete for 15 seconds, then withdrawn slowly and repeated at intervals of 150-250mm across the surface.[76]
- Ensure adequate curing - this is one of the most important aspects to making strong concrete, but is often bypassed in the field due to lack of water, knowledge or organization. Adequate curing is necessary to keep the process of hydration going as long as possible – the longer the time, the stronger the concrete. This hydration process will stop once the concrete has dried out, resulting a strength of concrete according to the time of curing. Although curing can continue even for years, 7 and 28 days are normally quoted (see graph) – curing should last at least 7 days, if not longer especially in cold weather. Curing involves sprinkling water on the concrete every day as well as covering it, preferably in a shady area. Covering can be done with material like plastic or sacking, but covering in wet sand also works well, as does putting the concrete entirely in water.



Concrete strength with curing
Neville, A.M. (1981) *Properties of Concrete.* Pitman.

[70] Personal communication with Dr Terry Thomas, Warwick University, UK.
[71] Personal communication with Bob Elson, WEDC, Loughborough University, UK.
[72] Davis, J.; Lambert, R. (1995). *Engineering in Emergencies.* IT, London, UK. p.570
[73] Watt, S.B.; Wood, W.E. (1979). *Hand Dug Wells and their Construction.* IT, London. p.158
[74] Personal communication with Bob Elson, WEDC, Loughborough University, UK.
[75] For example see: Harvey, P.; Baghri, S.; Reed, B. (2002) *Emergency Sanitation: Assessment and Programme Design*. WEDC, Loughborough, UK. p.91. See also: Davis, J.; Lambert, R. (1995). *Engineering in Emergencies*. IT, London, UK. pp.573-576.
[76] Davis, J.; Lambert, R. (1995). *Engineering in Emergencies.* IT, London, UK. p.572

Saline water quality

SUMMARY	Technical	Institutional	Financial & economic	Environmental
Saline water quality	• Diversify water sources (e.g. consider rainwater harvesting) • Consider promotion of household level solar distillation • Consider promotion of larger scale solar distillation plants that are owned & managed by specific individuals • Consider certain Managed Aquifer Recharge (MAR) techniques to dilute saline groundwater. • Reduce water-logging through reducing water table depth and evaporation by: ○ Lined irrigation canals ○ Irrigation techniques that limit volume of applied water ○ Better drainage ○ Planting vegetation with high water consumption rate ○ Deep tillage ○ Improved shade & windbreaks in plots	• Advocate for government legislation to halt drilling of new boreholes in areas of saline groundwater, and to try MAR techniques	•	•

Overview:
Brackish water is defined as starting at having a Total Dissolved Solids content of 1,000 mg/l, and saline water as having 10,000 mg/l.[77] Saline water is a problem in many areas of the world, but typical environments for saline groundwater are coastal areas and shallow aquifers in arid/semi-arid regions.[78] Salinity is derived from natural sources, but the biggest threat to groundwater is said to come largely from anthropogenic factors, where it is derived from saline intrusion in coastal regions, the percolation of irrigation water and wastewater returns to aquifers.[79] This section therefore looks at techniques for dealing with saline water as the issue is related to water availability in drought-prone areas.

Key techniques for siting:
- For use in areas where there are few alternative water sources to the available saline water. These techniques are probably too complicated for treated water with other impurities that can more easily be removed with other treatment processes.

[77] Multiply by 0.7 to get to EC in µS/cm – see: Weert, F. van; Gun, J. van der; Reckman, J. (2009) *Global Overview of Saline Groundwater Occurrence and Genesis*. International Groundwater Resources Assessment Centre (IGRAC), Utrecht, The Netherlands.
[78] See global map of groundwater salinity at www.igrac.net. See also: Weert, F. van; Gun, J. van der; Reckman, J. (2009) *Global Overview of Saline Groundwater Occurrence and Genesis*. International Groundwater Resources Assessment Centre (IGRAC), Utrecht, The Netherlands. p.7
[79] Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.5.

- Before embarking on treatment options for saline water, the first thing to try would be to diversify water sources (e.g. through rainwater harvesting).[80]

Key techniques for construction:

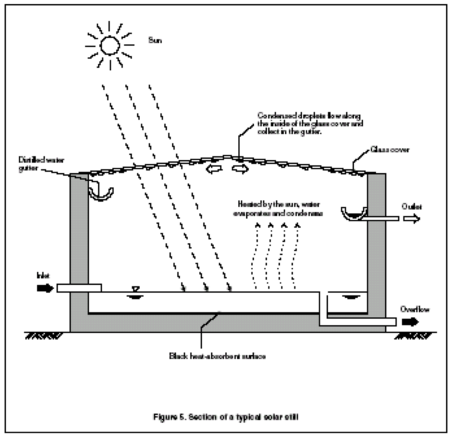


Figure 5. Section of a typical solar still

Typical single basin solar still
Shaw, R. (ed) (1999). *Running Water: more technical briefs on health, water and sanitation*. Practical Action Publishing, London.

- Household solar stills have not been widely promoted, yet can provide 2.5 – 3 litres per m^2 surface area per day.[81] However there is scope to increase yields – more efficient and expensive stills (Aqua Solaris) have been tried that can increase volume to 40 litres per m^2 per day.[82] Regarding the standard version that has been field tested, they require water temperature to be high, while the condensing surface to be as cool as possible – for this reason stills are most efficient in the early evening when water is still warm but temperature of the glass is a lot lower,[83] and stills continue to produce water during the night. The Watercone is a mass-produced innovation that can produce 1.5 litres maximum per cone per day, but tends to be expensive.[84] Solar stills can be constructed using local materials which are cheaper. There are key points to get right:
  - Keep water temperature in the solar still as high as possible:
    - Use a condensing surface with a low absorption capacity. Glass is most commonly used as it is "wettable" (i.e. water condensing in a film rather than forming droplets which reflect radiation) but should ideally be sufficiently thick to withstand rain, wind and some knocks – 1/8" or 3.2mm is adequate. Plastic should not be used due to the high temperatures.[85]
    - Keep water level in the still to between 0.5 – 2.5 cm deep only = less water to heat up = increased efficiency, but not too little that it will dry up.[86]
    - Insulate the base and walls of the still = retains the heat rather than losing it out the sides and base of the structure. Expanded polystyrene sheets 1" thick is widely available and is good for this purpose. The lining on top of this insulation will retain more heat if it is black.
    - Make the solar still waterproof – the easiest way to do this is to use a liner. EPDM or butyl rubber is a good choice as they will not break up or give unpleasant taste/odour to the water.[87]
    - Lining the walls inside the solar still with a reflective material (e.g. aluminium foil) may increase reflection of heat energy but has not been tried.
  - Avoid vapour leaks. Silicone applied using an application gun works well to seal the glass to the frame.
  - Width of glass is normally limited to between 0.65 – 0.9 metres.[88]
  - Add 3 times the daily clean water amount each morning to flush the still – water will flow out through the overflow. Failure to do this will result in salts deposited in the still.
  - The slope of the glass should be minimal. Water will run off glass even set at 1 degree tilt. As a guide, set the angle so that the distance from water level to glass is in the range of 5 – 7 cm in order to minimize air volume in the still, and to increase efficiency.[89]
  - Never allow the still to go dry otherwise it can melt the lining and insulation in the still.
- Communal solar stills have been constructed in some locations.[90] Like any other larger communal installations, there have been problems with maintenance. They may work however if they could be owned and managed by people who have a vested interest in the technology (e.g. water vendors).
- For volumes of water over 1m^3 per day, reverse osmosis (RO) or electrodialysis can be considered.[91] However, for rural areas and most small towns, it will be wise to avoid more complex systems unless you can guarantee technical competence in the design, construction and maintenance of the systems, as well a supply of spare parts and chemicals. If considering this route, it is particularly important is to get a full water analysis done prior to system design, and to have design carried out by RO specialists.[92]

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[80] As has been done in Senegal – see: Steenbergen, F.V.; Tuinhof, A. (2009) *Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retention, Reuse and Rainwater Storage*. BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), the Co-operative Programme on Water and Climate (CPWC) and the Netherlands National Committee IHP-HWRP. pp.70-73.
[81] Author's experience in Kenya. See also: Practical Action. *Solar distillation technical brief.*
[82] Koninga, J. de; Thiesen, S. (2005) Aqua solaris – an optimized small scale desalination system with 40 litres output per square meter based upon solar-thermal distillation. *Desalination.*
[83] Practical Action. *Solar distillation technical brief.*
[84] CARE Yemen (2004). *East of Aden Watercones Pilot Project Report.*
[85] http://www.appropedia.org/Understanding_Solar_Stills
[86] http://www.appropedia.org/Understanding_Solar_Stills
[87] http://www.appropedia.org/Understanding_Solar_Stills
[88] http://www.appropedia.org/Understanding_Solar_Stills
[89] http://www.appropedia.org/Understanding_Solar_Stills
[90] See: Alward, R. (1970) *Installation of a solar distillation plant on Ile de la Gonave, Haiti. Internal report No. I.67.* Brace Research Institute, McGill University, Canada. See also: Aadan, A.I. (1982) *Final report on solar water distillation project. Warbixin iyo gunaanud ee mashruuca kudha sannadka1981ka.* Jamhuuriyadda Dimoqraadiga Soomaaliya.
[91] Practical Action. *Solar distillation technical brief.*

- In areas of shallow saline groundwater, Managed Aquifer Recharge (MAR) techniques have been used to dilute this groundwater which can then be re-extracted. Examples are "Tajamar" infiltration ponds in Paraguay and roof water recharge systems in Mozambique (see MAR section for details).
- Salinization of shallow groundwater can occur due to water-logging (e.g. where irrigation is practiced) – this is because of a shallow water table and high evaporation rates. Techniques to reduce salinity include: [93]
    - Reducing water table depth. This can be done by reducing groundwater replenishment by lining irrigation canals and using improved irrigation techniques that limit volume of applied water (e.g. drip or sprinkler irrigation – see "Drip irrigation" section for details), but can also be done by lowering water tables through increasing groundwater discharge through better drainage or planting vegetation with high water consumption rate.
    - Reducing evaporation. Deep tillage can increase soil pores and reduce capillarity, and screens/trees/mulching/high plot perimeters can improve shade and act as windbreaks to reduce evaporation rates.
- Legislation can impact increasing levels of groundwater salinity – in Mozambique, the government prohibited the drilling of new boreholes in rural areas where salinity was an issue. This combined with rainwater MAR techniques proved to be a good combination at addressing the saline issue.[94]

Key techniques for extraction of water:
- For solar stills, extraction takes place by gravity of condensate to a gutter which leads to a reservoir.
- For MAR techniques, abstraction can take place with a borehole or hand dug well.

Advantages:
- Can be operated on household level = ownership & maintenance

Disadvantages:
- Cost can be reasonably high – between £50-£70 ($70 - $100) per m^2.[95] In Afghanistan, a locally-produced still was priced up at $65.[96]
- Cost is proportional to output, so there are no economies of scale when scaling up as there are with other treatment methods.[97]

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[92] Author's own experience.
[93] Weert, F. van; Gun, J. van der; Reckman, J. (2009) *Global Overview of Saline Groundwater Occurrence and Genesis*. International Groundwater Resources Assessment Centre (IGRAC), Utrecht, The Netherlands. pp.21-22.
[94] Godfrey, S.; Gonzalez, L. (2010) Crossfire: the key focus on challenging environments should be technological, paying special attention to physical design and construction. *Waterlines*, Vol.29 no.3, p.184.
[95] Practical Action. *Solar distillation technical brief.*
[96] Author's experience.
[97] Practical Action. *Solar distillation technical brief.*

Mechanical water extraction - handpumps

SUMMARY	**Technical**	**Institutional**	**Financial & economic**	**Environmental**
Handpumps	• Choose simple technologies that do not need specialist parts and that are repairable locally, even if they break down more frequently	• Consider handpumps where a viable sustainable handpump option has to be shown to work in an area	• Promote increased levels of ownership & responsibility (e.g. through cash contribution during construction)	•

Overview:
Handpumps are frequently installed on hand-dug wells and boreholes in rural areas, including many drought-prone areas. They facilitate a contamination-free method to extract water, but historically handpump functionality has been negatively affected by numerous issues related to user operation & maintenance, which in turn has resulted in a large percentage of handpumps that do not work. This section therefore looks at techniques to improve sustainability of handpump installations, as this is directly related to water availability in drought-prone areas.

Key techniques for implementation:

- Overall, it seems sensible that handpumps should be installed only when a viable sustainable handpump option has been shown to work in the area.
- Depending on pump standardization in country and depth to water table, it is preferable to choose simple technologies that do not need specialist parts and that are repairable locally. The rural poor prefer in any case to have cheaper, shorter-life technologies despite the need to maintain them more frequently.
- Even when simple technologies are chosen, it is not a guarantee that the pump will be maintained and owned. Experience in Madagascar manufacturing and installing the simple Canzee pump using standard community participation projects (where gravel, sand & labour is contributed) since 2004 showed that technical simplicity alone does not guarantee that pumps will be maintained – rather levels of ownership and responsibility are as or more important, yet difficult to generate perhaps due to lack of cash contribution during construction and lack of priority people give to water supply in general.[98]
- Centralized management of spare parts stock seems to be preferable to private sector supply chains for a variety of reasons related to the difficulties of sustaining handpump spares.[99]

[98] Personal experience of author, 2004-2010.
[99] For a discussion of the evidence and issues at stake, see: ACF-IN (2008) '*How to Make WASH Projects Sustainable and Successfully Disengage in Vulnerable Contexts: a practical manual of recommendations and good practices based on a case study of five ACF-IN water, sanitation & hygiene projects*. pp.181-183.

Surface water: Managed Aquifer Recharge (MAR)

Overview:
This section covers Managed Aquifer Recharge (MAR) techniques that are primarily used for getting surface water infiltrated in order to recharge aquifers and/or improve soil moisture for rain-fed crops, rather than techniques that are primarily designed to intercept and store water (but which may also incidentally recharge the aquifers). What is clear from research is that MAR techniques are not a substitute for demand management in resolving groundwater over-abstraction – MAR can make periodic contributions to redress quality and quantity but without demand management it is not a sustainable solution.[100]

Advantages in general:[101]
- Can facilitate recharge into surrounding ground which in turn improves soil moisture, improves agricultural productivity and recharges aquifers.
- Can lessen soil erosion and mitigate flooding.
- Can improve groundwater quality through dilution.
- Can provide a hydraulic barrier to lateral saline intrusion.

Disadvantages in general:
- Although some of the MAR techniques are simple in principle, they need a good knowledge of the physical, hydraulic, geochemical and microbiological processes in operation, and how to manage them for optimum performance.
- While it is clear that MAR has a positive impact at various levels, it is difficult to know exactly what impact MAR techniques will have on groundwater recharge, and it is possible that benefits might currently be over-emphasized.[102]
- Unknown effects on downstream users.

SUMMARY	**Technical**	**Institutional**	**Financial & economic**	**Environmental**
• Infiltration ponds	• Site in areas where the aquifer to be recharged is near the surface & base of the pond is permeable • Reduce siltation through silt traps (where the inflow channel is defined), covering base & sides of pond with a 0.5m thick layer of medium sand, using a rotational system of ponds, constructing ridges on the floor of the basin, ploughing of the basin floor • Pond depth should be correct depth (1-4 metres) • Pond size should be decided according to catchment area and number of fillings possible	• Consider promoting construction of ponds on private land where there is a direct benefit to the landowner and where de-silting is taken care of, yet where the wider community also benefits.		• Reduce siltation by keeping a good cover of perennial grasses and/or trees in the run-off area. Pasture management and user associations based on catchments can help to keep this cover.

[100] Gale, I.N.; Macdonald, D.M.J.; Calow, R.C.; Neumann, I.; Moench, M.; Kulkarni, H.; Mudrakartha, S.; Palanisami, K. (2006) *Managed Aquifer Recharge: an assessment of its role and effectiveness in watershed management*. British Geological Survey Commissioned Report, CR/06/107N. p.viii.
[101] Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP.
[102] See: Rathore, M.S. (2005) *Groundwater exploration and augmentation efforts in Rajasthan – a review*. Institute of Development Studies, Jaipur, India. See also: Palanisami, K.; Raviraj, A.; Thirumurthi, S.; Sellamuthu, K.M. (2005) *Inception Report For the research site at Kodangipalayam village, Coimbatore District, Tamil Nadu.* Water Technology Centre, Tamil Nadu Agricultural University, Coimbatore, India. p.7.

	per year			
• Contour trenches	• Site in areas with sufficient soil infiltration capacity & in natural runoff areas, but not on slopes over 10% • In order to efficiently retain all runoff in a catchment, contour trench dimensions/spacing need to be designed according to runoff volumes (calculated by the Soil Conservation Service (SCS) method using catchment area), detailed rainfall data (from which precipitation level and probable recurrence interval can be known), soil characteristics, soil infiltration rates & land use data. • Over-dimension trenches to allow for a lack of maintenance which would result in siltation and erosion of the banks. • Pilot contour trenches in an area before scaling up.	• Involve local people in design to be sure their participation continues.	• Improve access to low-cost loans with long-time repayment conditions so that farmers can replicate technology • Construct trenches primarily to favour plant growth and increase agricultural productivity rather than just as a means to increase groundwater levels = increased interest to ensure operation & maintenance.	
• Bunds	• Site bunds in natural runoff areas up to 1.5% slope where soils have sufficient infiltration capacity. Approach each site individually and to work with natural topographical features. • Do not site in clay areas, close to large water courses and where extensive levelling needed • Bund design has to be adjusted according to local conditions and experience in the area, preferably based on things like local knowledge on runoff, institutional capacity to build and manage them, soil type and rainfall intensity. • Do not underestimate runoff flows – in general, undamaged bunds are found in smaller catchments that are 4-5 times the size of the cultivated area. Smaller and more numerous	• Local people should have a good degree of control in programme implementation, and the focus should be on appropriate techniques that can be operated and maintained using local resources.	• Access to finance may be important in allowing farmers to implement bunds.	

	catchments may be preferable due to the reduced risk associated with them. • Bund height will vary from site to site, and is related to the slope of land and area to be inundated. Ideally it should allow retention of enough water to carry a crop to maturity from one single flood, without making it susceptible to large unexpected runoff flows. • Trapezoidal bunds work well in high rainfall intensity areas where spillways are located around the edge. The exact shape of the trapezoidal bund varies in shape according to the terrain. Tips of trapezoidal bunds should be reinforced with stonework to counter erosive forces as this is the edge of the spillway in these bunds. • Levelling the cultivated area within a bunded area spreads flood depth evenly. • A cut-off drain uphill of the bund allows high flows to be diverted if necessary, protecting the bund. • Bunds should be adequately compacted. • Plant drought-resistant (local) crop varieties.			
• Gully plugs / check-dams	• Site in natural runoff areas where soil has sufficient infiltration capacity. • Where earth is used, erosion or destruction of the structure needs to be avoided – to do this, a concrete spillway is often constructed. • As they use the existing drainage system, no design of trench is needed as with contour trenches.			
• Leaky dams	• Site dams so that water will not bypass the structure, where			

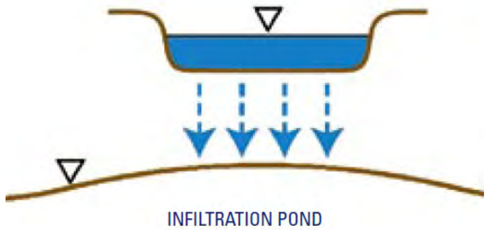
	riverbanks are equal in height and tall enough (height of dam + height of flood +10%), not near the bend in a river, and where riverbed is narrower = cheaper construction • Construct in similar way to sand dams (see "Shallow groundwater: groundwater dams" for further details) - wing walls required to avoid erosion around edges, spillway to be designed for river flow, downstream erosion of dam base avoided by making protective slab made from more rock-filled gabions. • Get the timing right: dams should be built during the dry season. • To prevent the water behind the dam percolating too quickly, adjustable sheets filled with small size gravel can be placed on the upstream side of the dam.			
• Controlled flooding	• Improvements in water distribution & moisture conservation may be more beneficial than focusing only on improving diversion structure efficiency. Where this is not yet practised, it should be promoted. • Efforts should be based on improving existing traditional low-cost intakes & diversion structures through incremental structural reinforcements, where emphasis is on provision for re-building parts of the system rather than sophisticated permanent solutions. • Physical changes to traditional systems should be made so as to be as flexible as possible, given the uncertain and highly variable nature of spate flows. • Site in areas of high volume and	• Farmers should be more involved in development of improved spate systems – the new system should build on existing practices and land rights, not undermine them as has happened in the past. • Systems should be self-reliant with regards to routine operation and repair, but some backstopping from public sector units is a good idea • Provision of bulldozers has been very popular and has enabled spate farmers to build or restore damaged structures more easily. Support however is too large for small farmer groups and is best organized on a regional basis through local government, or with subsidies to allow participation of the private		

	intensity river flows where conventional irrigation structures are not feasible, and where the practice is already in use • Simple, un-gated diversion structures made from gabions, rubble masonry or concrete are simpler for farmers to maintain using indigenous skills. Flow-restricting structures and rejection spillways need to be included at heads of canals to prevent large uncontrolled flows from damaging canals and irrigation infrastructure.	sector. • Spate systems rely on communal management and any user associations should be based on catchments or communally-used areas.		
• Drip irrigation	• Site in areas of small-scale farming where water scarcity or salinity is an issue. • The water tank capacity should be equal to one day retention of the daily water requirement. • A filter is needed prior to water entering the pipes in order to keep them clean from clogging. • The emitter design is the most important part of a drip system because it delivers water at the desired rate to the plant and also cause the most problems through blockages. • Bury main pipes underground to reduce visibility for theft		• Use the most economical system possible that will give results and that can be marketed and produced locally.	
• Well shafts & boreholes	• Site only in areas where rainwater does not infiltrate fast enough. • Avoid siting where there is a risk of chemical contaminants entering the well (e.g. fertilizers and pesticides from agriculture) and when the final water abstracted will be used for drinking. • Recharge of untreated water should infiltrate through a soil or sand layer before entering the aquifer & water point – this layer should be 1.5m above the water table and 5 metres from an			• Reduce the speed of the water as much as possible to avoid the pond from filling up with sand and clay – this can already be done by planting grasses and other catchment methods.

	abstraction point such as a hand dug well. • Site recharge well “upstream” from a well or borehole that dries up in the dry season. • When taking water directly from a roof, ensure that the downpipe has a sieve on the inlet and a first flush system. • When recharging untreated water, use a PVC cover piece to prevent too many sediments entering the pipe which is removed only 4 hours after rainfall.			

Infiltration ponds

Overview:
Infiltration ponds are large open water ponds that are either excavated or in an area of land surrounded by a bank, and normally will not exceed 15,000m^3. They store rainwater but with the main aim of infiltrating the water to aquifers where it can be extracted using wells or from springs. They are constructed in areas where the base of the pond is permeable and where the aquifer to be recharged is at or near the surface. Examples include dune infiltration ponds in South Africa, Tajamar ponds in Paraguay, and infiltration basins in Niger. Large dams can also be used to artificially recharge aquifers – in Jordan, one dam was constructed to recharge a well field 8km from the dam site, and experience from the past 6 years shows that groundwater levels have increased by 25-40 metres.[103] In Nepal, small ponds traditionally helped to recharge spring water.[104]



Infiltration pond
Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP.

Key techniques for siting:
- The aquifer to be recharged needs to be at or near the surface.
- The base of the pond needs to be permeable. Typical hydraulic loadings are 30 m/year for fine texture soils (e.g. sandy loams), 100 m/year for loamy soils and 300 m/year for coarse clean sands.[105] A field method to determine seepage rates in the bottom of reservoirs has been developed which can be used to assist in design.[106] Ideally infiltration rates should exceed evaporation rates.

Key techniques for construction:
- The main issue is to minimize silting, as this will reduce infiltration capacity through the base and sides. There are several techniques to minimize this:[107]
  - Any diversion and intake structures should be made so as to minimize input of silt to the ponds. Sedimentation basins can act reduce silt load before water enters infiltration pond. What might work better is to keep a good cover of indigenous grasses in the run-off area. Kambiti Farm in Kitui District provides a good example of previously degraded land being managed and where open dams did not silt up due to pasture management.[108] Contour lines with trees or grasses in the runoff area also work.[109] If the

[103] Steenbergen, F.V.; Tuinhof, A. (2009) *Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retention, Reuse and Rainwater Storage.* BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), the Co-operative Programme on Water and Climate (CPWC) and the Netherlands National Committee IHP-HWRP. pp.18-21, 26-29, 30-33, 44-46, 68.
[104] Merz, J.; Nakarmi, G.; Weingartner, R. (2004) Potential Solutions to Water Scarcity in the Rural Watersheds of Nepal’s Middle Mountains. *Mountain Research and Development* Vol 23 No 1 Feb 2003: 14–18.
[105] Bouwer (2002) in :Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.11.
[106] See: Dekker, T.; Rodrigues, L. N.; Olsthoorn, T.; Giesen, N. van de (2009) *Deep Seepage Assessment in Small Reservoirs.* Small reservoirs toolkit. Available from www.smallreservoirs.org. See also: Dekker, T. (2007) *Modeling the Buriti Vermelho Catchment: In Search of the Best Model with Low Data Availability.* MSc thesis, TU Delft, The Netherlands.
[107] Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.11.
[108] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya.* SASOL / Maji Na Ufanisi, Nairobi, Kenya.

inflow channel is defined, silt traps can be tried out to reduce silt load as is done with Charco dams in Tanzania. In this case, stones laid across the channel form mini dams and perennial vegetation can be grown between these mini dams to reduce flow velocity of water, thereby encouraging silt deposition.[110]
  - Where aquifer material is fine, clogging may occur rapidly but can be delayed by covering the base and sides of the pond with a 0.5m thick layer of medium sand.
  - A rotational system of ponds can allow some to dry while others are used – the ones that dry up can be scraped to restore infiltration rates, while the drying process kills of algae. In this case, the pond should be shallow enough to allow rapid draining when scraping is needed.
  - Constructing ridges on the floor of the basin and controlling water level can allow fine silt to deposit in troughs, allowing most infiltration to take place on the sides of the ridges.
  - Mechanical ploughing of the floor of the basin can increase permeability.
- De-silting will most probably need to be carried out at some stage. There may be more sustainable ways of doing this compared to the usual approach used in the recovery stage of DCM, where this process is often paid for by NGOs and where there is a lack of community will to contribute. Experience of infiltration ponds in India shows that securing participation is very difficult to achieve when users/farmers do not see any direct benefit from the ponds.[111] An institutionally-resilient way to de-silt (or even construct) ponds may be to promote ponds on private land, where one landowner has a vested interest to maintain and de-silt the pond, thus reducing the need for NGO intervention in the longer run. Experience in India seems to support this where the farmer providing the land for the *johad* (pond) would be the prime beneficiary, of the recharged water on adjacent land, but where the community also benefited.[112]
- Pond depth should be deep enough to prevent excessive algae and water plant growth, but not too deep so that anaerobic conditions are avoided – this means a depth of between 1-4 metres.[113]
- Pond size should be decided according to catchment area and number of fillings possible per year.[114] In order to efficiently capture runoff in a catchment, similar design techniques to contour trenches (see appropriate section) could be employed for infiltration ponds.

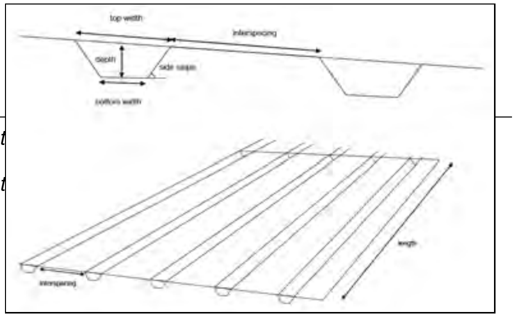
Key techniques for extraction of water:
- Boreholes, hand-dug wells and possibly springs in vicinity.

Advantages:
- Facilitate recharge into surrounding ground which in turn improves soil moisture, improves agricultural productivity and mitigates against drought.
- Can assist recharge of shallow wells, boreholes and springs.
- Can reduce salinity in groundwater.

Disadvantages:
- They can silt up easily due to lost vegetation cover in catchment area. De-silting takes time and money.
- Maintaining dams requires communal effort and communal institutions don't seem to be strong enough.
- High evaporation rates.
- High cost of construction – in India, costs estimated at $5,000-10,000 for ponds that are 10,000-15,000m^3 in volume.[115] This is similar to other non-percolation ponds (see "Natural ground catchment & open water reservoir" for details).

<u>Contour trenches</u>

Overview:
Contour trenches are not irrigation channels, rather they are trenches dug to slow down and attract runoff water which then infiltrates into the soil. Small scale contour trenches can also be used within field level.



Contour trenches
Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam.* Final Report Executive Summary. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands.

[109] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, const* pp.58-60.
[110] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, const* pp.25, 58-60.
[111] www.fao.org/docrep/W7314E/w7314e0q.htm
[112] Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.22.
[113] NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions.* Netherlands Water Partnership. p.47
[114] www.fao.org/docrep/W7314E/w7314e0q.htm
[115] www.fao.org/docrep/W7314E/w7314e0q.htm

Key techniques for siting:

- Locate trenches in natural runoff areas, but not on slopes over 10%.[116]
- Soil in vicinity needs to have sufficient infiltration capacity and potential sub-surface storage capacity.

Key techniques for construction:

- In order to efficiently capture runoff in a catchment through appropriately sized trenches, the following information and analysis is needed:[117]
    - Catchment area, gathered from topographical maps
    - Detailed rainfall data which is used to create a rainfall frequency analysis where precipitation level and probable recurrence interval.
    - Using this data, the predicted runoff for a particular intensity of rainfall can be shown using the Soil Conservation Service (SCS) method, which is a simple way to calculate runoff in ungauged catchments. To calculate runoff, the following is needed: precipitation for a particular rainfall recurrence interval (e.g. 5 years), catchment area, soil characteristics, and land use in catchment. For a given recurrence interval, the total amount of runoff for the catchment can then be calculated.
    - Soil infiltration rates based on physical soil investigations on site.
    - Total trench capacity can then be determined that can store the runoff volume minus what would infiltrate in the trenches during the rainfall event.
    - Trench dimension and spacing in the catchment can then be calculated. This then has to be checked with local preferences and adjusted accordingly. Trenches in Vietnam were originally designed as rectangular trenches 4m wide by 1m deep, but modified according to requests from local people to trapezoidal trenches 2.5m wide at top and 1m wide at base and 0.75m deep.[118] Trenches should also then be over-dimensioned to allow long-term runoff volume to be stored despite a lack of maintenance – things like siltation and erosion of the banks will reduce infiltration capacity and volume over time.
- It seems wise to pilot contour trenches in an area before scaling up.
- Trenches are dug in line with topographical contours.
- Constructing trenches primarily to favour plant growth and increase agricultural productivity (as was the case in Vietnam) rather than just as a means to increase groundwater levels, seems to be a good approach because there can be increased interest to ensure operation & maintenance of the trenches (in Vietnam, people wanted to establish a group of landowners to take care of the structures in order to ensure continued crop yields.[119] The knock-on effects on shallow groundwater levels are thereby made sustainable since the primary concern for people was an economic one.
- Excavated soil can be used to fill up existing gullies.
- Involvement of local people in the design of the project ensures that their participation continues.
- In Vietnam, after trenches were completed farmers were discussing ways to access to low-cost loans with long-time repayment conditions so that they could replicate the technology. Access to finance therefore seems to be important in scaling up this technology.[120]

Contour trench
Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam.* Final Report Executive Summary. Royal Haskoning, / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands.

Key techniques for extraction of water:

- Water that infiltrates is used as soil moisture for crops cultivated after a rainfall event.
- Water can also be used directly for pumped irrigation.
- Shallow wells in the area can be used.

Advantages:

- The Project Impact Assessment from the Vietnam project showed that positive impacts were that trenches facilitate recharge into surrounding ground which in turn improves soil moisture, they improve agricultural productivity and grazing potential, increase water for livestock and therefore mitigate against drought. They also reduce soil erosion.[121]

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[116] NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions*. Netherlands Water Partnership. p.55

[117] Based on information in: Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam.* Final Report. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands. pp.82-85.

[118] Ertsen, M. (2009) *Re-hydrating the Earth by Contour Trenching in Vietnam: Summary of the Hydrological Research within the Partners for Water project "Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam".* TU Delft, The Netherlands.

[119] Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam.* Final Report Executive Summary. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands. p.3 & 15.

[120] Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam.* Final Report Executive Summary. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands. p.17.

- Can assist recharge of shallow wells. Experience from Vietnam showed that in 5 out of 7 shallow wells that were near the trenches with water tables of between 3 and 18 metres below ground level, showed an increase in water levels after rainfall events of over 60mm because of infiltration from the contour trenches.[122]
- Can reduce salinity in groundwater.
- Gully plugs: no trench design required, just uses existing gully drainage pattern.

Disadvantages:

- It seems that recharge of groundwater is not certain according to local sub-surface conditions – in Vietnam, water levels in 2 out of the 7 wells near the trenches were unaffected.[123] This is probably due to certain geological layers blocking infiltration. So it is always a possibility that trenches will not affect water levels.
- Trenches silt up and will need maintenance.
- Lack of understanding by landowners about advantages of contour trenches = difficult to convince them during the first year to give their land for trench construction (experience of Vietnam).
- Can increase land fragmentation.
- Costly and in-depth analysis of hydrology/runoff gullies, recharge capacity/permeability needed which is difficult if no in-depth rainfall data available.
- Expensive cost of implementation where mechanical excavating machinery is used. Cost of excavation in Vietnam was around 1,000 Euro per hectare.[124]

<u>Bunds</u>

Overview:
Bunds are small barriers to runoff coming from external catchments to the field where crops are to be grown. They slow down sheet flow on the ground surface and encourage infiltration. They can vary in design and include non-enclosed systems (e.g. trapezoidal bunds where water escapes around the edges), and enclosed systems (e.g. bunded fields where water enters via a channel and escapes from a spillway in the bund once the field is flooded). In certain site-specific examples, they are used to create small artificial glaciers which are created in order to release melt water to time better with short sowing seasons.

Other types of similar techniques exist, but at smaller scale and within the field scale rather than on a larger scale of collecting runoff from elsewhere. Technically these function in a similar way as bunds to slow down and retain runoff water, but they are not really researched or documented thoroughly regarding which type works better and in what conditions. These are not dealt with in detail here but include:[125]

  - Strip cultivation & contour ridges = crops planted in lines along contour, with unplanted areas between rows that maximize runoff into cultivated areas.
  - Vetiver grass (or other indigenous grass) can be planted in contours, spaced every 1 metre drop in elevation. Vetiver grass has the advantage that it does not spread to fields, and cattle do not like to eat it.[126]
  - Micro-catchments = similar to strip cultivation where upslope land allocated for runoff, which is harvested downslope – catchment to cultivated area ratio ranges from 1:1 to 5:1.
  - Pitting systems = shallow planting holes dug for concentration of surface runoff
  - Demi-lunes and negarims = micro-catchments using semi-circular bunds (demi-lunes) or square areas enclosed by bunds turned 45 degrees to contour to concentrate water at one end (negarims).
  - Conservation tillage = tillage that reduces soil disturbance and therefore minimize soil and water loss.
  - Trash lines = made of crop residues that are concentrated to form organic bunds along the contour. Grass & weeds stabilize them in 2 years.
  - Terraces (e.g. Fanya Juu) = trench dug along contour, where soil is thrown uphill.

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[121] Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam.* Final Report Executive Summary. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands. p.10-11

[122] Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam.* Final Report Executive Summary. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands. p.12

[123] Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam.* Final Report Executive Summary. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands. p.12.

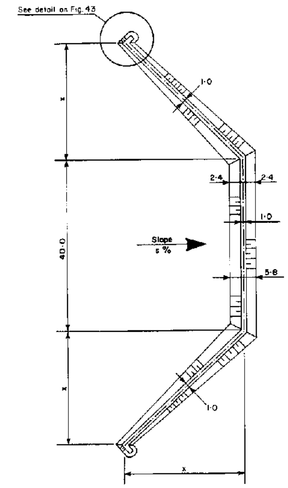
[124] Based on information in: Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam.* Final Report Executive Summary. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands. p.41.

[125] See: http://www.fao.org/docrep/U3160E/u3160e07.htm#5.8.2%20technical%20details. Also see: Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs.* Stockholm International Water Institute.

[126] NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions.* Netherlands Water Partnership. p.49

Key techniques for siting:

- Locate bunds in natural runoff areas, preferably in sites already shaped by topography – indicators include seeing where water flows during flood times, and soil / vegetation types. The key is to approach each site individually and to work with natural topographical features – experience in the area will influence the design.[127]
- Avoid the following areas:[128]
    - Clay areas – bunds made from soil with high clay content develop leaks through pipes in the bund structure which form due to cracks when it dries.
    - Proximity to large water courses.
    - Sites needing extensive levelling.
- Soil in vicinity needs to have sufficient infiltration capacity.
- Ideally the slope should not be greater than 1.5% otherwise earthworks get prohibitive.[129]
- For artificial glaciers, altitude needs to be over 4,600 metres.[130]



Trapezoidal bund
FAO -
http://www.fao.org/docrep/u3160e/u3160e1q.gif

Key techniques for construction:

- In general it seems that there are no universal principles or standard designs that would apply everywhere. Experience from Turkana shows that bund design has to be adjusted according to local conditions, preferably based on things like local knowledge on runoff, institutional capacity to build and manage them, soil type and rainfall intensity. A key aspect is that local people should have a good degree of control in programme implementation, and the focus should be on appropriate techniques that can be operated and maintained using local resources. However, social/institutional constraints are not the only (or even primary) concern when building bunds – it is clear from Turkana experience that technical considerations are often overlooked.[131] A few lessons learned are listed here which might apply generally:
    - In Turkana, the erratic nature of rainfall intensity and lack of good rainfall data meant that designing bunds based on certain assumed runoff coefficients was difficult - sometimes runoff was vastly underestimated, and this was the reason for 90% failure rate of earthworks during the first 2 years of a large bund building programme where high runoff flows damaged bunds.[132] The Turkana experience showed that undamaged bunds were related to catchment size – smaller catchments that were 4-5 times the size of the cultivated area were not damaged, whereas larger catchments caused bunds to be overtopped due to under-designed spillways. Smaller and more numerous catchments were therefore deemed to be preferable due to the reduced risk associated with them.[133]
    - Bund height will vary from site to site, and is related to the slope of land and area to be inundated. The challenge it seems is to size the field/bund area to ensure retention of enough water to carry a crop to maturity from one single flood, without making it susceptible to large unexpected runoff flows – in Turkana this meant designing bunds to allow 30cm of flood depth (confirmed by local knowledge), while in India it meant a flood depth of 15cm.[134]
    - Trapezoidal bunds work well in high rainfall intensity areas, and spillways around the edge worked better than spillways in the centre of the bund where erosional forces were concentrated. Even stone-faced spillways (as per Israeli design) were not always robust. Therefore type of bund has to be applicable to the local conditions. The exact shape of the trapezoidal bund varies in shape according to the terrain.[135]
    - Turkana experience showed a few tips for construction of trapezoidal bunds. Levelling the cultivated area within a bunded area is a good thing to do since it spreads flood depth evenly. A cut-off drain uphill of the bund allows high flows to be diverted if necessary, protecting the bund. Tips of trapezoidal bunds should be reinforced with stonework to counter erosive forces as this is the edge of the spillway in these bunds. Low-tech levelling devices help uneducated people to be trained in designing their own bunds.[136]

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[127] Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. p.26, 73, 89.
[128] Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. p.89.
[129] http://www.fao.org/docrep/U3160E/u3160e07.htm#5.8.2%20technical%20details
[130] http://ipsnews.net/news.asp?idnews=49369
[131] Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. pp. 86-87, 116-118.
[132] Sometimes bunds were designed for runoff coefficients of 18% where in reality it sometimes increased to 64%. See: Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. pp.86-87.
[133] Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. p.29, 91. In Sudan, catchments are even only 2-3 times the cultivated area – see www.unep.or.jp/ietc/Publications/TechPublications/TechPub-8a/bunds.asp
[134] Steenbergen, F.V.; Tuinhof, A. (2009) *Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retention, Reuse and Rainwater Storage*. BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), the Co-operative Programme on Water and Climate (CPWC) and the Netherlands National Committee IHP-HWRP. pp.56-58.
[135] Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. pp.31, 88
[136] Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. pp.31, 117-118.

- Bunds should be adequately compacted. If animals are used to create the bunds, they can help to compact the soil with their hooves.[137] It also seems best to make bunds in the middle of the dry season so that they can settle under impact of human and livestock movement, in order to make them sturdy enough for the rainy season. [138]
  - Experience from South Africa indicates that access to finance therefore seems to be important in allowing farmers to implement bunds.[139]
  - Due to the uncertain nature of flood events, it is important to plant drought-resistant (local) crop varieties in the fields which give better results.[140]
- In the site-specific case of artificial glaciers, the following methods are used:
  - Before the onset of winter, water is channelled from existing streams through 1.5" GI pipes into shadow areas of mountains close to villages. The water is made to flow out onto a sloping hill face where at regular intervals along the mountain slope, small stone embankments are situated to impede the flow of water which helps to create shallow pools. These pools freeze rather than infiltrate, but water is later released for crop irrigation prior to the usual time when snow melts on mountain tops. In this way, water is available more reliably for crops during a very short sowing season.[141]

Key techniques for extraction of water:
- Water is not extracted, it is only used for improving soil moisture.

Advantages:
- Can assist recharge of shallow wells.
- Can reduce salinity in groundwater.
- Smaller scale = ownership possible = higher rate of success.[142]

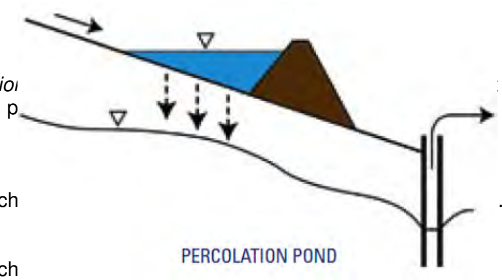
Disadvantages:
- High cost and effort involved in certain kinds of earthworks, which can be a problem for poorer families or vulnerable families (e.g. single headed households). One way to address this to reduce donor dependency might be to use grain from harvests to pay off a loan that was used for the earthworks.[143] Artificial glaciers in India were costing around $6,000 but it depends on the site. [144]
- Breached bunds will require repair work.
- Sometimes it seems difficult to convince farmers of the gain to be had from using the techniques.
- Sedimentation within bunded areas means that bunds have to be regularly heightened.[145]

<u>Gully plugs / check-dams</u>

Overview:
Gully plugs or check-dams are earth or concrete overflow weirs constructed in natural gullies in the land surface, which impede water with the same result as contour trenches, although they may be more categorized as a type of floodwater rather than runoff harvesting technique. They have been used widely in Kenya and India. These dams can also be made as leaky dams (see section below). Sand dams that have been built in riverbeds with no coarse sand transport may end up being used in this way.

Key techniques for siting:
- Locate in natural runoff areas
- Soil in vicinity needs to have sufficient infiltration capacity.

Key techniques for construction:



Check dam / gully plug
Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP.

137 Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. p.89.
138 Steenbergen, F.V.; Tuinhof, A. (2009) *Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retentio* … für Geowissenschaften und Rohstoffe), the Co-operative Programme on Water and Climate (CPWC) and the Netherlands National Committee IHP-HWRP. p
139 Wilk, J.; Wittgren, H.B. (eds). (2009) *Adapting Water Management to Climate Change*. Swedish Water House Policy Brief Nr. 7. SIWI, 2009. p.10.
140 Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. p.95.
141 http://news.nationalgeographic.com/news/2001/08/0830_artglacier.html
142 Dijk, J. A. van (1995) *Taking the Waters. Soil and water conservation among settling Beja nomads in Eastern Sudan*. African Studies Centre Research
143 Cullis, A.; Pacey, A. (1992) *A development dialogue: rainwater harvesting in Turkana*. IT Publications, London, UK. p.116.
144 http://ipsnews.net/news.asp?idnews=49369
145 Dijk, J. A. van (1995) *Taking the Waters. Soil and water conservation among settling Beja nomads in Eastern Sudan*. African Studies Centre Research

- These can be made of temporary or permanent materials in natural gullies in the land surface. Materials used are concrete, earth, vegetation, stone and brushwood.[146] Where earth is used, erosion or destruction of the structure needs to be avoided – to do this, a concrete spillway is often constructed.
- As they use the existing drainage system, no design of trench is needed as with contour trenches.

Key techniques for extraction of water:
- Water that infiltrates is used as soil moisture for crops cultivated after a rainfall event.
- Water can also be used directly for pumped irrigation.
- Water can also be used from shallow wells and boreholes in the immediate area.

Advantages:
- Can assist recharge of shallow wells.
- Can reduce salinity in groundwater.
- Reduces velocity of water = less erosion & sediment transport
- No trench design required, just uses existing gully drainage pattern
- Cost effective – these dams can use locally available materials. Cost in India reported to be between $200-400 for temporary dams (made from brush wood, rocks, soil) and $1,000-3,000 for permanent dams (made from stones, bricks, cement). Variation depends on materials used and size of gully.[147]

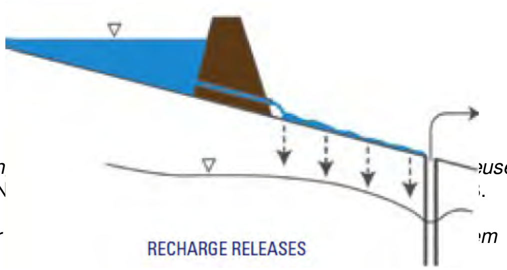
Disadvantages:
- They can silt up and will need maintenance
- Levels of infiltration can be slow due to silt build-up.
- Unclear land tenure can result in ownership of the structure.[148]

<u>Leaky dams</u>

Overview:
A floodwater harvesting technique, these are permeable structures built across seasonal riverbeds which retain flash flood water that has a high silt load. The idea is to retain the high-energy floods and stimulate settlement of suspended sediment behind the dam. Water with a lower sediment load is then available to leak through the dam and infiltrate the downstream riverbed which is not blocked by sediment deposits. They have been proven to be able to recharge local aquifers.

Key techniques for siting:
- Good practice is somewhat similar to that for sand dams – see Groundwater Dams section for further details:
    - Ensure they are not built in an area where water will bypass the structure.[149] Riverbanks should be equal in height and tall enough (height of dam + height of flood +10%)[150], and dam should not be constructed near the bend in a river.
    - Site where river is narrower = cheaper construction.

Key techniques for construction:[151]
- Good practice is somewhat similar to that for sand dams (see "Shallow groundwater: groundwater dams" section for further details):



Leaky dam
Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP.

[146] www.fao.org/docrep/W7314E/w7314e0q.htm. Also: Steenbergen, F.V.; Tuinhof, A. (2009) *Managing the Water Buffer for Development and Climate Chan… …use and Rainwater Storage*. BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), the Co-operative Programme on Water and Climate (CPWC) and the N… .
[147] www.fao.org/docrep/W7314E/w7314e0q.htm
[148] E.g. in Ethiopia, this issue led to progressive abandonment of cropping in gullies. See: Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water… …m analysis and research needs*. Stockholm International Water Institute.
[149] VSF (2006). *SubSurface Dams : a simple, safe and affordable technology for pastoralists. A manual on SubSurface Dams construction based on an experience of Vétérinaires Sans Frontières in Turkana District (Kenya), September 2006.* p.21.
[150] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.12.
[151] Information from: Kahlown, M.A.; Abdullah, M. (2004) Leaky Dam to Rejuvenate Depleting Aquifers in Balochistan. *Pakistan Journal of Water Resources*, Vol.8 (2) July-December, 2004. Also: Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.24

- Construct wing walls to avoid erosion around edges.
  - Spillway is designed for river flow, and therefore varies according to the site.
  - Avoid downstream erosion of dam base by making protective slab made from more rock-filled gabions.
  - Get the timing right: dams should be built during the dry season, but don't build dams too close to the rains in order to avoid dam being washed away.
- The dam can be made from rocks of various sizes (boulders, cobbles, stones, large gravel) that are found in and around the riverbed. In Pakistan, rocks of 200mm diameter were used.
- In Balochistan, the rocks are held within wire mesh nets that are built in 5 steps to total height of 4.9 metres. The exact height of the dam will vary and depend on the riverbed topography.
- A reinforced concrete cut-off 1.5 metres deep and 2 metre toes on both sides of the dam ensure stability.
- To prevent the water behind the dam percolating too quickly, experience in Pakistan has shown that it helps to put adjustable sheets filled with small size gravel on the upstream side of the dam body.

Leaky dam
Partners voor Water (2009) *Re-hydrating the earth by sustainable, small-scale sub-surface water retention techniques, Vietnam.* Final Report Executive Summary. Royal Haskoning / Westerveld Conservation Trust / IHE Delft, Nijmegen, The Netherlands.

Key techniques for extraction of water:
- Water that infiltrates is used as soil moisture for crops cultivated after a rainfall event.
- In Balochistan, pipes have been added on top of the 2nd and 4th steps which discharge surplus water downstream.
- Water can be used via shallow wells and boreholes in the area.

Advantages:
- Can assist recharge of shallow wells.
- Can reduce salinity in groundwater.
- Reduces velocity of water = less erosion & sediment transport.
- Since most of the sediment settles out behind the dam, water is free to infiltrate in a sediment-free area downstream. If the main aim is infiltration of the water to recharge groundwater, then this is the main advantage of leaky dams over the similar technology of gully bunds / check dams.

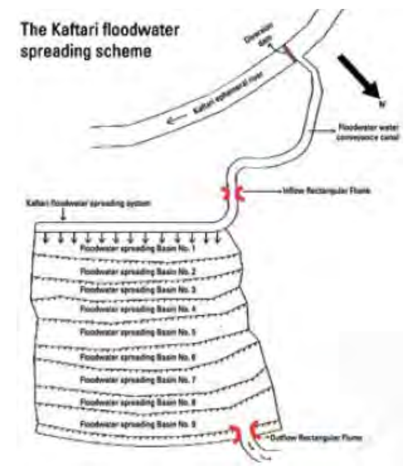
Disadvantages:
- They can silt up and will need maintenance.
- Possible similar issue as with gully plugs, namely unclear land tenure can result in ownership of the structure.
- Cost – a 5-step dam 4.9 metres high cost around $26,000 to construct.[152]

<u>Controlled flooding / irrigation</u>

Overview:
This is a floodwater harvesting technique where water is diverted from a river and with the help of diversion structures and canals, is spread evenly over a large surface area where it is used for irrigation, filling ponds, watering grazing land and recharging groundwater. The concept is that a thin sheet of water flows over the land but at minimum velocity in order to avoid disturbing the soil cover. This includes spate irrigation, but also standard channel irrigation which takes river water via channels to fields – only the former is focused on in this section.

Key techniques for siting:
- In areas of high volume and intensity river flows where conventional irrigation structures are not feasible.
- Spate systems should probably be promoted in areas where the practice is already in use.

Key techniques for construction:[153]
- In general, experience of projects since the 1970's has shown that:



Controlled flooding
Esfandiari, M.; Rahbar, G. (2006) Monitoring of inflow and outflow rate from Kaftari artificial recharge of groundwater system in Dorz-Sayban Region in Southeastern Iran. Section 9, pp. 149-158. In: B. Neupane, R. Jayakumar, A. Salamat and A. Salih (eds.), *Management of Aquifer Recharge and Water Harvesting in Arid and Semi-arid Regions of Asia.* UNESCO and IHP, Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi, India.

152 Kahlown, M.A.; Abdullah, M. (2004) Leaky Dam to Rejuvenate Depleting Aquifers in Balochistan. *Pakistan Journal of Water Resources*, Vol.8 (2) July-December, 2004.
153 Information taken from: Steenbergen, F. van; Lawrence, P.; Mehari Haile, A.; Salman, M.; Faurès, J.-M. (2010) *Guidelines on spate irrigation.* FAO irrigation and drainage paper 65. FAO, Rome, Italy.; Also see: *Summary report.* Proceedings of the Subregional Expert Consultation on Wadi Development for Agriculture in the Yemen 1987. Both are available at www.spate-irrigation.org

- It is better to concentrate efforts on low-cost diversion structures and to avoid sophisticated technological solutions, and that efforts should be based on improving existing intakes.
- Farmers should be more involved in development of improved spate systems – the new system should build on existing practices and land rights, not undermine them as has happened in the past.

- Spate floods are variable and difficult to predict using conventional rainfall-runoff models because rainfall is often not correlated to runoff in ephemeral rivers that feed spate systems. Large scale permanent structures built to resist the hostile conditions of full river flow are economically unfeasible and also still prone to damage and siltation. Siltation brings nutrients but is also this creates one of the major difficulties with spate irrigation – sediment load tends to be between 3-10% in seasonal rivers that feed spate systems, with particle size varying from silt to boulders. Silt causes problems of silting up channels, raising farmland and causing river courses to change direction and miss the diversion structure altogether. There are also large quantities of floating debris which can cause problems for intakes. The following are recommended:[154]
    - Provision for re-building parts of the system after major floods can be a more cost-effective option than designing more permanent structures. Traditional diversion structures work well at fraction of cost of other types and also work better – they can breach in high floods = heavy silt-laden water does not come out onto land.[155]
    - Improvements in water distribution and moisture conservation may be more beneficial than focusing only on improving diversion structure efficiency (see “Bunds” section). Where this is not yet practised, it should be promoted.
    - Physical changes to traditional systems should be made so as to be as flexible as possible, given the uncertain and highly variable nature of spate flows. Traditionally, spate irrigation has incorporated this flexibility with farmers moving to different areas when needed.
    - Incremental structural reinforcements to existing traditional intakes have been proven as cost-effective and successful than larger scale interventions.
    - Simple, un-gated diversion structures made from gabions, rubble masonry or concrete are simpler for farmers to maintain using indigenous skills. Flow-restricting structures and rejection spillways need to be included at heads of canals to prevent large uncontrolled flows from damaging canals and irrigation infrastructure.
- Systems should be self-reliant with regards to routine operation and repair, but some backstopping from public sector units is a good idea:
    - Spate systems rely on communal management and dialogue due to their scale. Projects should not attempt to unnecessarily formalize agreements for maintenance – farmers should be the drivers for this. However, any user associations should be based on catchments or communally-used areas.[156]
    - Provision of bulldozers has been very popular and has enabled spate farmers to build or restore damaged structures more easily. Problems with that is that sometimes downstream effects become too great since farmers upstream can build much larger structures, and also that bulldozers cannot easily be run and maintained in a self-sustaining fashion due to high costs. Support is therefore too large for small farmer groups and is best organized on a regional basis through local government, or with subsidies to allow participation of the private sector.

Key techniques for extraction of water:

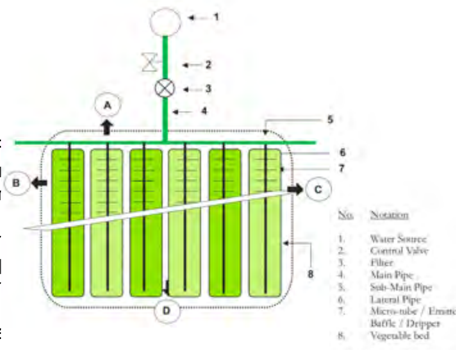
- Water is not extracted, it is only used for improving soil moisture.

Advantages:

- Minimum land preparation is needed, so is very cost-effective compared to other infiltration methods.
- Most of the sediment load in the river water will settle on the land (e.g. 70%) – this can be advantageous for agriculture. The system can also be very good at infiltrating runoff water – measurements in Iran showed that 83.5% of the river water was infiltrated.[157]

Disadvantages:

- Large surfaces of land have to be made available for it to work.
- River flows in ephemeral rivers can be unpredictable in time and volume = unpredictable spread on the land and damage to structures.



Low-cost drip irrigation system
IDE/CGIAR (2007) *Technical manual for IDEal micro irrigation systems.*
IDE – International Development Enterprises / CGIAR, Lakewood, USA.

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[154] Detailed design available from: Steenbergen, F. van; Lawrence, P.; Mehari Haile, A.; Salman, M.; Faurès, J.-M. (2010) *Guidelines on spate irrigation.* F ... ally. See also: Ratsey, J. (2008). *Design manual volume 2: guidelines for wadi diversion and protection works*. The European Union’s Food Security Programme fo ... oment Authority. See also: European Union (2008) *Design manual volume 1: Technical design criteria*. The European Union’s Food Security Programme for Yen ... it Authority. All available from www.spate-irrigation.org

[155] Steenbergen, F.V.; Tuinhof, A. (2009) *Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retentior* ... lt für Geowissenschaften und Rohstoffe), the Co-operative Programme on Water and Climate (CPWC) and the Netherlands National Committee IHP-HWRP. p

[156] Such associations have worked well with large scale irrigation in India – see: Wilk, J.; Wittgren, H.B. (eds). (2009) *Adapting Water Management to Clin* ... 7. SIWI, 2009. p.11

[157] In the spreading system in Kaftari, Iran, 70% of the suspended load in the river was settled on the land. See: Gale, I. (Ed) (2005) *Strategies for Manage* ... MAR and UNESCO-IHP. p.23.

- Too much sediment load in the river water can reduce recharge rates over time. High deposition of sediments also means farmland level gets raised above village = village floods. Also riverbanks can breach as a result.[158]
- Labour intensive work to create embankments for conveying storm water (in Eritrea, banks are between 5-10 metres high).[159]
- Unintentional negative impacts on water downstream when not carefully designed. This is especially the case in rivers where the floodwater never reaches the sea – in this case, all water is already allocated in the basin and withdrawal in one place will be more likely to negatively affect another.

Drip irrigation

Overview:
Micro irrigation includes drip irrigation and sprinkler systems. Drip irrigation provides farmers the most efficient way to grow crops in water scarce areas through providing water at a controlled and regular rate to the root zone. Historically it has been too expensive for small-plot farmers, but now it is available at low cost and also adapted for small-scale farming and can reduce water losses by 30 - 70% when compared to conventional methods of crop irrigation, while greatly reducing labour and accurately delivering fertilizers. This makes cultivation during the dry season possible, with resulting yield increases of up to 30%.[160]

Key techniques for siting:
- Drip irrigation is suitable for any plot under 0.4 hectare (one acre), but their modular design allows for expansion above that.

Key techniques for construction:[161]
- Use the most economical system possible that will give results. IDE in Cambodia lowered the cost of drip systems by:
    - Replacing conventional emitters with holes and micro tubes
    - Shifting water distribution lines extending to crops
    - Customizing system layouts for small plots
    - Reducing cost of water storage – the use of a hanging plastic water storage bag also lowers the cost. Experience shows that costs are reduced by three-quarters by doing this, resulting in cost of about $5 for a 200 litre bag that will cover 20 m^2.
- The water tank capacity should be equal to one day retention of the daily water requirement. It should be placed at sufficient height to allow flow by gravity – approximately 1 metre height for an area of 100m^2, 1.5 metres for 500 m^2, and 2 metres for 1,000m^2.
- A filter is needed prior to water entering the pipes in order to keep them clean from clogging.
- Pipes vary in size and are made from varieties of polyethylene (PE) and soft PVC.
- The emitter is the most important part of a drip system because it delivers water at the desired rate to the plant and maintains water application uniformity over the entire irrigated area. An emitter should match particular field conditions including type of crop, spacing of the plants, terrain, water requirement, water quality, operating time and pressure head. At the same time, the emitters cause the most problems through blockages (particles, salts or algae) and need to be maintained.
- Try to bury main pipes underground to reduce visibility for theft.

Key techniques for extraction of water:
- Water is not extracted, it is only used for improving soil moisture.

Advantages:[162]
- Uses commonly extruded plastic pipes, so low-cost systems are replicable in many countries.
- Low cost – in Nepal, costs ranged between $0.11 and $0.17 per m^2 of irrigated area, depending on the scale of irrigation.[163]
- Water-saving compared to other methods.

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[158] Steenbergen, F. van; Lawrence, P.; Mehari Haile, A.; Salman, M.; Faurès, J.-M. (2010) *Guidelines on spate irrigation*. FAO irrigation and drainage paper 65. FAO, Rome, Italy. p.208. Available from www.spate-irrigation.org
[159] Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.
[160] See: http://www.ideorg.org/OurTechnologies/DripIrrigation.aspx. See also: Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.
[161] IDE - International Development Enterprises / CGIAR (2007) *Technical manual for IDEal micro irrigation systems*. IDE/CGIAR, Lakewood, USA.
[162] IDE - International Development Enterprises / CGIAR (2007) *Technical manual for IDEal micro irrigation systems*. IDE/CGIAR, Lakewood, USA.
[163] Mikhail, M.; Yoder, R. (2008) *Multiple use water service implementation in Nepal and India: experience and Lessons for scale-up*. IDE, CPWF and IWMI. p.37.

- Salt concentration in root zone is reduced due to regular application of water.
- Improved yields and quality of crop. Since water is given at regular but frequent intervals and at a required quantity as compared with traditional systems, plants have better metabolism and produce a better crop in terms of both quality and quantity. The soil-water-air ratio is also favorable for most cash crops.
- Roots are very well developed when using drip irrigation – such systems provide the proper soil-air-water ratio for root respiration.
- Labour-saving.
- Saves fertilizer.

Disadvantages:
- Possibilities of theft.
- Damage by rodents.

Well shafts & boreholes

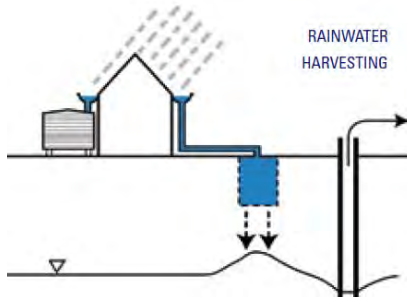
Overview:
Large diameter wells and smaller diameter boreholes can be used to directly recharge or dilute aquifers where low permeability strata overlie the aquifers and where other infiltration methods are not effective. The important thing is that water of high enough water quality is used for this purpose. Although this method of recharge is practised with deep and high-yielding boreholes, this technique mainly describes recharge at family level in areas where hand dug wells run dry at the end of the dry season or where groundwater is saline – this is a relatively new technique and is still being developed.

Key techniques for siting:

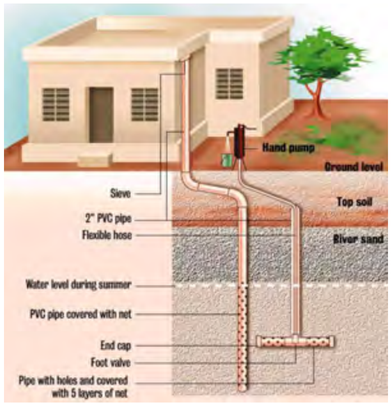
- Site only in areas where rainwater does not infiltrate fast enough where there is high runoff.
- Avoid where there is a risk of chemical contaminants entering the well (e.g. fertilizers and pesticides from agriculture) and when the final water abstracted will be used for drinking.

Key techniques for construction:

- Water to be recharged should be high quality since blockage due to suspended sediment, microbial growth or chemical precipitation is more likely over the smaller infiltration area of a well or borehole. In Namibia, water from the water treatment works is further treated with granular activated carbon and chlorination before being injected to avoid such problems.[164] In certain cases in India, open large diameter wells that ran dry due to falling water tables (resulting from overexploitation) are being used to recharge shallow aquifers directly from runoff water that enters the wells – the problem with such structures is that there is no process of water infiltrating through the soil to the aquifer, which would not only reduce sediment and microbiological load, but also have potential chemical contaminants like nitrates and pesticides. Direct recharge of untreated water via open wells is therefore discouraged in preference to infiltration through a soil or sand layer.[165]
- One source of higher quality water that is a realistic source of recharge water is rainwater from roof catchments. This has been used to recharge shallow aquifers in Mozambique where groundwater was saline, with the result that the water was diluted.[166] Ground runoff is also being used where potentially contaminated runoff water is used to recharge aquifers but where it still must infiltrate a certain amount of soil later – however the risk of aquifer contamination and screen blockage is increased. Field data so far indicates that hand dug wells that previously dried up now have water all year round – an evaluation after 3 years showed that out of 120 hand-dug wells that had recharge boreholes created close by to aid recharge, very few were drying up like they were before. In addition, families in the area were starting to replicate the system on their own.[167]
- Key construction techniques with this system are: [168]
    - The tubewell is sited 5 – 10 meters "upstream" from a well or borehole that dries up in the dry season, or in an area of saline groundwater.
    - When taking water directly from a roof, ensure that the downpipe has a sieve on the inlet and a first flush system.
    - A hole (e.g. 2") is drilled with a step auger or a soil punch. The depth should be such that it passes the compact top layers and reaches the permeable layers – in general 4 – 6 meters is enough depending on the site.
    - The recharge hole should not reach the groundwater layer (aquifer) to avoid contamination of the groundwater with surface water. Ideally minimum distance should be 1.5m above the water table and 5 metres from an abstraction point such as a hand dug well. The water table can be known by observing in the hand-dug well.
    - Test the recharge capacity of the hole after drilling by filling up the hole with water. It should absorb at least 2 litres per minute – if not, drill deeper.



Roof to aquifer recharge
Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas*. IAH-MAR and UNESCO-IHP.



Roof to aquifer recharge
Unicef / Ara Centro. (2009) Qualidade de agua na recarga de aquifero: experiencia em curso na vila de Nhamatanda, Provincia de Sofala.

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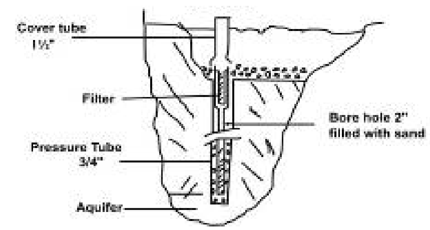
164 Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.15, 27.
165 Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.6, 14-15.
166 Unicef / Ara Centro. (2009) Qualidade de agua na recarga de aquifero: experiencia em curso na vila de Nhamatanda, Provincia de Sofala.
167 See: Holtslag, H.; Wolf, J. de (2009) *The tube recharge*. Connect International. See also: Grove, J. (2009) *Report on recharge system and drip irrigation*. DAPP, Zimbabwe.
168 Information from: Unicef / Ara Centro. (2009) Qualidade de agua na recarga de aquifero: experiencia em curso na vila de Nhamatanda, Provincia de Sofala. Also: Holtslag, H.; Wolf, J. de (2009) *The tube recharge*. Connect International.

- Plug the hole for (e.g. with a cloth) to prevent debris entering, and make a small pond around the hole (0.5 – 1 metre deep, 1 – 5 metre diameter). Ensure the hole is on one side of this pond so that it can be accessed from ground level. The size of the pond depends on the required storage capacity, the infiltration capacity of the soil and the rainfall pattern but in general will be between 1 – 10m^3.
- Remove the plug and fill up the hole with gravel (5 – 30mm) until 2 metres from ground level.
- Install a filter which will screen out solid particles (e.g. leaves etc). This can be done using a PVC screen or sand filter, depending on the incoming water quality:
    - PVC filters are used in combination with ground runoff:
        - In general it is best to reduce the speed of the water as much as possible to avoid the pond from filling up with sand and clay – this can already be done by planting grasses and other catchment methods (see "Natural ground catchment & open water reservoir" for details) .
        - The PVC filter pipe can be between 25 – 100mm and acts as a screen to allow water to infiltrate into the gravel layer (i.e. PVC has horizontal slots cut in the side). The pipe protrudes just above the base of the pond.
        - A PVC cover piece is fabricated which is closed at the top and flares at the base so that it fits over the protruding pipe – the purpose of the cover is to prevent too many sediments entering the pipe and is removed only 4 hours after rainfall. Once water has infiltrated, the cover is replaced until the next time.
        - Cleaning involves swabbing the inside of the PVC with a cloth.
    - Sand filters can also be used instead of the PVC filter system – this is where sand replaces the need for a cover piece and the need to wait 4 hours. It can be used with rooftop catchments where no surface runoff enters the hole, and could be done with or without a PVC pipe.

Key techniques for extraction of water:

- Water can be abstracted from the same borehole or well used for injection/recharge – this is called Aquifer Storage Recovery (ASR).
- Water can also be abstracted from a separate borehole or well than the one used for injection/recharge – this is called Aquifer Storage Transfer and Recovery (ASTR). In the case of roof rainwater recharge systems in Mozambique, this design was used where the pump would extract water from a separate place close to the screen connected to the roof catchment.[169]



Runoff to aquifer recharge
Holtslag, H.; Wolf, J. de (2009) *The tube recharge*. Connect International.

Advantages:

- Can assist recharge of shallow wells. Allows groundwater aquifers to be treated as massive storage tanks where in times of surplus, the aquifer can be recharged while in times of drought the water can be extracted. One example of this is the "water bank" concept for Windhoek's water supply in Namibia.[170]
- Can reduce salinity in groundwater.
- Low cost and simplicity = replicable by users without donor funds.

Disadvantages:

- Water quality requirements of recharge water are high.
- A good understanding of the hydrogeology of the aquifer is needed.
- Technology needed to construct these structures can be quite complex, requiring engineering skills.

[169] Unicef / Ara Centro. (2009) Qualidade de agua na recarga de aquifero: experiencia em curso na vila de Nhamatanda, Provincia de Sofala.
[170] Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.27.

Surface water: ground catchment & storage

SUMMARY	Technical	Institutional	Financial & economic	Environmental
General	• Consider pros & cons of handpumps before installing one (see "Mechanical extraction: handpumps" for details). • If using direct abstraction, promotion of household water treatment should be advocated. Biosand filters at household level (biosand filters are a good choice due to their ability to remove cyanobacterial toxins present in many open water bodies). Other technologies however may be more suitable for mobile communities (e.g. SODIS or ceramic filters, depending on turbidity levels).			• Fish (e.g. Tilapia, mudfish) can be introduced where relevant to eat mosquito larvae, while at the same time providing a source of nutrition. • For reservoirs near urban environments or where the runoff area has intensive agriculture practised in its vicinity, promote diversification of water resources to provide alternatives for direct drinking purposes.
• Natural rock catchment & open water reservoirs	• Site on rock that is bare and free of vegetation/soil with no fractures. • Site the dams for rock catchments to maximize the natural topography - deeper = more volume to surface = less evaporation • Gutters should almost follow the contour but should slope a minimum of 3%. Gutters should be high enough to direct water, but where runoff velocity is very high, some kind of wall structure is needed to slow velocity of runoff before it reaches the gutters. • Reservoir size (and therefore dam height) should be decided according to water demand, evaporation losses, length of critical period and average rainfall. • Dam wall can be built onto rocks with slope of up to 15%, width of dam base must always be 3/5 of dam height, width of crest	• Smaller scale dams owned privately might have more chance of success in terms of participation in the construction and maintenance processes. • Phased construction might provide a manageable way for users to construct their own dams, whereby each dry season the dam is raised until experience shows that capacity is sufficient for water demand.	• Access to finance will help to allow farmers to implement dams.	

	should be 30cm, special attention should be paid to the rock-wall base as this has potential for leakage, and the upstream side of the dam wall should be rendered with up to 30mm of mortar.			
• Natural or artificial ground catchment & lined sub-surface tanks	• Seepage and cracks must be avoided – good quality construction work with adequate supervision is vital. This is especially important in areas with swelling soils that can affect the integrity of the lining. • Follow proper concreting guidelines. • Build round tanks in preference to rectangular ones. • Do not site tanks near big trees whose roots might crack the walls. • Type of tank will vary depending on the swelling ability of the surrounding soil. • Concrete floors need to be laid with vibration where possible. • Reduce evaporation by constructing a roof (e.g. living roof with income-generating possibilities) – where soil type allows, excavated water cellars naturally have a small roof area compared to larger sub-surface water volume. Sand-filled reservoirs also can reduce evaporation. • Consider increasing overall water availability through innovative cost-effective rehabilitation of existing excavated tanks which lose water due to seepage. Lining with plastic could be an option as long as it is protected when installed (e.g. with sand layers). • Reduce siltation where the inflow channel is defined through silt traps.	• Support the notion of private ownership & management. A fence can be constructed to improve private ownership. • Support the capacity of the government or private sector to be able to provide (for payment) a tankering scheme to fill tanks during the driest parts of the year.	• Expect higher levels of contribution from beneficiaries who will end up being the private owners of the berked. • Promote smaller tank structures (under $30m^3$) = less reinforcement needed, more manageable to construct and cover, while being more affordable to families. More tanks can be added in subsequent years, thus spreading out costs. • Improve access to micro-finance (possibly introducing it combined with subsidy) and especially to women, so that users can replicate technology. • Consider trying tanks made from cheaper materials and repair tanks more often. In some soil types, an impermeable stable soil can act as a lining. Other options include plastic linings held in place using bows of metal and wood, and linings of powdered anthill material, lime, cement and sand. The areas where such linings might work are probably site-specific but might be worth experimenting with.	

	• Add a coarse mesh after the silt trap before inlet to prevent large debris from entering the tank. • Dig deeper tanks = less evaporation but more water quantity. • Where catchments have low runoff coefficients, this can be increased by modifying the existing surface or creating an artificial surface – e.g. compacting existing soil, cement-soil mix, concrete, or buried plastic. • Create a fence around the tank to prevent children's access and large vehicles from driving too close and damaging the lining.			
• Natural ground catchment & open water reservoirs	• Site reservoirs where base will be impermeable (e.g. unfissured rock or clay) in order to save costs and prevent having to find a form of lining. • Site reservoirs so as to minimize excavation. • Site small reservoirs (5-10 ha) in large watersheds to be sure of water quantity. Hydrology comes into play in the design for larger reservoirs (>15 ha) in which case follow storage design procedures. However, when constructing valley dams specifically (those in a seasonal watercourse), the rule of thumb is not to build small reservoirs (below 10,000 m^3) in catchments larger than 400 ha (1,000 acres). • Material used for the dam wall should be impermeable with high clay content (55% minimum). Avoid unwanted components in the clay. • The dam should have a cut-off (minimum 2.5m wide) • Dam material to be compacted properly	• Consider promoting construction of ponds on private land where there is a direct benefit to the landowner and where de-silting is taken care of, yet where the wider community also benefits. • In pastoralist areas, it might be good to site ponds in areas where traditionally pasture is used first after the rains. In this way, as much water as possible can be used to cover water demand before it is taken by seepage and evaporation, leaving other sources with less seepage and evaporation (e.g. sand dams) to be used later on in pasture accessed during the dry season. • For new dams, any land ownership issues should be solved prior to construction. • Water user groups may work better which are ethnically homogeneous or female homogeneous.	• Improve access to low-cost loans with long-time repayment conditions so that farmers can replicate technology. • Promote excavation with oxen where possible as this is the most cost-effective means of excavation. • Phased construction might provide a manageable way for users to construct their own ponds, whereby each dry season the pond is deepened until experience shows that capacity is sufficient for water demand.	• Reduce siltation by keeping a good cover of perennial grasses and/or trees in the run-off area. Pasture management and user associations based on catchments can help to keep this cover. • Where runoff zone has intensive agriculture where chemicals are used, diversify water sources to provide alternative water for direct consumption due to contamination risk.

	• Design should prevent overtopping of dam crest: water level should be 1m less than dam crest, which itself should be 10% higher at the centre (convex shape) • Crest width to be 3 metres minimum. For dams over 3 metres, width needs to be greater (4 metres minimum). The crest needs to have a slope of 1 : 50 from downstream to upstream side of crest. • The spillway outlet needs to be sized & made robust enough to resist erosion. The spillway needs to be kept clear from debris. • The spillway channel should not allow erosion of the dam structure. Spillway slope should be 1 : 33. • Dam embankment needs to be protected both upstream and downstream • Protect upstream slope • A rock toe drain will help to collect seepage water. • Reduce siltation where the inflow channel is defined through silt traps • Include seepage in design calculations – determine it using field methods. • Reduce seepage by covering the pond base with clayey soil and compacting it. • Reduce evaporation by digging deeper to have a larger volume to surface area ratio (e.g. Charco dams) and planting trees around the pond will act as a windbreak. • Regularly inspect dam components at differing time intervals according to recommended schedules.			

Natural rock catchment & open water reservoir

Overview:
These are naturally occurring catchments of bare rock that have high runoff coefficients (around 0.9). Water can be stored as an open reservoir behind a retaining structure, with storage capacities ranging from 20 – 4,000 m^3, or can be stored directly in a covered storage tank that collects water directly from the catchment.

Key techniques for siting:
- The rock that makes up the catchment should be bare and free of vegetation/soil. It should have no fractures or cracks that would result in a loss of water through seepage.
- Site the dams for rock catchments to maximize the natural topography – to get the best volume, make dams on the lower side of existing rock pools.

Open rock catchment reservoir, Kenya
Erik Nissen-Petersen in: Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs.* Stockholm International Water Institute.

Key techniques for construction:
- In general, it seems that smaller scale dams owned privately might have more chance of success in terms of participation in the construction and maintenance processes.
- Water can be stored as an open reservoir – this can be done behind a stone masonry or concrete dam built directly onto the rock, or behind an earth dam in a non-rocky area at the base of the rock face (for earth dams, see "Natural ground catchment & open water reservoir" for details). Water can also be stored in a covered tank that gets water directly from the rock catchment.
- Cracks/fissures should be sealed up with mortar or concrete.
- Siltation should be reduced by ensuring that the rock catchment is clear of soil and debris, and maintaining it in this state.
- Open water in certain areas can have a high evaporation rate, depending on the climate. Some ways to reduce this might include:
  - Siting the dam to best use the natural topography to get the deepest reservoir possible = larger volume to surface area ratio.
  - Covering the catchment or building tanks to collect the water directly.
- Gutters are needed to direct water on the rock catchment towards the reservoir. They can be made from stone masonry using rocks gathered from the catchment during cleaning. Gutters should almost follow the contour but should slope a minimum of 3%.[171] Gutters should be high enough to direct water, but where runoff velocity is very high, some kind of wall structure is needed to slow velocity of runoff before it reaches the gutters.[172]
- Reservoir size (and therefore dam height) can be decided according to water demand (to a certain extent depending on size of catchment), evaporation losses, length of critical period and average rainfall according to the following:[173]
  - Determine water requirement (R litres/day)
  - Estimate area of reservoir (A m^2), evaporation losses from reservoir (E mm/day) and therefore the volume losses per day (A x E litres/day)
  - Estimate length of critical period during which water entering the catchment is less than water requirement & losses (T days) = when water requirements met by using water from reservoir
  - Estimate average rainfall entering the catchment reservoir during critical period (Q litres/day) – this should be rainfall x catchment area x runoff coefficient (usually taken as 0.9). Catchment area will decrease with increasing slope (e.g. 23% fewer square metres if slope is 40%).[174]
  - Calculate effective storage required (S litres) = (R + AxE – Q) x T
  - Site should be then surveyed to estimate area (A m^2) of reservoir for different values of water level (D) – this will give reservoir capacity which should be greater than storage required (S) to allow for a safety margin. Reservoir capacity can be estimated by the following: (length x width x maximum depth) / 6.[175]

Covered rock catchment reservoir, Kenya
Nissen-Petersen, E. (2006) *Water from Rock Outcrops: A handbook for engineers and technicians on site investigations, designs, construction and maintenance of rock catchment tanks and dams.* DANIDA.

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[171] Nissen-Petersen, E. (2006) *Water from Rock Outcrops: A handbook for engineers and technicians on site investigations, designs, construction and maintenance of rock catchment tanks and dams.* DANIDA. p.36
[172] Runoff overtopping gutters was a problem in some projects, and "break walls" were sometimes recommended prior to gutters. See: Gicheruh, C.M. (2008). *Advisory for technical and managing staff on technical and administrative procedure: water supply project, Mutomo District, Kenya.* Report No. 2008/14 undertaken for GAA. Earth Water Ltd, Nairobi, Kenya.
[173] Adapted from calculations for earth dams: Pickford, J. (ed) (1991). Technical Brief 48. Small earth dams. In: Shaw, R. (ed) (1999). *Running Water: more technical briefs on health, water and sanitation.* Practical Action Publishing, London. p.62.
[174] Slope can be estimated using simple protractor and plumb bob – for this and list of slopes and catchment areas, see: Nissen-Petersen, E. (2006) *Water from Rock Outcrops: A handbook for engineers and technicians on site investigations, designs, construction and maintenance of rock catchment tanks and dams.* DANIDA. p.25

- Height of dam will be D plus 1m (for flood level & safety margin).

- Dam wall can be built onto rocks with slope of up to 15%, width of dam base must always be 3/5 of dam height, width of crest should be 30cm, special attention should be paid to the rock-wall base as this has potential for leakage, and the upstream side of the dam wall should be rendered with up to 30mm of mortar. Procedures for dam wall construction are given in certain guides.[176]
- Phased construction might provide a manageable way for users to construct their own dams, whereby each dry season the dam is raised until experience shows that capacity is sufficient for water demand. In this case, start with a dam of 2 metres height, then build on it successively to a total of 5 metres in 3 more stages.[177] The advantage of doing this is that you build according to enthusiasm and seeing how much water is stored.
- Access to finance will help to allow farmers to implement dams.
- Fish can be introduced to eat mosquito larvae, while at the same time providing a source of nutrition.[178]

Key techniques for extraction of water:

- For where water is gathered directly into tanks, extraction can be via pipes. For open water catchments, this can be done through direct abstraction (pump or pipe taking water off) in the case of catchments directly on rock surfaces, or indirect abstraction where water is stored behind earth dams (for the latter, see "Natural ground catchment & open water reservoir" for details). Abstraction method ideally should attempt to extract the water in a way so as to minimize disturbance of the settled water, thus reducing treatment requirements later.
  - Direct abstraction from the pond is one option, via a bank-mounted pump (motorized pump or handpump) which uses a floating intake to reduce sediment intake. An outlet pipe and strainer through the dam wall to the downstream side is another option, but these have potential problems of weakening the dam wall (see "Shallow groundwater: groundwater dams" section). In addition, piping will have to secured externally when traversing rocks, so care has to be taken to secure pipes with anchor posts.
  - Regarding handpumps, see "Mechanical extraction: handpumps" for details on the pros/cons of handpumps.
  - However, even with preventive methods to reduce turbidity (silt trap, extraction method) the water is still turbid & contaminated and will require treatment.
  - For direct abstraction, promotion of household water treatment is advocated. Choice of household water treatment technology should be based on efficiency of removing contaminants present in the water. For open water that may be prone to cyanobacterial blooms, biosand filters are a good choice due to their ability to remove cyanobacterial toxins.[179] Other technologies however may be more suitable for mobile communities (e.g. SODIS or ceramic filters, depending on turbidity levels). For reservoirs near urban environments or where the runoff area has intensive agriculture practised in its vicinity, diversification of water resources is a good idea to provide alternatives for direct drinking purposes. Strengthening controls and restrictions on use of illegal substances will also help.[180]

Advantages:

- High runoff coefficient = similar to roof catchments in that even small showers produce water.
- Minimal seepage where open storage on rock catchments is concerned.
- Maintenance is simple and cheap.
- Rock catchments do not occupy farmland and often no one owns the land = easy to implement.

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[175] Nissen-Petersen, E. (2006) *Water from Rock Outcrops: A handbook for engineers and technicians on site investigations, designs, construction and maintenance of rock catchment tanks and dams*. DANIDA. p.27
[176] For example, see: Nissen-Petersen, E. (2006) *Water from Rock Outcrops: A handbook for engineers and technicians on site investigations, designs, construction and maintenance of rock catchment tanks and dams*. DANIDA. See also: Gicheruh, C.M. (2008). *Advisory for technical and managing staff on technical and administrative procedure: water supply project, Mutomo District, Kenya*. Report No. 2008/14 undertaken for GAA. Earth Water Ltd, Nairobi, Kenya.
[177] Nissen-Petersen, E. (2006) *Water from Rock Outcrops: A handbook for engineers and technicians on site investigations, designs, construction and maintenance of rock catchment tanks and dams*. DANIDA. p.44
[178] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA.
[179] See: Bojcevska, H.; Jergil, E. (2002) *Removal of cyanobacterial toxins (LPS endotoxin and microcystin) in drinking-water using the Bio-Sand household water filter*. Minor field study in Mozambique, September – November 2002. Uppsala University, Uppsala, Sweden. See also: Grützmacher, G.; Böttcher, G.; Chorus, I.; Bartel, H. (2002) *Removal of Microcystins by Slow Sand Filtration*. Wiley Periodicals.
[180] Cecchi, P. ; Leboulanger, C.; Bouvy, M.; Pagano, M.; Nemy, V. (2009) *Agricultural intensification and ecological threats around small reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org.

Disadvantages:

- Not many sites suitable.
- If building tanks that store water directly, storage capacity is limited compared to an open reservoir.
- Cost is high – experience from Kenya shows that a 56 m^3 dam cost $4,000 including labour (= $71 per m^3 of storage).
- Vectors can breed in open water.
- Microbiological and chemical water quality is likely to not be acceptable for direct consumption (see "Natural ground catchment & open water reservoir").

<u>Natural or artificial ground catchment & lined sub-surface tanks</u>

Overview:
These are natural, artificial or modified catchments that have low to relatively high runoff coefficients. Water from these catchments is captured and stored in lined sub-surface reservoirs excavated below ground level. The reservoirs are known by different names (berkeds in Somaliland, taankas in India, hemispherical sub-surface tanks in Kenya – also included in this category are excavated water cellars such as the shuijiao in China) and have been lined with many different materials. These tanks normally have a larger depth to surface ratio compared to open ponds and their scale means a roof of some description is a possibility. When the lining is constructed well, there will be no leakage, and water will either evaporate or be abstracted. These tanks are often privately-owned by one or more families, but can be communal.

Key techniques for siting:

- Site in a place where run-off is seen to flow after rains.
- Artificial catchments are created where infiltration of runoff zone is high.
- Care should be taken when siting in clayey areas, but the type of clay is more important – see below.
- Do not site tanks near big trees whose roots might crack the walls – see below.
- Do not site tanks where heavy vehicles will pass close to tank wall – see below.
- Do not site sub-surface tanks in areas of high water tables to reduce risk of flotation.

Key techniques for construction:

- The reason for constructing a sub-surface tank is to retain the water. Therefore one of the most important aspects is that seepage and cracks must be avoided. Therefore good quality construction work with adequate supervision is vital to create a sound structure – this is especially important in areas with swelling soils that can affect the integrity of the lining. While ownership and management of tanks is important, such privately-owned tanks have often failed due just to the technical construction component. Construction materials vary and include the natural soil formation itself, clay, stone masonry, bricks/cement, ferrocement, anthill/lime/cement and plastic/rubber lining. Material may affect cost (see below) but choice may also depend on what is available and the type of surrounding soil. Some generally applicable issues are detailed below to prevent cracking/seepage:
    - Round tanks are inherently stronger than rectangular ones.[181] Hemispherical and cylindrical designs are commonly used.
    - Type of tank will vary depending on the swelling ability of the surrounding soil – this is generally a problem in clayey areas, but type of clay is more important – montmorilonite, calcium-containing clays (in marls/gypsum sediments) and black cotton soils are all prone to swelling and can crack sub-surface tank walls that are not built robustly enough.[182] Therefore it is important to construct the right type of tank for the area. When in doubt, avoid making sub-surface ferrocement or anthill/lime/cement tanks in unstable soil.
    - Do not site near big trees whose roots might crack the walls.[183]
    - Do not site near where heavy vehicles will pass which might crack the walls.
    - Admixtures can be added to the concrete mix in order to reduce the amount of water needed. Research has shown that superplasticizers work best by reducing the amount of water that needs to be added when mixing concrete, which results in 35% less shrinkage. The resulting end material is stronger and can reduce the amount of micro cracks in mortar by half compared to normal mortar while resulting in 76% fewer leaks. In general, the amount of plasticizer to be added should not be greater than 2% of the dry material weight.[184] A plasticizer that can be used that is possibly available is household washing up liquid. In hot climates though, more research is needed in the field application of

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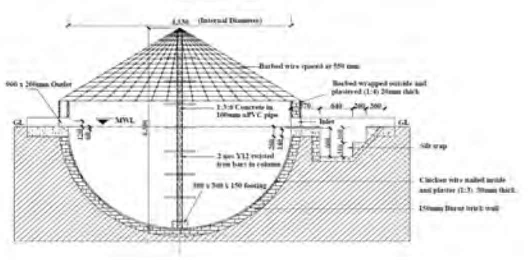
[181] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA.
[182] Personal communication, Dick Bouman, Aquaforall. See also: Worm, J.; Hattum, T. van (2006) *Rainwater harvesting for domestic use*. Agrodok 43. Agromisa Foundation and CTA, Wageningen, The Netherlands. p.43.
[183] NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions*. Netherlands Water Partnership. p.29.
[184] http://en.wikipedia.org/wiki/Plasticizer

plasticizers, since the reduction of water used (and increased strength of product) may not be that great due to more water needed to prevent drying out between mixing and application.[185]

- Key construction issues for good workmanship (which also relate to preventing cracking/seepage) and costs for specific lining types are detailed below:
  - Stone Masonry:
    - In Somaliland it cost between $39 - $43 per m^3 of storage for a new berked and $8 per per m^3 for a rehabilitated berked, excluding about 30-45% of local contribution (e.g. 493m^3 new berked = $19,550; rehabilitated existing berked = 4,000 USD).[186] In India, stone masonry sub-surface tanks cost $28 per m^3 of storage (35m^3 tank cost $990).[187]
    - Floor to be made from concrete which needs to be laid with vibration in order to be sure they are leak-proof.[188]
    - In clayey areas, be sure to build the tank robustly enough to resist cracking. Sample dimensions & mixtures for walls and floor for stone masonry tanks in an area of swelling clay are:[189]
      - Walls: 0.4m wide, 2 blocks thick
      - Floor leveling mixture: 0.05m thick, ratio 1:4:6 (not used in rehabilitated berkeds as level floor foundation already exists)
      - Floor: 0.16m thick, unreinforced concrete, ratio 1:2½:4

Stone masonry round berked under construction showing wires for roofing materials, Somaliland
Eric Fewster, BushProof / Caritas

  - Bricks/cement
    - In Kenya, brick/cement tanks cost $37 per m^3 of storage (21m^3 tank cost $780).[190] In Sri Lanka, brick tanks cost 28 per m^3 of storage (5m^3 tank cost $140).[191]
    - In clayey areas, be sure to build the tank robustly enough to resist cracking.
  - Ferrocement
    - Ferrocement tanks in other areas seem to cost in the range of $30.5 (60$m^3$ tank cost $1,830)[192] to $32 per m^3 storage (60m^3 tank cost $1,900) including all costs.[193]



Hemispherical underground tank made from bricks, Kenya
Nissen-Petersen, E. (2006) *Water from Roads: A handbook for technicians and farmers on harvesting rainwater from roads.* DANIDA.

  - Anthill/lime/cement – in Kenya, anthill material and lime has been added to reduce cost of lining. The lower capital cost though does mean more maintenance work.[194] However there does not seem to be too much field data on how these function in the longer term.
    - The following plaster mixture proved to work better: 4 parts anthill soil, 1 part cement, 2 parts lime, 6 parts river sand.
  - Plastic/rubber
    - In general it would appear that choosing a plastic/rubber lining is not an option in most circumstances due to combinations of fragility, expense and feasibility for welding together sheets for larger ponds. Below the pros and cons of various liners are discussed:
    - There are five main types of liner constructions: Polyethylene, Polythylene, PVC liners, EPDM/rubber, and polypropylene. As an indication of costs, an EPDM/rubber sourced in the UK is around $6.5 per square metre not including shipping costs.[195] Choice of lining needs further consideration:
      - Needs to be food grade since the water it stores is for drinking.
      - Cost: Polyethylene and Polythylene liners typically cost half that of Polypropylene and EPDM. PVC and PVC-E liners are the next step up from Polyethylene and polyethylene in terms of cost. Compared to other liners, PVC is somewhat more affordable, while being somewhat puncture resistant at the same time but in terms of durability, the typical 20-mil (i.e. 0.020") thick PVC is somewhat mediocre in terms of durability. EPDM is more expensive than Polyethylene, polyethylene, and PVC liners, but can last for up to 20 years. Polypropylene is an expensive material but can last for up to 40 years.

185 Personal communication with Dr Terry Thomas, Warwick University, UK.
186 Experience from CARITAS berked programme, Somaliland, 2008.
187 Personal communication with Frank Greaves, Tearfund.
188 Experience of CARITAS berked programme, Somaliland, 2008.
189 Based on experience of CARITAS berked programme, Somaliland, 2008.
190 Nissen-Petersen, E. (2006) *Water from Roads: A handbook for technicians and farmers on harvesting rainwater from roads.* DANIDA. p.23.
191 http://www2.warwick.ac.uk/fac/sci/eng/research/dtu/pubs/rn/rwh/cs02/
192 Nissen-Petersen, E. (2006) *Water from Roads: A handbook for technicians and farmers on harvesting rainwater from roads.* DANIDA. p.30.
193 NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions.* Netherlands Water Partnership.
194 Nissen-Petersen, E. (2006) *Water from Roads: A handbook for technicians and farmers on harvesting rainwater from roads.* DANIDA. p.24.
195 Greaves, F. (2009) *WASH Assessment trip to CCSMKE, Kenya: 9th - 18th March 2009.*

- Durability:
    - Polyethylene and Polythylene liners typically only last one season.
    - Polyethylene will readily conform to any shape, however, it does not have the sturdiness that is required for a permanent pond liner.
    - Polythylene, on the other hand, is extremely rigid and can be stiff to work with. Polythylene can be damaged easily by rocks, and has to be handled with care. If polyethylene is damaged, it cannot be seamed together without expensive welding equipment.
    - PVC and PVC-E liners are the next step up from polyethylene and polyethylene, and they can last for up to 10 years.
    - Polypropylene is an expensive material but it is the most durable pond liner material in existence because it can last for up to 40 years. Polypropylene, however, is not as flexible as EPDM liners.
    - EPDM (Ethylene Propylene Diene Monomer) rubber liners are recommended for most pond installations because of their delicate balance between longevity, flexibility, affordability, and their lack of toxic plasticizers. Because EPDM liners are rubber-based, they are extremely flexible (much more so than PVC liners) - the extra flexibility of EPDM comes in handy when working with irregular folds and shelves that are commonly found in a pond. They also do not contain any plasticizers that can make the liner brittle and crack with age. A 45-mil EPDM liner can last for up to 20 years because of its natural resistance to UV, and its puncture resistance.
- Sheet size: ideally we should not have to weld sheets together in situ.
    - The main advantage of polypropylene is that it comes in large sheets larger than 50' x 100'. If you are building an extremely large pond, polypropylene may be a viable option.
    - A limitation of EPDM is its size they typically arrive in sheets ranging from 5' x 10' to a 50' x 100' roll.

- High cost of tank construction will decrease water availability because smaller tanks can be made. Ways to increase storage are to build with cheaper lower quality materials, use less material for construction and reduce labour costs. In this way, sub-surface tanks can become a more realistic option. Ideas include:
    - Use existing soil as a natural lining if it is relatively impermeable. In China, clay has been used to line excavated water cellars (called Shuijiao) in areas where the natural soil (loess) is already fairly impermeable. The lining process is difficult and time-consuming and has been replaced largely by ferrocement or plastic. However, it proves that in some areas it is possible to construct a low-cost tank.[196] In Somaliland, similar water cellars were observed that were excavated in impermeable stable soil formations – runoff water entered through a small inlet channel. Other tanks are sealed with a 10cm unreinforced cement lining – it seems that 30m^3 is the most economical size = most volume without needing reinforcement – such tanks cost $189 or about $6.3 per m^3 of storage (materials only presumably).[197]
    - In Kenya, tank linings have been made with powdered anthill material and lime which substitute some of the cement and bricks, bringing cost to $9.8 per m^3 of storage.[198]
    - Reduce the size of structures = increased cost per m^3 storage but more manageable to construct in terms of cash flow, and easier to cover. This way, tanks are more affordable to families, and more tanks can be added in subsequent years, thus spreading out costs.
    - However, care needs to be taken with cheap linings – in some areas with swelling clay and differential settlement, linings can easily crack, as has often been observed in some areas.[199] The areas where cheap linings might work therefore may be site-specific, and depend on the clay content of the soil. For plastic linings, experience from India shows that these can be punctured by rodents, crabs or insects if there is no rodent/insect-proof layer before the plastic.[200]
- Access to finance is a main obstacle to promotion of rainwater harvesting for households, and is important so that users can replicate the technology – however, so far there are few examples on a global level with micro-credit for rainwater harvesting.[201] (For details, see "Roof catchment & storage").
- Sub-surface tanks are usually small enough that it is viable to have a roof to limit evaporation (and improve water quality if possible = less algae build-up). Shading can reduce evaporation by around 30%.[202] Placing local bush or grass materials on a frame of wires doesn't seem to work well because they get blown off, and also still let light in = algae growth. Corrugated iron roof on wooden frame works well but is expensive (about $20 per m^2 in Somaliland).[203] In addition, if the tank is not fenced, animals walking on the roof can damage it.[204] The challenge is to make a roof that is cost-effective for small-scale farmers – one idea is to investigate income-generating roofs since that can help pay for the structure (e.g. passion fruit).[205] Excavated water cellars by their nature have small area roofs.

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196 Gould, J.; Nissen-Petersen, E. (1999). *Rainwater Catchment Systems for Domestic Supply.* IT, London. pp.94-95

197 Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.

198 Nissen-Petersen, E. (2006) *Water from Roads: A handbook for technicians and farmers on harvesting rainwater from roads.* DANIDA. p.24.

199 Personal communication with Dick Bouman, Aquaforall: 55% of berkeds observed in Puntland, Somalia, had failed due to cracked linings. Personal experience of Eric Fewster in Somaliland revealed similar problems.

200 http://www2.warwick.ac.uk/fac/sci/eng/research/dtu/pubs/rn/rwh/cs19/

201 From lessons learned over various rainwater harvesting projects globally – see: Nijhof, S,; Jantowski, B.; Meerman, R.; Schoemaker, A. (2010). Rainwater harvesting in challenging environments: Towards institutional frameworks for sustainable domestic water supply. *Waterlines*, Vol.29 no.3, pp.211, 218.

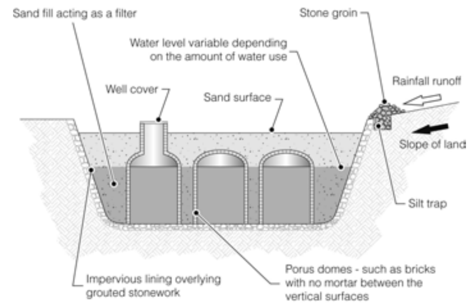
202 Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.

203 Experience of CARITAS berked programme, Somaliland, 2008.

204 Nissen-Petersen, E. (2006) *Water from Roads: A handbook for technicians and farmers on harvesting rainwater from roads.* DANIDA. p.28.

205 Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.

- Dig deeper tanks = less evaporation but more water quantity to last longer into dry season. Perhaps a rule of thumb should be that depth should be greater than the maximum PET rate for the area in question. For example, the average length and width of berkeds from projects in Somaliland were 11.4 and 6.3 metres, while average water-holding depth was 2.9 metres, whereas PET rates ranged from 1.75 – 2.25 metres per year.[206] Problem: deeper = more investment.
- Another method to reduce evaporation and at the same time improve water quality is to use a lined sand-filled tank. It appears that plastic pond liners are in general more tolerant to earth tremors than solid lining like concrete[207] – in some situations when the rains might cause swelling of the surrounding ground which might move the existing wall in a similar way, the plastic lining might in fact still be functional. In such a case it might be good to try out the following method which has been tried in Botswana in a lined rectangular tank:[208]
    - Use a plastic lining to create an impermeable layer on top of the existing lining. Protect the lining with a sand layer both on the floor of the berked before the lining is laid (evens out floor, protects against sharp objects, dried clay fragments etc), and also on top of the plastic after it is laid (to protect from flotsam and when people walk on it).
    - Create an abstraction point (see "Shallow groundwater: hand-dug, jetted & driven wells" for details).
    - Fill the remaining volume with sand.



Sand-filled sub-surface tank, Botswana
Image courtesy of WEDC. © Ken Chatterton. In: Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK.

- In case of cracked linings, the following could be tried to salvage the tanks:
    - If the crack is only at the base, covering the tank base with clay and compacting it might work. Addition of powdered anthills or lime is said to make this lining more robust.[209]
    - If the cracks are also found in the walls, then rehabilitation or an alternative lining might be a solution (see above). Taking the example of berkeds in Somaliland, many remain unused due to previous poor workmanship, yet rehabilitation is expensive (\$8 per m^3), requires skill and is not always successful. In some cases it is also not even possible to rehabilitate – some cracked berkeds can be rehabilitated if the original walls were made solidly enough, but otherwise there are many berkeds that can never be rehabilitated.[210] In such cases, plastic linings might be worth trying.
- Add a coarse mesh after the silt trap before inlet to prevent large debris from entering the tank.
- Where catchments have low runoff coefficients, this can be increased by modifying the existing surface or creating an artificial surface:
    - In China, soils with reasonable infiltration capacity had a runoff coefficient of 2%, which was increased to 20% after the soil was compacted.[211]
    - Artificial lining of catchments is a possibility. Various catchment types and their runoff coefficients are: concrete (73-76%), cement-soil mix (33-42%), buried plastic sheet (28-36%).[212]
- Shallow drainage canals can be dug to direct the runoff into the tank.
- Silt intake into sub-surface tanks ideally should be limited – how much silt will accumulate will depend on the area. In China, 80m^3 had accumulated in 4 years.[213] Ideas to limit silt include:
    - Keeping a good cover of grasses or vegetation in the run-off area (see "Ground catchment & storage: open reservoirs" for details).
    - Silt trap prior to tank intake. However, experience from Somaliland shows that silt traps (small mini reservoirs prior to main tank) are not very effective. A better method might be to replicate silt traps used in Charco dams where perennial vegetation is grown between small dams in the intake channel to encourage deposition (see "Ground catchment & storage: open reservoirs" for details).
    - Alternatively where vegetation may not grow due to climate, stones similar to roughing filter can be used on intake to increase sedimentation before water enters the tank. A roughing filter operates through increasing the surface for sedimentation and could be designed into t he berked intake where stones of 3 different sizes between 25 and 5mm are used in 3 separate sections. But if it is to function properly its area needs to be designed based on flow rates and inflow water quality. The filtration rate should be calculated by flow (m^3/hr) divided by surface area (m^2) and then different filtration rates are suitable for different water qualities – this information may be hard to estimate in the field though. More details available from relevant literature[214].

[206] This is based on 133 rectangular berkeds that were constructed & rehabilitated under the CARITAS programme between 2007 and 2009.
[207] http://searchwarp.com/swa46256.htm
[208] Tank size 76.5 m^3. Information comes from: Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK. p.54.
[209] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. pp.62-63.
[210] Experience from CARITAS berked programme, Somaliland, 2008.
[211] Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.
[212] Gould, J.; Nissen-Petersen, E. (1999). *Rainwater Catchment Systems for Domestic Supply.* IT, London. p.53.
[213] Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.
[214] Such as: Wegelin, M. (1996). *Surface water treatment by roughing filters : a design, construction and operation manual.* (SANDEC report; no. 2/96). St. Gallen, Switzerland. This and other references can be downloaded here: http://www.irc.nl/docsearch/results?lmt=20&txt=roughing

- Create a fence around the tank to prevent children from possibly falling in, and to prevent large vehicles from driving too close and damaging the lining.
- Support the notion of private ownership & management. A fence can be constructed to improve private ownership.
- Fish can be introduced to eat mosquito larvae, while at the same time providing a source of nutrition.[215]
- Support the capacity of the government or private sector to be able to provide (for payment) a tankering scheme to fill tanks during the driest parts of the year.[216]

Key techniques for extraction of water:
- Can be done through direct abstraction (pump or buckets taking water off). Abstraction method ideally should attempt to extract the water in a way so as to minimize disturbance of the settled water, thus reducing treatment requirements later. Using a pump (motorized pump or handpump) which uses a floating intake can reduce sediment intake. However, even with preventive methods to reduce turbidity (roof, silt trap, extraction method) the water is still turbid & contaminated and will require treatment. A form of handpump could be installed but that would not solve the problem with turbidity and contamination.
- Regarding handpumps, see "Mechanical extraction: handpumps" for details on the pros/cons of handpumps.
- For direct abstraction, promotion of household water treatment is advocated. Choice of household water treatment technology should be based on efficiency of removing contaminants present in the water. For open water that may be prone to cyanobacterial blooms, biosand filters are a good choice due to their ability to remove cyanobacterial toxins.[217] Other technologies however may be more suitable for mobile communities (e.g. SODIS or ceramic filters, depending on turbidity levels). For reservoirs near urban environments or where the runoff area has intensive agriculture practised in its vicinity, diversification of water resources is a good idea to provide alternatives for direct drinking purposes. Strengthening controls and restrictions on use of illegal substances will also help.[218]

Advantages:
- Less evaporation than natural ponds due to less surface area to depth.
- Good for areas where ground would otherwise be permeable.
- They work well when privately owned = maintained.

Disadvantages:
- Experience shows that sub-surface tanks often cannot hold enough water for whole dry season.[219] Making bigger berkeds is possible but more difficult and cost is too high = unaffordable = not replicable.
- The cost of underground tanks can be high and variable in cost per m^3 of storage (seem to average around $30-40 per m^3 of storage, sometimes a lot more depending on various factors – sub-surface hemispherical tanks made from stone masonry and bricks/cement in Ethiopia cost in the range 113 - 219 Euro per m^3 of storage including all costs, with costs varying with parameters such as trucked water for construction and solidity of construction (more solidly built tanks in clay areas cost more).[220]). Therefore the costs currently limit the replicability of the technology for poorer families and potential to scale things up.
- Considerable amounts of silt accumulate in tanks but how much will depend on the area.
- Flotation of the tank may occur in areas with a high groundwater table.
- Heavy vehicles driving near to tank can cause damage.
- Leaks in sub-surface tanks are hard to detect.
- Artificial catchments take up potentially valuable land surface and are difficult to keep clean. Concrete catchments tend to crack.
- When built in a remote area, construction is difficult due to lack of water and large distances to transport materials.
- Microbiological and chemical water quality is likely to not be acceptable for direct consumption (see "Natural ground catchment & open water reservoir")

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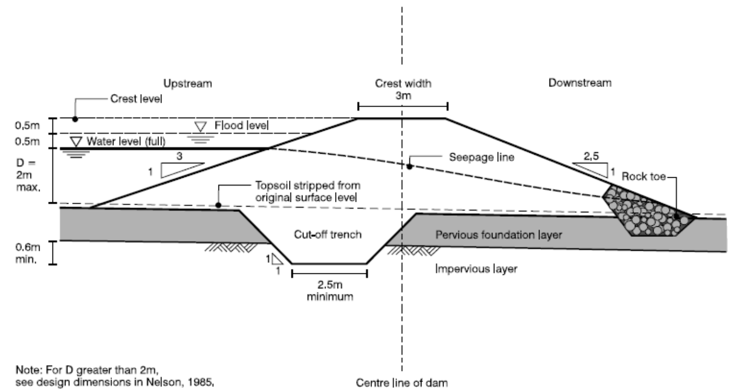
[215] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA.
[216] It has been argued that where the market is functioning well, interventions that address market-related issues during drought are more effective at protecting livelihoods than those that address food supply problems. Taking that argument in our case, supporting the private sector to be able to provide a water service could be more effective than concentrating too much on technology? See: Eldridge, C. (2002) Protecting livelihoods during drought: some market-related approaches. *Humanitarian Exchange* No.22, HPN, ODI, London, UK.
[217] See: Bojcevska, H.; Jergil, E. (2002) *Removal of cyanobacterial toxins (LPS endotoxin and microcystin) in drinking-water using the Bio-Sand household water filter*. Minor field study in Mozambique, September – November 2002. Uppsala University, Uppsala, Sweden. See also: Grützmacher, G.; Böttcher, G.; Chorus, I.; Bartel, H. (2002) *Removal of Microcystins by Slow Sand Filtration*. Wiley Periodicals.
[218] Cecchi, P. ; Leboulanger, C.; Bouvy, M.; Pagano, M.; Nemy, V. (2009) *Agricultural intensification and ecological threats around small reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org.
[219] Even though most berkeds in Somaliland were deeper than the annual evapotranspiration rate, rate of abstraction in the cold dry season can be very high when human and livestock water needs are considered. Experience from the CARITAS berked programme in Somaliland was that berkeds will be used up within 2-3 months.
[220] Aquaforall (2008) *Final Report for Aqua4All supported Projects for implementation of 10 RWH system in Borena Zone South Ethiopia.*

Natural ground catchment & open water reservoir

Overview:
This category covers a range of large open water ponds that store rainwater. Natural depressions (pans) also hold rainwater in a similar way but are not modified or designed. Ponds described in this section include those that are either excavated and/or which might make use of the natural topography, and which in most cases involve an embankment around part of the pond to retain the water (the material for which may have come from excavation works). They come by different names in different countries, but names include johads and “hafirs”. These reservoirs can also be formed in existing seasonal water courses or valleys, in which case they may also be called valley dams, which are essentially the same as gully plugs (see relevant section). They can have limited to high aquifer recharge capacity – for ponds purposely built to increase groundwater recharge, see section on infiltration ponds under Managed Aquifer Recharge (MAR). This section discusses ponds constructed with the primary goal of storing surface water for various water uses (e.g. irrigation, livestock), although they may well also recharge groundwater. Ponds can be lined as well as unlined.

Key techniques for siting:

- The base of the pond needs to be impermeable – e.g. unfissured rock or clay – in order to save costs and prevent having to find a form of lining.
- Try to site ponds to minimize excavation – use natural or man-made topographical features (e.g. borrow pits from road construction, or sloping ground).
- In general ponds should be sited in areas of high intensity rainfall is needed = high runoff, causing ponds to fill with water rather than water infiltrating into the soil.
- In general, it makes sense to build small reservoirs (5-10 ha) in large watersheds – when built with a good spillway, there is no problem and reservoirs fill up quickly. Siting in this case is best determined by proximity to a village, topographical geometry or presence of roads/access. Hydrology comes into play in the design for larger reservoirs (>15 ha).[221] However, when constructing valley dams specifically (those in a seasonal watercourse), the rule of thumb is not to build small reservoirs (below 10,000 m^3) in catchments larger than 400 ha (1,000 acres) because otherwise the amount of overflow is excessive to the point of creating washed-out spillways.[222]
- In pastoralist areas, it might be good to site ponds in areas where traditionally pasture is used first after the rains. In this way, as much water as possible can be used to cover water demand before it is taken by seepage and evaporation, leaving other sources with less seepage and evaporation (e.g. sand dams) to be used later on in pasture accessed during the dry season.



Open water reservoir with dam
Nelson, K. D. (1985) *Design and Construction of Small Earth Dams*. Inkata, Melbourne, Australia.

Key techniques for construction:

- In general, it seems that smaller scale dams owned privately might have more chance of success in terms of participation in the construction and maintenance processes.
- In general, small dams tend to fail much more frequently than larger dams, and this seems due to poorer siting and design, lack of design, poor construction techniques and lack of maintenance.[223] One example in Sudan demonstrates this where breached dam embankments were attributed to a gross underestimation of the runoff volume, as well as poor overall design.[224] Proper design, construction and maintenance are therefore important. The following are guidelines used for hillside dams maximum 3m high, where water is retained by an embankment.[225] For heights over 3m, other guidelines are available.[226]
    - Material used for the dam wall should be impermeable. It should have a high clay content (55% minimum),[227] as long as cracks do not form which would induce piping and leakage. The following materials are to be avoided: organic material including topsoil and that with roots/stones, decomposing material, material with high mica content,

[221] Giesen, N. van de.; Liebe, J. (2009) *Hydrological Impact Assessment of Ensembles of Small Reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org
[222] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. p.63.
[223] Mufute, N.L. (2007) *The development of a risk-of-failure evaluation tool for small dams in Mzingwane catchment*. MSc thesis. University of Zimbabwe, Harare, Zimbabwe. p.10.
[224] Dijk, J. A. van (1995) *Taking the Waters. Soil and water conservation among settling Beja nomads in Eastern Sudan*. African Studies Centre Research Series No.4. Aldershot: Avebury (Ph.D. thesis). p.218.
[225] Pickford, J. (ed) (1991). Technical Brief 48. Small earth dams. In: Shaw, R. (ed) (1999). *Running Water: more technical briefs on health, water and sanitation*. Practical Action Publishing, London.
[226] Nelson, K. D. (1985) *Design and Construction of Small Earth Dams*. Inkata, Melbourne, Australia.
[227] For techniques to assess impermeability & clay content, see: Stone, L. (2003) *Earthen dams for small catchments: a compilation of design, analysis and construction techniques suitable for the developing world*. Michigan Technological University, USA. pp.12-13.

cracking clays, calcitic clays, fine silts, schists and shales, and sodic soils (high sodium concentration). Piping is often a major reason for structural failure of dams and can be recognized by increased seepage rates, discoloured seepage water, sinkholes on or near the embankments and whirlpools in the water.[228]

  - The dam should have a cut-off (minimum 2.5m wide) which locks it into the subsoil foundation.
  - Strip topsoil away from dam foundation since it contains organic matter.
  - Dam material to be laid in 100-200mm deep layers and compacted (with roller or vehicles/animals) when at optimum moisture content (= when material can be rolled to pencil thickness without breaking, yet is as wet as possible without clogging roller).
  - During construction, an addition 10% is added to the design to allow for settlement after construction.
  - Upstream slope should be 1 : 3, downstream slope should be 1 : 2.5.
  - Design should prevent overtopping of dam crest. Water level should be 1m less than dam crest – e.g. for 3m high dam, normal water level (known as D) should be 2m high, leaving 0.5m for floodwater level (= height of spillway) and at least another 0.5m as a safety margin for water rising due to wind/wave action and wear and tear on the dam crest.[229]
  - The dam crest should be 10% higher at the centre (convex shape) so that in case of catastrophic overtopping, water will escape from the edges which will require less repair work. [230]
  - Crest width to be 3 metres minimum. For dams over 3 metres, width needs to be greater (4 metres minimum). The crest needs to have a slope of 1 : 50 from downstream to upstream side of crest.[231]
  - Dam embankment needs to be protected both upstream and downstream. This can be done by covering with topsoil and planting spreading grasses (e.g. couch, star or Kikuyu grasses) to protect against erosion. In arid and semi-arid areas where grasses may not grow without irrigation, it has been suggested to cover the embankment with graded rocks (riprap) with maximum size of 600mm. [232]
  - Protect upstream slope: a floating timber beam secured 2 metres from dam will do this (needs to be replaced every 10 years), also stone or brush mattress on upstream slope will reduce erosion. Graded rocks (riprap) has been also suggested to protect the upstream slope, with maximum size of 600mm.[233]
  - A rock toe drain will help to collect seepage water (which is inevitable with all earth dams) – this is built up to 1/3rd the dam height with a graded sand/gravel layer separating the dam material from the rock toe (to stop clay particles being washed out).
  - The spillway outlet needs to be made robust enough to resist erosion (see section on siting). It can be made from concrete, but cheaper way is to use a grassed spillway. If grass will not grow well, riprap (graded rocks) can be used. Velocity not to exceed 2.5 m/s. Spillway inlet widths vary according to the flood flow, but minimum width to be 5.5 metres. The spillway needs to be kept clear from debris as this has resulted in overtopping in the past.
  - The spillway channel should not allow erosion of the dam structure, and ideally should be lined, with walls to channel the water in the right direction. In place of lining, grass again will suffice – short perennial grasses (e.g. Kikuyu grass) planted in contour lines with 30cm spacing will resist erosion, or another way is to build low stone masonry walls at 2 metre spacing which can act as a staircase to slow down floodwater.[234] The end of a lined spillway channel needs to have a cut-off down to solid ground or should terminate on rock, in order to prevent undercutting of the channel. Spillway slope should be 1 : 33.[235]
- The cheapest form of excavation is where oxen are used.[236]
- Phased construction might provide a manageable way for users to construct their own ponds, whereby each dry season the pond is deepened until experience shows that capacity is sufficient for water demand. For hillside dams with a retaining wall, the wall height and thickness will need to be designed though accordingly.[237]
- Siltation is probably the greatest risks for failure with ponds and dams.[238] The idea is to keep silt out in order to reduce the need for subsequent de-silting, and to have de-silting mechanisms and institutional arrangements that actually work.

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[228] Mufute, N.L. (2007) *The development of a risk-of-failure evaluation tool for small dams in Mzingwane catchment*. MSc thesis. University of Zimbabwe, Harare, Zimbabwe. p.10.
[229] Pickford, J. (ed) (1991). Technical Brief 48. Small earth dams. In: Shaw, R. (ed) (1999). *Running Water: more technical briefs on health, water and sanitation*. Practical Action Publishing, London. See also: www.fao.org/docrep/W7314E/w7314e0g.htm
[230] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. p.62.
[231] Mufute, N.L. (2007) *The development of a risk-of-failure evaluation tool for small dams in Mzingwane catchment*. MSc thesis. University of Zimbabwe, Harare, Zimbabwe. p.13.
[232] Mufute, N.L. (2007) *The development of a risk-of-failure evaluation tool for small dams in Mzingwane catchment*. MSc thesis. University of Zimbabwe, Harare, Zimbabwe. p.13.
[233] Mufute, N.L. (2007) *The development of a risk-of-failure evaluation tool for small dams in Mzingwane catchment*. MSc thesis. University of Zimbabwe, Harare, Zimbabwe. p.13.
[234] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. p.63.
[235] Mufute, N.L. (2007) *The development of a risk-of-failure evaluation tool for small dams in Mzingwane catchment*. MSc thesis. University of Zimbabwe, Harare, Zimbabwe. p.13, 37.
[236] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. pp.17-18.
[237] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. p.31.
[238] Mufute, N.L. (2007) *The development of a risk-of-failure evaluation tool for small dams in Mzingwane catchment*. MSc thesis. University of Zimbabwe, Harare, Zimbabwe. p.9, 14.

- Keeping a good cover of indigenous grasses in the run-off area seems to prevent silt build-up. Kambiti Farm in Kitui District provides a good example of previously degraded land being managed and where open dams did not silt up due to pasture management.[239] Contour lines with trees or grasses in the runoff area also work.[240]
    - If the inflow channel is defined, silt traps can be tried out to reduce silt load as is done with Charco dams in Tanzania. In this case, stones laid across the channel form mini dams and perennial vegetation can be grown between these mini dams to reduce flow velocity of water, thereby encouraging silt deposition.[241]
    - De-silting will most probably need to be carried out at some stage. There may be more sustainable ways of doing this compared to the usual approach used in the recovery stage of DCM, where this process is often paid for by NGOs and where there is a lack of community will to contribute. Experience shows that while animals seem to be a good option for effective de-silting, food-for-work or cash-for-work incentives are commonly still needed to entice communities to improve their own ponds. Projects found that to be effective, it is better to train only a few animals for de-silting work to save damaging the equipment, but farmers tend not to want to use their animals to work on someone else's land.[242] This lack of ownership in communal projects is a recurring thread of failure in WASH projects, and should require new and innovative ways to engender ownership and management of facilities. An institutionally-resilient way to de-silt ponds may be to promote ponds on private land, where one landowner has a vested interest to maintain and de-silt the pond, thus reducing the need for NGO intervention in the longer run. Experience in India seems to support this where the farmer providing the land for the *johad* (pond) would be the prime beneficiary, of the recharged water on adjacent land, but where the community also benefited.[243] Experience from Somaliland showed an example of a successful balli which was privately owned where the owner sold water to the community – while this might at first seem exploitative, it was one of the ballis that continued to function every year.[244] Experience from Bolivia backs this up, where farm ponds constructed for communal use often encountered problems of ownership and maintenance, whereas individually owned ponds proved a better option.[245] In Zimbabwe, communities using dams commented that it was difficult for even committed members of the community to work on maintenance tasks as there was little return for work that benefited everyone. [246]
- Research shows that a large number of small reservoirs designed to hold water have high seepage rates (up to 24mm/day), so this is important to know for design purposes. However, seepage is often disregarded in design calculations as it is difficult to quantify. A field method to determine seepage rates in the bottom of reservoirs has been developed which can be used to assist in design.[247] While in general it may be better to just design for extra seepage loss in pond volume, seepage can still be reduced by:
    - Covering the pond base with clayey soil and compacting it with vehicles or animals. Addition of powdered anthills or lime is said to make this lining more robust.[248]
    - Large open reservoirs have been lined in the past with natural or artificial liners, but it is expensive and the lining material is prone to damage by cattle and ultraviolet light,[249] not to mention when de-silting is required (Further details – see "Natural ground catchment & lined sub-surface tanks")
- Open water in certain areas can have a high evaporation rate, depending on the climate. Evaporation estimates may be higher than the real situation though - land-based pan evaporation measurements usually exceed reservoir evaporation due to the extra energy a pan receives through its sides and bottom.[250] Even so, water lost to evaporation can be considerable. Some ways to reduce this might include:
    - Digging deeper to have a larger volume to surface area ratio. The Charco dam from Tanzania incorporates this through hemispherical design.[251] The problem might be greater levels of investment needed with increased depth. Experience digging reservoirs in Sudan using food-for-work showed that the deeper the dam, the higher the food ratio.[252]
    - Planting trees around the pond will act as a windbreak, thereby reducing evaporation.[253]

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[239] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. SASOL / Maji Na Ufanisi, Nairobi, Kenya.
[240] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. pp.58-60.
[241] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. pp.25, 58-60.
[242] IIRR, ACACIA & CordAid (2004) *Drought Cycle Management: A toolkit for the drylands of the Greater Horn*. pp.104-5.
[243] Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP. p.22.
[244] Author's experience from Wajaale, Somaliland, 2008.
[245] NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions*. Netherlands Water Partnership. p.33
[246] Mufute, N.L. (2007) *The development of a risk-of-failure evaluation tool for small dams in Mzingwane catchment*. MSc thesis. University of Zimbabwe, Harare, Zimbabwe. p.43.
[247] See: Dekker, T.; Rodrigues, L. N.; Olsthoorn, T.; Giesen, N. van de (2009) *Deep Seepage Assessment in Small Reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org. See also: Dekker, T. (2007) *Modeling the Buriti Vermelho Catchment: In Search of the Best Model with Low Data Availability*. MSc thesis, TU Delft, The Netherlands.
[248] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. p.61.
[249] Nissen-Petersen, E. (2006) *Water from Roads: A handbook for technicians and farmers on harvesting rainwater from roads.* DANIDA. p.39.
[250] Liebe, J.; Giesen, N. van de. ; Steenhuis, T. (2009) *Evaporation Losses from Small Reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org.
[251] For construction guidelines, see: Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. pp.23-27.
[252] Moelyowati, I.; Boesner, S. (2001) *Water Baseline Survey Report in North Darfur – Sudan, 6th to 22nd May 2001*. Medair, Switzerland.
[253] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA. p.23.

- Research from Ghana suggests that for new dams, any land ownership issues should be solved prior to construction. Water user groups are also recommended which are ethnically homogeneous or female homogeneous as they might work better for longer term sustainability.[254]
- Pond size (and therefore dam height) can be decided according to water demand, evaporation & seepage losses, length of critical period and average stream flow according to the following:[255]
    - Determine water requirement (R litres/day)
    - Estimate area of reservoir (A m^2), evaporation & seepage losses (E mm/day) and therefore the volume losses per day (A x E litres/day)
    - Estimate length of critical period during which stream flow is less than water requirement & losses (T days) = when water requirements met by using water from reservoir
    - Estimate average stream inflow during critical period (Q litres/day)
    - Calculate effective storage required (S litres) = (R + AxE – Q) x T
    - Site should be then surveyed to estimate area (A m^2) of reservoir for different values of normal water level (D) – this will give reservoir capacity which should be greater than storage required (S) to allow for a safety margin. Reservoir capacity can be estimated by the following: (length x width x maximum depth) / 6.[256]
    - Height of dam will be D plus 1m (for flood level & safety margin).
- Construct during the dry season.
- Experience from South Africa indicates that access to finance seems to be important in allowing farmers to implement ponds.[257]
- Various dam components should be regularly inspected at differing time intervals according to recommended schedules, after which maintenance work should be carried out. This is often missing especially in communal dams.[258]
- Fish can be introduced to eat mosquito larvae, while at the same time providing a source of nutrition. Mudfish are a good option as they can survive dry periods in the silt at the base of pond.[259]

Key techniques for extraction of water:

- Can be done through direct abstraction (pump or pipe taking water off) or indirectly with some kind of shallow well connected hydraulically with the pond, equipped either with or without handpump. Abstraction method ideally should attempt to extract the water in a way so as to minimize disturbance of the settled water, thus reducing treatment requirements later.
    - Direct abstraction from the pond is one option, via a bank-mounted pump (motorized pump or handpump) which uses a floating intake to reduce sediment intake. An outlet pipe and strainer through the dam wall to the downstream side is another option, but these have problems of seepage which can occur through poorly compacted material beside the pipe – this can be reduced by placing seepage collars along pipework.[260]
    - However, even with preventive methods to reduce turbidity (silt trap, extraction method) the water is still turbid & contaminated and will require treatment.
    - For direct abstraction, promotion of household water treatment should be advocated. Choice of household water treatment technology should be based on efficiency of removing contaminants present in the water. For open water that may be prone to cyanobacterial blooms, biosand filters are a good choice due to their ability to remove cyanobacterial toxins.[261] Other technologies however may be more suitable for mobile communities (e.g. SODIS or ceramic filters, depending on turbidity levels). For reservoirs near urban environments or where the runoff area has intensive agriculture practised in its vicinity, diversification of water resources is a good idea to provide alternatives for direct drinking purposes. Strengthening controls and restrictions on use of illegal substances will also help.[262]
    - Indirect abstraction is another option, where water filters through soil/sand to reach an abstraction point. Where banks are permeable, hand-dug wells can access seepage water with or without handpumps. Where banks are impermeable, it might be possible to extract water through a man-made filter in the pond base or between the pond and well shaft.[263]
    - Regarding handpumps, see "Mechanical extraction: handpumps" for details on the pros/cons of handpumps.

Advantages:

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[254] Kinderen, I. van (2006) *Social capital in rural dry season farming communities and its effect on the use and implementation of small water reservoirs*. MSc thesis, TU Delft, The Netherlands.
[255] Pickford, J. (ed) (1991). Technical Brief 48. Small earth dams. In: Shaw, R. (ed) (1999). *Running Water: more technical briefs on health, water and sanitation*. Practical Action Publishing, London. p.62.
[256] Nissen-Petersen, E. (2006) *Water from Rock Outcrops: A handbook for engineers and technicians on site investigations, designs, construction and maintenance of rock catchment tanks and dams*. DANIDA. p.27
[257] Wilk, J.; Wittgren, H.B. (eds). (2009) *Adapting Water Management to Climate Change*. Swedish Water House Policy Brief Nr. 7. SIWI, 2009. p.10.
[258] For example schedule and risk score analysis for dams see: Mufute, N.L. (2007) *The development of a risk-of-failure evaluation tool for small dams in Mzingwane catchment*. MSc thesis. University of Zimbabwe, Harare, Zimbabwe. p.14, 37, 45.
[259] Nissen-Petersen, E. (2006) *Water from Small Dams: A handbook for technicians, farmers and others on site investigations, designs, cost estimates, construction and maintenance of small earth dams*. DANIDA.
[260] For number and size of collars, see: Nelson, K. D. (1985) *Design and Construction of Small Earth Dams*. Inkata, Melbourne, Australia.
[261] See: Bojcevska, H.; Jergil, E. (2002) *Removal of cyanobacterial toxins (LPS endotoxin and microcystin) in drinking-water using the Bio-Sand household water filter*. Minor field study in Mozambique, September – November 2002. Uppsala University, Uppsala, Sweden. See also: Grützmacher, G.; Böttcher, G.; Chorus, I.; Bartel, H. (2002) *Removal of Microcystins by Slow Sand Filtration*. Wiley Periodicals.
[262] Cecchi, P. ; Leboulanger, C.; Bouvy, M.; Pagano, M.; Nemy, V. (2009) *Agricultural intensification and ecological threats around small reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org.
[263] Pickford, J. (ed) (1991). Technical Brief 47. Improving pond water. In: Shaw, R. (ed) (1999). *Running Water: more technical briefs on health, water and sanitation*. Practical Action Publishing, London. p.59.

- Even though main purpose might not be groundwater recharge but rather water for uses like livestock, ponds nevertheless facilitate recharge into surrounding ground – can recharge wells around the pond so there is continued water after pond dries up.

Disadvantages:

- They silt up very easily due to lost vegetation cover in catchment area, leading to soil erosion under intense rainfall and high run-off volumes. Example from Kitui District in 1979 – 43 out of 59 open dams were silted up or broken.[264] De-silting takes time and money.[265]
- Maintaining dams requires communal effort and communal institutions don't seem to be strong enough.
- High combination of evaporation and seepage rates means that water in ponds does not last very long – e.g. 4-6 months in India.[266]
- Vectors can breed in open water.
- Microbiological and chemical water quality is likely to not be acceptable for direct consumption.
    - Water is likely to have a high microbial content due to runoff from contaminated land, as well as communal access to the water by humans and animals.
    - Where runoff is from agricultural areas, there is a possibility of pesticides and fertilizers entering the pond water and sediments – some of which have harmful effects for the aquatic environment and human health. Tests in Côte d'Ivoire showed that in pond water originating from runoff via vegetable plots, levels of pyrethroid compounds were significant. Lack of information and awareness, combined with lax legislation means that many different chemicals might be being used in agriculture.[267]
    - Water in ponds is also prone to cyanobacterial proliferation. Cyanobacteria can be harmful to human health and can cause minor disorders such as headaches, through to lethal deterioration of hepatic functions and promotion of liver cancer. However, the impact of cyanobacteria has largely been neglected in developing countries due to lack of expertise and inefficiency of monitoring programmes (if they exist). It seems that the start of the rainy season is the most likely time for cyanobacterial proliferation. There are several things that can be done to reduce risks by reducing nutrient loads entering the reservoir – such as rehabilitating vegetation in the runoff zone which can use some of the nutrient enriched water before it enters the reservoir.[268]
- High cost of construction – in Sudan, a hafir 80m x 60m x 3m deep (14,400m^3) for 400 beneficiaries cost $8,000. The hafir was completed in 3 months with 190 diggers, did not use food for work but spent the money on tools and installation of inlet/outlet.[269]

[264] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. SASOL / Maji Na Ufanisi, Nairobi, Kenya.
[265] In India, it took 100 people a period of 3 months to de-silt a 3,000m^3 pond and cost 3,700 Euro. See: Malik, D. (2008) Sustainable water security in the Thar Desert, India: Blending traditional wisdom with modern techniques. *33rd WEDC International Conference, Accra, Ghana, 2008: Access to sanitation and safe water: Global partnerships and local actions*. WEDC, Loughborough, UK. p.337.
[266] Malik, D. (2008) Sustainable water security in the Thar Desert, India: Blending traditional wisdom with modern techniques. *33rd WEDC International Conference, Accra, Ghana, 2008: Access to sanitation and safe water: Global partnerships and local actions*. WEDC, Loughborough, UK. p.336.
[267] Cecchi, P. ; Leboulanger, C.; Bouvy, M.; Pagano, M.; Nemy, V. (2009) *Agricultural intensification and ecological threats around small reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org.
[268] Cecchi, P. ; Berger, C.; Couté, A.; Gugger, M.; Zongo, F. (2009) *Cyanobacteria, cyanotoxins and potential health hazards in small tropical reservoirs*. Small reservoirs toolkit. Available from www.smallreservoirs.org.
[269] Moelyowati, I.; Boesner, S. (2001) *Water Baseline Survey Report in North Darfur – Sudan, 6th to 22nd May 2001*. Medair, Switzerland.

Surface water: roof catchment & storage

SUMMARY	**Technical**	**Institutional**	**Financial & economic**	**Environmental**
Roof catchment & storage	• Reduce seepage due to poor construction & siting, especially in areas with swelling soils that can affect the integrity of the lining. • Follow proper concreting guidelines. • Do not site tanks near big trees whose roots might crack the walls. • If taking water out by gravity, design the outlet of the tank so that there is no dead storage • Create a fence around the tank to prevent large vehicles from driving too close and damaging the lining/foundation. • Ensure the catchment itself is efficient (gutter, drainpipe, roof surface). Gutters are weak point (should have the correct material, slope & area plus splash guards). A first flush device and a mesh filter at the top of the downpipe may help reduce debris entering the tank. • No light should enter the tank to discourage microbial growth. • Water treatment of the inevitable alternative water sources needs to be promoted alongside roof rainwater harvesting.		• Increase storage through building with cheaper lower quality materials & repair more often – e.g. plastic lined tanks, thinner walled brick-cement tanks • Improve access to micro-finance (possibly introducing it combined with subsidy) and especially to women, so that users can replicate technology. • Promote smaller tank structures = more manageable to construct and cover, while being more affordable to families. More tanks can be added in subsequent years, thus spreading out costs.	

Overview:
These are rainwater harvesting structures that use existing roofs or roofs specially constructed for the purpose of harvesting rainwater. They are commonly combined with a storage tank to capture the available water and are constructed at both household and institutional level.

Key techniques for siting:
- Where there is a catchment, preferably with high runoff coefficient which will not alter taste (e.g. iron sheets).
- Do not site near big trees whose roots might crack the tank foundations – see below.
- Do not site tanks where heavy vehicles will pass close to tank foundations – see below.

Key techniques for construction:

- The reason for constructing a tank is to retain the water. Therefore one of the most important aspects is that seepage and cracks must be avoided in tanks. Therefore good quality construction work with adequate supervision is vital to create a sound structure – this is especially important in areas with swelling soils that can affect the integrity of the lining. Some generally applicable issues are detailed below to prevent cracking/seepage:
  - Take care when building in clayey areas – montmorilonite, calcium-containing clays (in marls/gypsum sediments) and black cotton soils are all prone to swelling and can crack sub-surface tank walls that are not built robustly enough.[270] For above-ground tanks, the foundation is a very important component to prevent cracks in the walls. Therefore it is important to construct an adequately robust foundation from concrete – when doing so, concrete needs to be laid with vibration in order to be sure it is leak-proof.[271]
  - Do not site near big trees whose roots might crack the walls.
  - Do not site near where heavy vehicles will pass which might crack the walls.
  - Admixtures can be added to the concrete mix in order to reduce the amount of water needed. Research has shown that superplasticizers work best by reducing the amount of water that needs to be added when mixing concrete, which results in 35% less shrinkage. The resulting end material is stronger and can reduce the amount of micro cracks in mortar by half compared to normal mortar while resulting in 76% fewer leaks. In general, the amount of plasticizer to be added should not be greater than 2% of the dry material weight.[272] A plasticizer that can be used that is possibly available is household washing up liquid. In hot climates though, more research is needed in the field application of plasticizers, since the reduction of water used (and increased strength of product) may not be that great due to more water needed to prevent drying out between mixing and application.[273]
- Many different types of tanks exist. Where water is harvested from a roof, tanks are normally above ground (for sub-surface tanks, see “Natural or artificial ground catchment & lined sub-surface tanks” section). Indicative volumes and costs (materials & labour only) are:[274]
  - Water jars from brick - $78 per m^3 storage (0.7 m^3 for $55)[275]
  - Water jars from ferrocement - $50 - $97 per m^3 storage (3m^3 for $150, 0.5m^3 for $46.5[276])
  - Concrete tanks cast in-situ with formwork - $60 per m^3 storage (5m^3 for $300). Do not make more than 1.75m high in order to withstand water pressure.
  - Tanks made from bricks or blocks - $50 per m^3 storage (10m^3 for $500)
  - Stone masonry tanks
  - Ferrocement tanks - $26 - $50 per m^3 storage depending on size (e.g. 11m^3 for $550, 46m^3 for $1,200). Experience from the RAIN Foundation seems to indicate a cost of between 40-100 Euro per m^3 storage for ferrocement tanks (including everything like materials, transport and labour).[277] Partial below-ground ferrocement tanks have also been made where part of the structure is underground and part is above ground - $24.5 per m^3 storage (e.g. 10.8m^3 for $265).[278]
- High cost of tank construction will decrease water availability because smaller tanks can be made. Ways to increase storage include to build with cheaper lower quality materials, use less material for construction, reduce labour costs and repair tanks more often. In this way, storage tanks can become a more realistic option. Ideas include:
  - Plastic lined tanks made from weaker/cheaper wall materials have proved to be cheap - $6.7 - $10 per m^3 of storage (e.g. 6m^3 for $40 = sheeting & iron sheets, while labour/mud provided by householder).[279] These tanks are made using a wood/mud frame with plastic lining the inside. While the feedback from trials in Uganda indicate that the plastic does not last more than 2 years (due to being punctured by something), because the plastic sheet is cheap ($1.6 per m^3 of storage),[280] it seems that this recurring cost is a lot more affordable than much larger one-off costs for more robust tanks. Issues with this kind of tank in some places is that termites can eat the wood. Round bamboo tanks are made in a similar way where bamboo gives external support to a plastic lining – costs are $10 - $15.5 (e.g. 1.5m^3 for $23; 23m^3 for $233).[281]
  - Thinner walled brick-cement tanks that are reinforced externally with steel wire every course of bricks can be cheaper and easier to construct than ferrocement tanks. Volumes can be up to 30m^3 and the tank is rendered inside and outside. Cost - $6.7 - $20 per m^3 of storage (e.g. 1m^3 for $20; 6m^3 for $40).[282]

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[270] Personal communication, Dick Bouman, Aquaforall. See also: Worm, J.; Hattum, T. van (2006) *Rainwater harvesting for domestic use*. Agrodok 43. Agromisa Foundation and CTA, Wageningen, The Netherlands. p.43.
[271] Experience of CARITAS berked programme, Somaliland, 2008.
[272] http://en.wikipedia.org/wiki/Plasticizer
[273] Personal communication with Dr Terry Thomas, Warwick University, UK.
[274] Worm, J.; Hattum, T. van (2006) *Rainwater harvesting for domestic use*. Agrodok 43. Agromisa Foundation and CTA, Wageningen, The Netherlands. p.45.
[275] Rees, D.; Whitehead, V. (2000) *Brick Jars: Instructions for manufacture*. DTU Technical Release Series TR-RWH07. Warwick University, UK. p.6
[276] Rees, D.; Whitehead, V. (2000) *Ferro-Cement Jar: Instructions for manufacture.* DTU Technical Release Series TR-RWH06. Warwick University, UK. p.6
[277] Pers. Comm. with Nijhof, also: Nijhof, S,; Jantowski, B.; Meerman, R.; Schoemaker, A. (2010). Rainwater harvesting in challenging environments: Towards institutional frameworks for sustainable domestic water supply. *Waterlines*, Vol.29 no.3, pp.213.
[278] Rees, D. (2000) *Partially Below Ground (PBG) tank for rainwater storage: Instructions for Manufacture.* DTU Technical Release Series TR-RWH 01. Warwick University, UK. p.6
[279] http://www2.warwick.ac.uk/fac/sci/eng/research/dtu/pubs/rn/rwh/cs20/; see also: Worm, J.; Hattum, T. van (2006) *Rainwater harvesting for domestic use*. Agrodok 43. Agromisa Foundation and CTA, Wageningen, The Netherlands. p.45.
[280] Personal communication with Dr Terry Thomas, Warwick University.
[281] http://www2.warwick.ac.uk/fac/sci/eng/research/dtu/pubs/rn/rwh/cs19/
[282] NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions*. Netherlands Water Partnership.

    - However, care needs to be taken with cheap linings. Plastic can be punctured by de-silting process, insects, rodents but less of a problem compared to using plastic for sub-surface tanks.
    - Reduce the size of structures = increased cost per m^3 storage but more manageable to construct in terms of cash flow, and easier to cover. This way, tanks are more affordable to families, and more tanks can be added in subsequent years, thus spreading out costs.
    - If taking water out by gravity, design the outlet of the tank so that there is no dead storage (i.e. water in the tank that cannot be used).
- Access to finance is a main obstacle to promotion of rainwater harvesting for households, and is important so that users can replicate the technology – however, so far there are few examples on a global level with micro-credit for rainwater harvesting.[283] An initiative is underway in Nepal to trial the promotion of rainwater harvesting tanks through a combination of subsidy and credit from micro-finance institutions (MFIs), mainly targeting women, where gradually over time the subsidy will be replaced by credit completely where rainwater harvesting systems will hopefully be one of the credit products for MFIs. Lessons learned from micro-credit for biogas plants in Nepal show that the system can work when initially mixed with government subsidy – total repayment period ranges from 5 – 7 years and interest rates vary between 11.5 – 16%.[284]
- Create a fence around the tank to prevent large vehicles from driving too close and damaging the lining.
- Apart from a storage tank, a roof catchment is needed. In some areas, separate raised roof sheets have been used but often a rainwater collecting system will use an existing roof. In many areas where thatched roofs are the norm, rainwater harvesting may not be so easy to implement.
- There are considerations in how to make the catchment itself more efficient:[285]
    - Gutters are weak point in all roofwater catchment systems and should have the correct material, slope and area in the design. Splash guards also ensure that all water is collected in high intensity rain showers.
    - Drainpipes, roof surfaces, storage tanks should be built of chemically inert materials in order to avoid contaminating rainwater (e.g. plastic, alumimium, galvanized iron, fibreglass)
    - A first flush device and a mesh filter at the top of the downpipe may help reduce debris entering the tank
    - No light should enter the tank to discourage microbial growth.
- Since rainwater is unlikely to meet all the yearly water demand due to costs and reliability of water supply compared to storage, a roof rainwater harvesting system (with its fairly clean water) should be first designed to meet drinking/cooking water needs first (8 litres/person/day) where other water demand is met from rival alternative sources (which will be probably unsafe). Even so, at some point these alternative sources may also be used for drinking/cooking needs. Therefore household water treatment of the alternative sources needs to be promoted when constructing rainwater harvesting systems.

Key techniques for extraction of water:
- By gravity, pump or bucket.

Advantages:
- Quality can be good compared to other sources.
- High runoff coefficient = similar to roof catchments in that even small showers produce water.
- Can be used for shallow groundwater recharge – see MAR section.

Disadvantages:
- The storage tank is the most expensive part of a roof rainwater system, and often they cannot hold enough water for whole dry season. Making bigger tanks is possible but more difficult and cost is too high = unaffordable = not replicable.
- The high cost of constructing roof rainwater harvesting systems, especially if trying to meet a significant proportion of daily water demand with larger storage capacity. When considering cost-benefit and the optimum storage capacity for roof rainwater harvesting systems, it has been found that for various scenarios involving alternative water sources, rainwater tanks are not an economically attractive method for tank sizes where most rainfall needs to be reliably collected.[286] Medium to high costs therefore will limit the replicability of the technology for poorer families and potential to scale things up.
- Size of catchment: often only larger houses (e.g. at institutions) will have a sufficient catchment area. Smaller household roof area will mean that it will not be feasible to collect enough to last to next wet season.

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[283] From lessons learned over various rainwater harvesting projects globally – see: Nijhof, S,; Jantowski, B.; Meerman, R.; Schoemaker, A. (2010). Rainwater harvesting in challenging environments: Towards institutional frameworks for sustainable domestic water supply. *Waterlines*, Vol.29 no.3, pp.211, 218.
[284] Nijhof, S.; Shrestha, B.R. (2010). *Micro-credit and rainwater harvesting*. Draft paper to be presented at the Pumps, Pipes & Promises conference in The Hague, November 2010.
[285] Gould, J.; Nissen-Petersen, E. (1999). *Rainwater Catchment Systems for Domestic Supply.* IT, London, UK.
[286] Thomas, T.; Rees, D. (1999) Affordable roofwater harvesting in the humid tropics. "Rainwater Catchment: An Answer to the Water Scarcity of the Next Millennium." *9th International Rainwater Catchment Systems Conference*. Petrolina, Brazil, July 1999.

- Type of catchment: in many dryland areas people have thatch roofs that are not (easily) suitable.
- Possible contamination by bird & animal droppings, insects and pollution from the air.

Surface water: fog collection & storage

SUMMARY	**Technical**	**Institutional**	**Financial & economic**	**Environmental**
Fog collection & storage	• Site in areas where clouds form normally below maximum height of terrain, in areas of prevailing winds between 3 - 12 m/s and with no obstructions to wind flow. For coastal installations, the upland areas should not be further than 10km from the coast • Net area needs to be large enough to collect the required amount of water. • Use correct net in a double layer = normally either polypropylene or polyethylene, u/v protected, with 35% shade coefficient, Raschel mesh weave, 1mm fibre size. • Space at 5 metre intervals along the contour and at a distance equal or greater to 60 times the fog collector height in an uphill/downhill direction • Cables should be protected within garden hose to prevent them causing erosion of the structure. • Reservoir capacity should be large enough to store maximum collectable water during high fog months.	• In high winds, nets would normally be taken down as part of normal operation and maintenance		

Overview:
These are rainwater harvesting structures that use large polypropylene nets to catch moisture in the air in the form of fog. These nets are placed perpendicular to the prevailing wind and collect water droplets which drip into a gutter that goes to a reservoir. Fog collection can be a good source of supplementary water in arid and semi-arid areas.

Key techniques for siting:

- Fog collectors need to be sited in areas where fog forms frequently. Upland areas are suitable where moisture in the air condenses, such as when air rises from lower elevations to higher elevations which are cooler. Both liquid content of the fog and sufficient wind speed are needed to collect significant quantities and will affect efficiency. The following are key siting principles:[287]
    - They need to be sited therefore in areas of prevailing wind where wind speed is sufficient (collection efficiency levels off at about 3 m/s). Avoid siting them where wind speeds exceed 12 m/s.

[287] Information from: NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions*. Netherlands Water Partnership, and personal communication with Dr. Robert Schemenauer (FogQuest),

- They should be sited in relevant upland areas where clouds normally form below maximum height of terrain
- For coastal installations, the upland areas should not be further than 10km from the coast

Key techniques for construction: [288]

- Net area needs to be large enough to collect the required amount of water. Typical dimensions per net might be 12m long x 4m high (48m^2). Typical collection rates vary according to the site but seem to average out at anywhere between 2 litres[289] up to 5 litres per m^2 per day, with maximums up to 10 litres per m^2 per day. The largest site in Guatemala produces 7,000 litres per day during the dry season.
- The type and configuration of net material will affect efficiency of collection:
  - Efficiency increases with smaller mesh size and fibre width.
  - Mesh to use is normally either polypropylene or polyethylene, u/v protected, with 35% shade coefficient. The weave and fibre s ize is important to improve efficiency – normally Raschel mesh weave is recommended with 1mm fibre size. It is important to realize that you cannot expect any type of mesh to work efficiently. A polypropylene net has a lifespan of about 10 years.
  - The mesh should be used in a double layer as this improves drainage of the collected water, since one layer rubs against the other layer.
  - Recently 3D mesh has been developed and tested and found to be 2-3 times more efficient than Raschel weave nets.[290]
- The configuration of fog collector structures affect robustness and efficiency:
  - Traditionally fog collectors are constructed as separate single flat-faced units, spaced at 5 metre intervals – this allows for the most efficient collection of fog. It also means that wind damage is less likely compared with collectors that are joined together. In general, these flat units are good for wind speeds up to 20m/s.[291]
  - In high winds, nets would normally be taken down as part of normal operation and maintenance. Otherwise where fog collectors are remotely located, different designs are being researched which may provide increased robustness.[292]
  - Fog collectors should not interfere with one another in an upwind/downwind axis – to prevent this, they should be placed a distance equal or greater to 60 times the fog collector height.
- Do not place collectors where there are obstructions upwind that might affect wind flows.
- Cables should be protected within garden hose to prevent them causing erosion of the structure.
- Reservoir capacity should be large enough to store maximum collectable water during high fog months.
- Regular maintenance work is needed to keep fog collectors functioning.

Fog collectors
FogQuest – www.fogquest.org

Key techniques for extraction of water:

- Water is collected in gutters that lead to a reservoir.

Advantages:

- Water quality can be good.
- Low costs. In Nepal, cost per m^2 was $60 which included all materials for nets and reservoirs, plus labour.[293]

[288] Unless otherwise stated, information from http://www.fogquest.org/aboutfogquest/faq.html, personal communication with Dr. Robert Schemenauer (FogQuest), and: NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions*. Netherlands Water Partnership.

[289] Abualhamayel, H.I.; Gandhidasan, P. (2010) Design and testing of large fog collectors for water harvesting in Asir region, Kingdom of Saudi Arabia. *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010*. pp.116-119.

[290] Sarsour, J.; Stegmaier, T; Linke, M.; Planck, H. (2010) Bionic development of textile materials for harvesting water from fog. *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010.* pp.88-91.

[291] Personal communication with Dr. Robert Schemenauer, FogQuest.

[292] One such design from South Africa was based on failed flat-net systems – the new design is to have 3 x 40m^2 panels joined in a equilateral triangle, then to join 4 such triangles together for support. Mesh used = poly yarn co-knitted with stainless steel for strength. See: Van Heerden, J.; Olivier, J.; Van Schalkwyk, L. (2010) Fog Water Systems in South Africa: An Update. *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010*. p.160.

[293] NWP; Aquaforall; Agromisa; Partners voor Water. (2007) *Smart Water Harvesting Solutions*. Netherlands Water Partnership. p.21.

Disadvantages:

- Unavailability of local polypropylene mesh.
- Susceptibility to storm damage due to site and fragility of nets/structures if maintenance is not performed.[294]
- Vandalism and lack of maintenance – presumably due to distance between structures and population.[295]

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[294] Fog collectors were damaged several times in storms, at times destroying almost all the nets – see: Lastra, C.d.l. (2002) *Report on the Fog-Collecting Project in Chungungo: Assessment of the Feasibility of Assuring its Sustainability.* p.7. Similar things happened in South Africa, and also there was severe abrasion between nets and supporting posts – see: Van Heerden, J.; Olivier, J.; Van Schalkwyk, L. (2010) Fog Water Systems in South Africa: An Update. *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010.* p.160

[295] These were serious problems in both South Africa and Chile. See: Van Heerden, J.; Olivier, J.; Van Schalkwyk, L. (2010) Fog Water Systems in South Africa: An Update. *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010.* p.160. Also see: Lastra, C.d.l. (2002) *Report on the Fog-Collecting Project in Chungungo: Assessment of the Feasibility of Assuring its Sustainability.*

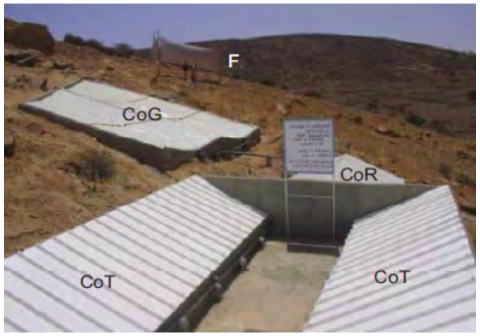
Surface water: dew collection & storage

SUMMARY	Technical	Institutional	Financial & economic	Environmental
Dew collection & storage	• Catchment area needs to be large enough to collect the required amount of water • Elevated collection surface will collect more water • Galvanized roof sheets that can be painted with special paint that enhances collection and laid at a certain pitch • Insulation is required under collectors			

Overview:
These are rainwater harvesting structures that collect dew at night which condenses on a surface from where water droplets drip into a gutter that goes to a reservoir. Quantity from dew varies according to location but at times has been show to constitute a significant proportion of normal rainfall. Dew collection is a possible supplementary source of water in arid and semi-arid areas, but has so far not been widely applied and is an area of further research.

Key techniques for siting:
- Areas with large areas of unused land.
- Areas with large diurnal temperature range (at least 12 degrees Celsius from day to night).[296]

Key techniques for construction:
- Catchment area needs to be large enough to collect the required amount of water, while also being practical to where it is collected.
- Typical collection rates vary according to the site – in Morocco rates of collection were 18.9 litres/m^2/yr (in an area of 215mm annual rainfall)[297] whereas in Spain rates increased to a range of 41.5 to 71.1 litres/ m^2/yr (in an area of between 246 – 324mm annual rainfall).[298]
- Efficiency of collection: seems that elevated surfaces collect 14% more water compared to one on the ground.[299]
- Galvanized roof sheets that can be painted with special OPUR paint – this paint enhances infrared cooling and remain hydrophilic due to photocatalytic reaction with ultraviolet light. Such a system was created in Morocco where painted sheets were underlain with a 2cm thick polystyrene insulation, and the roof pitch was 30 degrees. The system uses radiative cooling at night. Foil can also be used but is prone to damage.[300]
- Dew collection can also be used to create a form of micro irrigation where plastic trays are used to funnel dew to plant roots.[301]



Dew collectors, Morocco
Clus, O.; Lekouch, I.; Durand, M.; Lanfourmi, M.; Muselli, M.; Milimouk-Melnytchouk, I.; Beysens, D. (2010) Large Dew water collectors in a village of S-Morocco (Idouasskssou). *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010.*

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[296] http://www.invennovations.com/irrigation.html
[297] Lekouch, I.; Kabbachi, B.; Milimouk-Melnytchouk, I.; Muselli, M.; Beysens, D. (2010) Influence of temporal variations and climatic conditions on the physical and chemical characteristics of dew and rain in South-West Morocco. *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010.* pp.43-46.
[298] Ucles, O.M.; Moro, M.J.; Villagarcia, L.; Morillas, L.; Canton, Y.; Domingo, F. (2010) Is dewfall an important source of water in semiarid coastal steppe ecosystems in SE Spain? *5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010.* pp.172.
[299] Clus, O.; Lekouch, I.; Durand, M.; Lanfourmi, M.; Muselli, M.; Milimouk-Melnytchouk, I.; Beysens, D. (2010) Large Dew water collectors in a village of S-Morocco (Idouasskssou). 5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010. pp.243-245.
[300] Clus, O.; Lekouch, I.; Durand, M.; Lanfourmi, M.; Muselli, M.; Milimouk-Melnytchouk, I.; Beysens, D. (2010) Large Dew water collectors in a village of S-Morocco (Idouasskssou). 5th International Conference on Fog, Fog Collection and Dew, Munster, Germany, 25–30 July 2010. pp.243-245.
[301] http://www.energyboom.com/lego-dew-collection

Key techniques for extraction of water:
- Water is collected in gutters that lead to a reservoir.

Advantages:
- Water quality can be good.
- Can possibly be a supplementary water source to rainwater harvesting.
- Low costs especially for dew irrigation ($1 per plant).
- Possible to do on household level = ownership and maintenance.

Disadvantages:
- Variability in water collection, which also varies according to the season. Need to supplement water from other sources.

Shallow groundwater: hand-dug, jetted & driven wells

SUMMARY	**Technical**	**Institutional**	**Financial & economic**	**Environmental**
General	• Consider pros & cons of handpumps before installing one (see "Mechanical extraction: handpumps" for details). • If a bucket and rope is used, household water treatment should be advocated.	• When considering groundwater abstraction, demand management is as important as improving supply. MAR can make periodic contributions to redress quality and quantity but without demand management it is not a sustainable solution.[302]		
• Traditional hand-dug wells	• Site wells at a sufficient distance away from sources of contamination • Simplify construction methods to get a more robust end product in a safer fashion (e.g. in-situ & telescopic lining made with foundation ring & blocks) • Construct well using a telescopic system where the smaller lining can be deepened at a later date without affecting the permanent lining and slab • Dig wells during the latter half of the dry season • De-water well during caissoning within the water table – this can be done with de-watering pumps or bailers depending on budget or level of subsidence around well • Pay attention to safety when using a motorized pump: engines should be located downwind, a 100 – 150mm vent pipe can be temporarily put into the well for ventilation, submersible pumps should be fitted with circuit breakers, digger should be wearing construction harness attached to rope, and rescue & recovery action should be in place and			

[302] Gale, I.N.; Macdonald, D.M.J.; Calow, R.C.; Neumann, I.; Moench, M.; Kulkarni, H.; Mudrakartha, S.; Palanisami, K. (2006) *Managed Aquifer Recharge: an assessment of its role and effectiveness in watershed management*. British Geological Survey Commissioned Report, CR/06/107N. p.viii.

	practised regularly. • Where deepening the well further is not possible due to water/sand ingress, jetting in the bottom of the well can provide a means of faster recharge into the well from deeper in the aquifer • Where wells still dry up in the dry season, MAR techniques could be used upstream of the well • The use of porous concrete in part of the section of the well shaft which is underwater can help increase flow velocity into the well. Also perforated pointed steel pipes can be driven horizontally into the aquifer using a jack will also increase flow velocity			
• Riverbed hand-dug wells	• Site in riverbeds that are dry for part of the year, where water remains in the riverbed throughout the dry season. • Where intention is to abstract water using manual or motorized suction pumps site these wells within 30 metres of the pump location and where pump will be sited above maximum floodwater level but still within suction range (e.g. 6 – 7 metres). • Simplify construction methods to get a more robust end product in a safer fashion (e.g. cutting foundation ring and curved concrete blocks). • Ensure that wells are dug deep enough to allow enough flow during the dry season • For sand rivers that have a significant clay content where permeability will be low, flow velocity into the well can be increased by making a large gravel pack around the well			

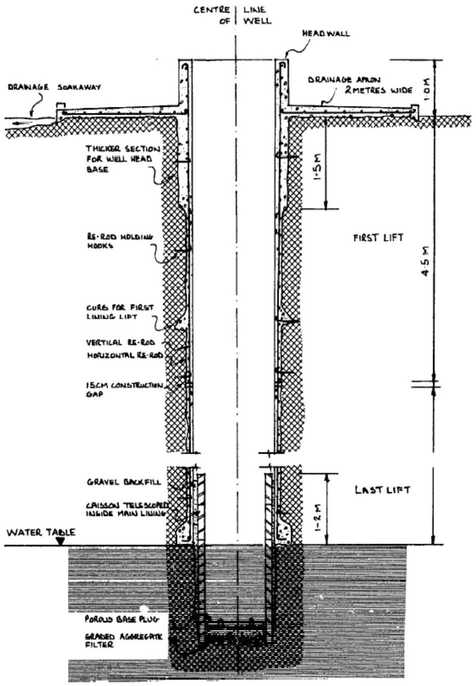
	shaft • For where the well is made within or partially within a riverbed where it will be flooded or have floodwater beside or close to it, well shaft should be buried at least 1.5 metres within sand, or be constructed with hydrodynamic head. Wells with hydrodynamic head probably best suited to riverbeds of low porosity and permeability. • The use of porous concrete in part of the section of the well shaft which is underwater can help increase flow velocity into the well. Perforated pointed steel pipes can be driven horizontally into the aquifer using a jack – this can also increase flow velocity into the well.			
• Riverbed infiltration galleries	• Site in shallow or fine sediment beds where there is poor permeability or lack of sand depth, or where riverbanks are too high to allow manual or motorized suction pumps to operate, and where water remains in the riverbed throughout the dry season • Site in a degrading river section where there is no deposition • Diameter of screen used is typically 75 – 300 mm PVC and varies from a few metres up to several hundred metres in length. Layouts vary according to the river widths. Yields are typically 15 litres/min/metre, but depends on depth from river to sump. • Ensure that galleries are dug deep enough to allow enough flow during the dry season = at least 1 metre depth within the saturated zone. • If more than one pipe are			

	installed, distance between pipes should not be less than 3 metres. • The top of the gallery should be ideally 1.5 metres minimum from the riverbed surface. • Graded gravel needs to be placed under and over the pipe to minimize clogging with sediments.			
• Riverbed jetted & driven wells	• The screens and pipework should be 1.5 metres minimum from the riverbed surface. • Screens used can be anywhere from 32 to 200 mm in diameter, and only 0.5 – 1 metre in length. Driven wellpoints made from steel require wingtips on the pointed end. • Jetting is one method of installing a screen into the saturated sand layer. • Flow velocity around the screen should be maximized. A gravel pack should be created around the screen. For sand rivers that have a significant clay content, permeability will be low – in this case, flow velocity into the well can be created by making a large gravel pack around the well shaft.			
• Infiltration wells	• Site wells at a sufficient distance away from sources of contamination • Site where water table is within 5 metres of ground surface, and where soils are stable • Site where water demand is low (e.g. for small communities) • Site in areas of stable soil that has no risk of collapsing. Digging should not go deeper than 5 metres. • Cheapest form of intake is to install the intake in the empty hole and fill with clay-free sand to the height of the wet season			

	water table level, after which the hole is backfilled with original soil. • Where wells still dry up in the dry season, MAR techniques could be used upstream of the well			

<u>Traditional hand-dug wells</u>

Overview:
This category describes shallow wells which draw water from a natural aquifer or man-made aquifer (e.g. near sand dam or around ponds) but which are not located inside a riverbed. It can include wells that are far from a river, or wells that receive water from shallow aquifers hydraulically connected to the river. Sometimes the holes dug are very large, allowing people and sometimes animals are able to walk into the well to where the water is.



Hand-dug well with telescopic lining
Watt, S.B.; Wood, W.E. (1979) *Hand Dug Wells and their Construction.* IT, London, UK.

Key techniques for siting:
- Site wells at a sufficient distance away from sources of contamination. For microbiological contamination, the distance from the source of contamination (e.g. latrine) to the water intake (screen) needs to be sufficient so as to pose a "low" to "very low" risk – this translates into a minimum of 25 days of potential travel of pathogens in the ground. Travel time is influenced by porosity, hydraulic conductivity (permeability) and hydraulic gradient. For medium size sand with an average porosity, the distance equivalent to 25 days is around 30 metres, but this can increase to over 100 metres for coarser sediments. However, the distance from contamination to water intake can reduce significantly where the screen intake is at a sufficient depth – this is due to greater variation of aquifer properties in vertical directions than lateral, meaning that a borehole with handpump could be placed very close to a latrine with low risk. However, screen depth must increase with increased extraction rate.[303]
- Care should be taken to avoid siting wells in perched aquifers (shallow aquifers with limited recharge capacity and water storage).

Key techniques for construction:
- Hand-dug wells have a tendency to have very little water or even dry up in the dry season. This is largely to do with the fact that the intake area is not deep enough inside the dry season water table. Shallow aquifers tend to reflect recharge more sharply than deeper aquifers, resulting in water table fluctuations of several metres between seasons – these fluctuations need to be accounted for in the construction method. Several techniques can ensure that wells are sunk deep enough:
  - Construct wells using a telescopic system, where an in-situ permanent lining is created above the water table, together with a smaller diameter telescopic lining that enters the water table. The advantage of this system is that the smaller lining can be deepened at a later date without affecting the permanent lining and slab (e.g. in case the well was not sunk deep enough the first time). Another advantage is that the shaft has less chance to go out of vertical alignment during caissoning (where a shaft is sunk by digging).
  - Use an effective method of de-watering during caissoning within the water table. Many hand-dug wells are dug without using a de-watering pump – consequently, the limit of penetration into the water table is about only 1 metre. Providing a de-watering pump will allow the shaft to be sunk deeper into the water table, but note:
    - Type of pump depends on the height from ground level to water table – for a suction pump, the limit will be 6-7 metres, after which a submersible pump and generator needs to be considered. The type of pump should allow a certain amount of solid particles to be pumped.
    - Attention needs to be given to safety considerations when using a motorized pump with someone digging in the well – engines should be located downwind so fumes do not enter the well, a 100 – 150mm vent pipe can be temporarily tied to the crossbeam to ventilate the well (in similar way to a VIP latrine), submersible pumps

303 Lawrence, A.R.; McDonald, D.M.J.; Howard, A.G.; Barrett, M.H.; Pedley, S.; Ahmed, K.M.; Nalubega, M. (2001). *Guidelines for assessing the risk to groundwater from on-site sanitation.* British Geological Society, Keyworth, UK.

should be fitted with circuit breakers in case of electrical shortcuts to avoid electrocution, digger should be wearing construction harness attached to rope, and rescue & recovery action should be in place and practised regularly.
    - Where using a de-watering pump results in subsidence around the well (in the case of flowing sands), another idea is to use a bailer instead of a pump. A bailer is normally used in percussion drilling, and consists of a heavy hollow metal tube with a valve on the bottom. When the bailer is dropped, sediment enters which does not come out when the bailer is removed. This method takes longer, but can be performed at ground level without a de-watering pump – since the water is not being pumped, flowing sand has less incentive to enter and the well shaft can sink slowly.[304]
    - Aim to dig wells during the latter half of the dry season when water table will be at their lowest.
- Where deepening the well further is not possible due to water/sand ingress, jetting in the bottom of the well can provide a means of faster recharge into the well from deeper in the aquifer, meaning the well dries up less quickly. In this case a larger diameter screen (can be wrapped with geotextile) is jetted into the well base with the end protruding above the bottom of the well, after which it is plugged using a small bag of gravel (see "Riverbed wells" section for details on jetting).[305]
- Where wells still dry up in the dry season, recharge techniques could be used upstream of the well (see "Surface water: Managed Aquifer Recharge (MAR) – Shallow wells & boreholes" for details).
- The use of porous concrete in part of the section of the well shaft which is underwater can help increase flow velocity into the well. Porous concrete is made using a of 1 : 1 : 4 (cement : sand : aggregate) and can be used for curved blocks or also for a central portion of any pre-cast concrete ring. Also perforated pointed steel pipes can be driven horizontally into the aquifer using a jack – this can also increase flow velocity into the well.[306]
- Simplify construction methods while getting a more robust end product in a safer fashion. Using in-situ lining & telescopic lining has the advantage that heavy lifting equipment for pre-cast rings is obsolete while procedures are inherently safer. In-situ lining is made using one-skin moulds that hold concrete against the dug wall of the hole, while the telescopic shaft can be made from curved blocks built onto a foundation cutting ring – the blocks can be extended as and when necessary.[307]

Key techniques for extraction of water:
- Can be done with handpump or mechanical pump (see "Mechanical extraction: handpumps" for details on the pros/cons of handpumps).
- A bucket and rope can be used but risk of contamination increases. In such a case, household water treatment should be advocated.

Advantages:
- Larger diameter = more water stored = good for low-yielding aquifers.
- Manual access = can be deepened or maintained easily at a later date.
- Can be privately owned/operated.

Disadvantages:
- Smaller wells can dwindle in supply during long dry periods and heavy use, especially in perched aquifer areas.
- Hand-dug wells often are built with pumps to abstract the water, so all disadvantages related to pumps also relate to boreholes, including operation and maintenance issues, lack of ownership, and spare parts availability. Where handpumps are used, all related handpump problems apply (see "Mechanical water: handpumps" for details).
- Hand-dug wells near a river have the possibility to be contaminated by pollution from agricultural runoff in river water.
- High cost of construction ($1,000 USD or more) – this is due to construction materials as well as the time taken to make a well (about 1 month depending on depth and ease of digging). Wells can be made cheaper however (see "Riverbed wells" and "Infiltration wells" sections).
- Significant amount of work involved.
- Slow rate of construction.
- Can be difficult to sink to required depth especially in areas of flowing sand.
- Aquifers cannot always meet water demand sustainably, especially for high demand applications. Water levels can drop over time, resulting in possible mining (where aquifer is compressed and cannot hold water any longer afterwards).

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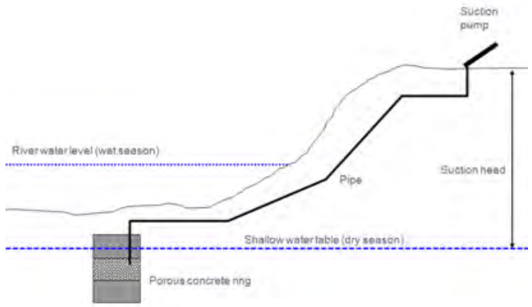
[304] Personal communication with hydrogeologist, Madagascar.
[305] Personal communication with Richard Cansdale, UK, concerning his experience in Senegal.
[306] Watt, S.B.; Wood, W.E. (1979) *Hand Dug Wells and their Construction*. IT, London, UK. pp.169-170.
[307] For an excellent construction manual, see: Watt, S.B.; Wood, W.E. (1979) *Hand Dug Wells and their Construction*. IT, London, UK. In addition, Medair (Madagascar) in 2004 created some more efficient designs of cutting ring and block moulds.

Riverbed hand-dug wells

Overview:
This category describes shallow wells which draw water from a natural or man-made aquifer specifically within a riverbed. The simplest version of these is a shallow hole dug every season in a riverbed which gets flooded with every flood event. Other versions allow the water to be accessed all year round through offset handpumps.

Key techniques for siting:
- Wells need to be sited in riverbeds that are dry for part of the year, allowing construction to take place.
- There should be water remaining in the riverbed throughout the dry season.
- Where wells are dug with the intention to abstract water using manual or motorized suction pumps, due to pumping requirements it is best to site these wells:[308]
    - Within 30 metres of the pump location.
    - In areas where there are no high banks and where maximum floodwater height is lower than these banks – this is so that suction pumps can still operate (effectively will abstract water between 6 – 7 metres height).

Key techniques for construction:
- Simplify construction methods while getting a more robust end product in a safer fashion. Pre-cast concrete rings can be used, but is more easily done with a cutting foundation ring and curved concrete blocks, some of which are made from porous concrete (see "Traditional hand-dug wells" for details).
- Ensure that wells are dug deep enough to allow enough flow during the dry season (see "Traditional hand-dug wells" for details).
- For sand rivers that have a significant clay content, permeability will be low, and yields will also be low. Increased flow velocity into the well can be created by making a large gravel pack around the well shaft – this gravel pack consists of aggregate and stones (rather than the traditional type of small diameter gravel pack used in boreholes).
- For where the well is made within or partially within a riverbed where it will be flooded or have floodwater beside or close to it:
    - The well shaft can be made so that it is buried within the sand, and is uncovered after each flood event for access to the water. A slab is made to cover the top ring and a manhole access cover is created for dry season access but which can be closed during a flood event. In such a case:
        - The top of the ring should be ideally 1.5 metres minimum from the riverbed surface. This is so that:
            - There is at least a minimum of infiltration that occurs from surface water during the wet season when the river is flooded
            - That there is less chance that the well shaft and pipework will be washed away in a flood event. Sand becomes mobile to a certain depth which differs for different rivers but has been recorded to be normally between 0.66 and 2 metres in seasonal riverbeds.[309]
    - The well shaft can also be made so that it protrudes from the riverbed sand level. A slab is made to cover the top ring and a manhole access cover is installed for dry season access. In such a case:
        - The well shaft needs to be protected – a hydrodynamic well head should be constructed to minimize damage from floodwater and the debris it contains. This well head has a shape of an upturned boat which deflects water and debris in the floodwater. The manhole cover opens in the upstream direction so that it closes when the floods arrive.[310]
        - Such a construction is probably best suited to riverbeds of low porosity and permeability where sediments have some stability and little is transported in floodwater, otherwise damage to the well could easily take place.[311]
- The use of porous concrete in part of the section of the well shaft which is underwater can help increase flow velocity into the well. Porous concrete is made using a of 1 : 1 : 4 (cement : sand : aggregate) and can be used for curved blocks or also for a central portion of any pre-cast concrete ring. Also perforated pointed steel pipes can be driven horizontally into the aquifer using a jack – this can also increase flow velocity into the well.[312]



Riverbed well with offset handpump
Eric Fewster, BushProof

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[308] Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK. p.47
[309] See: Foley, M.G. (1978). Scour and Fill in Steep, Sand-bed Ephemeral Streams. *Geological Society of America Bulletin*, Vol. 89, pp. 559-570. See also: Republic of Kenya; Democratic Republic of Sudan. (1981). *Road A1: Kenya-Sudan Road Link Lodwar-Juba. Hydrogeological Survey*. Ministry of Transport and Communications, Kenya; Roads and Bridges Public Corporation, and Regional Ministry of Communications, Transport and Roads, The Democratic Republic of Sudan. Norconsult AS (Kenya), Nairobi, Kenya.
[310] 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*. pp.34-36. RELMA, Nairobi, Kenya.
[311] Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK. p.54.

Key techniques for extraction of water:

- Can be done using rope and bucket. In such a case, household treatment should be advocated.
- Can be done with handpump or mechanical pump (see "Mechanical extraction: handpumps" for details on the pros/cons of handpumps). If a handpump or mechanical pump is installed, it needs to be a suction pump if the pump location is offset.

Advantages:

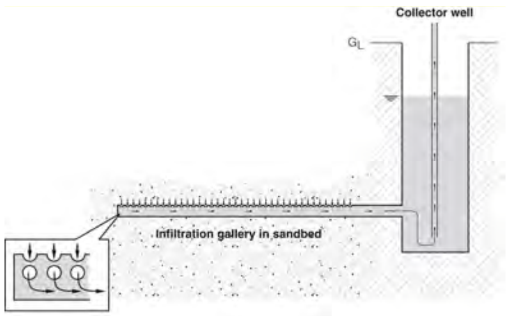
- Taps water in riverbed rather than through riverbanks (if very defined aquifer where water is confined to riverbed)
- Lower cost than making a lined well in the riverbank due to less lining needed
- Speedier construction and lower cost compared to fully lined well
- Safer to construct due to fewer hazards compared to deeper wells.

Disadvantages:

- Contamination possibility of water due to limited filtration depth between surface water to intake.
- Can be difficult to sink to required depth especially in areas of flowing sand.

Riverbed infiltration galleries

Overview:
This category includes horizontal channels that take water from a riverbed to a collector well in the riverbank. Channels are often screens (slotted or perforated pipes) that are inserted horizontally into a riverbed, but equally infiltration galleries can be made from channels with graded gravel as long as sediments are not washed into the collector well. Where screens are used, the screen diameter tends to be larger than that used normally for jetted/driven wells.



Infiltration gallery
Image courtesy of WEDC. © Ken Chatterton. In: Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK.

Key techniques for siting:

- Infiltration galleries are often installed in shallow or fine sediment beds where there is poor permeability or lack of sand depth – in this case, the length proves to be advantageous.[313]
- They can also be sited in areas where riverbanks are too high to allow manual or motorized suction pumps to operate.
- There should be water remaining in the riverbed throughout the dry season.
- Make it in a degrading river section where there is no deposition = coarser grains and no silt deposits blocking flow.[314]

Key techniques for construction:

- The length of screen required will be greater for an infiltration gallery than for a jetted or driven well – this is because in an infiltration gallery, water flows to the collector well under hydraulic head rather than being pumped out with a suction pump. Diameter of screen used is typically 75 – 300 mm PVC and varies from a few metres up to several hundred metres in length. Layouts vary according to the river widths.[315] Yields are typically 15 litres/min/metre, but depends on depth from river to sump.[316]
- Ensure that galleries are dug deep enough to allow enough flow during the dry season. In practical terms, this means aiming for at least 1 metre depth within the saturated zone. If more than one pipe are installed, distance between pipes should not be less than 3 metres.[317]
- The top of the gallery should be ideally 1.5 metres minimum from the riverbed surface. This is so that:
  - There is at least a minimum of infiltration that occurs from surface water during the wet season when the river is flooded

[312] Watt, S.B.; Wood, W.E. (1979) *Hand Dug Wells and their Construction*. IT, London, UK. pp.169-170.
[313] Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK. p.44
[314] Pickford, J. (ed) (1991). *The Worth of Water: technical briefs on health, water and sanitation*. Practical Action Publishing, London. p.92.
[315] Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK. pp.48-49.
[316] Pickford, J. (ed) (1991). *The Worth of Water: technical briefs on health, water and sanitation*. Practical Action Publishing, London. p.92.
[317] Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK. p.51.

- That there is less chance that the well shaft and pipework will be washed away in a flood event. Sand becomes mobile to a certain depth which differs for different rivers but has been recorded to be normally between 0.66 and 2 metres in seasonal riverbeds.[318]
- Graded gravel needs to be placed under and over the pipe to minimize clogging with sediments.

Key techniques for extraction of water:
- Water from infiltration galleries runs to collector wells from where it can be abstracted with a handpump or motorized pump. The collector well is a hand-dug well which acts as a waterproof chamber – it is dug deeper than the infiltration gallery to allow water to enter by gravity and to allow enough storage volume.
- Regarding handpumps, see "Mechanical extraction: handpumps" for details on the pros/cons of handpumps.
- A bucket and rope can be used but risk of contamination increases. In such a case, household water treatment should be advocated.

Advantages:
- Allows a method of extraction where sand depth is shallow or where sediments are fine and have low permeability.
- Cheap where it can be done without shuttering.

Disadvantages:
- Difficult to make deep enough to ensure water at all times. Laying deeper galleries involves digging deeper and preventing sand trenches from collapsing by using shuttering – this becomes a more involved and expensive process.
- Significant amount of work involved.
- Difficult to construct where riverbanks are not alluvial (where rock breaking techniques required).[319]
- Can clog up over time.

<u>Riverbed jetted & driven wells</u>

Overview:
This category includes short small diameter cylindrical screens (slotted or perforated pipes) that are inserted into unconsolidated sediments using water pressure or physical force, usually vertically or obliquely. Digging is not needed in this case.

Key techniques for siting:
- Due to pumping requirements, it is best to site these wells:[320]
  - Within 30 metres of the pump location.
  - In areas where there are no high banks and where maximum floodwater height is lower than these banks – this is so that suction pumps can still operate (effectively will abstract water between 6 – 7 metres height).
- There should be water remaining in the riverbed throughout the dry season.

Key techniques for construction:
- The screens and pipework should be ideally 1.5 metres minimum from the riverbed surface. This is so that:
  - There is at least a minimum of infiltration that occurs from surface water during the wet season when the river is flooded
  - That there is less chance that the well shaft and pipework will be washed away in a flood event. Sand becomes mobile to a certain depth which differs for different rivers but has been recorded to be normally between 0.66 and 2 metres in seasonal riverbeds.[321]

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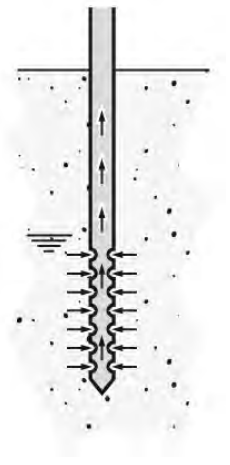
[318] See: Foley, M.G. (1978). Scour and Fill in Steep, Sand-bed Ephemeral Streams. *Geological Society of America Bulletin*, Vol. 89, pp. 559-570. See also: Republic of Kenya; Democratic Republic of Sudan. (1981). *Road A1: Kenya-Sudan Road Link Lodwar-Juba. Hydrogeological Survey*. Ministry of Transport and Communications, Kenya; Roads and Bridges Public Corporation, and Regional Ministry of Communications, Transport and Roads, The Democratic Republic of Sudan. Norconsult AS (Kenya), Nairobi, Kenya.
[319] Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK. p.68
[320] Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK. p.47
[321] See: Foley, M.G. (1978). Scour and Fill in Steep, Sand-bed Ephemeral Streams. *Geological Society of America Bulletin*, Vol. 89, pp. 559-570. See also: Republic of Kenya; Democratic Republic of Sudan. (1981). *Road A1: Kenya-Sudan Road Link Lodwar-Juba. Hydrogeological Survey*. Ministry of Transport and Communications, Kenya; Roads and Bridges Public Corporation, and Regional Ministry of Communications, Transport and Roads, The Democratic Republic of Sudan. Norconsult AS (Kenya), Nairobi, Kenya.

- Screens used can be anywhere from 32 to 200 mm in diameter, and only 0.5 – 1 metre in length. For jetted wellpoints, they are commonly made from plastic. For driven wellpoints, they are made from steel and require wingtips on the pointed end.[322]
- Jetting (also known as washboring) is one method of installing a screen into the saturated sand layer. There are various forms of jetting, with various pipe sizes. Key techniques are outlined below:[323]
  - About 1,000 litres of water is required, possibly more depending on ease of procedure and size of sediment particles. This water can be brought with a bowser, or can be created using a hole dug into the ground and lined with a plastic sheet.
  - A 2" Honda suction pump (600 litres/min) is normally used for both jetting and well testing, although larger capacity pumps will enable deeper jetting but will use more water per minute.
  - During the jetting process, water emerges from the end of the jetting pipe and flows upwards to ground level. If the flow of water stops (e.g. water runs out, or to change a pipe), in most circumstances the sand around the jetting pipe/screen will collapse, after which it is impossible to re-start the flow of water to the surface. However, in some cases the hole will remain open – only in these cases can you add another pipe and continue jetting, but otherwise the depth you can install the screen is dependent on the length of jetting that can be done in one go without stopping the pump.
  - Digging a large pit to the water table is advantageous since:
    - In collapsing sands, you can jet to the base of the pit, after which you can glue extra pipes onto the screen to reach ground level = deeper well achieved.
    - The chance of losing the water column is minimized due to less pressure head that the water must overcome in order to flow to the surface. With higher pressure heads (i.e. more distance from water level in ground to ground level), the water is more likely to choose the path of least resistance, which at some point will be to go into the aquifer rather than come to the surface. In such a case where you lose the water column in collapsing sands, the well will be finished at that depth.
  - A screen can have a ball valve at the end – in this case, the jetting pipe and screen are made from the same piece. Alternatively the screen can be separate from the jetting pipe, where the jetting pipe creates the hole and then is removed once the screen is installed to required depth.[324] If a screen with valve is chosen, care should be taken if installing handpumps as the ball valve has a tendency to open over time letting in sand.
  - Flow velocity around the screen should be maximized. This can be done by adding a layer of perforated drainage pipe around the screen, followed by geotextile. Additionally, a gravel pack should be created around the screen. This can be done by:
    - Throttling the pump speed down once the screen is at the required depth – this will remove fines while allowing coarse sediments to settle around the screen
    - For sand rivers that have a significant clay content, permeability in the riverbed will be low, and yields will also be low. Increased flow velocity into the well can be created by making a large gravel pack around the well shaft – this gravel pack consists of aggregate and stones (rather than the traditional type of small diameter gravel pack used in boreholes).[325]



Jetted / driven well point
Image courtesy of WEDC. © Ken Chatterton. In: Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction.* WEDC, Loughborough University, UK.

Key techniques for extraction of water:
- Can be done with handpump or mechanical pump. Handpump cylinder will need to physically be able to fit inside the screen that has been installed.
- Regarding handpumps, see "Mechanical extraction: handpumps" for details on the pros/cons of handpumps.

Advantages:
- Speed and low cost of construction
- High yields possible with small intakes.

Disadvantages:
- More difficult to do in sandy sediments that are mixed with clay.
- No storage capacity as with large diameter wells.
- Cannot easily access intake for maintenance or in case of problems.

[322] Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK. pp.44, 71-81.
[323] Based on personal experience of Eric Fewster, BushProof.
[324] Hussey, S.W. (2007) *Water from sand rivers: guidelines for abstraction*. WEDC, Loughborough University, UK. p.82
[325] Trials in Kenya showed that flow increased from 1,350 to 10,800 litres/hour with the addition of gravel around the screen. Source: Eric Fewster.

Infiltration wells

Overview:
This category describes shallow wells which draw water from a natural aquifer outside of a riverbed, but which have a partial lining. They are useful where recharge of the aquifer is low due to low permeability.

Key techniques for siting:
- Site wells at a sufficient distance away from sources of contamination. For microbiological contamination, the distance from the source of contamination (e.g. latrine) to the water intake (screen) needs to be sufficient so as to pose a "low" to "very low" risk – this translates into a minimum of 25 days of potential travel of pathogens in the ground. Travel time is influenced by porosity, hydraulic conductivity (permeability) and hydraulic gradient. For medium size sand with an average porosity, the distance equivalent to 25 days is around 30 metres, but this can increase to over 100 metres for coarser sediments. However, the distance from contamination to water intake can reduce significantly where the screen intake is at a sufficient depth – this is due to greater variation of aquifer properties in vertical directions than lateral, meaning that a borehole with handpump could be placed very close to a latrine with low risk. However, screen depth must increase with increased extraction rate.[326]
- Site where water table is within 5 metres of ground surface, and where soils are stable.
- Site where water demand is low (e.g. for small communities).


Infiltration well, Madagascar
Eric Fewster, BushProof

Key techniques for construction:
- Construction involves digging a hole to the water table in stable soil that has no risk of collapsing. Digging should not go deeper than 5 metres for safety reasons.
- Digging continues inside the water table but due to the low yield of the aquifer, digging can proceed without only buckets for de-watering purposes.
- An intake needs to be created which will be installed in the well before backfilling. The intake can normally be a screen that is connected to casing – this should be large enough diameter to fit the handpump cylinder. The intake can be installed in several ways:
    - A chamber can be constructed within the water table zone from suitable material (e.g. blocks) and covered with a slab – the intake pipe is placed through the slab, after which the hole can be backfilled to ground level, adding more sections to the intake section as required.
    - A cheaper way is to install the intake in the empty hole. Verticality is ensured using a spirit level, after which the intake is secured temporarily to beams at ground level. The hole is then backfilled with clay-free sand to the height of the wet season water table level, after which the hole is backfilled with original soil. In this way, an artificial aquifer is created around the intake and well volume is equivalent to the porosity of the sand.
    - A pump can then be installed within the intake screen.
- Where wells dry up in the dry season, recharge techniques could be used upstream of the well (see "Surface water: Managed Aquifer Recharge (MAR) – Shallow wells & boreholes" for details).

Key techniques for extraction of water:
- Can be done with handpump or mechanical pump. Handpump cylinder will need to physically be able to fit inside the screen that has been installed.
- Regarding handpumps, see "Mechanical extraction: handpumps" for details on the pros/cons of handpumps.

Advantages:
- Lower cost than making a fully lined well due to less lining needed.
- Speedier construction and lower cost compared to fully lined well.
- Good for low-yielding aquifers.
- Lower tech option = villagers can participate easier = less supervision required.

Disadvantages:
- Cannot easily access intake for maintenance or in case of problems.
- No possibility to line as you dig, therefore more safety concerns if soil is not stable.

[326] Lawrence, A.R.; McDonald, D.M.J.; Howard, A.G.; Barrett, M.H.; Pedley, S.; Ahmed, K.M.; Nalubega, M. (2001). *Guidelines for assessing the risk to groundwater from on-site sanitation*. British Geological Society, Keyworth, UK.

Shallow groundwater: groundwater dams

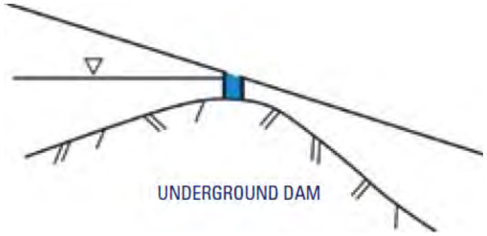
SUMMARY	**Technical**	**Institutional**	**Financial & economic**	**Environmental**
General	• Spend sufficient time and expertise to site dams correctly. Have one lead artisan per catchment to do this, and have sufficient technical oversight in the project. • Ensure they are not built in an area where water will bypass the structure. Riverbanks should be equal height and high enough (height of dam + height of flood +10%). Dam should not be near bend in river. • Construct in areas with gradient between 0.125 – 4% to get right balance between sand size & river width. Sand analysis or porosity/specific yield test of sand at site prior to construction can ensure correct particle size and therefore water volume and extractability. • Site where river is narrower and where there is a natural barrier to groundwater flow • Site where possibilities for the water to leak away are reduced: avoid areas with fractures in base layer (proven by absence of pre-existing dry season sub-surface flow), build onto true base layer, don't build where you see old riverbeds (terraced riverbanks), take care during construction if you see lots of large stones & boulders in riverbed. • Don't site where halite present in riverbanks upstream of dam site = may make water saline. Local people know it because animals like to lick it for salt. • Build dams during dry season but not too close to rains, to	• Promote catchment-level planning & management = spans several areas = all varying groups have vested interest in same source. Knock-on opportunity = can start to address improvements in soil/water conservation, food production & health. • Taking longer to build the dam (e.g. sand storage dam built in several stages – e.g. 3 stages over 3 years) may give enough time for catchment-based dam association to form & start functioning.		• Build in sequence in same river to avoid environmental damage occurring around a single source, but space dams so as not to influence each other. • Soil & water conservation techniques in upper part of catchment will increase recharge of water to sand river = water lasts longer.

	avoid trench filling up with water or dam being washed away. • When building dams in series, space them apart sufficiently so that they do not influence each other = overall water quantity increased. In Kenya, this distance was 700m but will vary according to site. • Keep extraction methods simple – avoid pipes in sand storage dams and consider pros & cons of handpumps before installing one (see "Mechanical extraction: handpumps" for details). If using direct abstraction, promotion of household water treatment should be advocated (e.g. SODIS).			
• Sub-surface dams	• Avoid using only clay to construct a sub-surface dam. • If using clay, ensure good quality clay (e.g. around anthills) is used, that top of dam is 0.3m submerged below original riverbed, and that a minimum of concrete is used at critical points (top of dam, upstream plaster, foundation).			
• Sand storage dams	• Construct using stone masonry = cheapest & easiest for beneficiaries to do • Construct in stages before each flood so that they do not exceed accumulation rate of coarse to medium sand during that flood event. This is especially important in upstream parts of catchment where local people indicate that the river dries up immediately after rainfall (indicating no base flow = higher chance of silt build-up upstream of your sand dam). • Stage height varies according to location and is determined in the field by building the first stage not more than 0.5m high and	• Take longer to build the dam (e.g. sand storage dam built in several stages – e.g. 3 stages over 3 years) may give enough time for catchment-based dam association to form & start functioning		

	monitoring rate of accumulation after first flood event. Height of stage likely to be between 0.3 and 1 metre. Stages are built into a spillway that was made during the initial/first construction. • Spillway to be designed according to peak river discharge in order to prevent erosion around wing walls. • Limit construction to riverbed widths of 25 metres. • Start constructing wing walls and work to centre of dam = wing walls get done & psychologically attractive to fill in dam that gets smaller towards the end. • Length of wing wall varies: loose riverbanks = 7 metres, hard soils = 5 metres, hard & impermeable soils or rocks = not needed. • Planting napier grass on upstream riverbanks controls erosion of wing walls. • Avoid downstream erosion problems by making protective slab (stilling basin) at base of large stones set in concrete. Dimensions to be designed, but not necessary where there is exposed rock bar downstream.			

Overview:
These are structures that reduce or stop the flow of shallow groundwater, usually in seasonal riverbeds, allowing more water to be available at shallower depths upstream of the structure. It appears water levels downstream also improve, with water lasting longer into the dry season due to reduced sub-surface flow upstream.[327] Groundwater dams are built onto rock or clay base at the base of the river. They are divided into two main types:

- Sub-surface dams: built where sand volume is already sufficient to store water. The structure is built inside the existing riverbed, and after a flooding event, water is increased due to a new and higher water level within the sand. These are easier to build than sand storage dams and can be made of stone masonry or reportedly even clay.[328] They are built onto a rock layer or can be founded on impermeable clay layer.
- Sand storage dams: built where sand volume is not sufficient to store water. Most of the structure is therefore built above the original riverbed, and sand washed downstream during flash floods deposit behind the wall and a new higher riverbed level is created upstream that holds water. These are more difficult to build than sub-surface dams and require thicker walls and more attention to design. Mostly these dams are built onto a rock layer, but where there is no rock and only clay, it can still work but as long as the foundation is keyed into the clay layer and where the wall does not protrude more than 0.5m above original sand level, otherwise there is a risk the structure overturns during a flood event.[329]



Sub-surface dam
Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP.


Sub-surface dam under construction
VSF (2006). *SubSurface Dams : a simple, safe and affordable technology for pastoralists. A manual on SubSurface Dams construction based on an experience of Vétérinaires Sans Frontières in Turkana District (Kenya), September 2006.*

Key techniques for siting:

- Ensure they are not built in an area where water will bypass the structure.[330] Riverbanks should be equal in height and tall enough (height of dam + height of flood +10%)[331], and dam should not be constructed near the bend in a river.
- Site where there are no possibilities for the water to leak away – e.g.
  - On impervious bedrock or clay rather than rock with fractures. A good indicator is whether there is some pre-existing sub-surface flow in the dry season or not.[332] If there are large stones & boulders seen in the riverbed, extra care should be taken when siting as seepage can occur under the dam in such cases.[333]
  - On the base layer rather than on intermediate clay lens within sand[334]
  - Between defined banks with no old riverbeds on either side which could allow sub-surface water around dam edge.
- Site in areas where gradient is suitable to get sand rather than silt. A flow of at least 0.45 m/s river flow means less silt deposition[335], and such areas will be where there is a suitable gradient – too flat and there will be too many small particles and silt. Flatter gradients also mean wider riverbeds, and for sand storage dams it should really be limited to 25 metres width.[336] An optimum gradient is said to occur between 0.125%[337] and 4%[338] but can be higher than this with consequence that sand volume stored is less. An easier field test might be to do a sand analysis to find size distribution, or a porosity & specific yield test from which one can extrapolate the likely sand type.[339] Medium sand will have the best balance between porosity and specific yield, and is therefore the type that is needed.

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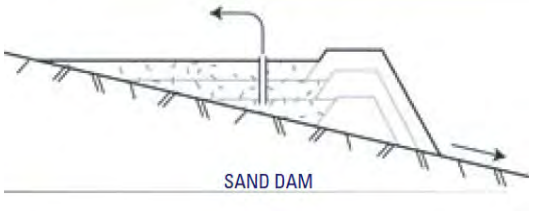
[327] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. p.49. SASOL / Maji Na Ufanisi, Nairobi, Kenya.
[328] Nissen-Petersen, E. (2000). *Water from sand rivers: a manual on site survey, design, construction and maintenance of seven types of water structures in riverbeds*. p.23. RELMA, Nairobi, Kenya. However, author's experience in Turkana District is to avoid using clay due to erosion during flash floods.
[329] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. p.40. SASOL / Maji Na Ufanisi, Nairobi, Kenya. / 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*. p.24 RELMA, Nairobi, Kenya.
[330] VSF (2006). *SubSurface Dams : a simple, safe and affordable technology for pastoralists. A manual on SubSurface Dams construction based on an experience of Vétérinaires Sans Frontières in Turkana District (Kenya), September 2006.* p.21.
[331] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.12.
[332] E.g. In area of sandstone/limestone/basalt in Ethiopia, the water in the sand drained within a month after flooding. Conclusion was that much care to be taken in areas where there is no pre-existing sub-surface flow during dry season. See: Hanson, G. (1987). *Groundwater dam research and development in the Hararghe region, Ethiopia*. National Water Resources Commission, Addis Ababa, Ethiopia.
[333] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.9.
[334] Author's experience of failed dam where it was built onto clay base which was in fact a clay lens within the sand and where the real base layer was deeper down.
[335] Wipplinger, O. (1958). *The Storage of Water in Sand*. Water Affairs Section, South-West Africa Administration.
[336] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.8.
[337] Sørlie, J.E. (1978). Water Conservation Techniques Proposed in North Turkana, Kenya. *Hydrology in Developing Countries: Nordic IHP Report* No. 2 pp. 99-112.
[338] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.8.
[339] 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*. pp.13-14. RELMA, Nairobi, Kenya.

- Site where river is narrower and where there is a natural barrier to groundwater flow = cheaper construction while maximizing sand already present. Such barriers can be found by seeing where water will remain in scoopholes after rains, or through probing, augering & trial pits, or other techniques such as drilling with air compressor.
- Avoid siting where halite (white & pink rocks) is present in riverbanks upstream. These may make the water saline.[340]
- Having a lead artisan per catchment area to decide on siting seems to help success rates.[341]
- Have a sequence of dams in the same river to avoid everyone using a single source with possible ecological damage as a result.[342] However, having dams too close together means their areas of influence overlap = although water levels rise in general, the total quantity of water available decreases. Presumably quantity is more important regionally, therefore minimum distances might be employed between dams (350m either side of dam was zone of influence in Kenya = 700m minimum, but this might vary according to site).[343]



Sand storage dam
Gale, I. (Ed) (2005) *Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.* IAH-MAR and UNESCO-IHP.

Key techniques for construction:

- Key into banks (sub-surface dams) or construct wing walls to avoid erosion around edges (sand storage dams). Where wing walls are built, a good technique is to start from the wing walls and work inwards to centre, since community enthusiasm lags by the time wing walls are constructed, yet they are essential to proper functioning.[344] Length of wing wall varies according to bank characteristic: loose riverbanks = 7 metres, hard soils = 5 metres, hard & impermeable soils or rocks = not needed.[345] Planting napier grass along upstream riverbanks was found to control erosion and fix the course of the rivers in flood.[346]
- For sand storage dams, the height of wall built before each flood event should not exceed accumulation rate of coarse to medium sand during that flood event, otherwise ponding & silt deposition will occur = lower specific yield and higher capillarity = limited extraction rate in wells upstream and more water lost to evaporation.[347] Calculations made in different dams at 1.3m depth showed that where finer material content (0.063 mm or less) is increased, specific yield is known to decrease remarkably.[348] Accumulation rate and therefore height varies according to location and should be adjusted at each site after the first flood event demonstrates the rate of accumulation. Height per stage will probably be between 0.3 metre[349] and 1 metre[350] per stage according to experience from past projects. Some silt deposition will always occur as velocities decrease toward the end of the flood event, the idea is only to limit its quantity in final sand volume. In upstream parts of a catchment it is recommended that sand dams are always built in stages, since the availability of coarse material is generally limited and base flow is small or absent (base flow = sub-surface flow which aids surface flow so that silt/clay can still be flushed away once rainfall stops, rather than sinking direct into sand bed).[351] It has also been suggested that to build in stages over several years is also more beneficial for functioning of dam committees.[352] The methodology of building subsequent stages is to build them within a spillway which was part of the first stage & wing wall construction.

Sand storage dam under construction, Somaliland
Eric Fewster, BushProof / Caritas

Completed sand storage dam, Somaliland
Eric Fewster, BushProof / Caritas

[340] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.11.
[341] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. p.36. SASOL / Maji Na Ufanisi, Nairobi, Kenya.
[342] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.1.
[343] Orient Quilis, R.; Hoogmoed, M.; Ertsen, M.; Foppen, J.W.; 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*; Volume 34, Issues 4-5, 2009, Pages 289-298.
[344] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. p.30. SASOL / Maji Na Ufanisi, Nairobi, Kenya.
[345] Munyao, J.N.; Munywoki, J.M.; Kitema, M.I.; Kithuku, D.N.; Munguti, J.M.; Mutiso, S. (2004) *Kitui sand dams: Construction and operation*. Sasol Foundation, Nairobi, Kenya. p.43.
[346] Beimers, P.B.; Eijk, A.J. van; Lam, K.S.; Roos, B. (2001) *Improved design sand-storage dams, Kitui District, Kenya*. Project report. TU Delft, The Netherlands.
[347] Author's experience in Somaliland was that sand storage dams that were built in 2 - 2.5 metres in one stage had low-yielding wells upstream presumably due to silt/clay in sand.
[348] Hanson, G. (1987). *Groundwater dam research and development in the Hararghe region, Ethiopia*. National Water Resources Commission, Addis Ababa, Ethiopia.
[349] 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*. p.49. RELMA, Nairobi, Kenya. However, author's experience in Turkana District is to avoid using clay due to erosion during flash floods.
[350] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. p.39-40. SASOL / Maji Na Ufanisi, Nairobi, Kenya.
[351] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.6.
[352] Ertsen, M.W.; Biesbrouck, B.; Postma, L.; Westerop, M.V. *Community organisation and participatory design of sand-storage dams in Kenya.*

- Spillway is designed for river flow, and therefore varies according to the site. Incorrect design leads to erosion around wing walls. Design of spillway first requires peak discharge to be known – there are field calculations that are possible in and around the dam site that enable this to be done. [353, 354] Top of spillway to slope by 0.15m from upstream to downstream side to reduce erosion on downstream side.[355]
- Avoid sub-surface dams made only of clay – they require skill to construct and can be damaged/destroyed during flooding.[356] Experience however has shown that dams can be made from clay successfully if the top of dam is 0.3m submerged below original sand bed, and if concrete is used at critical points (foundation, upstream plaster, top of dam) to ensure waterproofing & durability.[357] Clay suitability can be checked using an infiltration test.[358]
- Construct sand storage dams using stone masonry = cheapest & easiest for beneficiaries to do.[359]
- Avoid downstream erosion[360] of dam base by making protective slab at base of stones set in concrete. Dimensions to be designed according to free fall equation (where water will fall in flood). Large stones placed after stilling basin to prevent scour, but should be large enough to resist river flow.[361, 362] Not needed if rock bar is exposed on downstream side.[363]
- Ensure proper curing which is difficult when water is scarce and conditions are dry.
- Get the timing right: dams should be built during the dry season, but don't build dams too close to the rains in order to avoid trench filling up with water or dam being washed away.[364]
- Many other construction tips for good quality structure are available from various manuals.[365,366]
- Promote catchment-level planning & management = spans several areas = all varying groups have vested interest in same source. Knock-on opportunity = can start to address improvements in soil/water conservation, food production & health.[367] How to promote such management: previous dam committees ceased to function effectively after the construction phase. Taking longer to build the dam (e.g. sand storage dam built in several stages – e.g. 3 stages over 3 years) may give enough time for catchment-based dam association to form & start functioning.[368]

Key techniques for extraction of water:
- Can be done through scoop holes and/or shallow wells upstream of the dam, either with or without handpump (see "Shallow groundwater: hand-dug, jetted & driven wells" for details). See "Mechanical extraction: handpumps" for details on the pros/cons of handpumps.
- Where water is abstracted directly, risk of contamination increases. In such a case, household water treatment should be advocated (e.g. SODIS).
- In certain designs for sand dams, a pipe is shown that takes water by gravity through the dam wall.[369] These are said to not work well due to either blocked intake, broken tap on outlet side[370] and possibility of weakening dam wall.[371]

Advantages:

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[353] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* pp.18-19.
[354] Beimers, P.B.; Eijk, A.J. van; Lam, K.S.; Roos, B. (2001) *Practical work report : Building sand-storage dams*. TU Delft, The Netherlands. pp.41-45.
[355] Beimers, P.B.; Eijk, A.J. van; Lam, K.S.; Roos, B. (2001) *Practical work report : Building sand-storage dams*. TU Delft, The Netherlands. p.58.
[356] Author's experience in Turkana with failed dam. Also see: RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.5.
[357] VSF (2006). *SubSurface Dams : a simple, safe and affordable technology for pastoralists. A manual on SubSurface Dams construction based on an experience of Vétérinaires Sans Frontières in Turkana District (Kenya), September 2006.* pp.45, 48.
[358] Good explanation of clay testing here: VSF (2006). *SubSurface Dams : a simple, safe and affordable technology for pastoralists. A manual on SubSurface Dams construction based on an experience of Vétérinaires Sans Frontières in Turkana District (Kenya), September 2006*. p.32. Also: Nissen-Petersen, E. (2006) *Water from Dry Riverbeds*. Danish International Development Assistance (DANIDA). pp.36-37.
[359] Deemed to be the best overall based on SASOL's experience: RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.7.
[360] This was the major cause of repair work in Kitui dams – see: Ertsen, M.W.; Biesbrouck, B.; Postma, L.; Westerop, M.V. *Community organisation and participatory design of sand-storage dams in Kenya.* Also: Beimers, P.B.; Eijk, A.J. van; Lam, K.S.; Roos, B. (2001) *Practical work report : Building sand-storage dams*. TU Delft, The Netherlands.
[361] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.19.
[362] Beimers, P.B.; Eijk, A.J. van; Lam, K.S.; Roos, B. (2001) *Practical work report : Building sand-storage dams*. TU Delft, The Netherlands. p.82.
[363] Beimers, P.B.; Eijk, A.J. van; Lam, K.S.; Roos, B. (2001) *Practical work report : Building sand-storage dams*. TU Delft, The Netherlands. p.78.
[364] Author's personal experience in Kenya. Also see: Hanson, G. (1987). *Groundwater dam research and development in the Hararghe region, Ethiopia*. National Water Resources Commission, Addis Ababa, Ethiopia.
[365] For example: RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change*.
[366] Beimers, P.B.; Eijk, A.J. van; Lam, K.S.; Roos, B. (2001) *Practical work report : Building sand-storage dams*. TU Delft, The Netherlands.
[367] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. SASOL / Maji Na Ufanisi, Nairobi, Kenya. p.31
[368] Ertsen, M.W.; Biesbrouck, B.; Postma, L.; Westerop, M.V. *Community organisation and participatory design of sand-storage dams in Kenya.*
[369] 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, Nairobi, Kenya. pp. 49-52.
[370] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. p.40. SASOL / Maji Na Ufanisi, Nairobi, Kenya.
[371] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.24.

- Socio-economic indicators, hydrologic data and vulnerability indicators show that groundwater dams are a successful adaptation to cope with drought, and can reduce vulnerability.[372]
- Little evaporation compared to surface water.[373]
- Large volumes can be stored (equivalent to the porosity of the sand). However, water is not only stored in the sand but also the riverbanks which recharge the sand during dry periods.[374,375] Soil- and water conservation measures in the upstream areas of the catchment should increase infiltration of rain water = creating more sub-surface flow within the catchment = better recharge to sand river reservoir.[376]
- Regional groundwater recharge.
- Risk of contamination of stored water is reduced compared to open sources.
- Better quality water than open water due to filtration effect of sand and where livestock & human collection points can be separated.
- Low potential O+M requirements.
- Long lifespan if constructed well.
- Sand can be sold for cash to building industry.
- Mimics rainfall so possibly less local environmental degradation compared to permanent source.[377]
- Low cost per cubic metre of water stored – the cost of a sand dam in Kenya yielding 2,844 m^3 of water was $3,260 = $1.15 per m^3 storage.[378]

Disadvantages:
- Site-specific technology – not suitable everywhere.
- Designs vary according to the area. Needs experienced artisan to site the dams – it seems that projects can fail if dams are not sited and constructed properly – in this way they can be more complicated than other technologies. In Kenya, experience shows that up to 80% of dams might not be functioning as they should due to poor design.[379]
- If the dam needs to be built in stages, it can be difficult to get the community to turn up the next season for the following stage of work.
- Cost: although cost per volume is cheap, the actual structure that needs to be made is expensive.

[372] Lasage, R. Aerts, J.; Mutiso, G.-C.M.; 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*, Volume 33, Issues 1-2, 2008, Pages 67-73.
[373] At 0.6m depth, evaporation reduced by 90%. See: Hellwig (1973). Evaporation of Water from Sand, 4: The Influence of the Depth of the Water Table and Particle Size Distribution of the Sand. *Journal of Hydrology*. Vol. 18. pp. 317-27.
[374] Borst, L., Haas, S.A. (2006), *Hydrology of Sand Storage Dams, A case study in the Kiindu catchment, Kituï District, Kenya*. Master thesis, Vrije Universiteit, Amsterdam, The Netherlands.
[375] Hoogmoed, M. (2007). *Analyses of impacts of a sand storage dam on groundwater flow and storage: groundwater flow modelling in Kitui District, Kenya.* Vrije Universiteit, Amsterdam, The Netherlands.
[376] RAIN, Acacia Water, EHRA, Afd, Sasol (2008) *A practical guide to sand dam implementation: water supply through local structures as adaptation to climate change.* p.6.
[377] No visible degradation seen around dams built in Turkana. See: Vanrompay, L. (2003) *Report on the Technical Evaluation and Impact Assessment of Sub-surface Dams (SSDs).* VSF-B Turkana Livestock Development Project (TLDP), Kenya. p.10.
[378] SASOL & Maji Na Ufanisi (1999) *Where there is no water – a story of community water development and sand dams in Kitui District, Kenya*. SASOL / Maji Na Ufanisi, Nairobi, Kenya. p.38.
[379] Pers. Comm. With Nissen-Petersen – in: Falkenmark, M.; Fox, P.; Persson, G.; Rockström, J. (2001) *Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs*. Stockholm International Water Institute.

Shallow groundwater: spring protections

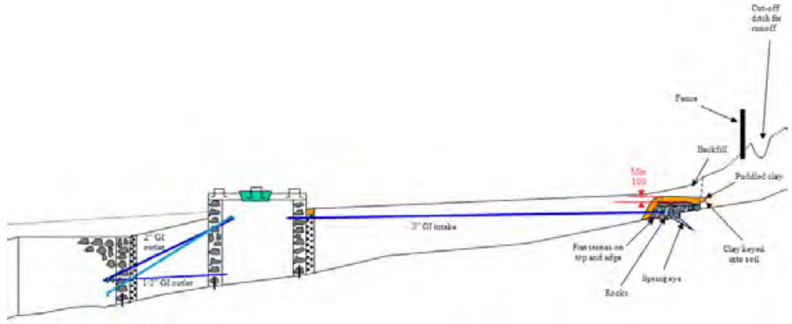
SUMMARY	**Technical**	**Institutional**	**Financial & economic**	**Environmental**
Spring protections	• Improve flow by excavating carefully at spring eyes. • Take water away from spring eye to avoid damaging it by back pressure or foundation works. Water ideally should be taken downhill from spring eye to an outlet. • A holding reservoir can be constructed if dry season flow rate is insufficient to meet peak demand from users, or if spring yield is not reliable. Size of reservoir to be determined according to balance between constant inflow and peak outflow rates. • For economical ways to store larger quantities during all the hours of flow, a pond or tank with impermeable lining can be constructed for irrigation purposes. • Design for dry season flow rates. • Spring eye to be protected with 100mm of rocks covered with 100mm of puddled clay. • A cut-off drain 10m above the spring eye will reduce possible contaminated runoff from reaching the spring eye. • A fence should be constructed 10m above spring eye and around the water collection area.		• In remote areas, use of plastic tanks can save money and labour days. Best compromise between quality and amount of work is to make the intake with concrete, all tanks (sedimentation, break pressure or reservoir) from plastic tanks buried underground, and concrete tapstands.	

Overview:
These are structures that protect and store spring water.

Key techniques for siting:
- Dependent on location of spring.

Key techniques for construction:
- Improve flow by excavating carefully at spring eyes.

- Try to take water away from spring eye to avoid damaging it by back pressure or foundation works. Water ideally should be taken downhill from spring eye to an outlet.[380]
- A holding reservoir is not always necessary. It can be constructed if dry season flow rate is insufficient to meet peak demand from users, or it might be a wise investment with decreasing reliability of spring flows. Size of reservoir to be determined according to balance between constant inflow and peak outflow rates.
- In remote areas, use of plastic tanks can save money and labour days. 10 years of experience in Lao PDR showed that the best compromise between quality and amount of work was to make the intake with concrete, all tanks (sedimentation, break pressure or reservoir) from plastic tanks buried underground, and concrete tapstands. Using a combination of plastic and concrete (rather than only concrete for everything) saved about half the number of labour days. In terms of cost, the combination option was 8% more expensive but cheaper if free village labour was factored in.[381]
- For areas of water scarcity, any unused overflow water can be captured and stored in a pond or tank with impermeable lining to be used for irrigation purposes as and when needed.[382]
- Design for dry season flow rates.
- Spring eye to be protected with 100mm of rocks covered with 100mm of puddled clay.
- A cut-off drain 10m above the spring eye will reduce possible contaminated runoff from reaching the spring eye.
- A fence should be constructed 10m above spring eye and around the water collection area.



Spring protection, Madagascar
Eric Fewster, BushProof / Medair

Key techniques for extraction of water:
- By gravity to pipes and taps

Advantages:
- Spring water has good quality and may not need treatment.
- When taken by gravity, operation & maintenance costs reduce due to no need for pumping.

Disadvantages:
- Water available is limited to spring yield.

[380] Pickford, J. (ed) (1991). Technical Brief 34. Protecting springs – an alternative to spring boxes. Shaw, R. (ed) (1999). *Running Water: more technical briefs on health, water and sanitation*. Practical Action Publishing, London. pp.6-8.
[381] Frangi, B.; Romagny, L.; Chancel, N. (2004) Building of spring-fed gravity-flow water supply systems in remote mountain villages of Lao PDR. *People-centred approaches to water and environmental sanitation. 30th WEDC International Conference, Vientiane, Lao PDR, 2004.* p.564-565.
[382] Merz, J.; Nakarmi, G.; Weingartner, R. (2004) Potential Solutions to Water Scarcity in the Rural Watersheds of Nepal's Middle Mountains. *Mountain Research and Development* Vol 23 No 1 Feb 2003: 14–18.

Shallow to deep groundwater: boreholes

SUMMARY	**Technical**	**Institutional**	**Financial & economic**	**Environmental**
Boreholes	• Consider pros & cons of handpumps before installing one (see "Mechanical extraction: handpumps" for details). • Correctly ascertain water demand including all present and future domestic and non-domestic water use through conducting pump testing of boreholes if drilling records not available. Don't forget to factor in other needs such as livestock which are often left out during programme design. • Evaluate the likely recharge to the aquifer, and how this might vary with time. This estimate can be based on a water balance. • In proven areas where the geology is well understood and borehole success is high (e.g. over 70%), it may not be necessary to site wells using geophysical survey techniques. • Site selection needs to take into account community preferences with respect to convenience. • Site boreholes at a sufficient distance away from sources of contamination. • Do not site new boreholes in areas where saline intrusion is a known problem. • Continually monitor water resources to enable programme re-examination and adjustment. Handpumps at boreholes should also be retrofitted with access for dipper tapes. • Low-cost boreholes provide optimum value for money but	• In the end it should be communities that should be able to monitor water usage in order for them to make informed decisions to prevent localised depletion of water sources and prevent failure of pumps and infrastructure. • Achieve greater regional coordination between water providers (NGOs, government, private sector) to allow more impact on groundwater assessment and to gain a common approach. • When considering groundwater abstraction, demand management is as important as improving supply. MAR can make periodic contributions to redress quality and quantity but without demand management it is not a sustainable solution.[383]		• Even where aquifers can give sustainable yields, avoid boreholes when attempting to improve access to water in pastoralist & agropastoralist areas, focusing efforts instead on rainwater collection techniques which create water sources that are less permanent and more in balance with the varying availability of pasture. • Stop drilling in areas where saline groundwater is a problem & concentrate on rainwater-groundwater dilution. • Integrated Water Resource Management (IWRM) can have a part to play in assisting recharge of groundwater aquifers. It is known that presence of vegetation in one part of the catchment can significantly affect groundwater recharge by encouraging infiltration.

[383] Gale, I.N.; Macdonald, D.M.J.; Calow, R.C.; Neumann, I.; Moench, M.; Kulkarni, H.; Mudrakartha, S.; Palanisami, K. (2006) *Managed Aquifer Recharge: an assessment of its role and effectiveness in watershed management*. British Geological Survey Commissioned Report, CR/06/107N. p.viii.

	drilling needs to be carried out correctly. • Drill deep enough to start with. Well drillers should be encouraged to drill deeply enough that they have 3-4 meters of water in the well at the end of the dry season. • Deepening boreholes might be an option where recharge is known to be sufficient for demand, but where the borehole was not drilled deep enough originally. • Contingency boreholes can be drilled in drought-prone areas (including pastoralist & agropastoralist areas) in productive aquifers – these can be uncapped and used during drought periods but are not permanent as they should be closed off during normal periods to avoid creating permanent settlements around the water source as well as limiting land & aquifer degradation.			

Overview:
These are narrow wells that tap water in shallow to deep aquifers, and are equipped with a handpump or motorized pump.

Key techniques for siting:[384]

- This largely depends on the geology – water is found in different sediments in differing quantities and levels of extractability. Finding the correct place to make a borehole is sometimes difficult but sometimes can be relatively easy, and is done using various methods that are suitable for different conditions (e.g. geophysics).
- Conduct improved water resource assessments and hydrological analysis when siting wells and boreholes in order to assess risk for both the resource and infrastructure. Water demand in drought-prone areas is not only related to domestic consumption but also to other needs such as livestock, but these are often not factored into the water demand during programme design. If boreholes are sited incorrectly in unproductive aquifers or if they do not take the actual present and future demand into account, the aquifers could be over-utilized as a result:
    - Correctly ascertain water demand including all present and future domestic and non-domestic water use through conducting pump testing of boreholes if drilling records not available.[385]
    - Consider the water balance in the wider context. Although a well may be capable of delivering a certain yield in the short to medium term, if the groundwater is not regularly replenished by infiltration from rainfall or river flow, then that yield will not be sustained over the long term. It is therefore important to evaluate the likely recharge to the aquifer, and how this might vary with time. This estimate can be based on a water balance.[386]

[384] See: Carter, R.; Chilton, J.; Danert, K.; Olschewski, A. (2010) *Siting of drilled water wells: a guide for project managers*. DRAFT version. RWSN, St. Gallen, Switzerland. See also: Danert, K.; Armstrong, T.; Adekile, D.; Duffau, B.; Ouedraogo, I.; Kwei, C. (2010) *Code of Practice for Cost Effective Boreholes*. RWSN, St. Gallen, Switzerland. p.7. Available at http://www.rwsn.ch/documentation/skatdocumentation.2010-08-23.4523209156/file
[385] Oxfam (2010) *Introduction to Community-Based Water Resources Management: A Learning Companion*. Oxfam Disaster Risk Reduction and Climate Change Adaptation Resources.
[386] Danert, K.; Armstrong, T.; Adekile, D.; Duffau, B.; Ouedraogo, I.; Kwei, C. (2010) *Code of Practice for Cost Effective Boreholes*. RWSN, St. Gallen, Switzerland. p.7. Available at http://www.rwsn.ch/documentation/skatdocumentation.2010-08-23.4523209156/file

- In proven areas where the geology is well understood and borehole success is high (say over 70%), it may not be necessary to site wells using geophysical survey techniques. Geophysical surveys should only be undertaken where the costs of drilling an unsuccessful borehole may justify the expense.[387]
- Site selection needs to take into account community preferences with respect to convenience.[388]
- Site boreholes at a sufficient distance away from sources of contamination. For microbiological contamination, the distance from the source of contamination (e.g. latrine) to the water intake (screen) needs to be sufficient so as to pose a "low" to "very low" risk – this translates into a minimum of 25 days of potential travel of pathogens in the ground. Travel time is influenced by porosity, hydraulic conductivity (permeability) and hydraulic gradient. For medium size sand with an average porosity, the distance equivalent to 25 days is around 30 metres, but this can increase to over 100 metres for coarser sediments. However, the distance from contamination to water intake can reduce significantly where the screen intake is at a sufficient depth – this is due to greater variation of aquifer properties in vertical directions than lateral, meaning that a borehole with handpump could be placed very close to a latrine with low risk. However, screen depth must increase with increased extraction rate.[389]
- Do not site new boreholes in areas where saline intrusion is a known problem.

Key techniques for construction:

- Continually monitor water resources to enable programme re-examination and adjustment. This includes budgeting for basic groundwater and surface monitoring equipment such as dipper tapes and flow metres for boreholes, and rain gauges and staff gauges for measurement of rainwater and surface water levels. Handpumps at boreholes should also be retrofitted with access for dipper tapes. In the end it should be communities that should be able to monitor water usage in order for them to make informed decisions to prevent localised depletion of water sources and prevent failure of pumps and infrastructure.[390]
- There are a variety of low-cost drilling techniques that can produce cost-effective boreholes (e.g. jetting, sludging, rota-sludging, EMAS). Projects and communities can benefit from implementation of such boreholes where optimum value for money is invested over the long term. However the lowest cost is not always the most cost-effective, particularly if construction quality is compromised to save money. Cheap drilling or poor construction quality can lead to premature failure of the well or contamination of the water supply. Boreholes that are subsequently abandoned by the users are clearly not cost-effective. The following principles apply regarding low-cost drilling:[391]
    - Construction of drilled water wells and supervision is undertaken by professional and competent organizations which adhere to national standards and are regulated by the public sector.
    - Appropriate siting practices are used.
    - The construction method chosen for the borehole is the most economical, considering the design and available techniques in-country. Drilling technology needs to match the borehole design.
    - Procurement procedures ensure that contracts are awarded to experienced and qualified consultants and drilling contractors.
    - The borehole design is cost-effective, designed to last for a lifespan of 20 to 50 years, and based on the minimum specification to provide a borehole which is fit for its intended purpose.
    - Adequate arrangements are in place to ensure proper contract management, supervision and timely payment of the drilling contractor.
    - High quality hydrogeological and borehole construction data for each well is collected in a standard format and submitted to the relevant government authority.
    - Storage of hydrogeological data is undertaken by a central government institution with records updated and information made freely available and used in preparing subsequent drilling specifications.
    - Regular visits to completed boreholes are made to monitor their functionality in the medium as well as long term with the findings published.
- Drill deep enough to start with. This requires a good understanding of the hydrogeology, good siting practices, as well as good supervision and contract management (see above). Well drillers should be encouraged to drill deeply enough that they have 3-4 meters of water in the well at the end of the dry season.[392]
- Deepening boreholes might be an option where recharge is known to be sufficient for demand, but where the borehole was not drilled deep enough originally. This can be done for substantially lower cost than drilling a new borehole, but results depend on age/condition/design of existing well and properties of deeper aquifer:[393]

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[387] Danert, K.; Armstrong, T.; Adekile, D.; Duffau, B.; Ouedraogo, I.; Kwei, C. (2010) *Code of Practice for Cost Effective Boreholes*. RWSN, St. Gallen, Switzerland. p.7. Available at http://www.rwsn.ch/documentation/skatdocumentation.2010-08-23.4523209156/file

[388] Danert, K.; Armstrong, T.; Adekile, D.; Duffau, B.; Ouedraogo, I.; Kwei, C. (2010) *Code of Practice for Cost Effective Boreholes*. RWSN, St. Gallen, Switzerland. p.7. Available at http://www.rwsn.ch/documentation/skatdocumentation.2010-08-23.4523209156/file

[389] Lawrence, A.R.; McDonald, D.M.J.; Howard, A.G.; Barrett, M.H.; Pedley, S.; Ahmed, K.M.; Nalubega, M. (2001). *Guidelines for assessing the risk to groundwater from on-site sanitation*. British Geological Society, Keyworth, UK.

[390] Oxfam (2010) *Introduction to Community-Based Water Resources Management: A Learning Companion*. Oxfam Disaster Risk Reduction and Climate Change Adaptation Resources.

[391] Danert, K.; Armstrong, T.; Adekile, D.; Duffau, B.; Ouedraogo, I.; Kwei, C. (2010) *Code of Practice for Cost Effective Boreholes*. RWSN, St. Gallen, Switzerland. Available at http://www.rwsn.ch/documentation/skatdocumentation.2010-08-23.4523209156/file

[392] Personal communication with Jon Naugle, Enterprise Works / Relief International.

[393] Roscoe Moss Company (1990) *Handbook of ground water development*. John Wiley & Sons, USA. p.350

- Deepening is easier to do in aquifers with naturally-developed gravel pack = can also deepen and develop gravel pack further down. For those with gravel packs, you need to drill out base plug and stabilize existing gravel pack with pressure grouting.
    - Deeper screen/casing in general is 4" smaller in diameter than the original.
    - When deepening, rotary mud flush does not work well as drilling mud contaminates upper aquifer. Best to use percussion with following variations:
        - In stable formations, open hole drilled followed by screen
        - In loose/unconsolidated formations, blank casing with top and bottom drive shoes is driven to required depth and then perforated in situ
        - A machined vertical slot screen with top and bottom drive shoes is installed by driving
- Even where aquifers can give sustainable yields, there are also issues related to the permanence of borehole water that can increase longer term vulnerability of certain communities to drought, especially pastoralist communities where boreholes can have a negative impact by changing migration and pasture management patterns while increasing environmental degradation and conflict. It is therefore suggested to avoid boreholes when attempting to improve access to water in pastoralist & agropastoralist areas, focusing efforts instead on rainwater collection techniques which create water sources that are less permanent and more in balance with the varying availability of pasture.[394]
- Contingency boreholes however can be drilled in drought-prone areas (including pastoralist & agropastoralist areas) in productive aquifers – these can be uncapped and used during drought periods but are not permanent as they should be closed off during normal periods to avoid creating permanent settlements around the water source as well as limiting land & aquifer degradation.[395]
- Integrated Water Resource Management (IWRM) can have a part to play in assisting recharge of groundwater aquifers. It is known that presence of vegetation in one part of the catchment can significantly affect groundwater recharge by encouraging infiltration.[396]
- Achieve greater regional coordination between water providers (NGOs, government, private sector) to allow more impact on groundwater assessment and to gain a common approach.

Key techniques for extraction of water:
- With handpump or mechanical pump.

Advantages:
- Can be privately owned/operated
- Allows a buffer in drought conditions as water does not fluctuate as much compared to shallow and surface water sources.

Disadvantages:
- Aquifers cannot always meet water demand sustainably, especially for high demand applications. Water levels can drop over time, resulting in possible mining (where aquifer is compressed and cannot hold water any longer afterwards).
- Boreholes require pumps to abstract the water, so all disadvantages related to pumps also relate to boreholes, including operation and maintenance issues, lack of ownership, and spare parts availability. Where handpumps are used, all related handpump problems apply (see "Mechanical water: handpumps" for details).
- Boreholes can create permanent water sources, which in turn can change migration and pasture management patterns, while increasing environmental degradation and conflict.
- High capital and ongoing cost of maintenance.
- Medium to high level of technical skill needed for borehole implementation, operation and maintenance, depending on drilling method and pump type installed. Even low-cost manually drilled boreholes require considerable experience to complete successful boreholes, and even the most simple handpumps require a degree of skill to maintain.
- Water quality can be variable with higher levels of minerals in some areas, sometimes being potentially harmful to health (e.g. in the case of fluoride or arsenic).

[394] Oxfam found in Wajir, Kenya, that permanent boreholes created for livestock resulted in a shift in traditional herding patterns = overgrazing of pastures normally used only at end of dry season. See: Oxfam (2000) *Integrating drought cycle management in programming: a series of briefs for practitioners.* See also: IIRR, ACACIA & CordAid (2004) *Drought Cycle Management: A toolkit for the drylands of the Greater Horn*. See also: Government of Kenya (2007) *National Policy for the Sustainable Development of Arid and Semi Arid Lands of Kenya*.
[395] IIRR, ACACIA & CordAid (2004) *Drought Cycle Management: A toolkit for the drylands of the Greater Horn.* Also see: Oxfam (2010) *Introduction to Community-Based Water Resources Management: A Learning Companion*. Oxfam Disaster Risk Reduction and Climate Change Adaptation Resources.
[396] In Tanzania, it was observed that the clearance of vegetation in a catchment had impacted recharge rates: Personal communication with Jon Naugle, Enterprise Works / Relief International.

Water trucking & water vendors

SUMMARY	**Technical**	**Institutional**	**Financial & economic**	**Environmental**
Water trucking		• Support the capacity of the government or private sector to be able to provide (for payment) a water trucking scheme to during the driest parts of the year.		

Overview:
Water trucking is common in areas of water stress, and exists in the form of large tankers as well as smaller water vendors.

Key techniques for siting:
- Good to promote in areas where water trucking and vending exists already.

Key techniques for construction:
- Support the capacity of the government or private sector to be able to provide (for payment) a water trucking scheme to during the driest parts of the year. It has been argued that where the market is functioning well, interventions that address market-related issues during drought are more effective at protecting livelihoods than those that address food supply problems. Taking that argument in our case, supporting the private sector to be able to provide a water service could be more effective than concentrating too much on technology? [397]

Advantages:
- Allows water to be delivered to water-stressed areas where water supply cannot meet demand.

Disadvantages:
- High cost of water which varies according to the setting (e.g. $17 per m^3 in Somaliland).[398] This is a consumable and includes no investment for the user as with other water options.

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[397] Eldridge, C. (2002) Protecting livelihoods during drought: some market-related approaches. *Humanitarian Exchange* No.22, HPN, ODI, London, UK.
[398] Author's experience: $100 for truck of 6,000 litres.

Criteria of applicability of drought-resilient WASH techniques

Not every technology is possible or recommended in every setting, and even then often the technique might have to be adapted to the specific environments where they are introduced. The specific applicability criteria of each technology are shown under each previous section as "Key techniques for siting". In conjunction with these sections, the following questions should form a framework for any evaluation:

- Has site selection taken into account community preferences?
  - ✓ E.g. with respect to convenience.
- Has siting of the structure helped to improve water quantity?
  - ✓ E.g. sand dams should not be built on fractured rocks, infiltration gallery should be built in degrading section of river to avoid clogging.
- Has the siting of the structure minimized the likelihood to be prone to failure?
  - ✓ E.g. sand dams sited where river cannot erode the edges.
- Has site selection improved water quality?
  - ✓ E.g. boreholes in non-saline areas.

Framework for evaluation of WASH projects in drought-prone areas

Used in conjunction with relevant sections on specific technologies, the following questions should form a framework for any evaluation:

Technical

- Are there methods of improving construction and design of existing techniques in the area which could improve water quantity?
  - ✓ E.g. telescopic lining in hand-dug well, leak-proof tanks, deep enough wells, spacing of sand dams in series, proper gravel packing in boreholes or around infiltration gallery, use of porous concrete.
- Are there methods of improving existing water quantity of existing facilities in-situ?
  - ✓ E.g. jetting in bottom of hand-dug well to increase recharge.
- Are there alternative / additional technical options that would be suitable in the area, which could be introduced to increase water availability by maximizing rainwater capture over groundwater abstraction?
  - ✓ E.g. depending on site, any rainwater harvesting techniques such as groundwater dams or sub-surface tanks.
- Are there alternative / additional technical options that would be suitable in the area, which could be easier to construct?
  - ✓ E.g. infiltration wells versus standard hand-dug wells, maximizing topography when constructing dams or ponds.
- Are there alternative / additional technical options that would be suitable in the area, which could be quicker to construct?
  - ✓ E.g. jetted wells versus hand-dug wells.
- Are there methods of improving water quantity through increasing storage capacity?
  - ✓ E.g. building deeper tanks, or more tanks, or reducing evaporation.
- Are there methods of improving water availability through simpler abstraction and where maintenance and repair is more likely to occur?
  - ✓ E.g. no handump and household treatment, proven pump where spares available, simple technology repairable locally using local skills.
- Can water availability be improved through some type of Managed Aquifer Recharge (MAR)?
- Can sustainability of groundwater resources be checked through analysis of recharge and water balance?
- Has water demand been correctly ascertained?
- Has the structure been properly sized and designed according to factors like demand, recharge and catchment?
- Has there been / is there sufficient technical expertise to ensure proper design and construction?
- Are there methods that can improve health and safety of people during construction and use of infrastructure?
  - ✓ E.g. limit hand-dug well depth prior to lining, blocks versus pre-cast concrete rings.
- Are there water quality issues that affect water availability and can these be addressed?
  - ✓ E.g. salinity and solar stills.
- Are there water quality issues that affect vulnerability and can these be addressed?
  - ✓ E.g. bacteriological & chemical issues addressed through household water treatment or water source diversification.
- Are water resources monitored continually?
- Is the project timeframe likely to help improve technical viability of infrastructure?
  - ✓ E.g. building sand dams over years = less silt build-up = more water available.
- Are there non-WASH but related activities that could reduce vulnerability?
  - ✓ E.g. drought-resistant crop varieties.

Institutional

- Is the type of management structure in place the one most likely to improve water availability given the type of infrastructure?
  - ✓ E.g. catchment-based communal association = pasture management = less siltation = more water stored.
- Would different implementation and management styles result in improved sustainability of infrastructure?
  - ✓ E.g. communal or private ownership, decentralization.
- Would different ways of managing communal supplies improve water availability?
  - ✓ E.g. clear regulation and audit process = more trust = money keeps flowing to keep up maintenance.
- Is the project timeframe and choice of project funding donor likely to help improve institutional management of infrastructure?

    - ✓ E.g. building sand dams over years = more chance of user association functioning.
- To what extent has the project truly been demand-responsive and participative, and would improving this lead to improved sustainability of infrastructure?
    - ✓ E.g. how much continual learning and adjustment is taking place, how much were local concerns fed into design.
- What areas of project implementation could benefit from having greater involvement of local people, especially women, and could this improve sustainability of infrastructure?
    - ✓ E.g. decision on technology, involvement in construction and maintenance, water resources monitoring.
- Are there areas of existing local knowledge that could be built on in project design, which would improve involvement of local people and sustainability of infrastructure?
    - ✓ E.g. using local artisans, heeding ownership and regulation traditions.
- What possibilities exist to improve water availability through demand management?
    - ✓ E.g. drip irrigation.
- Can sustainability of groundwater resources be monitored through increased cooperation (NGO, government, private sector) and application of Integrated Water Resources Management in the area?

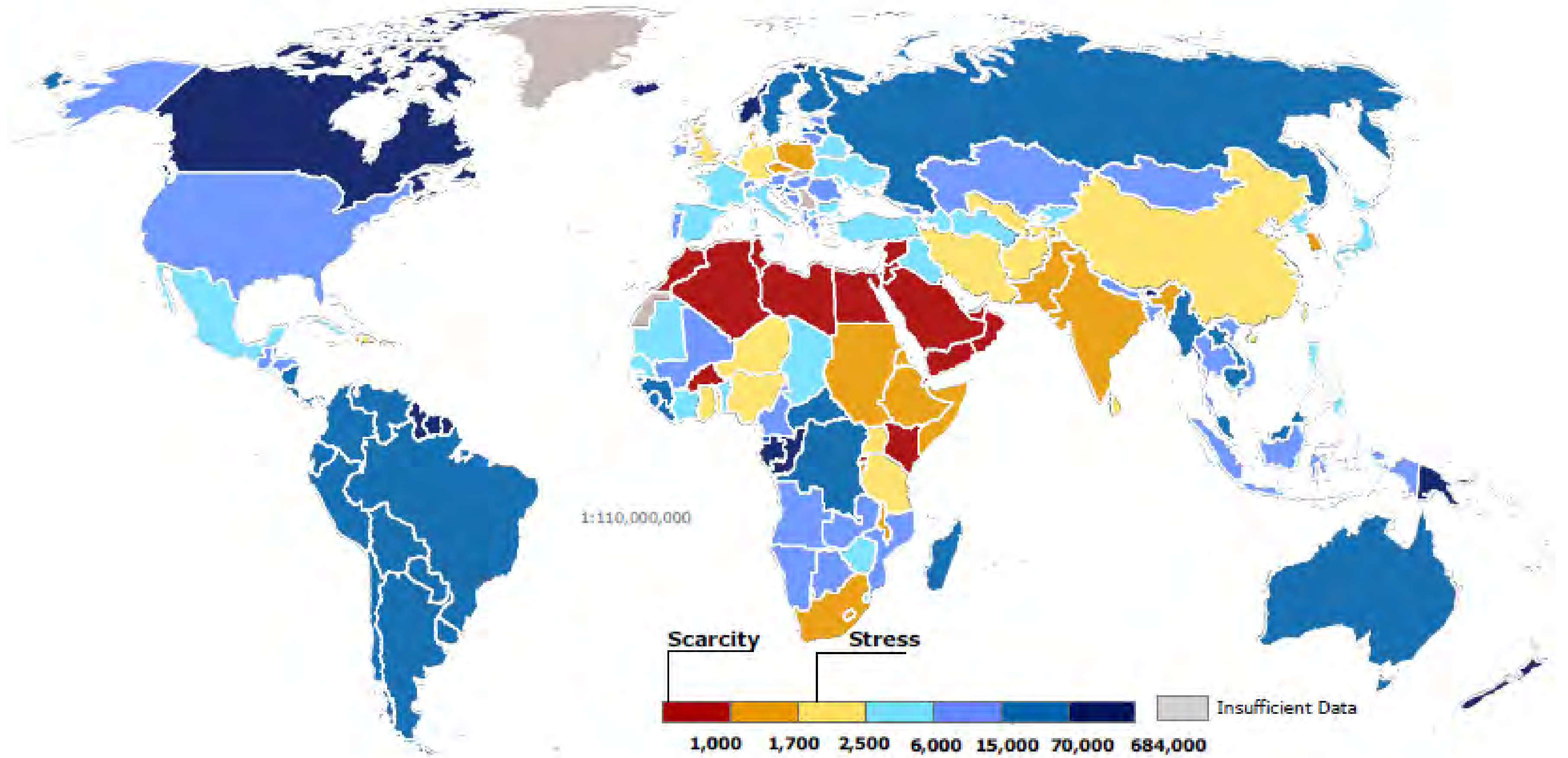
<u>Financial / economic</u>

- Are there ways of improving access to finance which can improve water availability?
    - ✓ E.g. micro finance, low-cost loans.
- Are there methods of improving ownership levels of infrastructure?
    - ✓ E.g. increased contribution including cash, private ownership.
- Are there alternative / additional technical options that would be suitable in the area, which could be cheaper to construct?
    - ✓ E.g. more affordable storage linings, smaller tank sizes.
- Are there alternative / additional technical options that would reduce risks of failure for investors in technology?
    - ✓ E.g. smaller structures.
- Are there methods of constructing infrastructure to make it more affordable and replicable to users?
    - ✓ E.g. staged construction.
- Are there methods of constructing infrastructure to allow for economic use of water?
    - ✓ E.g. private ownership, use of water for crops, living roof to reduce evaporation.

<u>Environmental</u>

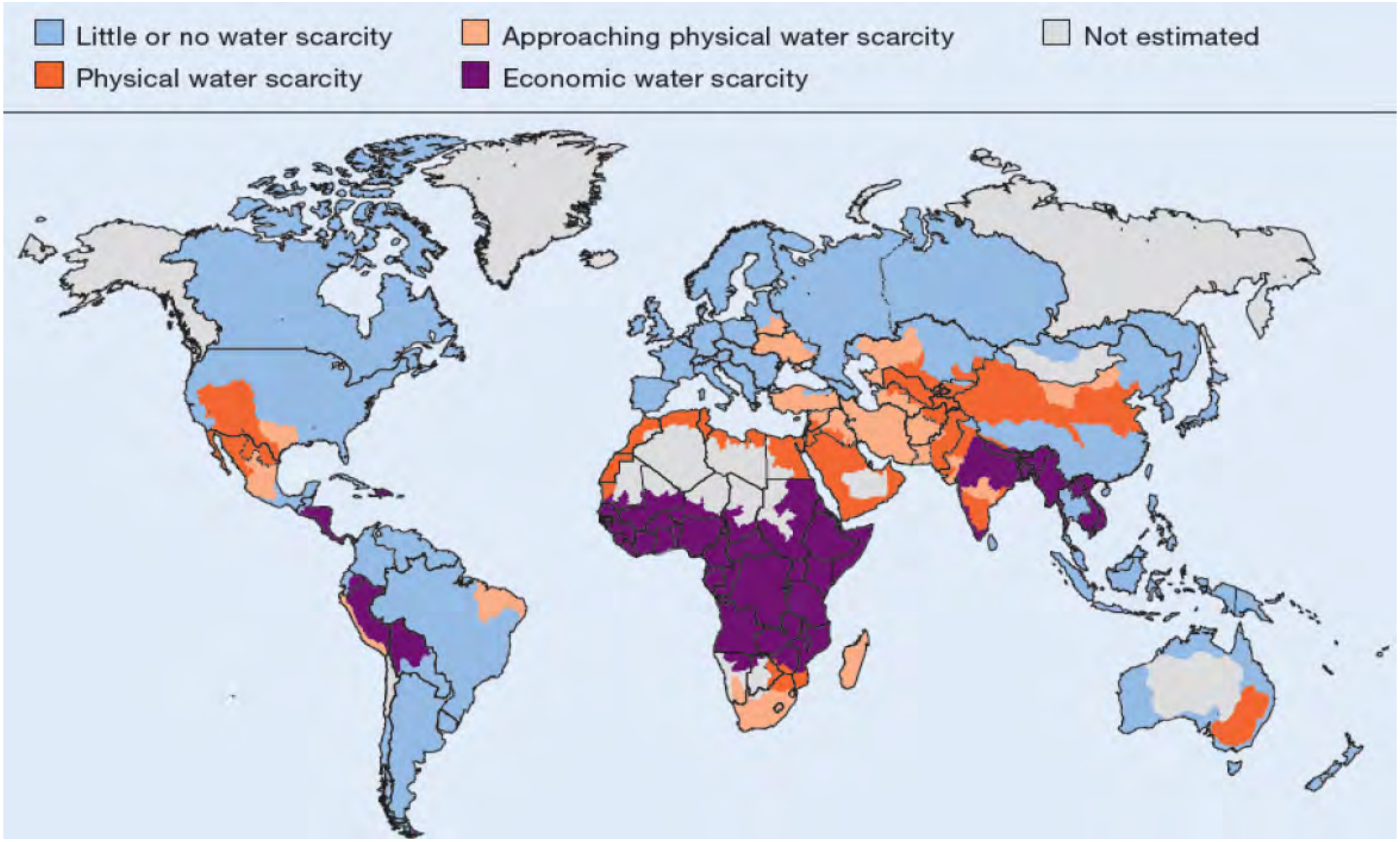
- Are there methods of environmental control that can improve water availability?
    - o E.g. vegetation in runoff zone = less siltation = more water stored.
- Are there possible environmental effects of improving water availability which could increase vulnerability?
    - o E.g. downstream effects, degradation around permanent water points.
- Are there methods of implementation that can reduce pressure on existing pasture and water sources?
    - o E.g. by creating new seasonal water points away from towns.

Annex 1: Water stress in relation to population



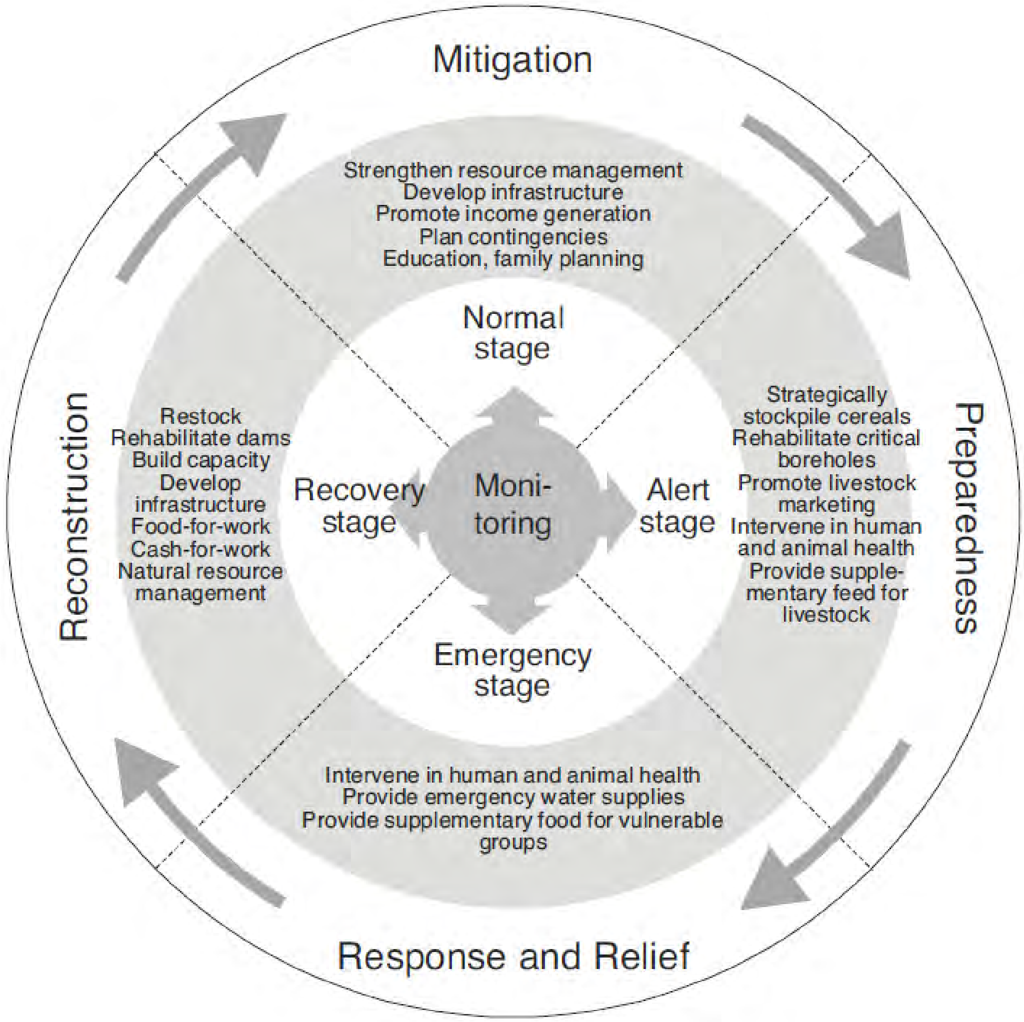
Figures are in m^3 of water per person per year for 2008. Source: FAO Aquastat database: http://www.fao.org/nr/water/aquastat/globalmaps/index.stm. Quoted in: USAID (2010) *Summary of the World Water Crisis and USG Investments in the Water Sector, May 15, 2010.*

Annex 2: Water scarcity in relation to population demand



Those areas in red will lack sufficient water resources to meet basic needs while those in purple will have enough water available but will lack the financial and/or technical resources to get the water from where it is to where it's needed, when it's needed. Source: IWMI, UN –World Urbanization Prospects. Quoted in: USAID (2010) *Summary of the World Water Crisis and USG Investments in the Water Sector*, *May 15, 2010.*

Annex 3: Drought Cycle Management



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he drought management cycle. Source: IIRR, ACACIA & CordAid (2004) *Drought Cycle Management: A toolkit for the drylands of the Greater Horn.* p.41