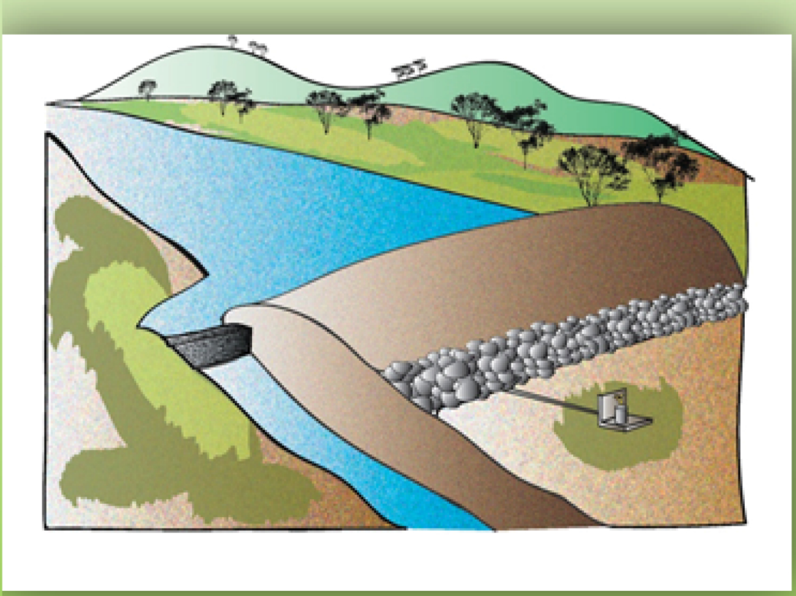
BEST PRACTICES FOR WATER HARVESTING AND STORAGE WITHIN VALLEYS



Nile Basin Initiative – NELSAP

Regional Agricultural Trade and Productivity Project (RATP)

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Best Practices for Water Harvesting and Storage within Valleys

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About this Training Manual

The Nile Basin Initiative (NBI) is a partnership of the riparian states (Burundi, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Rwanda, Sudan, Tanzania and Uganda**,** Eritrea is participating actively in the NBI as an observer) that seeks to develop the river in a cooperative manner, share substantial socioeconomic benefits, and promote regional peace and security through its shared vision of "sustainable socioeconomic development through the equitable utilization of, and benefit from, the common Nile Basin water resources". NBI's *Strategic Action Program* is made up of the *Shared Vision Program (SVP) and Subsidiary Action Programs (SAPs).* The SAPs are mandated to initiate concrete investments and action on the ground in the *Eastern Nile (ENSAP) and Nile Equatorial Lakes sub-basins (NELSAP).*

NELSAP through its sub basin programs implements pre-investment programs in the areas of power, trade and development and natural resources management. As part of its pre-investment framework, the Regional Agricultural Trade and productivity Project (RATP), in concert with the NELSAP, intends to promote and disseminate best practices on water harvesting and small scale irrigation development as a contribution towards agricultural development in the NEL Countries. NELSAP has previously implemented completed a project called Efficient Water Use for Agriculture Project (EWUAP). One of the recommendations of EWUAP was the need to develop Training/Dissemination materials on "*adoption of low cost technologies for water storage, conveyance, distribution, treatment and use for agriculture that can be adapted by communities and households of the rural and peri-urban poor*". This Training Manual is the initiative of NELSAP, for that purpose.

This Training Manual summarizes the major components of water harvesting techniques practiced in valleys, where channel flow is the predominant source of water. It covers four specific technologies adaptable by smallholder farmers in the Nile Basin countries. These are small earth dams, weirs, subsurface dams and sand dams. For each technology, the salient characteristics of the technology are described, as well as the planning, design, construction, management operation and maintenance.

This manual is meant to improve the skills of engineers, technicians, extension workers, managers and practitioners engaged in water harvesting, especially those working in smallholder agriculture in Africa. It is meant to inform, educate, enhance knowledge and practice targeting smallholder agricultural livelihoods in the NEL region. The information contained here may not be exhaustive and thus, readers are encouraged to seek further information from references cited in this publication and elsewhere.

Acknowledgements

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Table of Contents

Definition of Key Terms

Term	Definition/Brief description
Aggregate	The gravel or crushed stone normally used for making concrete
Appurtenant works	Structures or materials built and maintained in connection with dams. These can be spillways, low-level outlet works and conduits
ASAL	Arid and semi-arid lands
Auxiliary spillway	A secondary spillway designed to operate only during large floods.
Barrage	A special kind of dam which consists of a line of gates that can be opened or closed to control the amount of water passing the dam. They are used to control and stabilize water flow for irrigation systems
Bentonite	A clay type that has a high swell to shrink ratio. It is fine-textured colloidal clay, when wet; absorbs water several times greater than its own weight and, at complete saturation, swells to as much as 8 to 15 times its original volume.
Blue water	The proportion of rainfall which flows on or beneath soil surface to accumulate in rivers, streams, springs, swamps, lakes, ground water, aquifers or into storage structures such as dam, ponds and tanks, and which is extractable as liquid fresh water.
Cement mortar	Binding agent is composed of cement, sand and water used in construction
Check dam	A small water retaining structure built across a valley to reduce the flow velocity in a watercourse, control soil erosion or for water storage.
Clay mud	is a mixture of clay soil and water (thick mud) so that it can be pasted to the tank wall/surface for lowering seepage.
Cofferdam	A temporary structure enclosing all or part of the construction area so that construction can proceed in the dry.
Concrete	A mixture of cement, sand, gravel or crushed stone and water used for construction.
Curing	The action of applying water to structures under construction so that the cement and concrete works can get strong as it dries.
Crest	The highest point or level top of a dam.
Dam	A structure/barrier constructed across a stream, river or valley for the purpose of conserving, storing or controlling the flow of water.
Dam height	The vertical dimension from the downstream toe of the dam at its lowest point to the top of the dam.
Dry dam	A dam used to control flooding and which holds water only during extreme flood events that would otherwise cause damage downstream.
Diversionary dam	A dam structure designed to divert all or a portion of the flow of a river/stream from its natural course.
Earth dam	A dam whose embankment is constructed basically using compacted earth

Energy Dissipater	A structure constructed in a waterway which reduces the energy of fast-flowing water
Evaporation	The amount of water that leaves a water surface or land as vapor. Evaporation can be beneficial or non-beneficial. Non-beneficial evaporation includes that from open water bodies (tanks, ponds, reservoirs, canals) and from bare soil.
Freeboard	The vertical distance between the design high water level and the top of the dam.
Freshwater resources	Water available in rivers and aquifers of sufficient quality to be used for human purposes and which is replenished on an annual basis by precipitation.
Gravity Dam	A dam constructed of concrete and/or masonry and/or laid-up stone that relies upon its weight for stability.
Levee	An embankment or short wall constructed along a river/ stream or watercourse to protect adjacent land from flooding.
Low-level outlet	An opening at low level used to drain or lower the water level in a dam.
Maximum impoundment capacity	The volume of water held when the water surface is at the top of the dam crest.
Overtopping	Water flowing over the crest of a dam due to inadequate spillways.
Percolation	Movement of water downward through the pores of the soil.
Percolation ponds	Ponds excavated to hold runoff water and increase groundwater recharge. They may also be used for livestock watering.
Piping	Contact erosion along the bottom of an embankment in the dam-foundation interface.
Reservoir	A large body of water impounded within a constructed retaining structure, such as a dam, weir, pond or pan.
Rip-rap	Blanket foundation or wall made of large stones thrown together irregularly or loosely.
Runoff	Water that flows away from a catchment after falling on its surface in the form of rain.
Sand river	A river whose bed is covered by appreciable amounts of sand. Most sand rivers are ephemeral and are located in ASAL zones.
Seepage	Water leaking from the ground or a dam embankment. Also described as the flow of water through the soil pores under a pressure gradient.
Silt	Sediment made up of fine particles carried or laid down by moving water.
Siltation	The action of accumulation of soil, gravel and other colloidal matters in rainwater harvesting structures
Spillway	A conduit or channel built on a dam and designed to pass water from the upstream to the downstream side of a dam. Flood water is drained from a dam through spillways.
Spillway design flood	The largest flow that a given project is designed to pass safely.
Water harvesting	Activities where water from rainfall and/or surface runoff is collected, diverted, stored and utilized.
Weir	A type of small overflow dam used within a river channel to create an impoundment reservoir for water abstraction or for flow measurement purposes (also called an overflow dam).

1. INTRODUCTION

1.1 What is water harvesting in valleys?

Water harvesting within valleys is the harnessing, storage and delivery of excess water that would otherwise naturally flow in a watercourse. Water harvesting in a watercourse is distinguished from natural river flow by the fact that the water targeted for storage flows as excess floods during the rainy season, and base flow, if any, is not stored but is allowed to leave the storage structure. For smallholder agriculture and rural drinking water supplies, four types of structures are distinguished, which form the subject of this manual. These are:

(i) Small earth dams,
(ii) Weirs
(iii) Subsurface dams, and
(iv) Sand dams.

1.2 Background notes on water harvesting

The introduction to rainwater harvesting has already been presented in both Training Manuals 1 and 2 of these series. They have provided background material on why RWH is important, its benefits, limitations and general precautionary measures. Also covered in the two Manuals and repeated here are the methods of planning water harvesting and storage systems, prevention and control of common problems in storage structure, hygiene in rainwater storages and uses, water quality standards, treatment of stored rainwater, operation, maintenance and management of water harvesting and storage systems.

Thus, these facts are also tenable for water harvesting in valleys and will not be repeated here. However, specific factors, such as determining water storage volume for each type of structures are described. More specifically, this manual focuses on the distinguishing features of water harvesting within valleys as a niche way of storing excess flood flows. This means channel flow through watercourses such as rivers, streams, gullies and generally, various types of valleys. Most large projects on water harvesting are based on storages in valleys.

1.3 Comparative advantages of water harvesting in valleys

Water harvesting within valleys has certain merits over surface and ground sources that can make it play a leading role as the main source of water supply for urban/domestic and agricultural purposes.

- By their very nature, valleys flow with water in their natural course which may be stored without the need for diversions.
- The harvestable water is usually available in larger volumes than with surface-based types of catchments
- The slope and space to dissipating both the energy and excess water is naturally available within the valley
- There is less danger of soil erosion in areas below the storage since water flows its course.
- The cost of construction per unit volume of water stored is relatively low since no excavations are needed.

- Harvested rain water, in most cases, does not need pumping as it can be delivered to areas downstream by gravity.

- The operation and maintenance of water stored in valleys is relatively low.

1.4 Major limitations of valley water harvesting systems

- Finding a suitable site for the storage structure within valleys may result in the water being far away from users, unlike surface methods where water can be harvested and stored at home.
- The cost of dam construction and auxiliary works can be expensive, requiring earth moving machinery and purchase of materials and construction costs
- The designs of storages in valleys tend to carry a certain level of risk in case of collapse/failure.
- There is need for professional designs by engineers, surveyors and other technical requirements make the technologies beyond the reach of individual farmers.
- They are usually constructed as community based projects, thus are prone to the constraints associated with communally owned and operated infrastructures.
- Like other RWH structure, seepage losses are common problems with storages in valleys, especially earth dams.
- Since they are designed with open water surface within valleys, water storages suffer high evaporation losses especially in hot areas.
- Siltation problems are common in valley water storages as soil erosion in upper catchments always finds its way into valleys.
- Socio-economic constraints such as ownership of land where the storage structure is situated can hamper the development and/or management of water and its use.

3.

4. SMALL EARTH DAMS

2.1 What is a small earth dam?

A dam is a structure or barrier constructed across a valley, a river or stream to conserve, store or to control the flow of water (figure 2.1) The water may be used for drinking water supplies, hydro-electric power generation, irrigation, or environmental conservation. There are many types of dams, based on their use, construction material, size and shape. Depending on construction material, dams can be made of concrete, rock-fill, masonry or earth. Concrete dams may take various forms. These include gravity dams which are huge structures designed to use their own dead weight to resist the horizontal force of the water. An arch dam is built with its convex front facing the upstream side of the valley or reservoir, and derives its strength essentially to its shape. Thus an arch dam uses less concrete than a gravity dam. Concrete-buttress dam is a gravity dam reinforced by structural supports, thereby reducing material needed to construct the wall itself by using support buttresses around the outside base.

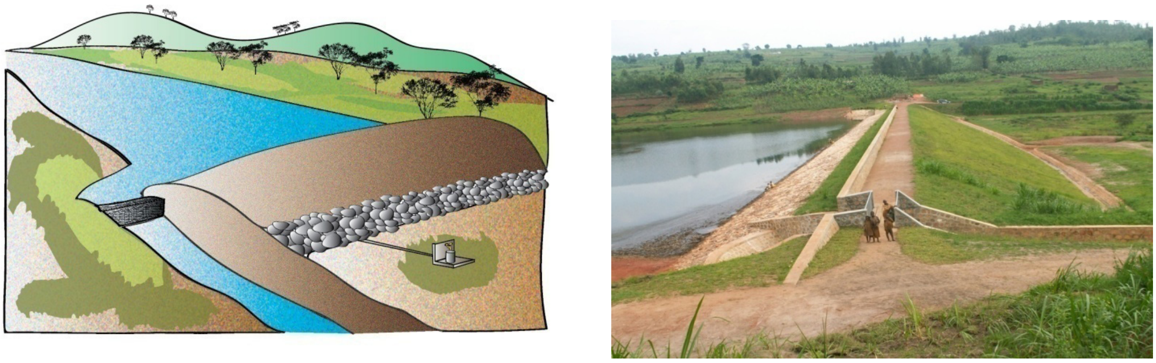


Figure 2.1 (a) Sketch of a three-dimensional view of an earth dam

(b) Earth dam and reservoir *(photo courtesy of Jean Muhinda)*

Earth dams utilize soil of good compaction quality to build up the embankment, and are variously known as earth-fill dams. Earth dams rely on their weight to hold back the force of water, just like gravity dams. The cross-sectional profile of an earth-fill dam is a broad-based triangle. Thus, ***a small earth dam is*** one whose embankment is basically constructed using compacted earth.

A small earth dam has a crest height ranging from 2 to 5 m high, while the reservoir capacity is at least 5,000 m^3 but less than 1 million m^3 storage volume. They can be designed by local technicians, built and managed/maintained by user communities. The dams can be of uniform material, or have clay core for better seepage control (Figure 10). They also have spillways to protect them from overtopping excess runoff flows.

Small earth dams are usually constructed for rainwater harvesting or on small rivers to retain flood runoff during the rainy season, on a watercourse which may be a perennial river or a dry riverbed. The dam wall has a clay core, while the outlet has a stone apron and spillway to discharge excess runoff. Sediment traps and delivery wells may help to improve water quality but, as with water from earthen dams, it is usually not suitable for drinking without being subject to treatment. Small earth dams can provide adequate water for irrigation projects as well as for livestock watering.

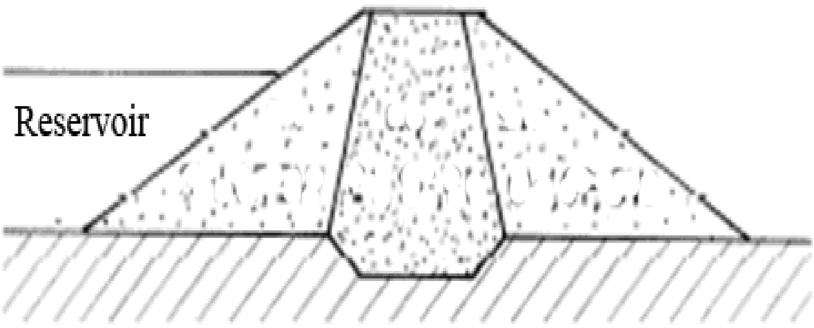


Figure 2.2. Sketch of an earth dam cross-sectional profile *(Source: Danida, 2006)*

2.2 Why construct a dam?

Dams have various uses. These include:

Irrigation: Small earth dams are particularly useful for providing water for irrigation in dry areas, and from streams which have low or no flows during the dry season.

Water supply: Small earth dams are particularly useful for drinking water supplies to rural as well as urban communities. The multi-purpose nature of dams makes them ideal for community water supplies for irrigation, livestock watering and domestic use. *Water diversion*: Small dam can be used to divert water for irrigation, power generation, or other uses. Sometimes, they are used to divert water to another drainage or reservoir to increase flow there and improve water use in that particular area.

	
Figure 2.3 Water diversion from small earth dam using a weir *(photos by B. Mati)*	**(b) Diversion chute from an earth dam**

Stabilize water flow: Dams are often used to control and stabilize water flow, often for agricultural purposes and irrigation

Hydro-power generation – Small earth dams can be used for hydropower generation. This is particularly possible in dams having a steady flow and built across a gorge where there is a relatively good head drop. Many countries have rivers with adequate water flow that can be dammed for power generation purposes.

Land reclamation: Dams are used for land reclamation and to prevent inundation of water to an area that would otherwise be submerged. This facilitates reclamation of such areas for other use. Normally dykes or levees are used for diverting the water

Flood prevention: Dams are sometimes constructed to impound excess flows during the rainy season and prevent flooding of downstream areas or infrastructure. They help to stabilize river flow especially of ephemeral streams.

Recreation and aesthetics: Earth dams provide a water body that can be used for recreational activities such as swimming, fishing, or tourism. Other than the water itself, a dam allows for creation of greenery and ecosystem restoration which are added benefits to agricultural use.

2.3 Types of earth dams

2.3.1 Earth-fill dams

Earth-fill dams, also called earthen, rolled-earth or simply earth dams, are constructed as a simple embankment of well compacted earth. Earth dams are trapezoidal in shape. They are constructed where the foundation or the underlying material or rocks are weak to support the masonry dam or where the suitable competent rocks are at greater depth. Earthen dams are relatively shorter in height and broad at the base. Earth dams are mainly built with clay, sand and gravel. The upstream face of an earth dam is usually protected from erosion by a surface layer of flat rock, called rip-rap.

There are three sub-types of earth dams; (i) homogeneous type dams are constructed with a single type of soil throughout the cross-section, (ii) a zoned type dam, has an impervious core zone surrounded by a relatively pervious zone, and (iii) a diaphragm type dam, whereby a tall impervious wall of less than 10 m thickness replaces the impervious zone. Modern zoned-earth embankments employ filter and drain zones to collect and remove seepage water and preserve the integrity of the downstream shell zone. Because earthen dams can be constructed from materials found on-site or nearby, they can be very cost-effective in regions where the cost of producing or bringing in concrete would be prohibitive.

2.3.2 Rock-fill dams

Rock-fill dams are a variation of earth dams, whose embankments are constructed using loose rocks and boulders instead of soil. However, an impervious zone is created on the upstream face of the dam, made of masonry, concrete, plastic membrane, steel sheet piles, timber or other material. The impervious zone may also be constructed as a central cross-sectional pillar within embankment in which case it is referred to as a core. Rock-fill dams can be made with a steeper slope hence narrower than earth dams. When suitable rock material is available at site, transportation is minimized leading to cost savings during construction.

In cases where clay is utilized as the impervious material, the dam is referred to as a composite dam. To prevent internal erosion of clay into the rock fill due to seepage forces, the core is separated using a filter. Filters are specifically graded soil designed to prevent the movement of fine grained soil particles into the rock fill. Rock-fill dams are stable and more resistant to earthquakes due to the fact that the embankment structure contains loose particles which can vibrate independently. However, proper compaction and good quality control must be ensured during construction to prevent projectfailure and seepage problems.

2.3.3 Regulating dam

A regulating dam is one that is designed with a capacity to store the flash floods from a single day's rainfall, and then release it slowly thus reducing the danger such a flood would have posed e.g. causing erosion downstream. The reservoir therefore has a permanent water outlet that releases the stored water at a flow rate of minimum risk. The stored water drains away continuously until the reservoir is dry in a day or two, ready to receive the next flash floods. An adequate spillway must be provided to guard against the collapse of the dam. The dam embankment can be earthen, concrete or packed stone gabions.

2.3.4 Dry dam

A dry dam also known as a flood retarding structure. It is a dam designed to control flooding. It normally does not hold back any water and allows the channel to flow freely, except during periods of intense flow that would otherwise cause flooding downstream, that time, it stores water temporarily. A dry dam is a kind of regulating dam, but without water storage during the dry season.

2.3.5 Silt trap dams

Silt trap dams are made across water courses/rivers to protect downstream structures from sedimentation. They are designed like ordinary earth dams, but the spillway is raised to enable sediments to sit in the dam. A simple technique, which can be adopted by smallholder farmers, involves using old gunny bags packed with soil packed on each other (Figure 2.4). The soil is scooped form adjacent areas. It is a very low cost technique. This type of structure is temporary and should not exceed 2 m high since it is not very strong. The embankment made of soil-packed bags can be re-built each season to improve its storage capacity. As the soil accumulates, the embankment is grassed to improve its stability.

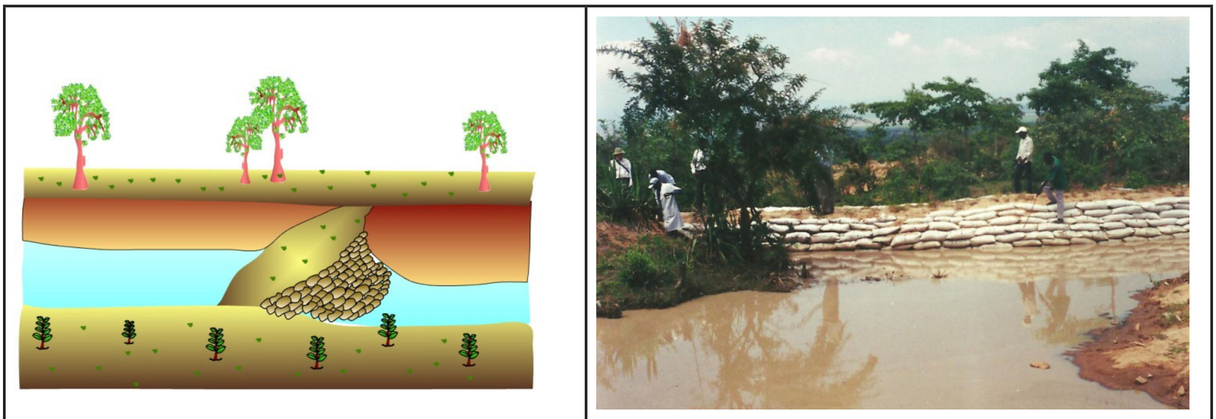


Figure 2.4 (a) Sketch of a silt trap dam made of soil-packed sacks

(b) Silt trap dam made of soil-packed gunny bags *(photo by B. Mati)*

2.3.6 Valley dams

Valley dams are the dams normally built across valleys and small seasonal water courses, which, may be on the boundaries between two or more landowners. Valley dams are normally made of earth, and are thus earth fill dams (Figure 2.5). However, they are shorter and thus have smaller reservoirs. Since valley dams can collapse during exceptionally heavy rainfall due to poor maintenance, incorrect design or poor construction work, this could endanger people and structures downstream.

Figure 2.5 (a) Valley dam for water harvesting *(photos by B. Mati)*

(b) Valley dam with rock toe

2.3.7 Hillside dam

A hillside dam is an off-stream storage reservoir, constructed on sloping land or on a hillside. The system comprises a small dam, a collection area, a reservoir, a dyke, a spillway and a water draw-off device. It is constructed in hilly areas to capture runoff from catchments of area 100 to 2,000 ha. The water may enter the dam from surface runoff harvesting from the catchment above it, or it is brought by pipe or canal to the dam (pumped or by gravity). The main advantage of a hillside dam is that water may be taken downhill by gravity for irrigation or other purposes.

The dam embankment can be made of compacted earth, although concrete can also be used. The storage capacity of the reservoir can be about 10,000 to 400,000 m^3. Since it lies on a hill, water is easily withdrawn by gravity through a pipe. Hill reservoirs tend to be more expensive than other conventional water harvesting systems because of their size and location, but they have many advantages as the water can reach larger downstream areas due to the height difference. The difference with ordinary pans and ponds is that a hill reservoir may not be located in a valley, thus making it possible to harvest large volumes of water from hills (Figure 2.6).

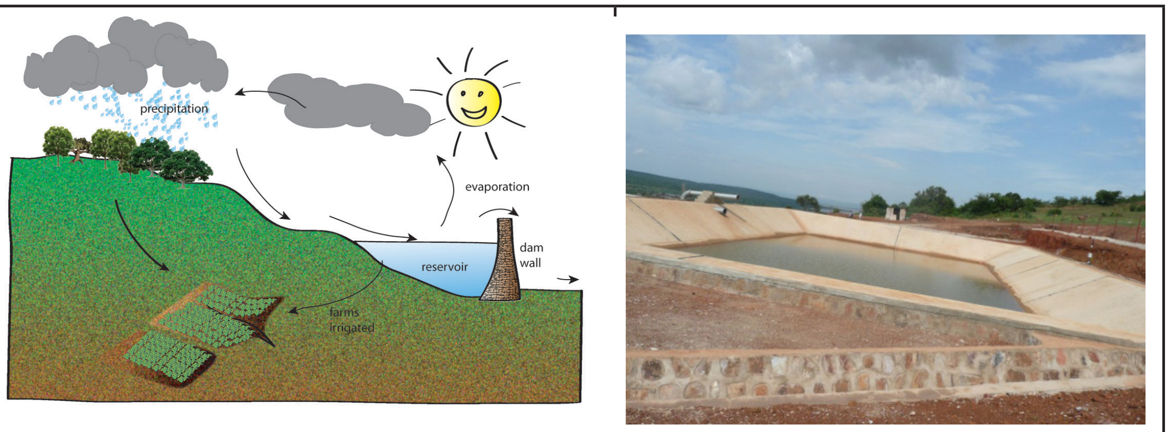


Figure 2.6 (a) Illustration of a hill reservoir system with irrigated area

(b) Hill reservoir lined with concrete *(photo by B. Mati)*

The storage to excavation ratio of hillside dams can be quite low (1.5 is common) and increasing the value is desirable. The site should be as flat as possible, and with good soil suitability and catchment yield. If necessary, the dam can be covered with concrete or clay grouting to prevent seepage. Although hillside dams are less prone to failure than gully dams, they still require sound design and construction to be successful.

2.3.8 Hafir dams

"Hafir" dams are usually small earthen reservoirs dug into the ground in gently sloping areas that receive runoff either from flood flow diverted from streams or from large catchment areas. Generally, they have a volume ranging from 500-10,000 m^3 and are used to store water for human and livestock consumption. Hafirs are located in natural depressions and the excavated soil is used to form an embankment around the reservoir to increase its capacity. Wing walls and improvements to the catchment apron may help to increase runoff into the reservoir, but seepage and evaporation are often high in the dry season. Hafirs differ from water pans in that they are generally bigger in size, and also have good sedimentation basins. In hafirs, watering areas are well allocated, the site is securely fenced and the reservoir is de-silted every season. The major drawback with hafirs is the requirement of periodic cleaning to remove silt, which is not an easy task. Sediment traps and delivery wells may help to improve water quality but, as with water from earth dams, it is not usually suitable for drinking without some form of treatment.

2.3.9 Gully dams

Gully dams are also off-stream dams since they tend to be located on an artificial watercourse which is on a hillside. Most gullies are formed from severe soil erosion due to uncontrolled surface runoff emanating from catchments above the gully or from road drains. Thus, a gully dam combines water harvesting with soil conservation (Figure 2.7). The method takes advantage of only those gullies or depressions which are stable enough and suitable for water storage.

A gully dam is designed just like any other small earth dam. However, care is taken to anchor the dam properly to the sides. Also, a large spillway is usually recommended at the centre of the structure, to act as a weir and thus prevent excess water from undermining the structure. The banks of the dam are built from soil material dug from an excavation contained within the storage area (see Figure 1). Gully dams are commonly used for storages ranging from 1,000 to 50,000 m^3. They normally offer a low capital cost per unit of the stored water capacity.

Figure 2.7 (a): Sketch of a plan view of a gully dam

(b) Gully dam in an active gully *(photo by B. Mati)*

Water yield from gully dams can be delivered by gravity downstream for use in irrigation or livestock watering. All gully dams have a significant risk of failure either due to insufficient water, excess water, spillway erosion, bank overtopping, bank failure or excessive seepage. The demands for quality design and construction increase as banks increase in height. It is preferred to make the banks as low as possible to reduce chances of failure. In all cases considerable attention must be paid to compaction of the bank and consequently, the moisture content of the material when being packed into the bank. Gully dams generally have larger water flows moving into the storage than hillside dams. This is good for replenishment of dam water but it also demands careful design and construction of the spillway (and freeboard) to safely cope with flood flows. Ultimately, a gully dam may fill with sediment, thus it is also a silt trap dam.

2.4 Design of small earth dams

2.4.1 Components of a dam

A small earth dam comprises a water impoundment zone or reservoir, the dam embankment itself, water outlet and delivery works, spillway and control facilities. The inflow of water into the reservoir must be monitored continuously and the outflow should be controlled to achieve optimum benefits. Under normal operating conditions, the reservoir is controlled by the outlet works, consisting of a channel or conduit at stream level with control gates. The main parts of a dam include:

a) ***Heel***: Contact with the ground on the upstream side

b) ***Toe:*** Contact on the downstream side

c) ***Abutment:*** Sides of the valley on which the structure of the dam rest

d) ***Galleries:*** Small room- like structures left within the dam for checking operations.

e) ***Diversion tunnel:*** Tunnels are constructed for diverting water before the construction of dam. This helps in keeping the river bed dry.

f) ***Spillways:*** It is the arrangement near the top to release the excess water of the reservoir to downstream side

g) ***Sluice way:*** An opening in the dam near the ground level, which is used to clear the silt accumulation in the reservoir side.

h) ***Dead storage:*** The amount of water that remains in the dam at the lowest level. It also comprises the part of the reservoir that cannot be drained by an outlet or by pumping. The latter depends largely on the suction arrangements of the pumping set up. Note should be taken that it is not always wise to drain a dam completely, most especially if 'cracking clays' have been used in the embankment, core or reservoir floor.

2.4.2 Requirements of a good dam design

The design of an earth dam considers the technical, social, economic and environmental data. Preliminary designs and cost estimates are prepared and reviewed by hydrologic, hydraulic, geotechnical, and structural engineers, as well as geologists. Environmental quality of the water, ecological systems, and cultural data are also considered in the site-selection process. Factors that affect the type and size of structure include the topography, geology, foundation conditions, hydrology, possibility of earth movements, and availability of construction materials. The foundation of the dam should be as sound and free of faults as possible. All dams are designed and constructed to meet certain basic requirements, which include:

(i) It should consider peak flood flows, and the design of spillways and other protective structures,

(ii) The dam should remain stable under all conditions, i.e. during construction, while in operation, both at the normal reservoir operating level and under all flood and drought conditions.

(iii) The dam wall and its foundation must be watertight to control seepage and maintain the desired reservoir level.

(iv) The dam should have sufficient spillway and outlet capacity

(v) A freeboard is usually included in the design to prevent floodwater overtopping.

(vi) Impacts of the dam on the water table of affected areas, and whether this is desirable or not.

(vii) Reservoir silting, which should be minimized or accounted for in the dam design,

(viii) Environmental impacts on river aquatic life e.g. riparian vegetation, fish and fisher-folk,

(ix) Impacts on human habitations, and resettlement. There are costs associated with the compensation for land being flooded as well as population resettlement. This may also include the removal of toxic materials and buildings from the proposed reservoir area.

2.4.3 Site selection criteria

The most suitable site for a small earth dam is where the valley will enable the construction of a straight embankment dam. Such sites are normally found at valley cross-sections where a natural deep gorge exists. Sometimes, a natural depression on sloping ground can provide a good site for a curved hillside dam. It is essential to select a site where the dam foundation will be watertight and without seepage, while it accords ease of construction and a stable structure can be assured. Thus, small earth dams should be sited in areas which bear the following characteristics:

(i) The site should be located where surface runoff from rains on the catchment area, or other runoff flows, can fill the dam reservoirs at least once a year. The dam must have the potential to fill with runoff (most years) or store sufficient water between runoff events that fill the reservoir. It is essential that the dam and reservoir have sufficient depth and volume to last through extended periods of drought.

(ii) A topographical survey of the proposed dam site is normally done to determine features such as slope, width and height of dam, reservoir capacity, as well as to estimate costs, prepare necessary information for licensing and provide construction details.

(iii) The dam site should be selected on a natural valley which will provide a relatively high depth to surface area ratio (for a given design volume), to minimize evaporation losses. A simple way of identifying such a site is where the valley is bounded by steep hillsides. The dam can also be sited just below the confluence of two tributaries to gain more volume. One of the best sites for construction of a dam is a narrow part of a deep river valley; the valley sides then act as natural walls. The primary function of the dam's structure is to fill the gap in the natural reservoir line left by the stream channel. The sites are usually those where the gap becomes a minimum for the required storage capacity. The current use of the land to be flooded should be dispensable.

(iv) Thorough site investigations are needed especially for the dam foundation to avoid cracked, loose soil or other weaknesses that may cause seepage or failure. The dam foundation must be solid impermeable rock with no soil pockets or fracture lines, while rock surfaces should not be fractured or cracked, to avoid causing leakage losses. In some cases, field pumping tests are performed to evaluate seepage potential.

(v) Soil conditions must be suitable for both compaction and the prevention of seepage losses through the dam. Pre-construction soil testing should be done at the proposed site. This testing can be accomplished by digging several test pits where the dam and reservoir is to be located. Soils should be checked to depths at least a metre below that of any proposed excavation for the dam or reservoir. T

(vi) There should be no soil erosion in the catchment area, no anthills, pits, sewage outlets, saline or calcareous soils. An assessment of the hazard potential downstream should be done. Watershed activities that could affect the water quality or quantity of runoff are also assessed.

(vii) Location must be convenient for the user group. This could be where people and livestock are in need for water and where the community has implemented soil conservation measures on any cleared land in the catchment area of the dam

(viii) Land tenure and ownership also affect site location. The dam should, wherever possible, be located on public land with access road for the community members and users of the dam.

(ix) Location of the dam also considers the cultural and socio-economic conditions so as to serve a large population, without infringing on laws, customs and social structures of beneficiary communities. Whenever possible, local communities should be supportive of the dam.

2.4.4 Dam capacity and side slopes

A typical design of a small earth-fill dam is shown in Figure 4. For stability, the upstream slope must be a minimum of 3:1. Erosion protection is required to protect the dam from wave action. This protection can be achieved with a combination of smaller and larger rocks (or other suitable material) and, with smaller projects, a floating log boom. The downstream slope requires a minimum 2:1 slope, seeded with native grasses to prevent surface erosion. The top or crest of the dam should be a minimum of 3 m wide (preferably 5 m) to accommodate road traffic and minimize the potential for erosion. The crest elevation should be a minimum of 1 m above the full supply level (FSL) of the reservoir. The dam should be fenced to prevent livestock traffic, as this traffic can be a major cause of slope and crest degradation. The water storage capacity of a dam and reservoir (shown in Figure 2.8) can be estimated as follows:

Dam capacity = [Reservoir Length x Width (at the dam) x (Max. depth of the Water)]/3

Design of earthen Bund

The various components of an earthen bund include:
(a) Foundation including key trench or cut-off,
(b) Height of bund,
(c) Side slopes,
(d) Top width,
(e) Free board, and
(f) Settlement allowance.

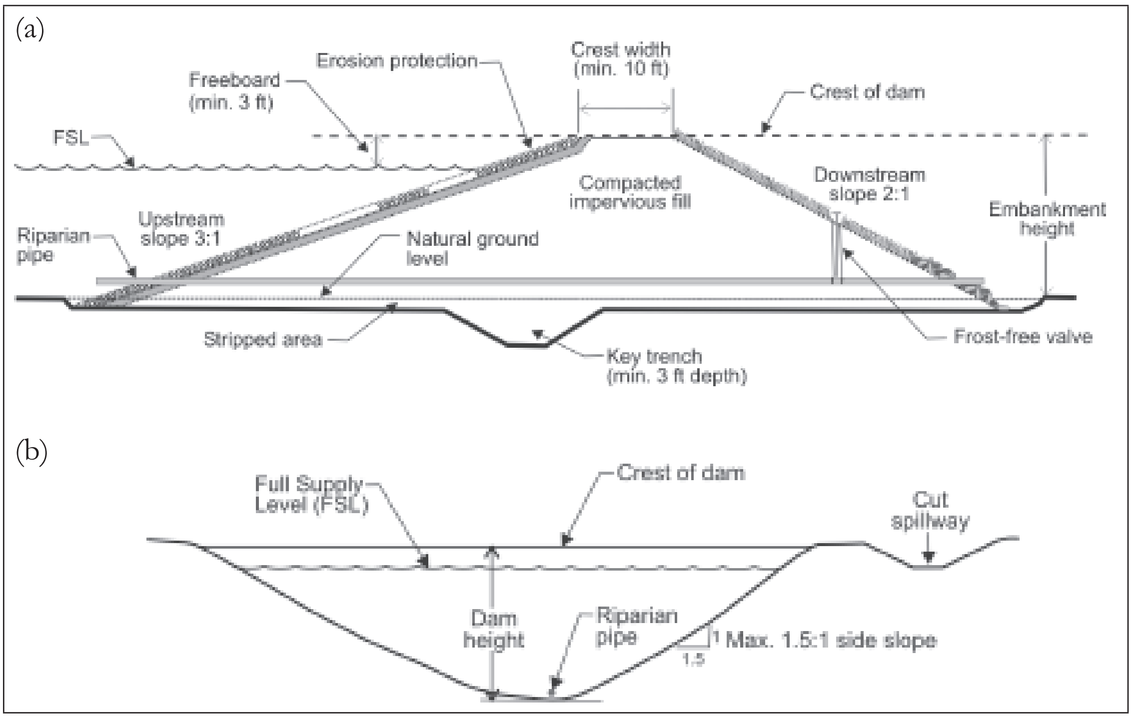


Figure 2.8 (a)Sketch showing components of a small earth fill dam, and (b) The cross-sectional area

It is possible to construct a stable and economical earthen bund on any foundation. Sites with foundation conditions requiring relatively expansive construction measures should be avoided. The most satisfactory foundation is one that consists of, or is underlain at a shallow depth by a thick layer of relatively impervious consolidated material. Such foundations cause no stability problems.

Where a suitable layer occurs at the surface no special measures are required. It is sufficient to remove the top soil (with vegetation and roots) and plough the area to provide a good bond with the new fill material of the bund.

Where the impervious layer is overlain by pervious material (sand), a compacted clay cut-off extending from the surface of the ground into the impervious is required to prevent excessive seepage and to prevent possible failure by piping.

Determining Top width

The minimum allowable top width (W) of the embankment shall be the greater dimension of 3 m or W, as calculated by the following formula:

$W = (0.67H + 3)$; where H is the height of the embankment (in metres)

The sides of the dam embankment (Figure 5) should slope at an angle that will provide a stable structure depending on the type of fill materials (Table 1). The upstream slope of earth dams should be no steeper than 1 vertical on 3 horizontal. The downstream slope of earth dams without seepage control measures should be no steeper than 1 vertical on 3 horizontal. If seepage control measures are provided, the downstream slope should be no steeper than 1 vertical on 2 horizontal. The upstream side should be covered with stone pitching (rip-rap) and filter with recommended depth of 20 to 30 cm.

Height of Bund

The height of bund will depend upon the volume of runoff to be stored and topography of the reservoir area. The height of the bund should also be selected in such a way that its cost per unit of storage (cum volume) is kept at a minimum. While calculating the cost corresponding to any height some allowance for settlement and free board, and temporary flood storage may be added to give the actual bund height or in other words the actual quantity of earth work.

Top Width of Embankment

Adequate top width is provided to the bund so that it can be used as road way and communication routes adjoining villages or watersheds. Simple formulae for top width (T.W.) as a function of height (H) may be used.

Up to 10 m height, $T.W. = H/5+2$
10 to 15 m height, $T.W. = H/5+3$

Where,
H = Maximum height in m
T.W. = Top width in m

Side Slope of Bund

Adequate upstream and downstream side slopes of the embankment must be provided to satisfy the stability requirements of reservoir filled with water, sudden drawdown to minimise the erosion, and to facilitate establishment of good sod forming grass. The maximum side slopes recommended in case of small earth dams are given below in Table 2.1.

Table 2.1: Side slopes of earth dams according to fill materials used

Side slopes (horizontal to vertical)	Side slopes (horizontal to vertical)	
	Upstream	Downstream
Clay, clayey sand, sandy clay, silty sand	3:1 – 3.5:1	2.5:1 – 3:1
Silty clay, clayey gravel, silty gravel	3:1 – 3.5:1	2.5:1 – 3:1
Silts or clayey silt	3.5:1 – 4:1	3:1 – 3.5:1

(A slope of 3:1 means 3m horizontal distance for every 1m in height). Source: MWRI, 2009

Foundation Cutoffs

Usually a cut-off joining the impervious stratum in the foundation with the base of the dam is needed. The most common type of cutoff is one constructed of compacted or puddled clay material. A trench, also called key-trench, is cut parallel to the central line of the bund to a depth that extends well into the impervious layer. The trench should have a bottom width of not less than 1.5 meters but adequate to allow the use of mechanical equipment if necessary, to obtain proper compaction. The sides of the trench should be filled with puddled clay or with successive thin layers of relatively impervious material each layer being properly compacted.

Free Board

It is the added height of the bund provided as a safety factor to prevent waves and flood runoff from over-topping the embankment.

(i) Minimum free board (F.B.) for length of pond up to 400 m 50 cm
(ii) F.B. for length of pond up to 800 m 75 cm
(iii) F.B. for length of pond more than 800 m 100 cm.

Settlement Allowance

This includes the consolidation of the fill materials and the foundation materials due to the weight of the bund and increased moisture caused by the storage of water.

Hand compacted (manually constructed) fill = 10% of design height
Machine compacted = 5% of design height.

2.4.5 Spillways

A spillway is a conduit or channel made on a dam and designed to pass water from the upstream to the downstream side of a dam (Figure 2.9). Many spillways have floodgates so as to control the flow through the spillway. The spillway should be designed with a wide base and a gentle slope, which will reduce water velocity and spillway soil erosion. The spillway base and sides should also be seeded to grass. To prevent spillway erosion, riprap (a collection of loose stones) alone or in combination with geotextile material may be required if the base slope of the spillway is steep. Side slopes of the cut spillway should be no less than 2:1 (4:1 slopes are preferred).

Figure 2.9 (a) Spillway under construction *(photo by Jean Muhinda)*

(b) The completed spillway of a dam *(photo by B. Mati)*

The spillway should be located away from the dam fill, not through or directly adjacent to the fill. This placement will reduce the risk of the dam washing out. Culverts are often used in spillway design, and if undersized, they can restrict spillway flow and result in project failure.

Types of spillways

There are several designs of spillways depending on operation. They include:

- A fixed weir spillway – which is usually at the centre of the structure and allows the over-spilling for the common floods.
- A service spillway or primary spillway is one which allows the passage of normal flow.
- An emergency spillway is designed for extreme conditions, such as a serious malfunction of the service spillway.
- An auxiliary spillway releases flow in excess of the capacity of the service spillway.
- A fuse plug spillway is a low embankment designed to be over topped and washed away in the event of a large flood.
- Fusegate elements are independent free-standing blocks set side by side on the spillway so as to allow an increase in the normal pool of the dam without compromising the security of the dam because they are designed to be gradually evacuated for exceptional events.

2.5 Construction

2.5.1 Environmental impact assessment

Before the construction of any dam, an environmental impact assessment (EIA) is usually done to ensure that there will be no adverse effects on the human livelihoods as well as ecosystems affected by the dam. Reservoirs hold large quantities of water which could affect many ecological aspects of a river, particularly flow to downstream water users. An EIA can take several scenarios, such as the benefits to human society arising from the dam (agriculture, water, damage prevention and power), the harm or benefit to nature and wildlife, impact on the geology of an area. It also considers whether the change to water flow and levels will increase or decrease stability, and the disruption to human lives. Water releases from a reservoir including that exiting from a turbine usually contains very little suspended sediment, and this in turn can lead to scouring of river beds and loss of riverbanks; causing erosion. Reservoirs may also host pests and other disease causing organisms which were not endemic to the area. Positive environmental attributes of a dam should also be factored such as improved tree cover, and recharge of ground water resources.

2.5.2 Handling existing flows

An important consideration in dam construction is how to handle the stream flow around or through the dam site during construction works. Stream flow records provide the information for use in determining the largest flood to divert during the selected construction period. One common practice for diversion involves constructing the permanent outlet works, which may be a conduit or a tunnel in the abutment, along with portions of the dam adjacent to the abutments, in the first construction period. The stream is diverted into the outlet works by a cofferdam high enough to prevent overtopping during construction. A downstream cofferdam is also required to keep the dam site dry. See also Cofferdam.

A cofferdam is a temporary barrier, dam or embankment constructed to divert water from its normal course during the construction of a dam, bridge or such other structures. It can be made using concrete, steel sheet piling, or wood. When the construction is completed, the cofferdam may be demolished or removed. Sometimes, a coffer dam may be made as a closed or open channel, which is converted into a pipe shaft on completion of the project. The construction of an earth dam involves several steps which include the following:

2.5.3 Steps in construction

Stripping

This really means land clearing. The area covered by the base of the dam must be stripped of all vegetation and organic soil. The organic soil can be stockpiled and used on the downstream slope of the fill. All slopes steeper than 1.5:1 on sides of draw should be flattened to minimum of 2:1.

Key trench

A key trench (cutoff trench) is excavated below the base of the fill upstream of the centre line of the fill. The key trench is incorporated in the design for two reasons: to anchor the dam to the base material and to prevent piping (seepage under the fill). The key trench should be a minimum of three feet deep for a dam the height of about 4 m. It should extend the full length of the dam and reach one third to one half of the way up the side slope of the draw.

Fill construction

The earth dam is normally constructed using impervious clay or clay-based material (Figure 2.10). A simple field test is used to determine the suitability of the material for compaction requires adding a small amount of moisture to a handful of soil then rolling it between the palms and hands. The material having good compaction characteristics is the one which can be rolled to the diameter of a pencil, approximately six inches long, then bent into a loop without breaking.

Construction material taken from the surrounding hillsides or an excavation in the reservoir area must be placed close to horizontal in the fill in six inch layers and compacted. If the material is dry, moisture will have to be added, and suitable compaction equipment such as a sheep's foot packer used to obtain the proper compaction.

A simple test to evaluate proper compaction is to place the edge of the heel of a hard-soled boot on the fill and push down hard with all your weight. If only a mark is left, compaction is satisfactory. If the heel sinks in, compaction is poor. No rocks over 15 cm in diameter should be placed in the fill.

	
Figure 2.10 (a) Earth-fill dam under construction *(photos by Bancy Mati)*	**(b) Earth dam construction nearing completion – front is lined with masonry**

2.6 Safety features

Dams can fail if the structure is breached or suffers significant damage. Dams may also fail slowly through siltation of the reservoir or loss of water through seepage. If a dam fails due to structural weakness, it can cause extensive damage including fatalities and this should be avoided at all costs. It is therefore necessary to monitor signs of weakness such as cracks, submergence or seepage around the structure. Most dams are designed with mechanisms to permit the reservoir to be lowered or even drained in the event of such problem. Cracks and other fissures can be remedied through rock grouting – which involves pressure pumping of concrete mix into weak fractured rock. Small earth dams should be fenced and the catchment area protected from damage so as to reduce siltation damage. Animals and people should not access water directly from the dam, but the design should incorporate water off-take structures to minimize human traffic and trampling. Communities must be trained on the acre, utilisation and management of the dam.

Vegetation control

Trees and bushes are not permitted on earth dams because:

(i) Extensive root systems can provide seepage paths for water,

(ii) Trees that blow down or fall over can leave large holes in the embankment surface that will weaken the embankment and can lead to increased erosion, and

(iii) trees and bushes obscure the surface limiting visual inspection, provides a habitat for burrowing animals and retards growth for grass vegetation. The stumps of cut trees should be removed so grass vegetation can be established and the surface mowed. Stumps should be removed either by pulling or with machines that grind them down. All woody material should be removed to about 15 cm below the ground surface. The cavity should be filled with well compacted soil and grass vegetation established.

Grass vegetation is usually planted on dam embankments as it is an effective and inexpensive way to prevent erosion and stabilise the surface. Grass also enhances the appearance of the dam and provides a surface that can be easily inspected.

2.7 Maintenance of earth dams

Earth fill dams require regular inspection and maintenance. An inspection before spring runoff is critical to ensure the spillway is not blocked with snow or other material. All blockages must be removed to prevent overtopping and the dam washing out. During runoff, additional inspections should be carried out to watch for signs of erosion, spillway blockages (ice or debris) or overtopping of the dam. After the dam is free of snow, a visual inspection can be completed to assess the slopes for erosion, rodent damage, seepage or slumping. Burrowing rodents such as beavers, muskrats and gophers should be removed from the dam immediately. All potential problems must be repaired as soon as possible to safeguard the dam. Side slopes should be cleared of tree growth on a regular basis.

3. WEIRS

3.1 What is a weir

A weir (sometimes called an overflow dam), is a small dam created across a valley or river channel and often used to create an impoundment reservoir. The term *weir* is also sometimes used to describe the crest of an overflow spillway on a large dam. In most cases, weirs take the form of a barrier across the river that causes water to pool behind the structure (just like a dam), but allows water to flow over the top. Weirs are commonly used to alter the flow regime of the river, prevent flooding, measure discharge. They are normally constructed using concrete, stone masonry or gabions. Most weirs are used to create a pool of water abstraction purposes but they are also used for flow measurement (Figure 3.1). They are also used for drinking water supplies or to control flooding and to help render a river navigable

Figure 3.1 Typical weir for flood water harvesting and stream diversion *(photo by B. Mati)*

3.1.1 Why construct a weir?

Weirs are particularly useful for RWH in ephemeral streams, and dry watercourses where they impound flood flows. Several weirs made across selected stream sections can impede excess flows during the rainy season so that water is retained on pervious dry watercourse for longer periods. Weirs differ from other dams in that they are designed to be overtopped and the spillway is at the centre of the weir crest. For that reason, weirs are normally smaller than dams with height of crest rarely exceeding 3 m. Some weirs remain completely submerged under water if the river has large flows. Since they are designed to be overtopped, sedimentation of the reservoir is a major limitation.

Weirs are also useful in restoration of degraded catchments and for water supply projects using river diversions. When used for integrated water resources management (IWRM), a series of several weirs can be constructed at suitable locations down the stream profile in a cascade manner. A weir acts like a mini percolation tank and are useful in facilitating ground water recharge in catchments with relatively high water tables (Figure 3.2). Weirs can be constructed for any weather situation, but for water harvesting, they are particularly useful in areas receiving less that than 1000 mm of rain per year.

Figure 3.2 (a) Weir used for spring protection *(photos by Bancy Mati)* **(b) Close-up view of same weir and notch**

3.1.2 Advantages and limitations of weirs

Advantages

- Like other water impoundments structures, weirs conserve flood flows which would otherwise be causing damage as flood flows.
- Weirs are cheaper and easier to design and construct as compared to earth dams and in certain cases, excavated ponds.
- When properly designed, weir may have fewer failure rates as compared to excavated pans because a weir simply raises the water level in its natural path of flow.
- Weirs can have an effect on ecosystems. They permit recharge of riparian lands and thus revegetation. This may attract animals due to improved habitat, e.g. wildlife, birds, fish and other aquatic animals.
- Weirs improve ground water recharge and the overall hydrology of watershed and can have a major impact on catchment restoration

Limitations

- A weir artificially reduces the velocity upstream of the river and this can lead to increased siltation.
- Weirs can also attract undesirable flora and fauna. Examples include water hyacinth, crocodiles, snails and certain disease vectors since the water is in a pool. It may lead to loss of biodiversity downstream if impoundment is excessive.
- Even though the water around weirs can often appear relatively calm, they can be extremely dangerous places to boat, swim, or wade.
- The weir can become a point where garbage and other debris accumulate. However, a walkway over the weir is likely to be useful for the removal of floating debris trapped by the weir, or for working staunches and sluices on it as the rate of flow changes. This is also sometimes used as a convenient pedestrian crossing point for the river.
- Since a weir typically increases the oxygen content of the water as it passes over the crest, this can have a detrimental effect on the local ecology of a river ecosystem, as increased oxygen affects certain aquatic plants and animals.

3.2 Types of weirs

There are different types of weirs, categorized according to the purpose for which it is made, materials used in construction, and crest characteristics. Some of the more commonly used types of weirs are described here.

3.2.1 Broad-crested weir

A broad-crested weir is a flat-crested structure, with a long crest compared to the flow thickness. When the crest is "broad", the streamlines become parallel to the crest invert and the pressure distribution above the crest is hydrostatic. These types of weirs are made of concrete, masonry or gabions and are overtopped across a crest at least 1 m wide (Figure 3.3). Practical experience has shown that the weir overflow is affected by the upstream flow conditions and the weir. Broad crested weirs are commonly used for water harvesting and as part of a diversion structure.

Figure 3.3 Broad-crested weir with stilling pool and diversion boxes *(photo by B. Mati)*

3.2.2 Sharp crested weir

A sharp-crested weir is designed with a crest that is fitted with metal plates at the crest to give it a sharp edge. This is done so as to allow the water to fall cleanly away from the weir. This in effect reduces the area of contact between water and weir crest thereby improving its efficiency. Sharp crested weirs come in many different shapes such as rectangular, V-notch and Cipolletti weirs. The most commonly used is the V-notch.

3.2.3 V-notch weir

The V-notch weir is a triangular channel section, used to measure small discharges. It is a sharp-crested weir fitted with a simple metal plate in the shape of a "V" cut into it. The upper edge of the section is always above the water level, and so the channel is always triangular simplifying calculation of the cross-sectional area. V-notch weirs are preferred for low discharges as the head above the weir crest is more sensitive to changes in flow compared to rectangular weirs.

3.2.4 Combination weir

The sharp crested weirs can be categorized into three groups according to the geometry of the weir::

a) The rectangular weir,
b) the V-notch or triangular weir, and
c) special notches, such as trapezoidal, circular or parabolic weirs.

For accurate flow measurement over a wider range of flow rates, a combination weir combines a V-notch weir with a rectangular weir.

3.2.5 Check dams

A check dam is really a weir, since it is a small retaining structure designed to reduce flow velocity in a stream or gully (Figure 3.4). Most check dams are used to control soil erosion or for gully rehabilitation. Check dams, like other weirs are designed with a notch at the centre. However, the notch is made relatively large so as to avoid bank erosion, since check dams should be overtopped only through the notch. Check dams may be made of concrete, packed stones, gabions, logs, brushwood or any other material that can help impound water and reduce flow velocity.

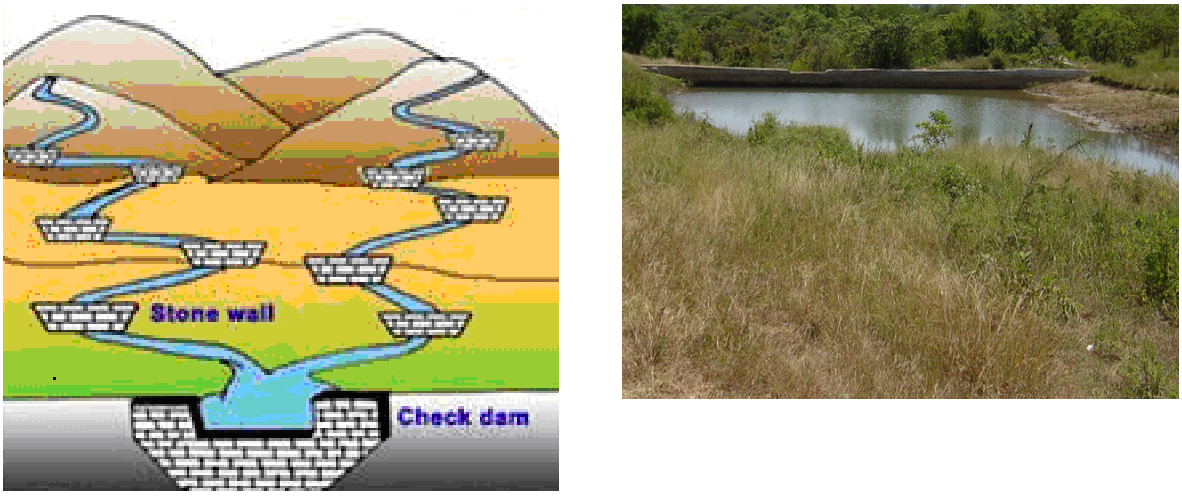


Figure 3.4 (a) Sketch of check dams in a watershed *(Source, L. Rufino, 2009)*

(b) A concrete weir used as a check dam across a valley *(photo by B. Mati)*

Wing dam – is a variation of a check dam, which is a structure that only partly restricts a waterway or gully, thus, creating a faster channel that resists the accumulation of sediments.

3.2.6 Gabion structures

A gabion is a type of check dam made of wire into which small stones are packed to create a kind of retaining wall (Figure 3.5). Normally, the empty gabion box is a cuboid wire netting measuring 1 m in all directions. It is used where stones are easily available to construct check dams. The locally available stones are packed in the steel wire mesh and tied up in form of rectangular blocks. The boxes are arranged across the stream to make it as a small dam by anchoring it to the stream banks. The height of such structures is around 0.5 to 1 m. They are normally used in streams with width of about 10 to 15 m. The excess water overflows the structure storing some water to serve as source of recharge. Gabions are used mostly for soil conservation in gullies or to stabilize slopes during road construction. A gabion structure can also be constructed across a small stream to conserve stream flows with practically no submergence beyond stream course.

Figure 3.5 View of a gabion check dam across a dry valley *(photo by B. Mati)*

3.2.7 Barrages

A barrage dam is a special kind of dam which consists of a line of large gates that can be opened or closed to control the amount of water passing through the dam. The gates are set between flanking piers which are responsible for supporting the water load. They are often used to control and stabilize water flow for irrigation systems. Barrages are particularly useful when used as check dams in ephemeral streams. The gates are opened during the rainy season to prevent excess water from over-flooding the valley, and closed when the floods dissipate to conserve and store water more safely. By opening the gates during periods of flood flows, sediments are removed thus making them self-cleaning weirs (Figure 3.6).

Figure 3.6 (a) Front view of barrage showing reservoir *(photos by Bancy Mati)*

(b) Downstream side of same barrage with a set of self-cleaning spillways

3.3 Design of weirs

3.3.1 Site characteristics

Concrete weirs are constructed across small streams having gentle slope and are feasible both in hard rock as well as alluvial formations. The site selected for concrete weir should have sufficient thickness of permeable bed or weathered formation to facilitate recharge of stored water within short span of time. The water stored in these structures is mostly confined to stream course and the height is normally less than 2 m. These are designed based on stream width and excess water is allowed to flow over the wall (Figure 3.7). In order to avoid scouring from excess run off, water cushions are provided at downstream side. To harness the maximum run off in the stream, series of such concrete weirs can be constructed to have recharge on a regional scale.

Figure 3.7 Weir located below rocky hills for RWH with piped water supplies *(photo by Bancy Mati)*

For selecting a site for concrete weirs the following conditions may be observed.

(i) The total catchment of the stream should normally be between 40 to 100 Hectares though the local situations can be guiding factor in this.

(ii) The soil downstream of the bund should not be prone to water logging and should have PH between 6.5 to 8. This is so as to avoid salinity or sodicity build up.

(iii) The lands downstream of concrete weir should have irrigable agricultural land. This is desirable but not an essential requirement, since a weir can be used for drinking water supplies or to control flooding.

(iv) Weirs should be built at sites that can produce a relatively high depth to surface area so as to minimize evaporation losses.

(v) Rocky surfaces should not be fractured or cracked, which may cause the water to leak away to deeper zones or beneath the dam.

(vi) Dam foundation must be of solid impermeable rock with no soil pockets or fracture lines.

(vii) Weir should be located at a convenient location for water users.

(viii) Catchment area should not have soil erosion. Preferably, catchment should be under natural vegetation, or at least a buffer zone should be created ahead to the weir to protect it from eroded sediments.

(ix) Weirs should be sited directly across the deep gorge of the watercourse to enable flows to pass at the centre of the structure and avoid scouring of the sides.

3.3.2 Determining flow rates over a weir

Weirs offer opportunity to measure the volumetric flow rate in small to medium-sized streams, or in industrial discharge locations. This is because the dimensions and geometry of the top of the weir are known. Since all the water flows over the weir, the depth of water behind the weir can be converted to a rate of flow. The calculation relies on the fact that fluid will pass through the critical depth of the flow regime in the vicinity of the crest of the weir. The discharge equation is simplified as follows:

$$Q = CLH^n$$

Where

Q is flow rate

C is a constant for structure

L is the width of the crest

H is the height of head of water over the crest

n varies with structure (e.g. 3/2 for horizontal weir, 5/2 for v-notch weir)

A weir may be used to maintain the vertical profile of a stream or channel, and is then commonly referred to as a grade stabilizer.

3.3.3 Determining width of weir crest

To determine the crest width for chosen overflow depth for a peak flow discharge, the calculation is based on the greater return period are recommended for larger structures with large, natural or improved catchments. Chosen flow depth should be small enough that impounding structure freeboard is not compromised. The weir formula below is used.

$$W = Q/(1.7 x h^{1.5})$$

where:

w = Width of drop structure cross-section (m)

Q = Design peak flow or crest capacity (m^3s^{-1})

h = Design depth of flow at crest (m)

3.4 Construction of weirs

Construction starts with land clearing and removal of unwanted vegetation, tree stumps and other impediments. Then the foundation is prepared. The foundation for core wall should have a trench dug to at least 0.6m wide in hard rock or 1.2 m in soft rock of impervious nature. The foundation should also extend to the wing walls. A core brick cement wall can be created at least 0.6 m wide to stand at least 2.5 m above stream bed and the remaining portion of trench is back filled on upstream side by impervious clay. The core wall is buttressed on both sides by an embankment made using good quality clays, while on the upstream face, stone pitching is done. Normally the final dimensions of the weir embankment should be around 2 to 3 m in height and width at least 1 to 3 m, generally constructed in a trapezoidal form. If the bedrock is highly fractured, cement grouting is done to make the foundation leak proof.

Auxiliary structures

A weir is normally fitted with auxiliary structures such as wing walls, toe, apron, water delivery infrastructure such as piped or canal outlets, taps, storage tanks, or pumps. The inlet pipes should be set just above the floor of the inlet and on a fall into impounding structure. Inlets should be designed in such a way as to regulate surges of flow from high run-off events that would otherwise damage the water impounding structure.

A trash rack or strainer screen should be installed at water off-take points to remove debris, dirt and other obstructions. The inlet structures can be constructed of concrete, sand bags, gabions or large diameter concrete pipes. Inlet pipes should be PVC and of at least 200 mm nominal bore. More pipes can be added to provide the required volume of flow from the weir. Weirs are preferably used with gravity off-take structures.

Operations and maintenance

The management, operation and maintenance of weirs adopts the same practices as with earth dams and ponds. See Chapters 4 and 5 of this manual for details.

4. SUBSURFACE DAM

4.1 What is sand river storage?

Sand river storage is water harvesting and storage in reservoirs designed to hold both water and coarse sand. The main structure is normally a dam constructed across a sand river. *A sand river*, on the other hand, is an ephemeral river mostly found in arid and semi-arid areas, and which carries short lived but heavy flash floods, laden with sand. The sand deposits originate from the upper catchments. Because the dry river beds are filled with sand, water in these rivers does not flow above the surface, it however flows slowly beneath the surface through the voids between the sand particles.

When river flows contain sand, it has been observed that course sand can produce up to 350 litres of water per meter cube of sand. This represents an extraction rate of 35% of the volume of the sand. The value is however lower in finer sands. Water in sand rivers can be tapped when other sources have dried up. Sand rivers have been used as traditional water sources in arid regions where communities dig holes or shallow wells within the sand bed to obtain water during the dry season. Water level in the sand falls and may dry up during the long dry seasons. Sand river storage is improved by construction of three types of dams;

(i) sand dam built of masonry,

(ii) (ii) subsurface dams built of stone masonry, or

(iii) (iii) subsurface dams built of clay.

This chapter focuses on subsurface dams.

4.2 What is a subsurface dam?

A subsurface dam is a reservoir created when an embankment is constructed across a sand river to restrict surface flow, allowing the water and sand carried by the flood to settle and get stored in the dam (Figure 4.1). However, in a subsurface dam, the embankment wall is below the surface of the stream bed.

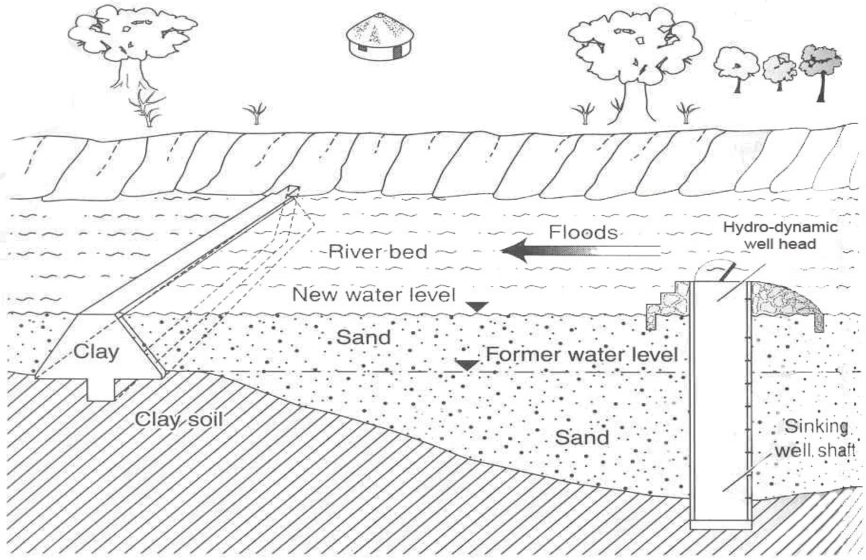


Figure 4.1 Illustrated view of a sub-surface dam and hand dug well built in the deepest part of the river bed *(Adapted from Gould and Peterson, 1999)*

A subsurface dam can be constructed with stone masonry or compacted clay. Subsurface dams may also be located where there is a natural dyke in the riverbed which stores water. Sometimes the structure is integrated with a drift for river crossing purposes, thereby costing much less. The water in the sand dam can be reserved for a long time due to low evaporative losses. Water from sub-surface dams is used for drinking, livestock watering and supplemental irrigation. The top of a sub-surface dam is level with the river bed.

4.3 Advantages and limitations of subsurface dams

Advantages

- Water storage in sand has several advantages, such as:
- Since the water is stored beneath the sand, it is not exposed to losses by evaporation are reduced. Evaporation can be zero when the water level is 60 cm or more below the sand surface.
- The water stored in subsurface dams is good quality for drinking, as it has been filtered by the sand and is stored underground away from contamination.
- Subsurface dams lie beneath the surface and thus cannot be damaged by floods, erosion, undermining or other physical impediments.
- Siltation is not a problem, since there is no retaining structure above the sand surface
- Subsurface dams do not suffer seepage problems (if well designed and constructed)
- Mosquitoes, and insects that carry water-borne diseases, cannot breed in underground water reservoirs. Frogs, snakes and other unpleasant reptiles and animals are also unable to live in, and pollute, water reservoirs in sand.
- Water conflicts are reduced since downstream water sources are not interrupted by a subsurface dam as the floodwater is not blocked.
- Design and construction can make use of local artisans, as it is not complicated
- The retaining wall can be constructed using clay soils found on nearby riverbanks instead of concrete.
- The cost of survey, design and construction is cheaper than for any other type of water supply structures in semi-arid, arid and semi-desert regions.
- During high flow, floodwater can still pass over the dam to reach people living downstream.
- Once built, subsurface dams require little or no maintenance.
- Ground water dams can also be used to green up catchments by utilizing lateral seepage of subsurface storage.

Major limitations

- The main limitation with subsurface dams is that since the water is stored below the ground, thus lifting devices or pumps are needed to extract the water for use.
- It requires a natural dyke which is difficult to get, or the ideal site may be located in a remote area away from water users.
- Site selection requires intensive geological and hydrological investigation.

- Low effectiveness of water storage: In case of a subsurface dam, water is stored in the pores of geological strata. Therefore, the volume of reserved water is determined by the volume of those pores (effective porosity), and reaches only 10 to 30% of the volume of the reservoir layer.
- Interception of downstream groundwater flow: A subsurface dam may prevent downstream groundwater flow, and exhausts groundwater in the downstream area. However, groundwater in the downstream area is not always recharged only with groundwater from the dam site area. It is also possible to design a dam with a structure that allows some of the reserved water to drain. Therefore, this problem can be avoided by appropriate site selection that considers the mechanism of groundwater flow.

4.4 Design of subsurface dams

4.4.1 Determining the storage capacity

The volume of water that can be extracted from a correctly constructed sand/subsurface dam depends on the coarseness and volume of sand that is contained in the dam. The maximum volume of extractable water is equivalent to 35% of the total volume of the sand. The volume of sand in a sand dam can be estimated using the following formula:

$$\mathbf{Q = \underline{L\ x\ T\ x\ D}}$$

Where
Q is the sand storage capacity, or volume, in cubic metres,
L is the length of the dam wall in metres at full sand level,
D is the maximum depth in metres, and
T is the throwback (maximum length of water surface) in metres.

Sand porosity

Clean coarse sand is best for a subsurface dam. The sand may be tested for porosity quite simply in the field. This is done by saturating 20 litres of sand with a measured volume of water. The water is then drained out of the container and measured by removing a plug from the bottom of the container. Typical porosities of sand are given in Table 4.1.

Table 4.1: Porosity and extractable volume of water from sand dams

	Silt	Fine Sand	Medium Sand	Coarse Sand	Fine Gravel	Coarse Gravel
Diameter *of Particles (mm)*	<0.5	0.5-1.0	1.0 -1.5	1.5 -5.0	5.0 -19.0	19.0 -70.0
Volume of Sand (litres)	20.0	20.0	20.0	20.0	20.0	20.0
Porosity (litres)	1.52	1.58	1.63	1.80	1.87	2.05
Porosity (%)	38%	40%	41%	45%	47%	51%
Extracted water (lt)	0.90	3.75	5.00	7.00	8.25	10.00
Extracted water (%)	5%	19%	25%	35%	41%	50%

(Adapted from Nissen Peterssen 2000)

4.4.2 Site selection

A subsurface dam should, preferably, be constructed on an underground dyke. A dyke is a layer of hard rock that is sticking up underground and naturally stopping the underground water from flowing. The correct siting of both types of dam is important for minimizing the construction work and maximizing the storage capacity of sand rivers. Potential dam sites should be:

- Locations on ephemeral (seasonal) sand river (dry river bed) which is periodically flooded during a normal season
- River beds comprising coarse sand, as this has large voids for maximum storage of water – the finer the sand the less water it can store.
- Sites free of boulders, fractured or saline rocks. If calcrete deposits are situated in or upstream of a reservoir, its water will be saline or brackish
- Locations where existing water holes remain for at least a month after the rains.
- Whenever possible, it is desirable to build the dam wall at the narrowest point where basement rock with low permeability makes a gorge with a vast aquifer upstream, as in the case of a surface dam.
- Coarse sand can store more water than fine-grained sand, thus riverbeds containing coarse sand are therefore preferable.
- Subsurface dams should not be located where waste from villages and other places can contaminate the riverbed
- The reservoir of subsurface dams should not contain salty soil or salty rocks, because that will make the water salty
- For soil conservation purposes, the dam should be built as close as possible to the head of the stream as this is where the water begins to erode the soil
- For water supply augmentation and soil conservation purposes, it might be better to build a series of small dams along the same stream, rather than building one large dam. A sequence of small dams increases deposition of silt in the water and improves infiltration more than a single large dam

Site survey

Site survey for ground water dams should preferably be carried out towards the end of a dry season when the water level is at the lowest in sand-rivers. Sand-rivers, which dry up rapidly after rains, indicate the non-existence of natural dykes suitable for underground reservoirs. Subsurface dams and even sand-storage dams can be built on such rivers beds with no underground dykes. However, a more cautious approach in conjunction with thorough and careful investigations is required since water-tightness of such a river-bed is uncertain. To avoid costly failures and disappointment of the communities who contribute free labour and local construction materials, it must be verified in advance whether the river-bed can actually hold water. The clay is also tested for permeability in a similar way using transparent plastic bottles.

4.4.3 Locating a natural dyke for subsurface dam

Underground dykes are easiest to locate a couple of months after flooding by looking for places with natural waterholes because there is always one or several dykes downstream, holding the water at that place. Dry, stunted vegetation on riverbanks with tall evergreen trees upstream may be another indicator. This is because water for the green trees is trapped above the dry area.
A natural dyke can be located through other means, such as:

- Digging trial pits
- Probing with an iron rod hammered into the sand
- Dowsing with two rods made from a brazing rod cut in two halves. By starting the subsurface dam with a natural rock dyke, it gets a solid impermeable base on which to build. Subsurface dams can be constructed in riverbeds with no dykes, but they might produce less water.

<u>Probing for underground dykes and reservoirs</u>

Probing of a river-bed is aimed at:

(a) finding underground dykes which can be used as foundations of dams,
(b) locating the deepest part of a reservoir to build a hand-dug well, (
c) estimating the volume of water in underground reservoirs, and (d) designing the dam wall.

Probing is done by hammering a Probing Rod, made of a 2.1 m. long ¾ Q-iron rod, down into the sand in a river-bed. The rod has small notches cut alternately on its sides at every10 cm for bringing up samples of sand and clay (Figure 4.2). Probing should begin at the water-hole yielding most water or presenting water for the longest period among all others, because that water-hole is most likely to be an indicator of the deepest section of the reservoir.

	
Figure 4.2 (a) Probing to identify natural dyke in sand river *(photos by Erik Peterssen)*	**(b) Assessing the water-retention properties of various clays for dam embankment**

When probing at a point is finished and all the observations have been noted down, the probing is given a temporary number: No. 1 for the first section probed. Probing will continue downstream at intervals of 20 m in the middle of the river-bed. The underground dyke, which dams up water for the water-holes, can be found somewhere downstream in the form of clay or a rock barrier protruding upwards from the floor of the river-bed. The highest point of the underground dyke can be discovered by probing a few feet downstream and upstream, as well as across the river-bed, on the dyke. The highest point of the underground dyke is where a ground water dam can be built with a minimum of materials and labour.

4.4.4 Construction of subsurface dam

Whenever possible, subsurface dams should be built of clay because it has proven more appropriate and less expensive than other advanced methods of investigations. Construction can be mechanized but is easily done using manual labour. A foundation is excavated across the sand river. The foundation should go down to the impervious layer below the sand (Figure 4.3). Therefore, where deep sand can be found, it is cost-effective to consider the possibility of subsurface sand dams for the storage of the harvested water. The clay is added at optimum moisture content and compacted either manually or using a compactor.

Figure 4.3(a) Foundation for a subsurface dam
(Source: VSF-DZG, 2006)

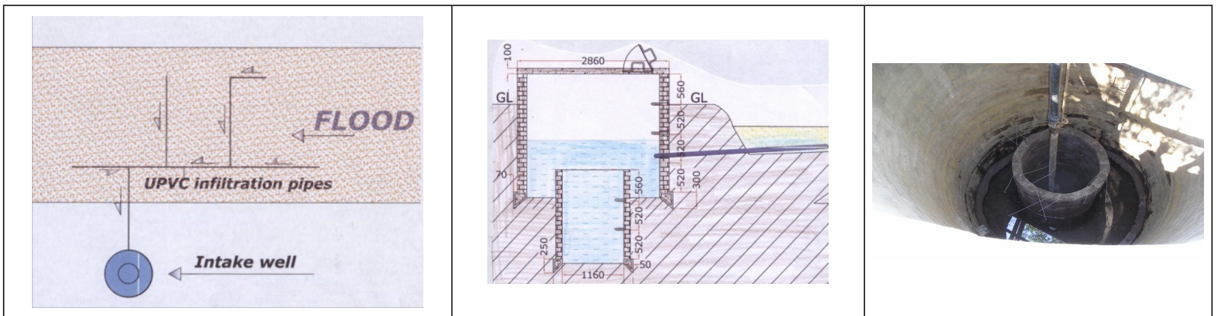
(b) Subsurface dam just after construction

(source: Erik Nissen-Peterssen, 2006)

4.5 Water extraction

Water is extracted from a sub-surface dam in two ways; either by a hand dug well sunk in the deepest part of the sand reservoirs, or water can be drawn from a river intake built as a hand dug well in a river bank near the deepest part of a sand reservoir. The well is excavated at the deepest part of the sand on the upstream side of the dam. The wells are fitted with hand pumps capable of withstanding. Alternatively, water can be drawn from a river intake built as a hand dug well in a river bank near the deepest part of the sand reservoir.

A perforated PVC pipe drains water from the sand to the intake. Water can also be gravitated downstream through GI pipe passing through the foundation of the dam. This needs a filter to keep sand out of the end of the pipe upstream. At the downstream side an underground tap stand can be constructed.



(a) Infiltration galleries within subsurface dam

(b) Inlet pipe from subsurface dam to well

(c) Shallow well details as water off-take point

Figure 4.4 Arrangement of water draw-off from a subsurface dam
(source Erik Nissen Peterssen, 2006)

4.6 Management and Maintenance

The quality of water in groundwater dams is generally better than water from other water harvesting systems since water here is stored in the ground and filtered as it moves through the sandy soil. However, the shallow subsurface risks contamination from seepage of surface pollutants. Once the clay wall subsurface dam is built, it demands very little maintenance. However, the user community should check the dam site for erosion after each large flood. Any erosion should be corrected by refinishing the clay wall and protecting it with large rocks, which cannot be moved by smaller flows.

With masonry subsurface dams, any channel erosion that might undermine or expose the dam should be arrested by filling it with large boulders and using silting traps to catch sandy material. It is a similar prescription for raised dams. Also with subsurface dams, there may be a need to control water use, thus requiring supervision, clear agreements among the users and monitoring of the available storage. For the latter, a piezometer (Figure 4.5) may be installed, which allows a caretaker or watchman to estimate how much water is left and if rationing has to be made stricter.

Figure 4.5 Piezometer within sand storage dam *(source Alemu Seifu, 2011)*

Hygiene and safety

The precautions to manage and maintain water quality and reliability in sub-surface and sand dams and to reduce the risk of contamination are:

- Ensure there is no open defecation in/ near the river bed upstream
- No tethering of donkeys at the well
- Check bathing/ laundry upstream of the dam
- There must be no pit-latrines on the bank upstream
- There must be no unprotected wells in the river bed near the protected well
- Regular maintenance of the protected well-site and the hand pump must be assured
- Ensure use and maintenance of a downstream gravity out-take
- Avoid use of pesticides/ chemicals upstream of the dam site.

5. SAND DAMS

5.1 What is a sand dam?

A sand dam is a reservoir created when a short wall is constructed across the sand river to restrict surface flow, allowing the water and sand carried by the flood to settle and get stored in the dam. Sand dams are similar to sub-surface dams except that the top of the dam wall exceeds the level of the sandy riverbed. This helps in trapping or retaining more sand thus providing more storage capacity. Sand dams require high banks on both side of the river because they raise both the sand and the water level. This therefore calls for an appropriate site selection. Sand dams are built of masonry or concrete to withstand floods above the sand bed. Because the water is stored under the sand it is protected from significant evaporation losses and is also less liable to be contaminated. Water from sand dams is used for livestock watering and can also be used for supplemental irrigation of crops.

Figure 5.1 (a) Sketch of a longitudinal section of a sand dam

(b) **A sand dam showing apron**

(source Alemu Seifu, 2011)

5.2 Advantages and limitations of sand dams

The same advantages and disadvantages apply for sand dams just like subsurface dams (see Chapter 4). However, sand dams differ in that since the reservoir can be above ground, the water can be delivered by gravity to lower areas through a pipe. However, unlike subsurface dams, sand dams are susceptible to flood risks and siltation. Another deviation is that sand dams are usually constructed using stone masonry or concrete and rarely is clay used. This is because the structure is exposed and could erode soil materials that were used in the embankment.

5.3 Design of sand dam

The design of the retaining wall of a sand dam is just like that of an ordinary weir (see Chapter 4). The design of the reservoir characteristics is as discussed for subsurface dams (see Chapter 5). Like with weirs, sand dams have a spillway at the centre of the embankment.

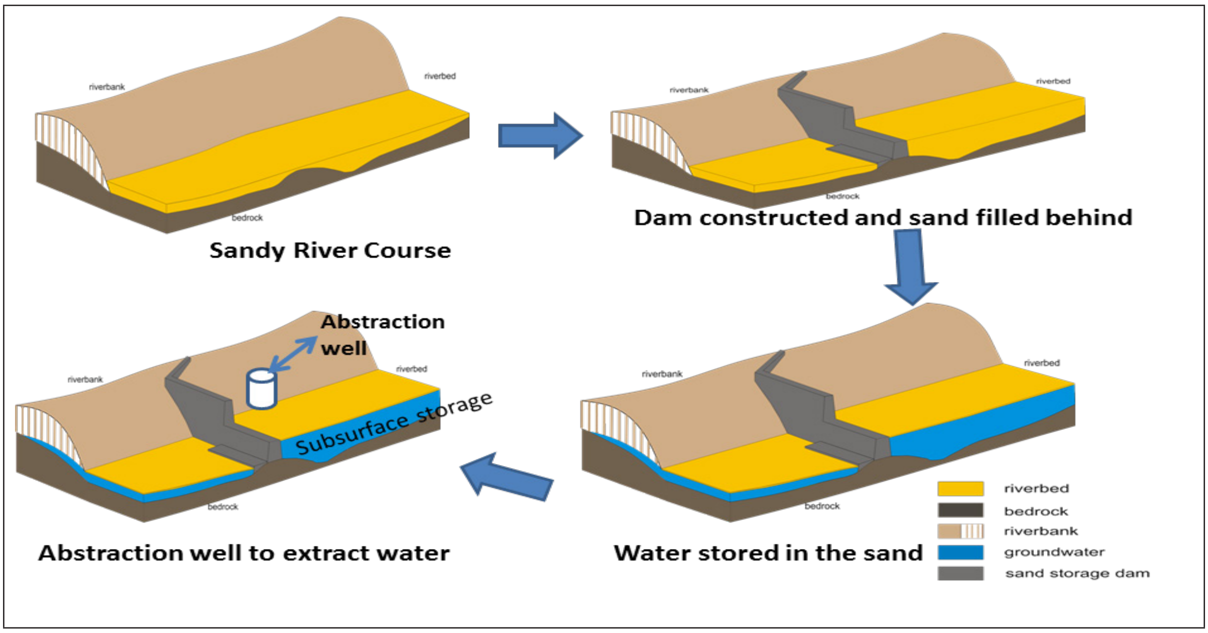


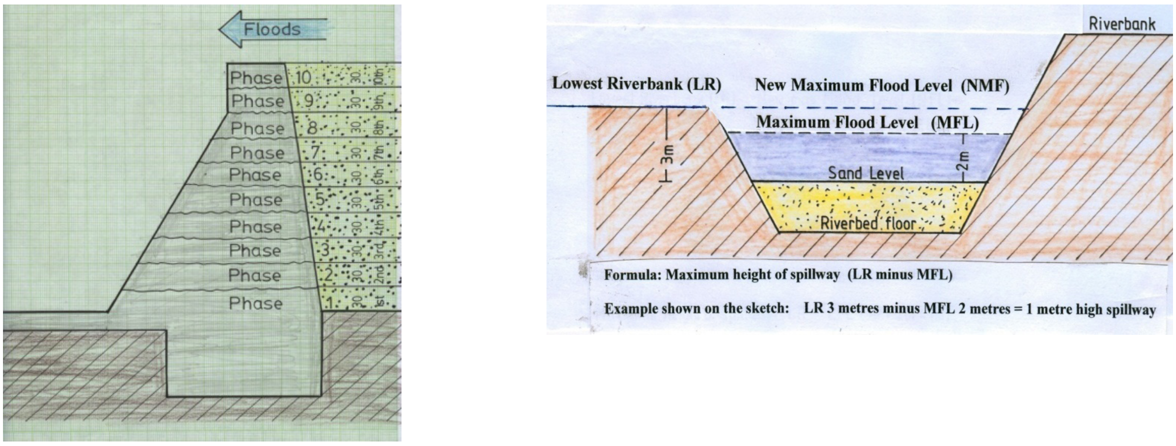
Figure 5.2 Illustration of the functions of a sand dam (adapted from Seifu, 2011)

Site identification

A sand dam should be located in a section of the stream which a straight reach with narrow width (less than 25m). The slope of the river bed should be gentle and not exceeding 5%. There should be no big boulders on the bed of the river rather coarse sand with no silt. The banks of the river should be stable and high enough river banks. The catchment should be free from contamination and salinity. It is preferable if local construction materials are available and accessible to majority of the beneficiaries.

Spillway

Sand dams have spillways, which are designed on the same principles as for concrete weirs (see Chapter 6). However, the recommended maximum height of the spillway can be calculated by deducting the Maximum Flood Level (MFL) from the height of the Lowest Riverbank (LR). The width of the spillway should be equal to the width of the surface of sand in a riverbed. The Maximum Flood Level (MFL) can be found by interviewing long time residents of the area and/or by estimation using visible indicators, such as debris in the river banks.



Formula: Maximum height of spillway (LR minus MFL)

Example shown on the sketch: LR 3 metres minus MFL 2 metres = 1 metre high spillway

Figure 5.3 (a)Longitudinal view of a sand dam *(source; Nissen Peterssen, 2006)*

(b) **Cross-sectional view of a sand dam**

5.4 Construction

Sand dams are built of rubble-stone masonry or concrete from a key trench and foundation dug into a river bed floor of soil, murram or bedrock without fissures beneath the sand. The dam wall protrudes above the sand level in riverbeds and, therefore, must have a wide foundation and wing walls built into the riverbanks to withstand the force of flash floods.

A sand storage dam is generally constructed in stages for several years (Figure 5.4), and the dam wall is increased by 0.3 m after floods have deposited sand to the level of the spillway. The basic idea is to limit the height of each stage in order to wash out the fine particle from the reservoir while allowing course particle to settle.

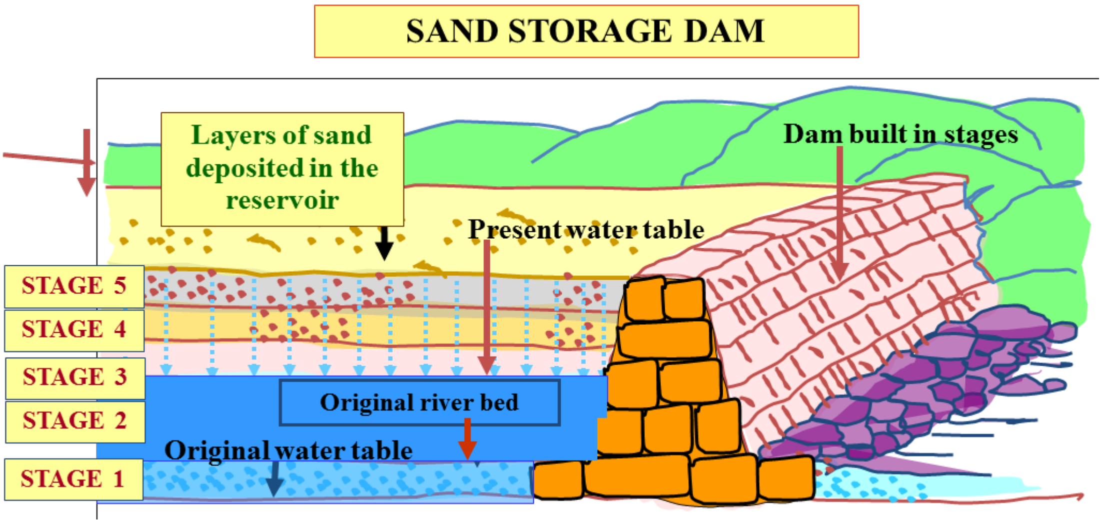


Figure 5.4 Illustration of construction of sand dam in stages *(Source: Agarwal and Narain, 1997)*

The foundation should go down to the impervious layer below the sand. This allows sand to be trapped upstream of the dam wall increasing the overall storage capacity of the riverbed. The construction of river intakes and hand-dug wells with hand pumps in the river bank can further help to improve water quality.

Sand dams may be built several metres high during rainy seasons, thus enlarging the sand and water storage to many thousands of cubic metres. The dams require high banks on each site of the sand-river because they will raise the sand and water level. Sand dams also require catchment areas that produce coarse sand from eroding rocks and heavy flash floods capable of transporting many tones of sand to the dam reservoir.

Figure 5.5 (a) Sand dam under construction *(photos by Bancy Mati)* (b) **Sand dam with gravity outlet to storage tank**

Management and maintenance

Same as for subsurface dams and weirs. See Chapters 4 and 5.

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