SUB-SURFACE FLOW DAMS FOR RURAL WATER SUPPLY IN ARID AND SEMI-ARID REGIONS OF DEVELOPING COUNTRIES

By

GEZAHEGNE, WOLDE

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ABSTRACT

The problem in arid and semi-arid regions of developing countries with irregular rainfall is storing water during a rainy season in order to preserve it for the dry one. An interesting and useful technique to solve the problem is to store water in sub-surface flow dams.

Two types of sub-surface flow dams are defined, namely sub-surface dams and sand-storage dams. The former is constructed below ground level and it arrests the flow in a natural aquifer, whereas the latter is raised above ground level and it impounds water in sediments accumulated by the dam itself.

Climatic conditions of low rainfall, high evaporation, topography and hydrogeology are the main factors which influence planning and construction of sub-surface flow dams. It is necessary to make good investigations of new dam sites as regards these factors, for the success of the dam.

Topographical and geological maps are appropriate instruments for regional investigations. The best instrument for finding actual sub-surface flow dam sites is air photo interpretation combined with map studies and field reconnaissance. It is important to incorporate data from studies carried out previously.

Bedrock foundation, water storage capacity, water discharge, recharge, specific yield and dimensioning of the dam are important factors to be considered when designing sub-surface flow dam schemes.

The most common types of sub-surface dams are clay, stone masonry and concrete walls. Sand-storage dams are usually constructed by concrete and stone masonry. Water is extracted mostly by hand pumps from large diameter wells, or when topography permits, by gravity.

Operation and maintenance requirements of sub-surface flow dam schemes are less than that of boreholes and conventional open storage dams, provided water is supplied by hand-pumps or by gravity.

1. INTRODUCTION

Many developing countries are located in the climatic regions where rainfall is seasonal and erratic. The supply of water in such regions is to a large extent a matter of storing water from the rainy season to be used during the dry one. Using ground water is one way of overcoming the problem, but in some areas good aquifers are not available, even if they are, their yield may not be adequate for the whole season. Experience has shown that conventional development of ground water in developing countries involves various problems related to operation and maintenance, especially with drilling equipment and pumps.

The technical solution most commonly applied to solve the storage problem is surface reservoirs created by means of dams. But, high construction cost of dams, evaporation losses, pollution risks, siltation and occupation of valuable land by water make this alternative less applicable.

Building sub-surface flow dams can be a good alternative. The most common reason for damming sub-surface flow is to store water below ground level in the reservoir upstream of the dam. A sub-surface flow dam may raise the ground water level and thereby improve the recharge to the adjacent aquifers. It can protect aquifers from pollution, and sub-surface works from unwanted ground water seepage.

There are two types of sub-surface flow dams, namely sub-surface dams and sand-storage dams. The former is built entirely below ground level and it arrests the flow in a natural aquifer, whereas the latter is raised above ground level and it impounds water in sediments accumulated by the dam itself.

Principle of sub-surface dam

An aquifer consisting of fairly permeable alluvial sediments in a small valley supplies water to a village by means of a shallow well. Due to consumption and the natural ground water flow, the aquifer is drained during the dry season and consequently the well dries. To prevent this, a trench is dug across the valley, reaching down to bedrock or any other solid, impervious layer. An impervious wall is constructed in the trench and when the dam is completed the trench is refilled with the excavated material (Fig 1.).

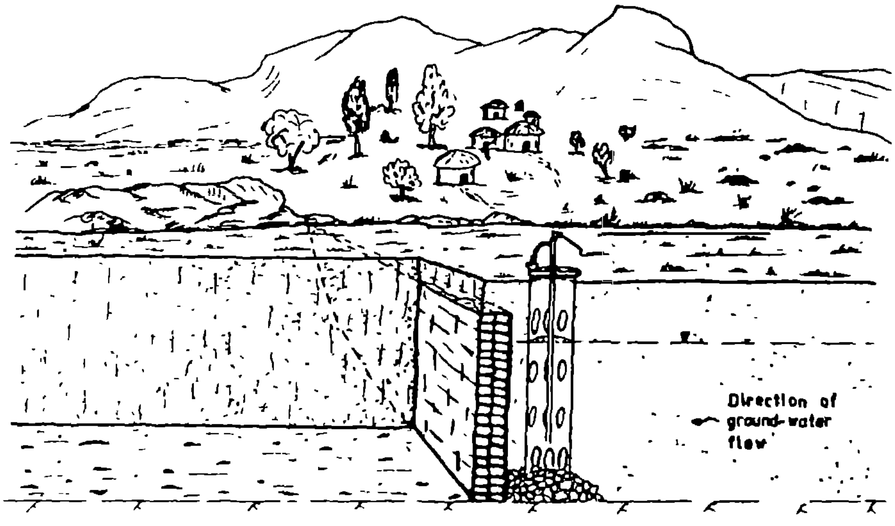

Figure 1. Principle of sub-surface dam (Hansson and Nilsson 1984).

A reservoir built in this way will not be drained and may be used throughout the dry season, provided that the storage volume is sufficient to meet the water demand.

Principle of sand-storage dam

The villagers collect water, from the small non-perennial streams at times when it carries water, or from holes dug in the shallow river bed for a short period after the rains. The quantity of water stored is not sufficient to supply water to the village during the entire dry period. By constructing a weir of suitable height across the stream bed, coarse particles carried by heavy flows during the rains are caused to settle, and eventually the reservoir will be filled with sand (Fig 2.).

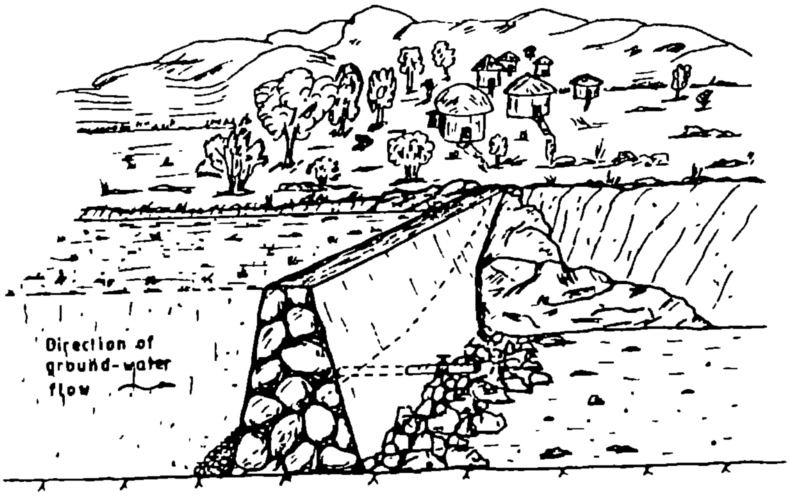

Figure 2. Principle of sand-storage dam (Hansson and Nilsson 1984).

This artificial aquifer will be replenished each year by the infiltrated run-off during the rains. If the dam is properly sited and constructed, water will be kept in the reservoir to be used during the dry season.

Damming sub-surface flow (ground water) for conservation purposes is certainly not a new concept. Sub-surface flow dams were constructed on the islands of Sardinia during ancient Roman kingdom. They were also known by old civilizations in North Africa (Nilsson 1984). More recently, various small scale damming techniques have been developed and applied in many parts of the world, notably in India as well as South and East Africa.

The purpose of this paper is to consider the construction of sub-surface flow dams as an alternative technical solution to water storage problem during the rainy season in order to preserve it for the dry one, in arid and semi-arid regions of developing countries.

2. FACTORS INFLUENCING PLANNING AND CONSTRUCTION OF SUB-SURFACE FLOW DAMS

2.1 Climate

Rainfall variability is a major constraint to human life in arid and semi-arid areas. The variations can be seasonal as well as interannual. Thus, every drop of water in these areas is valuable and has to be saved. Most of these areas are under dry monsoon and tropical dry climate.

In monsoon-climate areas the total amount of rainfall would generally be sufficient for the needs of people and agriculture, but during some parts of the year water is not available. Damming ground water is thus a means of bridging over the seasonal dry periods. It may also be possible to construct the dam in such climatic regions where water is available throughout the year, to increase the quantity or raise the ground water level in the aquifer.

The arid areas of the world are by Köppen's definition (cited by Nilsson 1984), those where the potential evaporation is larger than rainfall. The advantage of damming ground water as compared to common surface storage depends to a large extent on the losses from open-surface evaporation. Table 1 presents some values of potential evaporation from areas where sub-surface flow dams have been constructed or proposed.

Table 1. Rainfall and potential evaporation data from some dry areas (Nilsson 1984).

Area	Average rainfall mm/a	Potential evap. mm/a
Bartlett, Arizona	350	3090
Biskra, Algeria	130	1330
Lushferrandi, Somalia	360	2060
Machakos, Kenya	850	1600-1800
North Turkand, Kenya	200-600	>2500
Tarfaya, Morocco	110	850

The values vary from 1 to 3 m/a, and even if the reliability of some of these values may be questioned it is evident that evaporation losses from open water surfaces are considerable. The loss of say 3 m from a reservoir may represent quite a large portion of its total capacity.

Hellwig (1973) has studied quantitatively the evaporation of water from sand during experiments at Swakop River in Namibia. The evaporation from a saturated sand surface was found to be approximately 8 percent less than from an open water surface. The lowering of the water table by 0,3 m below the sand surface reduced the evaporation from a fine sand to 50 per cent of that from an open water surface. The evaporation loss when keeping the water level at 0,6 m below the sand surface in medium sand was 10 percent (Hellwig 1973). The relation between evaporation and depth of water table is shown in Fig 4.

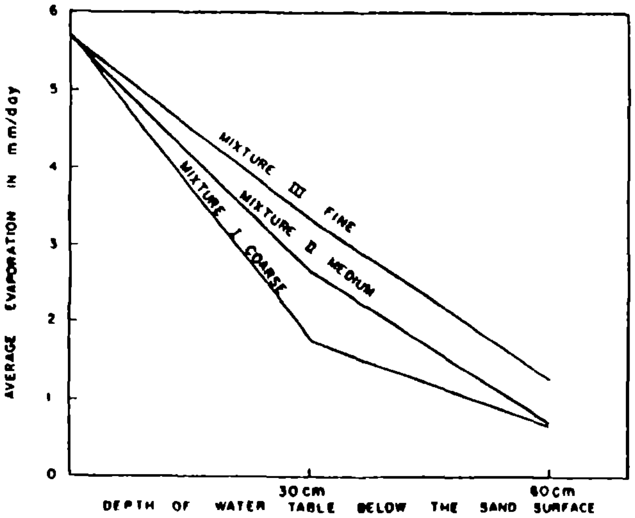

Figure 4. Evaporation as a function of depth to water table (Hellwig 1973).

The sorting of the material has a large influence on the extent of evaporation losses. It was found that a reduction of particles of less than 0,1 mm diameter from 9 percent to 0,7 percent in a layer of medium sand, reduced evaporation by 25 percent at the depth of 0,3 m. Therefore it is important that the accumulation of fine particles at shallow depths in sand-storage dams is avoided. Figure 5 shows evaporation as a function of particle size.

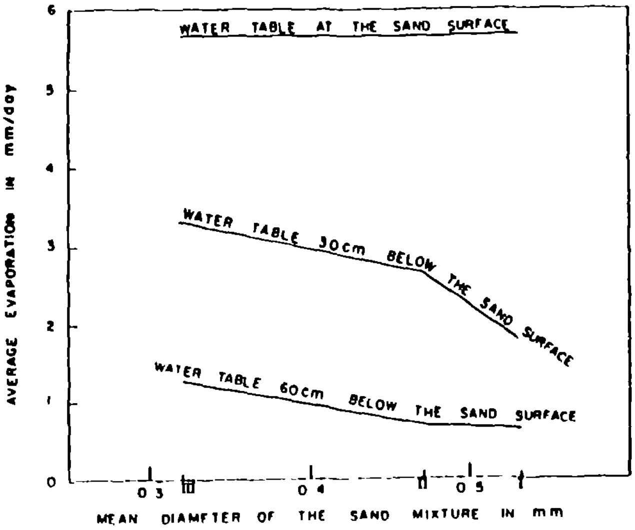

Figure 5. Evaporation as a function of grain size (Hellwig 1973).

Evaporation from the saturated sand body will result in precipitation of salts as well as concentration of the soluble salts in the water. The resulting deterioration of water quality is particularly noticeable in dams which are not fully utilized and where the water table remains at or near the surface. Water table control through strategically placed drains will generally solve this problem.

2.2 Topography

The topographical conditions govern to a large extent the technical possibilities of constructing the dams as well as achieving sufficiently large reservoirs with suitable recharge conditions and low seepage losses.

It is preferable to site sub-surface flow dams in well-defined narrow valleys or river beds and on tight bedrock foundation. This reduces costs as well as makes it possible to asses storage volumes and to control possible seepage losses. Storage volumes have to be maximized keeping the dam height as small as possible.

The slope of the ground water table and the extent of flow is generally a function of the topographical gradient. This fact indicates that the construction of sub-surface flow dams is feasible only at a certain minimum topographical gradient, which naturally varies according to local hydrogeological conditions.

Generally the gradient is from 1,5 to 4 percent, obtained from previously constructed sub-surface flow dams. For example, in Bihawana, Tanzania the gradient was 1,5 percent. In Ananganadi and Ottapalm, India the gradients were 3 and 4 percent respectively and Machakos (sand storage dam) Kenya it was 3 to 4 percent. In extreme cases sand storage dams have been constructed in gulleys of 10-15 percent slope like in Machakos, Kenya and Namibia (Nilsson 1984). The particle size of sediments accumulated along streams and in river beds is proportional to the topographical gradient, whereas the depth and the lateral extent of such deposits are inversely proportional to the gradient. The optimum relation between these two factors, and thus the most favourable sites for sub-surface flow dams, is found on the gentle slopes in the transition zone between hills and plains.

2.3 Hydrogeology

The most favourable type of aquifer for sub-surface flow dams is definitely surfacial river bed made up by sand and gravel. In-situ weathered layers, and deeper alluvial aquifers have also been dammed with success, although, such aquifers generally have smaller storage capacity and flow. Permeability values, however, are much more sensitive to the type of material constituting the aquifer.

The permeability of coarse sand, for instance, may be hundred times higher than that of a very fine sand and the presence of clay in a sand aquifer may reduce its permeability thousandfold (Bendinger 1961).

Difficulties which could be encountered when a sub-surface flow dam is constructed in an aquifer with fine-grained material are water extraction possibilities and available storage volumes, due to low permeability of the material. By construction of large diameter wells or collection chamber it can be possible to create a sufficient storage volume.

One good example of this is the sub-surface dam constructed at Gursum, in Hararghe Region, Ethiopia. The parent material at the dam site is silt and clay, with low permeability. A large excavation was made, and a resevoir of 200 m^3 was created and covered with concrete slab. The flow of ground water was blocked by the dam made of stone masonry plastered with cement. The system serves about 5000 people, augmented with some spring connection up stream of the dam, using perforated PVC pipes laid in a trench with a graded filter.

Matsuo (1977) has recommended a method of increasing the permeability and storage volume of sub-surface dams. It is the application of water jetting to ground up stream of the dam in order to remove fine particles (Fig. 6). However, the method is not economically feasible for rural water supply in developing countries.

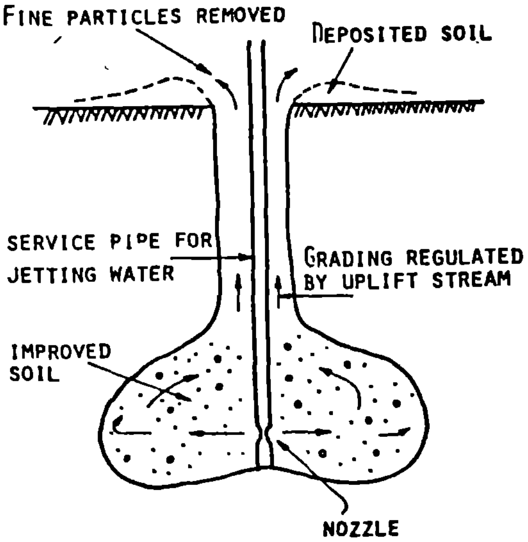

Fig 6. A scheme of soil improved by water jetting (Matsuo 1977).

Larsson and Cenderwall(1980) have proposed the construction of sub-surface dams in fractured hard-rock aquifers. Such dams would consist of grout curtains cutting off the flow in deep, permeable fracture zones, so that storage in over-lying aquifer is improved. The method is more suitable for large-scale application than for the small-scale rural water supply in developing countries. However, it can be used where needed.

Sub-surface dams are, mainly for reasons of the excavation techniques, suited for shallow aquifers. For example, the maximum depth of two dams constructed in residual soils in South India are four and nine meters (Nilsson 1984). The depth of sub-surface dams built in river beds is usually about three to six meters. Shallow aquifers that are commonly dammed by sub-surface dams are unconfined ones. Matsuo (1977), however, reports of a sub-surface dam on the Island of Kaba in Western Japan, which actually dams a confined aquifer at 10-25 m depth. Damming at this depth was possible by using injection of bentonite to create a curtain wall in the gravel aquifer. Recharge to the aquifer was increased by an extensive system of sand piles penetrating the confining layer (Fig 9.). Figure 7 a, b and c shows the site, geologic section, plan and vertical section of the sub-surface dam.

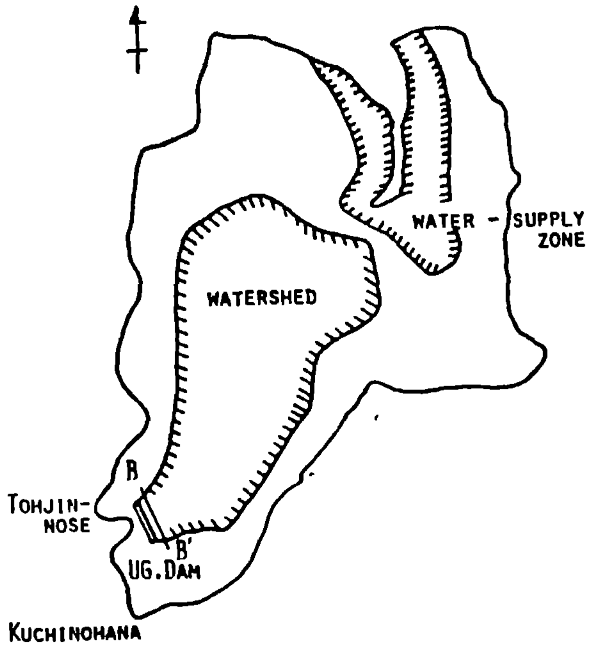

Figure 7. (a). Sub-surface dam site with influencing regions in Kaba Island (Matsuo 1977).

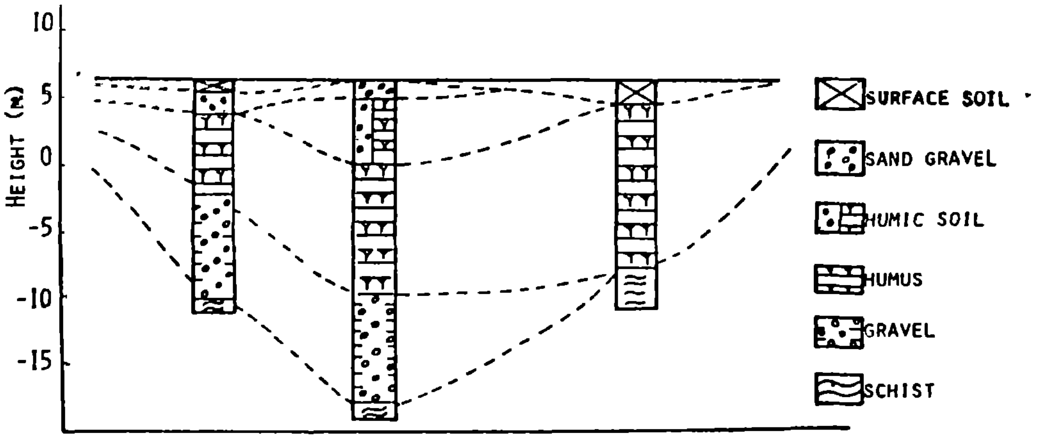

Figure 7. (b). The Geologic section (Matsuo 1977).

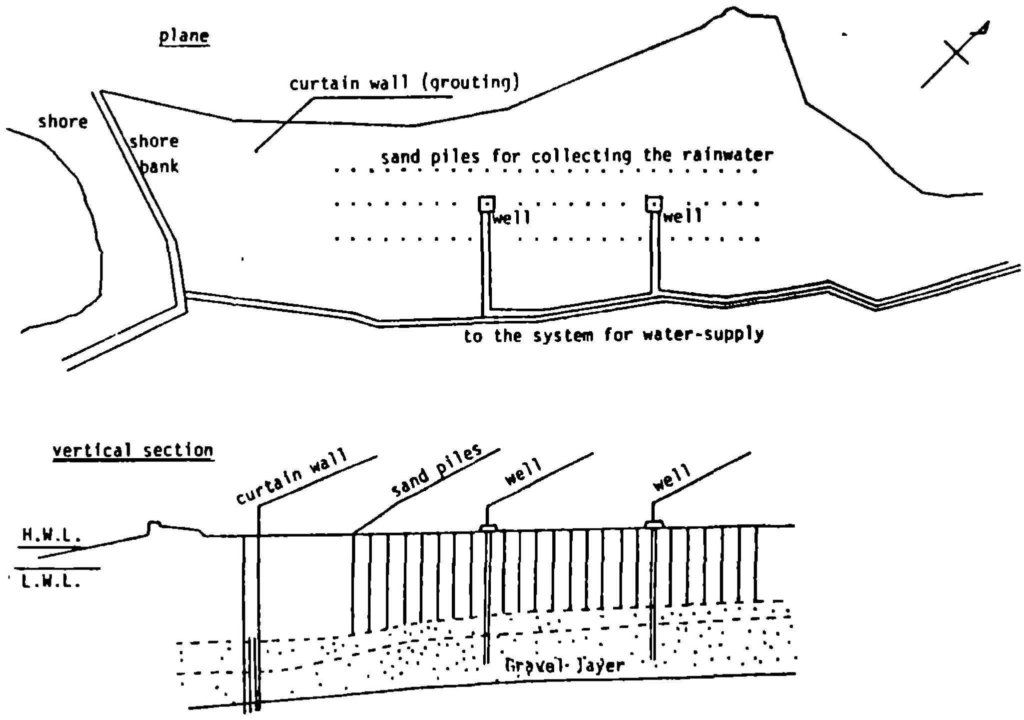

Figure 7. (c). Construction site plan and vertical section (Matsuo 1977).

By damming a deep, confined aquifer it may be possible to control large quantities of water with a relatively small dam area, but the hydrological conditions must be well known through advanced technique including geophysical investigations. In developing countries the system necessitates expensive technique which might not be appropriate. For large scale projects, where it is possible to accept high construction costs, it has certainly a high potential.

The basic idea behind constructing a sub-surface dam for storage purpose is to arrest the natural flow of ground water. Before the construction of the dam is commenced it is important to estimate the extent of flow. Permeability and ground water table fluctuations are the two most important factors to be considered to estimate the flow of the aquifer. This can be done by conducting a permeability test and a monitoring programme involving a few observation wells in the aquifer.

Most sub-surface flow dams should be founded on solid bed-rock, in order to avoid seepage losses below the dam. Under favourable conditions it may be possible to utilize an existing clay or other impermeable layer as the bottom of storage reservoir, even though it is not as effective as bedrock to stop seepage losses. Such layers are excellent, where the construction of sub-surface dams is considered for aquifer recharge purposes.

2.4 Sediments

Deposition character of sediment influences construction of sub-surface flow dams in river beds. Sediments are originated from type of parent rock material in the catchment through series of natural physical processes, weathering and erosion. Weathering processes disintegrate the rock, and soil particles are detached by erosion, transported and finally deposited in the storage reservoir.

Coarse particles of sand and gravel particles are required in the storage reservoir. The amount of coarse particles in the total sediment load is obtained from the type of parent rock in the catchment. The most favourable rocks are coarse granite, quartzite and sand stone, but also dams constructed in gneiss and mica-schist areas have been successful (Wipplinger 1958). Sediments originating from mica-schist areas tend to be more fine grained than those from, for instance, quartzite, but the irregular shape increases porosity (Wipplinger 1958). Areas underlain by rocks such as basalts and rhyolite tend to be less favourable (Wipplinger 1958).

Climate has a great influence on sediment characteristics which governs the relation between mechanical and chemical weathering. A lower rate of chemical weathering in arid climates may involve more coarse-grained sediments (Sundborg 1982). The total extent of erosion is largely dependant on rainfall intensity, slope and land use. The engineer planning the construction of sub-surface flow dam in river beds would be happy to find steep slopes with little vegetative cover in the catchment area. One should not be immediately discouraged if there are no sand deposits along the river, when surveying an area to find suitable site for sand-storage dams. This might be the result of a high-intensity rainfall pattern causing such heavy flows that deposition is not possible under natural conditions. Sand-storage dams constructed in Kerala, India are a good example of this (Nilsson 1985).

Data concerning sediment character of the area can be obtained from an authority in charge of doing soil conservation activities and construction of large dams. Erosion and sedimentation processes in dry climate areas of the world have been studied extensively, mainly in connection with soil conservation activities and the construction of large dams. However, the research has been focused on the total rates of erosion in the catchments and on the total rates of sediment deposition in the dams. These findings are not directly applicable to this study because sand storage dams utilize only a fraction of the total sediment load.

The planning engineer should be able to estimate the portion of sediment deposit, which can be used as a storage reservoir. If the engineer is in doubt, it is better to take soil samples and make sieve analysis of the sample. In case no sediment is deposited and large-scale project is going to be planned it is advisable to conduct pilot scale research work before big scale construction is commenced.

3. INVESTIGATION METHODS

Since the construction of sub-surface flow dams is a rather straight-forward affair and inexpensive, no technical investigations have been made as regards geology and hydrogeology. As a result, there are unfortunately many examples of sub-surface flow dams which have not been successful due to lack of good investigations. This may have been caused by unforeseen seepage losses through underlying fracture zones, erosion damages due to improper bed rock foundation etc.

One example is the first sand-storage dam constructed under research programme, at Gende-Balina in Hararghe Region, Ethiopia. The dam was constructed in 1983, but has not come into operation at the time of reporting this study, due to unforeseen seepage losses. This is because no geological investigations were made to identify underlying fracture zones and bedrock foundations. Therefore, proper investigation is important for the success of the dam.

3.1 Collection of existing data

When preliminary investigations are to be carried out on a certain area, existence of relevant data both published and unpublished from various sources must be checked. Such data may include the following:

- Existing geological, hydrogeological, hydrological and geophysical reports and papers.

- Existing topographical and geological maps, and aerial photographs.

- Information about existing boreholes and wells including location, height above sea level, depth and yield.

- Hydrological and geological data from existing underground and open pit mining within the area, if available.

- Meteorological data.

The information compiled from such existing data is analysed and used by the planning engineer in selecting sites.

3.2 Use of Maps and Aerial Photographs

3.2.1 Use of maps

Maps of various themes and geological are appropriate instruments for the regional studies of construction of sub-surface flow dams. Topographical and geological maps are used to evaluate important features related to the location of sub-surface flow dams. Geological maps can be used together with aerial photographs to locate and evaluate important geological features such as rock outcrops and faults. A hydrogeologist can make petrographical, stratigraphical and structural geological studies using maps to determine the type of rock in a given area; position and thickness of various bedrocks and important features such as rock outcrops faults and dikes (Davis and DeWiest 1967). Also thematic maps showing climatic, hydrological, hydrogeological, soil, vegetation or land use conditions will yield valuable information.

3.2.2 Use of aerial photographs

Aerial photographs are used in preliminary investigations to locate and evaluate important features related to occurrence of ground water, as well as correcting unreliable maps. The best instrument for finding actual sub-surface flow dam sites is air-photo interpretation combined with map studies and field control. Interpretation of aerial photographs requires special skills. Thus, it is usually carried out by a specialist who with the aid of a stereoscope can locate faults, dips and strikes of bedrocks, as well as establish nature of rock units (Brown et al. 1972). For instance, it is possible to differentiate rock types such as coarse-grained and fine-grained material (Brown et al. 1972). The information concerning rock type and nature can be used to establish porosity and permeability of the rock. Catchment area and drainage pattern can be examined by making use of aerial photos and a stereoscope.

Satellite data is available today in a variety of formats. Digital processing and false-colour techniques are developed and can be used in this context, but also a plain black and white satellite image at a scale of say 1:20 000 is sufficient to draw general conclusions about the geological environment, ground water conditions, surface-runoff, erosion and sedimentation processes (Hansson 1984).

3.3 Field Reconnaissance

The first task in field reconnaissance is to examine the accuracy of information given on the topographical and geological maps. There may be so many inaccuracies that it might be necessary to compile a more accurate map before proceeding with the investigation. During field reconnaissance, important natural features such as rock outcrops as well as man made features which are not shown on the existing maps should be recorded.

The local study following a regional analysis that has identified potential implementation areas, will involve more field work and detailed investigations. Field measurements of surface water discharge and sedimentation should be done as simple as possible. Existing gauges should be checked, to find out if they are functioning properly.

In case they are not, adjustment should be made before taking any measurements, and the reliability of past recorded data should be checked. If gauges are not available it is, for instance, possible to estimate peak flow levels from marks in the terrain or by interviewing people. Similarly the sediment transport and characteristics can be estimated to some extent from accumulation that has taken place close to existing rockbars.

A proper hydrogeological survey is essential in order to assess storage volumes, and in order to get good general picture of ground water conditions at the site, so that failures can be avoided. Such a study should always involve a water-level monitoring programme, covering at least one year before construction (Nilsson 1985). The observation wells which should be placed at suitable distances above and below the dam, should also be used for future evaluation of the functioning of the scheme. The hydrogeological study should include hammer sounding in addition to geological map, to determine the depth to bedrock. Seismic and resistivity measurements can also be used, for the case of large scale projects.

The aquifer material should be hydraulically classified through in-situ as well as laboratory tests. Samples should be taken from two or three different depths of the sand deposits by making use of hand or motor-powered auger drill. The stratification can be recorded during drilling. Samples may be dried and examined for:

- grain size and grain size distribution
- porosity
- specific yield.

This can be done in soil laboratory where equipment is available, or in the field, by taking equipment like sieves, balances and two different sizes of test cylinders.

One very useful geophysical method which can be considered during field reconnaissance is the VLF (Very Low Frequency). It is inexpensive and simple method to find out the presence of fractures that could drain the reservoir (Larsson 1984). Materials which can be used for the construction of the dam can also be identified during this field reconnaissance.

4. DESIGN AND CONSTRUCTION OF SUB-SURFACE FLOW DAMS

4.1 Design

4.1.1 Bed rock foundation

Sub-surface flow dams should be founded and anchored in solid rock, in order to achieve good stability, and in most cases to control seepage below the dam. Anchoring may be done by a concrete foundation on the rock surface. If the rock is weathered it is important that this profile is fully excavated before the dam foundation is made, otherwise there will probably be a seepage below the dam. When the rock is reached it is important to investigate possible open fracture zones. If we suspect that there might be fractures the rock surface should be cleaned properly and simple infiltration test could be made, by adding water on the cleaned surface. The sooner the infiltration of water shows that there are fractures, it might be possible to stop leakages by pouring very thin cement mortar into the fracture system.

4.1.2 Water storage capacity

Water is stored in sub-surface flow dams constructed across dry river beds, when flood waters enter the space between the sand particles. For the use of sub-surface dams constructed in a valley, where ground water flow can be perennial or not, a small or large diameter well can be created in the aquifer up stream of the dam. The sizes are governed by the permeability of the aquifer. The smaller the permeability of the aquifer the larger should be the well diameter and vise-versa. Permeability of the aquifer can be determined in laboratory or at the field by conducting a pump test.

The most common case of constructing sub-surface flow dams is, the construction across river beds, where sand deposits are used as storage reservoirs. The storage capacity of sand deposits depends on the porosity of the sand.

The greater the porosity of the sand particle the greater the storage capacity. Finer sand particles tend to be more rounded, the porosity is lower and water storage capacity is reduced (Burger and Beamont 1970). Water storage capacity is, therefore, a function of porosity and storage volume of sand deposit. It can be estimated theoretically from the formula:

$$\text{Water storage capacity } (m^3) = \frac{\text{porosity } (\%) \times \text{storage volume } (m^3)}{100} \qquad (1)$$

Method of determining porosity and storage volume, example:

A test cylinder, 2000 ml, is filled with 1000 ml of water, and sand added up to 2000 ml. The water level is adjusted to 2000 ml by a tap with a filter in the bottom of the test cylinder. The volume of drained water is measured in a 500 ml test cylinder, and porosity can be determined using the formula:

$$\text{porosity } (\%) = \frac{\text{volume of water (in test cylinder)}}{\text{total volume of (test cylinder)}} \times 100 \qquad (2)$$

To avoid air voids in the test cylinder, it is necessary to put the sand sample into the water and not the other way round. The equipment can also be used to determine specific yield (Fig 8.).

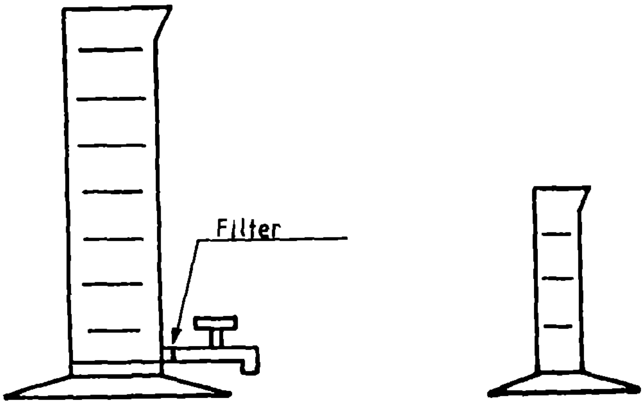

Figure 8. Equipment for measuring porosity and specific yield (modified from Wipplinger 1958).

Storage volume can be estimated from simple geometry of river bed (Fig. 9).

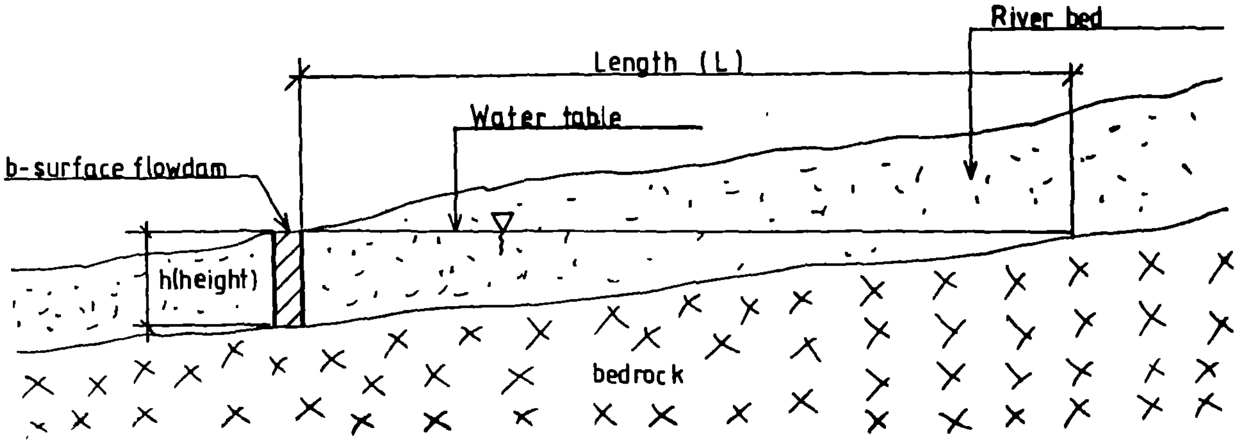

Figure 9. Sub-surface flow dam and geometry of river bed.

$$\text{Storage volume } (m^3) = \tfrac{1}{2}\left[h(m) \times L(m)\right] \times \text{average width of storage bed } (m) \qquad (3)$$

$$L = \frac{h(m) \times 100}{\text{slope of river bed } (\%)} \ (m) \qquad (4)$$

4.1.3 Water discharge and recharge

The amount of water that can be discharged (extracted) from the sand medium during the dry season and recharged during floods is governed by the permeability of the sand. For flow through a porous media the overall resistance to flow will also depend on the additional factors of particle size, size distribution and porosity. Furthermore, due to molecular attraction a layer of water about 0,1 microns thick adheres to sand grains (Terzaghiand Peck 1962). This represents the water in storage which cannot be extracted but is, however, a small amount compared with the total volume retained between the sand grains. Capillary action causes an upward movement of water through the voids between the sand grains and is related to the interfacial tensions between water, sand and air (Terzaghiand Peck 1962).

Investigations by Tolman (1937) revealed that for uniformly sized materials of equal porosity the amount of water that can be withdrawn from a sand medium increases with increasing grain size. Because these infinite number of parameters are combined in a particular sediment deposit, except in a few isolated cases, the volume of stored water that can be extracted from a sand medium has never been exactly evaluated. However, it is difficult to simulate in small apparatus the deposition of sand such as that found along the river bed in the vicinity of the sand-storage dam. Tests must be devised to enable this to be evaluated for any particular sand-storage dam. Therefore, it is practically reasonable to conduct a laboratory scale test of specific yield, in order to be able to determine the discharge (extractable) water. Discharge (extractable water) can be calculated theoretically from the formula:

$$\text{Discharge } (m^3) = \frac{\text{specific yield } (\%) \text{ x storage volume } (m^3)}{100} \qquad (5)$$

4.1.4 Specific yield

Specific yield is the amount of water that can be extracted from saturated sand volume, and is expressed in percentage. It can be determined in laboratory or in the field. The same equipment used for the determination of porosity (Fig 8.), can also be used for this purpose.

<u>Procedure of determining specific yield, example:</u>

A test cylinder, 2000 ml, is filled with 1000 ml of water, and sand is added up to 2000 ml. The water level is adjusted to 2000 ml by a tap with a filter in the bottom of the test cylinder. The test cylinder with 2000 ml of saturated sand sample is drained during 30 minutes. The volume of the drained water is measured. From this, specific yield is determined using theoretical formula:

$$\text{specific yield (\%)} = \frac{\text{volume of drained water (Vd)}}{\text{total volume}} \times 100 \qquad (6)$$

$$= \frac{Vd}{2000} \times 100\ (\%) \qquad (7)$$

4.1.5 Dimensioning of the dam

The main loads to which sub-surface flow dams can be exposed are soil and hydraulic loads. The characteristics of these loads depend on the dam wall material flexibility. If the dam wall material can deform a reasonable small size without any crack or damage, the active and passive soil loads are in balance, so that the dam wall requires a small dimension. Otherwise the dam wall should be dimensioned to carry the active soil and hydraulic loads. Sub-surface dam can be designed to resist only hydraulic loads because active and passive soil loads can balance each other. In case of sand-storage dam, the design should be done in such a way that the dam can withstand sliding and overturning forces, which can be caused by active soil pressure and hydraulic loads. Figure 10. shows an example with a vertical wall.

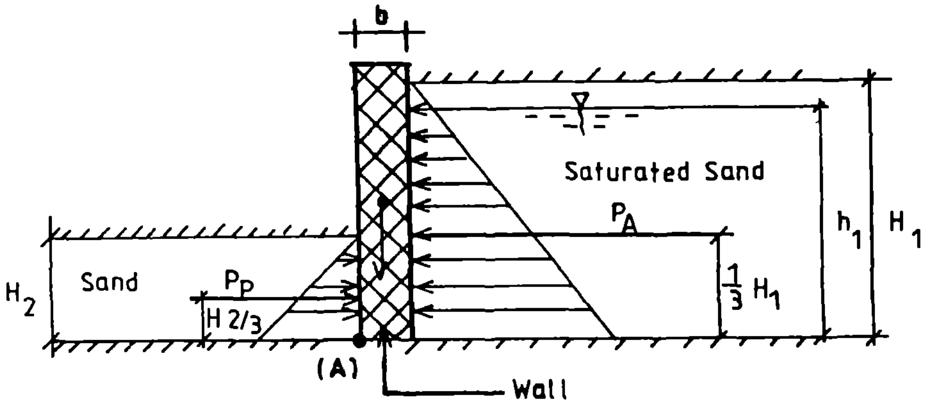

Figure 10. Pressure distribution on a vertical wall.

The thickness of the sand, h_1 (Fig 10.) shows that water level should not rise to surface level, so that pollution risk can be minimized. For the case of dimensioning, it is advisable to assume that the whole thickness of the sand, H_1, is saturated.

$$P_A = K_A\, \gamma_{s.s} H_1 \qquad (8) \qquad\qquad K_A = \frac{1 - \sin\phi}{1 + \sin\phi} \qquad (9)$$

$$F_A = \frac{K_a \gamma_{s.s} H_1^2}{2} \qquad (10)$$

$$P_P = K_p \gamma_s H_2 \qquad (11)$$

$$F_P = \frac{K_p \gamma_s H_2^2}{2} \qquad (12)$$

$$K_p = \frac{1 + \sin\phi}{1 - \sin\phi} \qquad (13)$$

$$F_V = \gamma_{wall} x A_{wall} \qquad (14)$$

where:

K = coefficient of active soil pressure

h_1 = depth of water (m)

$\gamma_{s.s}$ = unit weight of saturated sand

γ_s = unit weight of sand (KN/m³)

K_p = coefficient of passive soil pressure

F_V = vertical forces as a result of dam wall weight (KN)

A_{wall} = area of wall (m²)

γ_{wall} = unit weight of wall material (KN/m³)

ϕ = angle of internal friction (ϕ)

F_H = summation of horizontal forces

b = thickness of the dam (m)

Safety against sliding and overturning of the dam can be calculated using theoretical formula:

$$\text{safety against sliding } (F_s) = \frac{\tan\phi \; F_v}{F_h} \geq 1{,}5 \qquad (15)$$

$$\text{safety against overturning } (F_{o.s}) = \frac{M_o}{M_r} \geq 1{,}5 \qquad (16)$$

where:

M_o = overturning moment of active earth pressure and other active forces

M_r = resisting passive moment with respect to point (A) Fig. 12.) mainly due to the weight of wall.

Taking summation of moment about point A, (Fig. 12.).

$$M_o = \frac{1}{3}P_A H_1 \ , \ M_r = \frac{1}{3}P_p H_2 + \frac{1}{2}bF_v \ .$$

If both equations, (14) and (15) are less than 1,5 the thickness of the dam should be increased, and checked until they are satisfied.

4.2 Construction of Sub-Surface Dam

The most common way is to construct a dam in a trench excavated across a valley or a river bed. The earth work involved may be carried out by human labour since the excavation depths are generally not more than three to six meters.

The shape of clay-dike sub-surface dam (Fig. 11.) will determine the amount of earth work needed.

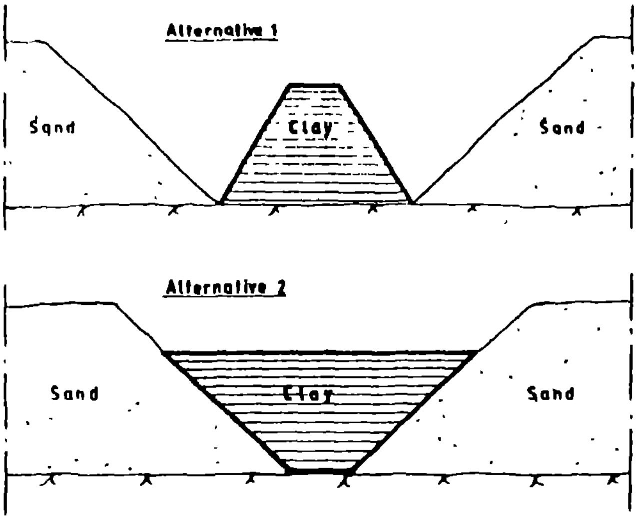

Figure 11. Schematic influence of clay-dike design on required earth work (Nilsson 1984).

Since the second alternative means that more clay will be required, the advantage of inverting the dike will have to be judged also in relation to the availability of clay and the cost for its transport and compaction.

Sub-surface dam is generally constructed at the end of the dry season, when there is little water in the aquifer. There is usually some flow and this must be pumped out during construction. After the dam has been constructed and drains installed, the trench is refilled with the excavated material. It is important that the refill is properly compacted by mechanical means and watering.

4.2.1 Construction materials

Various construction materials have been used to create the impervious screen. Figures 12-17 show some examples of materials that have been used (Nilsson 1984).

The clay dike (Fig. 12.) is an alternative that is very suitable for small schemes in highly permeable aquifers of limited depth, such as sandy river beds. Clayey top soils are generally available close to any construction site which means that they can be excavated and transported to the site at low cost. The use of clay is a labour-intensive alternative and there is no need for skilled labour. Possible drawbacks are the large excavations generally required, the need for proper compaction and the risk of erosion damage to the clay surface due to the flow of ground water. This can be avoided by protecting the dike with plastic sheets (Hansson 1984).

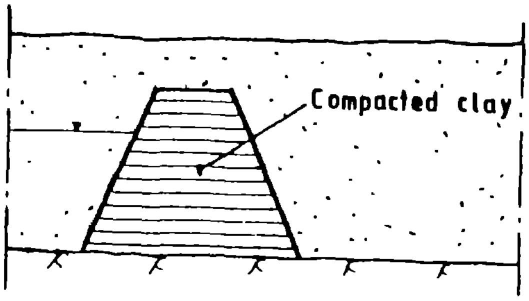

Figure 12. Clay dike.

A concrete dam covered on both sides with blocks or stone work (Fig. 13.) is an alternative involving more advanced engineering for which skilled labour is needed. It necessitates the use of formwork and the availability of cement and gravel. One advantage is that it is possible to raise the dam above the level of a river bed and use it for further sand accumulation.

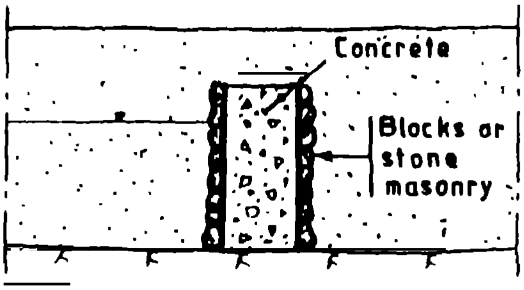

Figure 13. Concrete dam.

This kind of dam can also be constructed entirely of stone work (Fig. 14.).

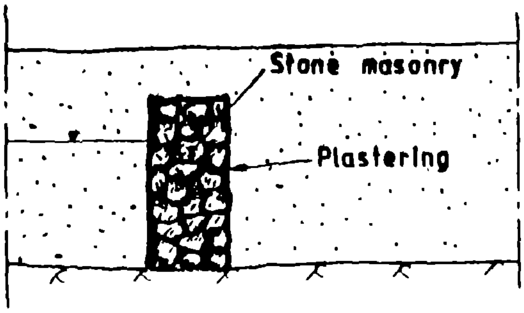

Figure 14. Stone masonry dam.

Sub-surface dam can also be constructed using ferrocement (Fig. 15.). Using ferrocement means that steel or wire mush in addition to concrete have to be used. Generally the material is available at a reasonable cost. The method involves the use of formwork but its main advantage is that very little material is needed to achieve a very strong wall. The structure has to be anchored to the solid reservoir bottom.

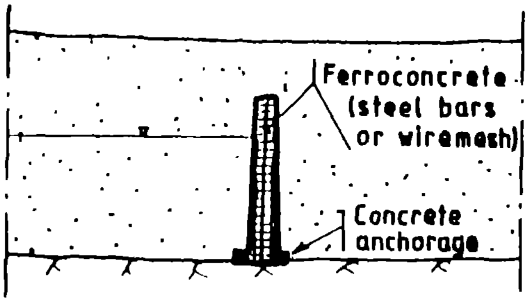

Figure 15. Ferroconcrete dam.

Bricks can be available or may be manufactured from local clay. Building brick wall to make it water tight is a fairly simple procedure (Fig. 16.). The relatively high cost of bricks is a drawback, however, and there are also some doubts as to the stability.

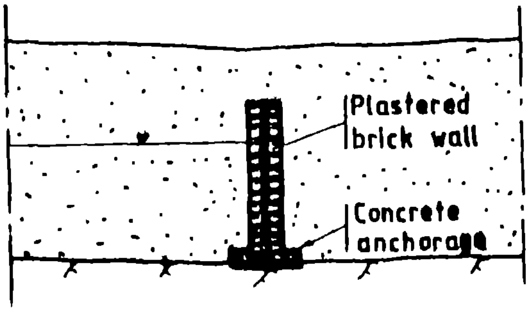

Figure 16. Brick wall.

Using sheets of steel corrugated iron or PVC to build up an impermeable wall has still not been done to any large extent (Fig. 17.). Even if skilled personnel would be needed, for instance, for welding of steel sheets, the construction would be quite simple and the result would be a strong and definitely impermeable structure.

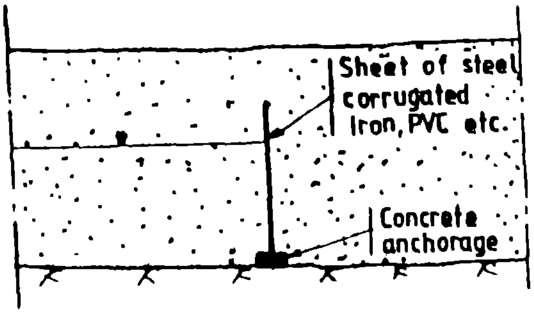

Figure 17. Sheets of steel, corrugated iron or pugwall.

Injected cutoffs have been used to arrest the flow in deep aquifers in North Africa and Japan (BCEDM 1978, cited by Hansson and Nilsson 1984); (Matsuo 1977), and to protect fresh water from pollution in Europe and the USA. For large projects and when a deep aquifer is dammed, it is certainly a feasible alternative. One example of this is the sub-surface dam constructed for the improvement of ground water reservoir and protection of migrating salt water into fresh water in Elassona region, Greece (Fig. 18.).

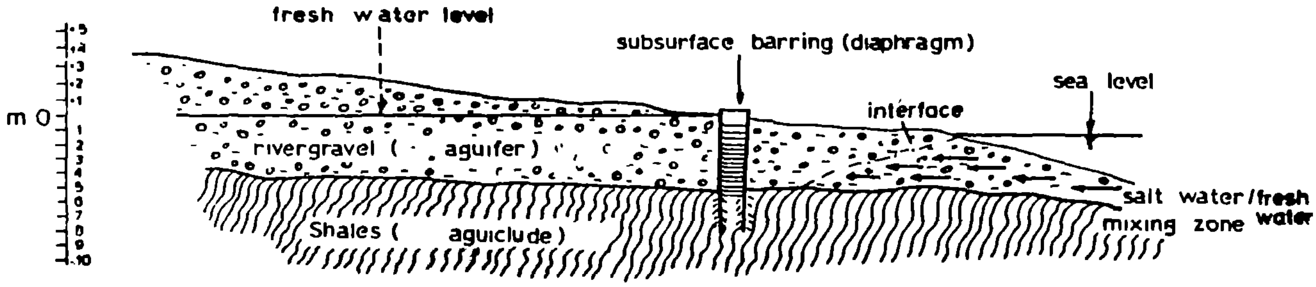

Figure 18. Schematic longitudinal section of an aquifer with sub-surface dam (Garagunis 1981).

The dam was constructed by excavating a ditch in the aquifer. This ditch is filled simultaneously with bentonite (of pulpy consistency) to avoid the ditch walls falling down.

The next step is to lay plastic pipes on either side of the ditch. With the help of these pipes it is possible to bring in the cement injections which will form the solid barrier in a later phase, when steel bars are inserted in the ditch. Due to its high unit weight the cement-concrete spreads and displaces the bentonite. In a final construction phase the ditch-filling is bound to the impermeable bed of the aquiclude by means of cement injections (Fig.19.). A further effect of this measure is the additional insulation of the underground.

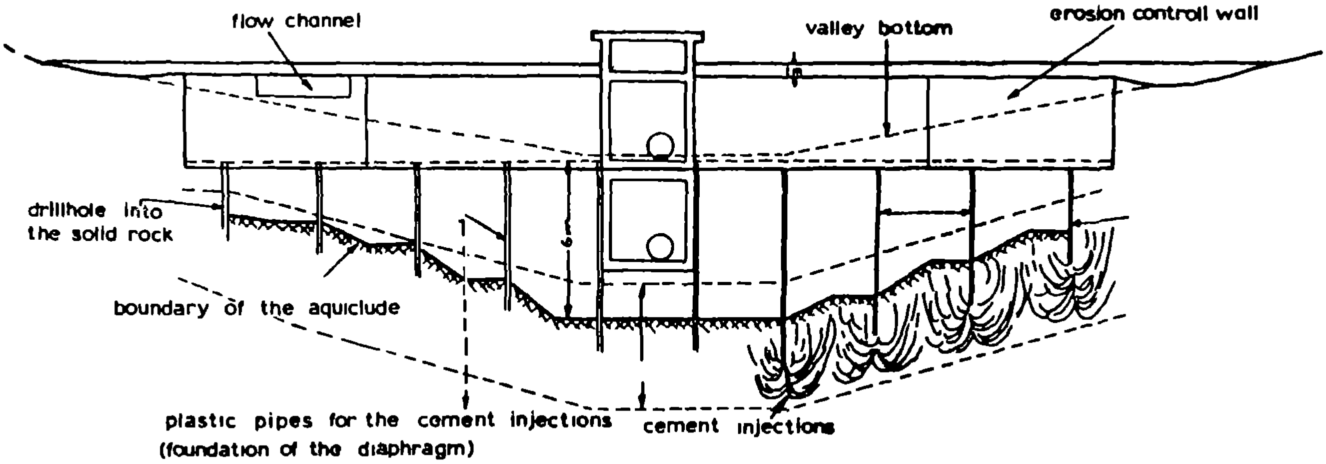

Figure 19. Sub-surface dam construction by cement injection method (Garagunis 1981).

4.2.2 Water extraction methods

A sub-surface dam is always combined with a drain along the upstream base of the dam. The function of this drain, which generally consists of gravel, perforated concrete ring or slotted pipe surrounded by a gravel filter, is to collect the water and transmit it to a well or through a gravity pipe to downstream areas. The well through which water from the dam is generally extracted may be placed in the reservoir or, for erosion protection reasons, in the river banks. Water from the well is mostly extracted by hand pumps, but for large scale schemes, engine running pumps can be used. When aquifers with low permeability are dammed it might be necessary to construct a series of large-diameter wells or collection chambers to create a sufficient storage volume.

It is also possible to extract water from the reservoir by gravity if the community to be served is located downstream of the dam and the topographical conditions are favourable. Figure 20. shows that a sub-surface dam where both extraction methods are shown.

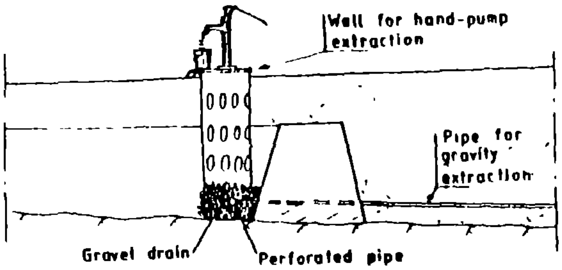

Figure 20. Water extraction methods from sub-surface dam (Nilsson 1984).

4.3 CONSTRUCTION OF SAND-STORAGE DAM

A sand-storage dam is commonly constructed in stages (Fig. 21.).

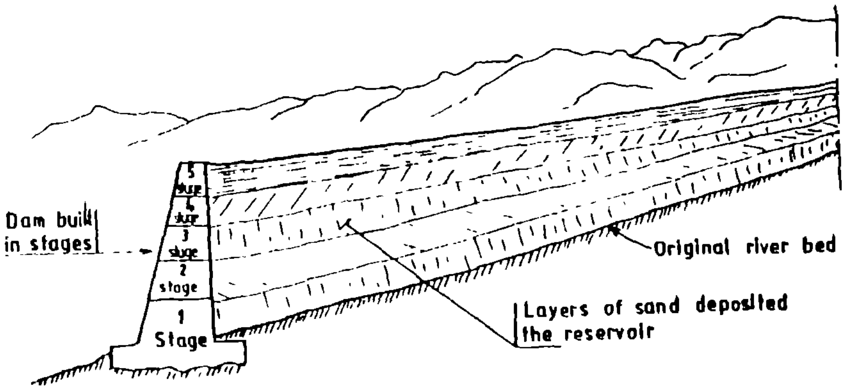

Figure 21. Construction of sand-storage dam in stages. (Burger and Beaumont 1970).

The basic idea is to limit the height of each stage in order to keep a sufficiently high water velocity, so that fine particles are washed out from the reservoir while the coarse particles settle. The height of each stage is determined by estimation of the sedimentation process in the reservoir founded on experience, from sedimentation in previous stages. The extent of natural sedimentation in the stream, or calculations of water velocities in the reservoir can also be used. There are several important reasons why to keep fine particles as little as possible in the reservoir, even though it is not possible to avoid completely. The specific yield and the permeability of the whole reservoir will be lower, and the evaporation losses higher with a higher percentage of fine particles (Hellwig 1973). Another very important factor is that particles in the upper layer will reduce the recharge rates considerably.

The method of constructing the dam by adding a new stage each season or even less frequently means that costs will be higher than they would be if the dam was constructed directly to full height. Two methods have been tried in order to solve this problem. One is to use a siphon, which discharges water over the dam and keeps the flow velocity in the reservoir sufficiently high. This method has not been found technically efficient and, furthermore, it is very costly (Burger and Beaumont 1970). Another simpler and cheaper method is to make openings (notches) in the dam wall, so that they can allow the accumulation of sediments only up to a certain height (Fig. 22.)

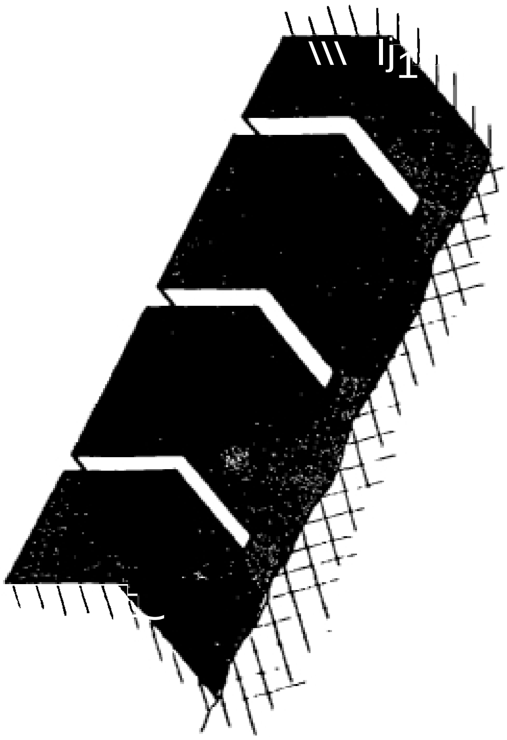

Figure 22. Sand-storage dam constructed with openings in the dam wall, to reduce retardation of the flow, which causes deposition of large quantities of fine materials.

The openings are then filled before the next rainy season and the reservoir is allowed to fill completely. This method has proved quite successful in Kenya (Hase 1985).

4.3.1 Construction materials

Concrete and stone are the most common construction materials used for sand-storage dams. Concrete and stone masonry sand storage dams are shown in Figures 23. and 24. They fulfill the basic requirement for a sand storage dam; they are sufficiently massive to resist the pressure exerted on them, by sand and water stored in the reservoir. In addition, they are water thight. They have the form of arch dams for larger reservoirs.

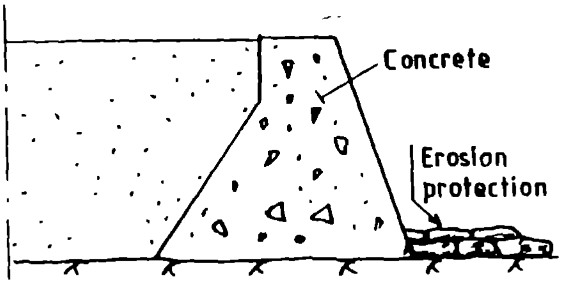

Figure 23. Concrete sand storage dam (Nilsson 1984).

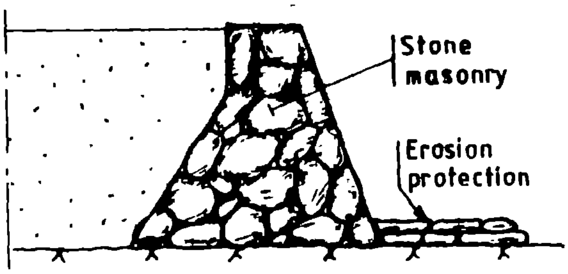

Figure 24. Stone masonery sand-storage dam (Nilsson 1984).

Sand-storage dam can also be made from stone gabions or large blocks which are sufficient to withstand the pressure. A gabion sand storage dam which is covered on the upstream side by a thick layer of clay is shown in Figure 25.

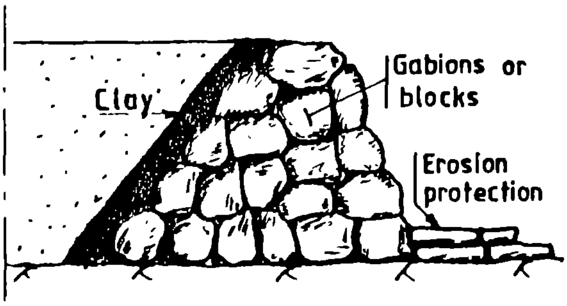

Figure 25. Gabion sand-storage dam with clay cover (Nilsson 1984).

4.3.2 Water extraction methods

Water extraction methods from a sand-storage dam are generally the same as those from sub-surface dam, with the important difference that sand-storage dams are even more suitable for gravity extraction. If the accumulated sediments are expected to be fine grained, it is fairly simple to arrange a system of drains along the reservoir bottom before the sedimentation takes place. They can be made up by slotted pipes covered by gravels as in the case of sub-surface dam.

Naturally the drains have to be able to withstand the erosive action of the water flow. A drain is generally placed at the reservoir bottom along the upstream side of the dam. This drain is connected to a well or a gravity supply pipe through the dam wall. A flushing valve can be installed in the dam to facilitate cleaning of the reservoir as well as to extract water, in case the long gravity pipe line is blocked. A sand-storage dam with water extraction methods is shown in Fig. 26.

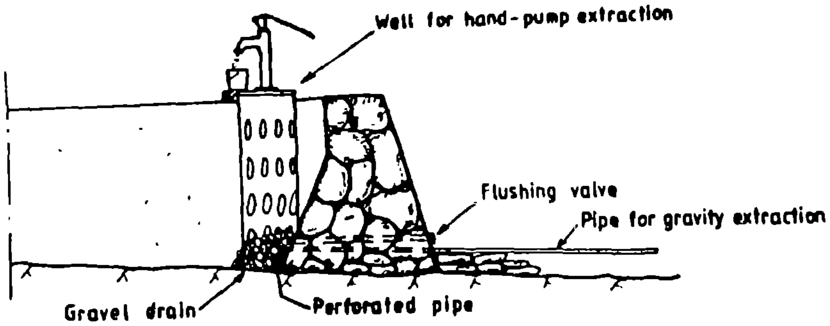

Figure 26. Water extraction methods from a sand storage dam (Hansson and Nilsson 1984).

5. CASE STUDIES

Although sub-surface flow dams were known during old civilizations, the interest of using them for water supply purposes has increased recently, in connection with rural development projects. Several research projects are planned or have already started to develop the technique. In Ethiopia a project carried out jointly by Ethiopian Water Works Authority and Swedish International Development Authority involving the siting and construction of several dams has started. UNESCO plans to start research projects in West and Southern Africa. The Central Ground Water Board of India has started to site and construct a number of dams in Kerala district, southern India. Royal Institute of Technology, Stockholm, has started developing regional plans and construction site recommendations for an area in southern India. Similar research project has been started in Brazil (Gwynne Power 1985).

Figure 3. shows a map where identified sub-surface flow dam sites are marked, and also where it has been proposed, after preliminary investigations, to implement the techniques.

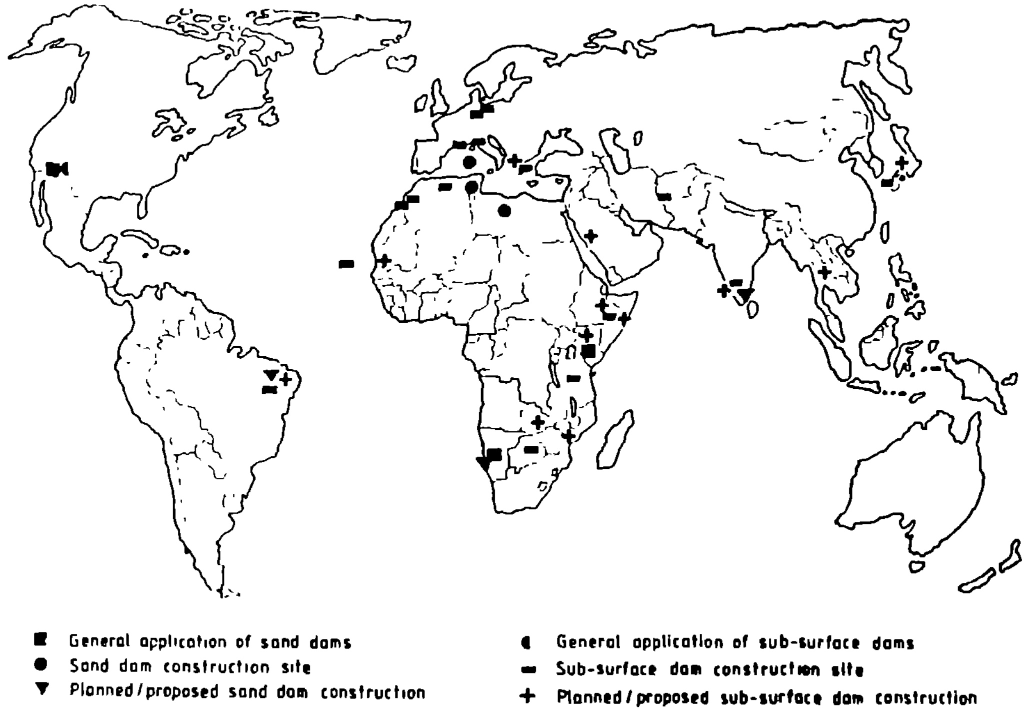

Figure 3. Identified sub-surface flow dam sites and areas for proposed or planned construction (Hansson and Nilsson 1984).

5.1 Europe

Tröften (1982, cited by Nilsson 1984) reported that sub-surface dams built by the Romans still exist in Sardinia. Several schemes in Germany, France and Italy where sub-surface dams have been used mostly to raise ground-water levels are presented by Gignoux and Barbier (1955), Guembel (1945) and Bceom (1978) (cited by Nilsson 1984). Sub-surface dams serving the purpose of arresting ground water flow in the existing aquifer, and protecting the intrusion of salt water into fresh water have been constructed in Greece (Garaguis 1981).

5.2 **Asia**

Sub-surface dams have been proposed for construction in Thailand and for several sites in Japan. A sub-surface dam has been constructed by means of jet injection, to increase water level on the island of Kaba, western Japan (Matsuo 1977).

5.2.1 South India

Two sub-surface dams have been constructed in Kerala, South India. The sites are situated in the Palghat Gap which is a graben dividing two hill ranges parallel to the West Coast. The altitude is about 50 m and average rainfall is 2400 mm, the main part of which comes in June-October (Ahnfors 1980).

Agriculture is intensive in the area. The water available during the rainy season is enough to grow one rice crop, and in part of the area two crops in a year. There is a need for additional water to expand the area covered by a second crop, and also to irrigate a third crop (Nilsson 1985). One factor restricting the use of sub-surface dams is that land holdings are generally small, and it is difficult to organize the co-operative effort needed when several farmers are involved (Nilsson 1985). Thus, the two existing dams are both situated on quite large farms. One was constructed by a private farmer and the other was built on a government seed farm by the Central Ground Water Board of India.

The private dam was constructed in Ottapalam in 1962-64. A large diameter well supplying water to the farm usually dried out during the dry season, and there was a need to find an alternative solution. A 130 m long dike reaching to bedrock was built across a narrow valley, surrounded by out-cropped rocks (Fig. 27.).

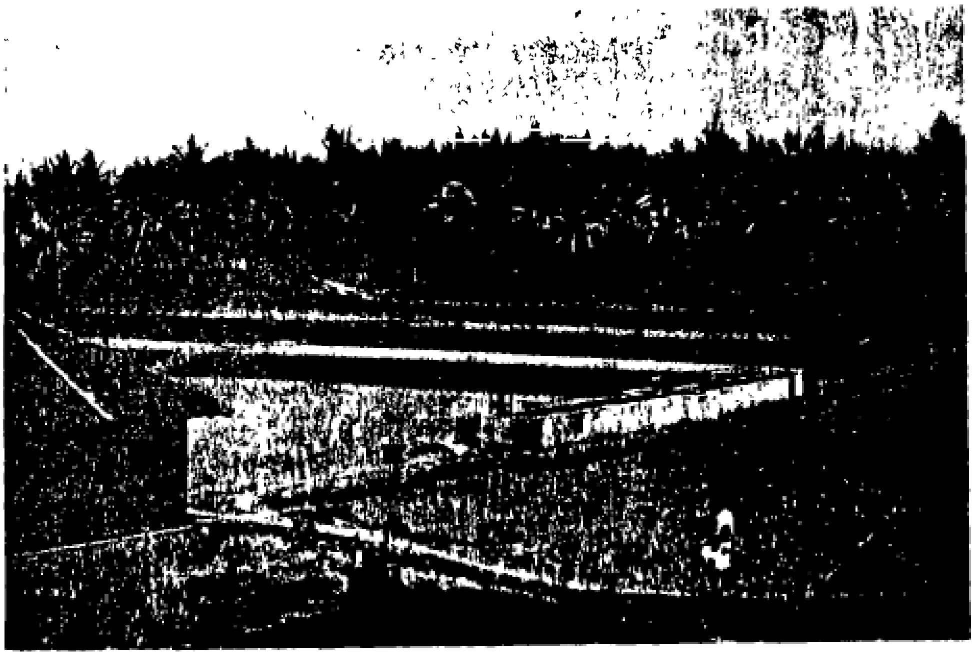

Figure 27. Sub-surface dam at Ottapalam, Kerala (Ahnfors 1980).

The depth to bedrock was established prior to excavation by steel-rod sounding. The average depth was five meters and a maximum of nine meters was located at the centre of the well. The aquifer consists of residual soils which, at least in the upper layers, are sandy. The transition between the weathered layer and the underlying fresh rock is distinct, and it was established during the excavation that the rock had no major fracture zones (Ahnfors 1980).

The dike consists of a 10 cm plastered brick wall. Water is extracted from the aquifer through a gravel drain along the dike to a series of infilteration wells feeding a pumping well. The catchment area of the dam is about 10 ha and water is used mostly for complementary irrigation of 1,5 ha of paddy, and at the end of the dry season for one ha of coconut trees.

The dam built by the Central Ground Water Board was completed in 1979. In addition to supplying water for supplementary irrigation at the seed farm it was also meant to serve as a pilot project for future dam construction (Ahnfors 1980). This dam was also constructed across a narrow valley and has a catchment area of about 20 ha.

The bedrock consists of gneiss and granite which crops out on the valley sides. The insitu weathered soils are sandy in the central parts of the valley and more fine-grained along the sides. The average specific yield determined from tension-plate and neutron-probe measurements is 7,5 percent. Other investigations carried out at the site were hammer sounding and resistivity measurements to establish the depth to bedrock which at the deepest section is four meters (Nilsson 1984).

The total length of the dam was about 140 m and the crest was kept one meter below ground level in order to avoid water logging in the upstream area (Larsson 1984). The main part of the dam is made up by a plastered brick wall but there are also sections consisting of tarfelt and polythene sheets (Fig. 28.). Two wells, connected to each other by drill holes through an unexpected rock bar, were constructed along the dike (Larsson 1984).

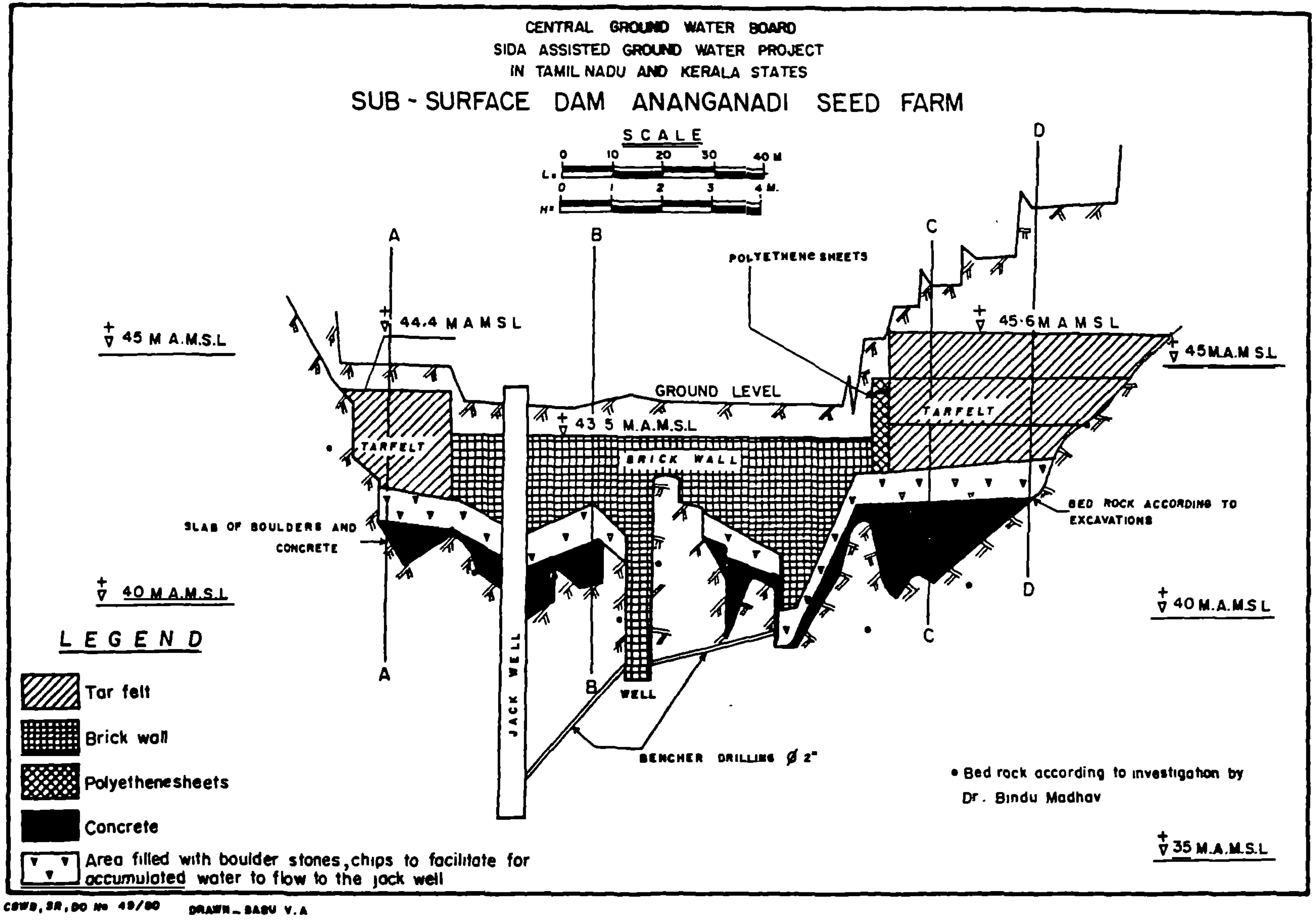

Fig 28. Sub-surface dam constructed by using different types of construction materials, at Ananganadi, Kerala (Larsson 1984).

It took three months to complete the dam at a total cost of US$ 7500, including pumping equipment. One third of this cost was for earthwork and the rest for equipment and construction materials. The storage volume of the reservoir was estimated to be 15 000 m^3. which would be sufficient for supplementary irrigation of the second paddy crop and the raising of a third crop of black gram in a command area of 6 ha. The cost/benefit ratio at eight percent interest rate was calculated to be 1,06 (Hansson and Nilsson 1984).

5.3 America

There is a long tradition of building sub-surface dams in the arid south-western parts of the United States and northern Mexico. Lowdermilk (1953, cited by Nilsson 1984) reported that sub-surface dams called "tapoon" have been constructed in sandy river beds in Arizona, and sand-storage dams have been built in the 18th century (Sykes 1937).

A large sub-surface dam has been built across Pacoima Creek, California. The dam has a length of 200 m and a maximum depth of 15 m and consists of a 60 cm thick concrete wall (Dixey 1931).

The suitability of sub-surface flow dams for rural water supply in the dry Nordeste Region of Brazil has been established by Pompeu Dossantos and Frangipani (1978, cited by Nilsson 1984), and there are also examples of old dams in that region (Dixey 1931). Recently, in 1985 there was a sub-surface dam constructed to be used by small holder farmers. The dam is built by excavation of four meter wide arced trench to bedrock level which is backfilled with clay to form a large sub-surface structure. Impounded water can be abstracted from the underground area, after it has passed through an upstream filler and into an underground storage tank (cistern) (Fig. 29.). This tank also provides drinking water for the family and workers as well as for cultivation (Gwynne Power, 1985).

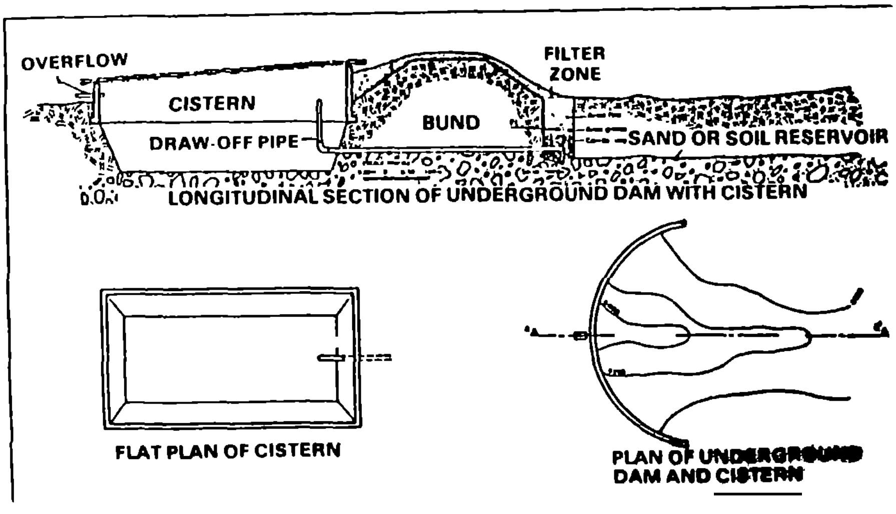

Figure 29. Plan and section of sub-surface dam with cistern (Gwynne Power 1985).

5.4 Africa

Robaux (1954, cited by Nilsson 1984) reported that several very large sub-surface dam schemes desingned to increase the ground water availability for irrigation purposes exist in north-western Africa notably in Morocco and Algeria. In Tunisia the "jessour" represents a special type of "sand" dam which is very slowly filled by sediments, and also used for growing olive trees (Gezahegne 1983).

Sub-surface flow dams are quite frequently used for water supply in East Africa. There exist examples of sub-surface dams in Dodoma Region, Tanzania, sand-storage dams in Machackos, Kenya and sub-surface flow dams in Hararghe Region, Ethiopia.

5.4.1 Dodoma, Tanzania

In Tanzania the known sub-surface dam schemes are constructed around Dodoma, but some are also reported to exist in the southern parts of the country (Mitchell 1954).

In 1927 a masonary wall with concrete core was built across the sand bed of a river. The objective was to provide water for human consumption as well as for cattle during the dry period. No detailed description of the construction is given, but apparently the dam was a combination of a sub-surface dam and sand-storage dam in order to trap sediments during the floods. The dam was completely filled with sand during the rains of late 1927. It was estimated that the total effective storage volume behind the dam would be 410 m^3 which would provide a daily supply of 2,3 m^3 during the dry season.

In 1928 another sub-surface dam was constructed at a place called Kikuyu. There are no construction details available. The objective was to supply water for town, stock and railway requirements. Therefore, it was probably quite a large scheme. It is stated that it functioned quite well during the year of 1928 when it supplied water for the railway requirements (Nilsson 1984).

A more recent scheme was constructed in the Bihawana area about 15 km south-west of Dodoma. The dam was constructed across the river bed some 500 m north of the Bihawana Roman Catholic Mission. The river bed consists of coarse sand and has at this particular site a width of about 20 m. The banks rise about one meter above the sand level and are covered by dense bush vegetation. Women collect water from the holes dug in the sand above the dam site. In the early fifties the fathers of the mission constructed a well in the river bed. It has a diameter of about three meters and has a concrete lining and top cover. This well was used for supply to the mission until the mid sixties when it was no longer sufficient for a safe supply during the dry season.

In 1967 a dam was constructed in order to trap water upstream which would be sufficient for water supply throughout the year. A trench was dug manually across the river three meters down to a layer of calcrete. A clay dam was built in the trench, by transporting clay from the vicinity of Bihawana. On the upper side of the dam a gravel pack was constructed and inside this at the bottom of the dam a slotted collector pipe of 18 cm diameter was placed. This pipe collects the water which flows by gravity to a sump well of six meters depth constucted in the river bank. The sump well is connected to a pump house from where the water is pumped to the mission. A pipe also connects the old well to the sump. The system has been in function since the year of construction and today it supplies water to some 25 people , 100 pigs and irrigation of a vegetable garden of about 0,1 ha. The sump-well never dries out but maintains a level of about 1 - 1,5 meters above the bottom even at the end of the dry season (Nilsson 1984).

5.4.2 Machakos district, Kenya

The following are based on a study visit made by the author in November, 1985. The visit was guided by one member of the Machakos Integrated Development Programme (MIDP). All necessary information concerning the visit and selection of sites to be visited were done according to the discussion made with Wilfrid Hase, water works supervision engineer of the MIDP, at his office.

The climate in the Machakos area is semi-arid. Rainfall varies with altitude, annual averages are over 1000 mm in the northern hills, but less than 500 mm in the southern and south-eastern parts.

There are over hundred sand-storage dams constructed in the district out of which some are built by local people. All the rest are constructed by MIDP. Those constructed by local people are old, but some were still functioning during the time of this report. One such old dam is shown in Fig. 30.

Figure 30. Old sand-storage dam constructed by local people, Machakos, Kenya.

The dam is serving about 300 people during the driest period. The people collect water in the traditional way by scooping shallow wells in the sand upstream of the dam during the dry season. During the wet season it is possible to get water even down stream of the dam (Fig. 30.).

A large number of sand-storage dams were constructed by MIDP. The dams were sited mainly by using air-photo interpretation with field reconnaissance. Dams were constructed where rock bars are available and natural basins exist for sand accumulation. All dams were built of stone masonry (Hase 1985).

Figure 31 shows a sand-storage dam constructed in Mukio. The dam was built on top of an already existing "drift" across a river. The additional height was about two meters. It was built in three stages. The dam wall is about

50 cm thick stone masonry plastered with cement mortar. It took 10 months to construct the dam.

Figure 31. Mukio sand-storage dam built on existing "drift" Machakos, Kenya.

Water is extracted from a well sunk along the river bank fitted with hand-pump. A cattle though was made quite near down stream of the dam and connected to the hand pump by a pipeline, so that animals can get water by gravity after pumping. There was no information about water quality of the dam. The quality might be poor because lots of animals are entering the reservoir area to get water whenever ground water rises to the surface. This could be minimized or avoided by constructing a fence around the reservoir area to limit the enterance. Alternatively a drainage could be made to keep water level below sand surface.

Figure 32 shows a sand storage dam constructed in Kyandili, Machakos. The dam was built with openings/notch method.

The whole dam height was constructed at one occasion instead of building it in stages, but a notch was left in the centre to allow silt outflow. The dam was filled up with coarse sand after two seasons.

Figure 32. Kyandili sand-storage dam built with openings/ notch method Machakos, Kenya.

The dam height is about three meters, made of stone masonry. It supplies about 1000 people during the time of this report. Water is piped by a gravity to a stand post (quite near down stream of the dam) where people can collect the water. A cattle trough is also constructed nearby the stand post (Fig 32.). The total cost of construction was about 30 000 Kenyan shillings in 1979. It included labour costs, since there was no community participation involved. Later when similar size of dam was constructed the cost was reduced by half because labour was provided freely from the community (Hase 1985).

5.4.3 Hararghe region, Ethiopia

The following are based on a study visit made by the author in November, 1985 and his previous working experience of about three years in the region, since September 1981.

The climate in Hararghe region is semi-arid. There are two different rainfall patterns in the region; the short rainy season from March to April and the main one from July to September. Rainfall varies with elevation. The average annual rainfall in Kolla zone of the region (below 1800 m above sea level) is less than 800 mm. The Woina-Dega zone of the region (between 1800 - 2400 m above sea level) receives about 2000 mm annually. The construction of sub-surface flow dams is concentrated in the Kolla zone of the region where water problem is acute and sandy river beds are available.

Figure 33 shows the first sand-storage dam constructed by Ethiopian Water Works Construction Authority (EWWCA) in 1981 at Bombas. Excavation was carried down to bed rock at three meters depth. The dam was made of solid concrete blocks and raised 0,8 m above the original sand level. Large boulders protect down stream portion of the dam wall against erosion.

Figure 33. Bombas sand-storage dam (flow is by gravity to water collection site) Hararghe, Ethiopia.

The dam supplies water for about 800 people during the time of this report. Water is piped by gravity to a steel tank about 400 m down stream of the dam, where the villagers collect water from a stand post. The total cost of the project including the pipeline and steel tank was about 25 000 Ethiopian Birr, in 1981.

Figure 34 shows a sub-surface dam constructed at Gursum by EWWCA to supply water for 5000 people in 1981. The dam wall was made of stone masonry plastered with cement. The parent material at the dam site is silt clay, with only low permeability. To overcome this, a large excavation was made. A reservoir of 200 m^3 was created and covered with concrete rings resting on a pillar of concrete blocks.

Figure 34. Sub-surface dam at Gursum (water is pumped from the well in the reservoir to an elevated tank) Hararghe, Ethiopia.

The sub-surface flow of water in the soil is blocked by the dam. Additional water is piped by gravity from a spring area upstream of the dam using perforated PVC pipes laid in a trench with a graded filter. Water is pumped from a well in the reservoir to an elevated tank, for distribution to communal water points in the town. The system has functioned well since constructed up to middle of 1984. Thereafter, water shortages have occured in the town up to the time of this report. This is because the rain failed continuously for two years and the yield decreased. The total cost of the project including distribution system was about 300 000 Ethiopian Birr, in 1981.

The positive experience gained from these two schemes has initiated a research and development project with the aim of further developing the technique and encouraging local application of sub-surface flow dams in Ethiopia. The project is being carried out by EWWCA with financial support from the Swedish International Development Authority (SIDA).

Figure 35 shows the first sand-storage dam constructed under research programme at Ganda-Balina near Dire-Dawa, in 1983.

Figure 35. Ganda-Balina sand-storage dam constructed for research purpose in Hararghe, Ethiopia.

The dam wall was made of stone masonry and was raised in two stages. The first stage was raised one meter above the original sand surface. This stage was completed in August 1983 and the reservoir filled with sand and water during a flood in September 1983. However, the decrease of the water level was very quick and in December 1983, the reservoir was empty. The dam had been under investigation to locate whether the leakage is under the dam or in the reservoir area. During the time of this report it was concluded that the dam is leaking in the reservoir area and water is draining into faults and fractures in the bedrock. In this case, ground water could probably be extracted through wells drilled into the basement rock because the dam would provide artificial recharge of the ground water. Figure 36 shows a sand-storage dam constructed at Kore, in 1985. The dam was made of stone masonry to its full ehight at a time. Clay and fine silt deposited in the reservoir area during the first flood (Fig. 36.). As a result the dam was not successful. This construction mistake could be avoided, either by building the dam in stages or using notch method to allow silt outflow when building the dam to its full height at once.

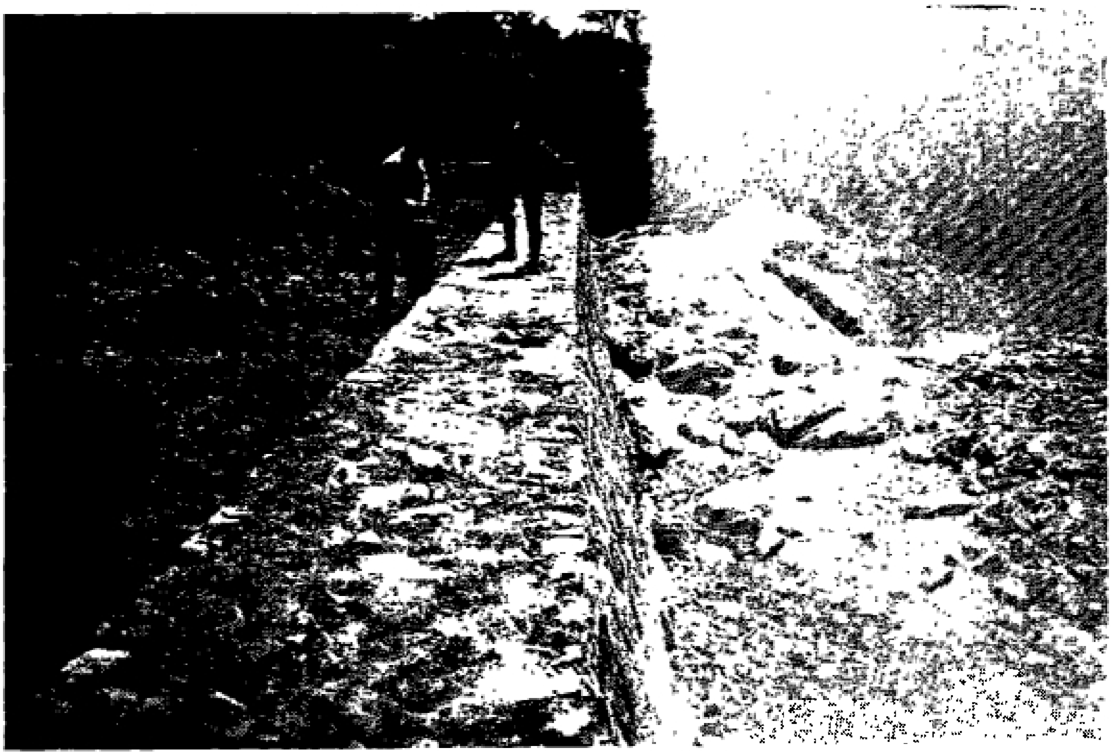

Figure 36. Sand-storage dam at Kore filled up with clay and fine silt because the dam was constructed to its full height at once without leaving openings/notches to allow silt outflow, Hararghe, Ethiopia.

5.5 Operation and Maintenance Experiences in Machakos District, Kenya and Hararghe Region, Ethiopia

5.5.1 Machakos district, Kenya

The operation requirement of the scheme is negligible because water is extracted from wells by hand pumps or it runs by gravity (Hase 1985). Sub-surface flow dam schemes are divided into two based on water extraction methods, they are:

1. Large diameter wells constructed upstream of the dam and fitted with hand pumps.

2. Gravity schemes.

   Operation and maintenance requirements of scheme (1) are:
   - repairing the dam if there is any damage
   - greasing of the hand pump parts
   - tightening of bolts and nuts
   - replacing some parts of hand pumps which are worn out etc.

   Operation and maintenance requirements of scheme (2) are:
   - repairing the dam if there is any damage
   - repairing pipe line if there is any leakage
   - replacing water taps if broken
   - repairing cattle troughs if damaged

Maintenance of scheme (1) happens once or twice in a year. However, this type of schemes are few in number. Quite a number of gravity schemes have been constructed in the district. Maintenance of these schemes happen once in two or three years time, mostly replacing of water taps (Hase 1985).

MIDP is responsible for all operation and maintenance of projects within the district. The office send a request form to the villagers (users) in order to know the performance of the scheme. The village committee or responsible person will fill in the form and send back to the office. Then action will be taken according to the request made. Generally the operation and maintenance cost of sub-surface flow dams in the district is very low as compared to bore-holes and conventional surface dams (Hase 1985).

5.5.2 Hararghe region, Ethiopia

The operation and maintenance conditions in this region are more or less similar to those of Machakos district, except in a few cases. Sand-storage dam at Bombas was constructed in 1981, and water is supplied by gravity. The dam was repaired once after one year service because down stream portion of it was damaged by erosion. Thereafter, the system has been functioning well with no maintenance requirements up to the time of this report.

Sub-surface dam at Gursum was constructed in 1981. Water is supplied by pumping from large diameter well to elevated steel tank. The pump was repaired once after three years service. Thereafter, the system has been functioning well without maintenance requirements up to the time of this report. Even though the break down was not so frequent the operation and maintenance requirement of this scheme was higher than that of gravity schemes and schemes fitted with hand pumps. Because labour and energy for running the pump were additional needs.

EWWCA regional office is responsible for all operation and maintenance of rural water supply in the region, except some economically capable areas or towns like Gursum. Gursum communities are responsible for operation and maintenance of their scheme. There is a water supply committee that charges people five Ethiopian cents for two buckets of water in order to cover operation and maintenance costs. EWWCA is assisting them technically for the case of major breakdowns. Generally sub-surface flow dam schemes fitted with hand pumps or run by gravity to supply water, require limited operation and maintenance except in large scheme cases where pumping is required.

6 ECONOMIC CONSIDERATIONS OF SUB-SURFACE FLOW DAMS

There are basically two different ways of approaching the economic feasibility of sub-surface flow dams. One is to relate the costs involved to the economic benefits gained from the improved water supply. The other is to compare the cost of a sub-surface or sand-storage dam to that of a conventional technical solution.

The first alternative is rather difficult to be made by benefit-cost analysis. The problem involved in benefit-cost analysis of water supply projects have been described by Carruthers and Browne (1977). Even though a problem such as determining the correct price and appropriate discount rate exist, the most difficult one is to evaluate the future benefits; what are the benefits and how much are they worth in economic terms? Because the project is supplying water for domestic purposes, not for irrigation, it is not easy to define the benefits economically even if the production and health effects are known to be positive. Therefore, the second alternative is rather an easy way to determine the economic feasibility of sub-surface flow dams.

Since the construction cost of sand-storage dam is higher than that of sub-surface dam, due to stage construction, it is rather logical to make the cost comparison of sand-storage dam to conventional open storage dam. The cost comparison of sand-storage dam for domestic water supply to conventional open storage dam under Namibian conditions has been done by Burger and Beaumont (1970).

Cost comparison of sand storage dam to conventional open storage dam in Namibia, example (one):

A conventional dam wall of 12 m height and 80 m length in a V-shaped valley with floor slope of 1:300 will retain approximately 575 000 m^3 of water. A sand storage dam of the same height on the same site with the sand deposit lying at a slope of say 1:700 will retain approximately 970 000 m^3 sand which, for an effective porosity of 15 percent would contain 146 000 m^3 of extractable water. According to efficiency charts developed by Wipplinger, cited by Burger and Beaumont (1970) an open storage dam of this depth yields 20 percent of the impounded water, i.e. 115 000 m^3 in total or 46 000 m^3/a, over a 2,5 year dry period. The sand storage dam over the same dry period would yield 70 percent of the retained water, i.e. 102 000 m^3 in total or 41 000 m^3/a.

In the theoretical case considered the sand storage dam supplies 300 000 m^3 of flood water to downstream users that would have been wastefully impounded in the open storage dam. For the sake of comparison a value of 0,2 cent/m^3 is placed on this water.

It is accepted that construction of small sand-storage dams in stages at intervals of one or more years is more expensive because the construction crew must be re-established on site at every raising of the dam wall. In the example it is assumed that the sand storage dam is completed in four stages over a period of eight years, and this makes the construction cost of sand-storage dam a bit higher than that of conventional open storage dam.

Water extracted from sand storage dams is physically pure whilst water from open storage dams requires treatment in purification works. The cost of purification considered that time in Namibian conditions was 4,0 cents/m^3.

For conventional open storage dams of the size of 12 m high and 80 m long, the expected useful life time will rarely exceed 30 years under Namibian conditions, and the safe yield diminishes from the initial maximum to zero over this period.

On the other hand, a properly maintained sand-storage dam is expected to yield a constant supply of water for a much longer period of time after the initial build-up period.

The argument for and against sand storage and conventional open storage dams can only be settled with due regard to the cost of capital and the time value of money. The cash flow analysis presented in Table 2. illustrates how this was done for an assumed cost of capital of 6 percent.

Table 2. Cash flow analysis for sand storage and conventional dam water supply projects in Namibia (Burger and Beaumont 1970).

	Year 0	1	2	3	4	5	6	7	8	9	10	11	12	13-30	31——
1. SAND STORAGE PROJECT															
(a) Capital expenditure	96 500	60 000	–	21 000	–	18 000	–	–	14 000	–	–	–	–	–	–
(b) Yield in m^3 p.a.	391 000	–	–	–	1 000	3 000	6 000	9 000	13 000	20 000	27 000	37 000	41 000	41 000	41 000
2. CONVENTIONAL DAM															
(a) Capital expenditure	89 600	95 000	–	–	–	–	–	–	–	–	–	–	–	–	–
(b) Purification @ ac/m^3	13 200	–	1 740	1 530	1 340	1 150	1 000	890	770	680	592	514	453	390-0	-
(c) Losses @ 0.2 c/m^3	4 400	–	600	580	540	510	480	440	410	380	350	330	300	270-0	–
Total (a), (b) & (c)	107 200	95 000	2 340	2 110	1 880	1 660	1 480	1 330	1 180	1 060	942	844	753	660-0	–
(d) Yield in m^3 p.a	330 000	–	46 000	43 000	40 000	36 500	34 000	31 500	29 000	27 000	25 000	23 000	21 500	19 500-0	-

Cost of water for sand storage project = 96500/391000 = 24.7 cent/m^3

Cost of water for conventional dam = 107200/330000 = 32.4 cent/m^3

NOTE Cost of capital = 6%

Apparently the total cost of using sand-storage dam is about 75 percent of that for a conventional open storage dam under these specific conditions.

Construction cost of sub-surface flow dams in Machakos district, Kenya and Hararghe region, Ethiopia, example (two):

The cost information is obtained from the MIDP office, Kenya and EWWCA regional office, Ethiopia during the study visit made by the author in November, 1985.

Table 3. shows the construction cost of these schemes.

Table 3. Construction cost of sub-surface flow dams in Machakos district, Kenya and Hararghe region, Ethiopia

Site name (location)	Dam Height (m)	Population Served	Year of Construction	Cost at the year of constr.	Per Capita Cost	Remark
Kyandili sand-storage dam, Kenya	3	1000	1979	30000Kshs (US$ 1800)	30Kshs	no community involvement
Kalama sand-storage dam, Kenya	3	1000	1980	15000Kshs (US$ 900)	15Kshs	community is involved
Bombas sand-storage dam, Ethiopia	3,8	800	1981	8000Et.Birr (US$ 4000)	10Et.Birr	no community involvment
Gursum sub-surface dam, Ethiopia	3	5000	1981	50000EtBirr	10Et.Birr	-." -

7 DISCUSSION

7.1 Advantages

By building sub-surface flow dams it is possible to store water under surface on a sandy river or in a v-shaped valley. The stored water is protected from sun and wind, resulting in less evaporation. In addition to this, the stored water is relatively well protected from surface pollution and the water is thus kept clean for the consumer.

By using local construction materials and methods it is possible to reduce the construction cost to a lower level.

By applying simple technology, labour-intensive methods and local construction materials, it is possible to save much foreign currency.

The construction of sub-surface flow dams is simple, so we need not have the strict quality control demanded for surface dams, and there is no disaster caused by the failure of sub-surface flow dams.

Sub-surface flow dam schemes have less operation and maintenance costs as compared to bore-holes and conventional surface dams, provided water extraction is by hand pumps from large diameter wells or by gravity.

7.2 Disadvantages

Sub-surface flow dams are not convenient everywhere. They require a suitable geological and topographical formation, aquifer rich in sand and gravel deposits, and reasonable walking distance to the consumption area. This gives such a scheme limited application.

7.3 Environmental Impact

Properly planned and executed sub-surface flow dam schemes have no direct negative impact on the surrounding environment. However, the technique is implemented in an environment where a small change may have long term physical as well as social consequences. This calls for cautiousness during the planning of the schemes.

The fact that the natural water flow is arrested means that there may be an effect on the sub-surface flow conditions in downstream areas. The study of such possible effects must be a part of the planning of the schemes.

The rise of ground water levels to surface means the risk of pollutin increases. This problem can be solved by fencing the recharge areas. Alternatively a drainage can be made to keep water levels below ground surface.

8 CONCLUSIONS

The great problem in arid and semi-arid regions of the developing countries with irregular rainfall is storing water during a rainly season in order to preserve it for the dry one. An interesting and useful technique to solve the problem is to store water in sub-surface flow dams. Two types of sub-surface flow dams are defined, namely sub-surface dams and sand-storage dams. A sub-surface dam is constructed below ground level and it arrests the flow in a natural aquifer, whereas a sand-storage dam is raised above ground level and it impounds water in sediments accumulated by the dam itself.

The advantages of this technique compared with open storage dams are:

- simple and inexpensive construction
- low or no evaporation losses
- no siltation
- good water quality.
- possess the potential for the inclusion of considerable amount of self-help labour.

- requires limited operation and maintenance
- no occupation of valuable land by water.

Some specific construction sites and areas where the methods have a great application were indentified. A number of fairly large projects exist in Europe and North-Western Africa. In Machakos district, Kenya, Hararghe region, Ethiopia and Namibia sub-surface flow dams are used quite extensively as storage reservoirs for rural water supply. A number of research projects are planned or have started in Africa, India, Japan and Brazil for further development of the technique.

Climatic conditions of low rainfall and high evaporation are the reasons for sub-surface storage of water. Topography governs to a large extent the construction alternatives and the possiblilities of achieving large reservoirs with good recharge. Sub-surface flow dams are generally built in river beds but also shallow residual-soil aquifers may have sufficiently good hydraulic characteristics. The parent rock, extent of erosion, weathering and the sediment transport conditions determine the type of sediments accumulated in a sand dam.

Although the construction of sub-surface flow dams is simple and inexpensive, it is necessary to make good investigations of new possible dam sites, as regards geology, hydrogeology and hydrology for the success of the dam. Topographical and geological maps are appropriate instruments for regional investigations. The best instrument for finding actual sub-surface flow dam sites is air photo interpretation combined with map studies and field reconassance. It is important to incorporate data from studies carried out previously. The hydrogeological study should include hammer sounding in addition to geological map, to determine the depth to bedrock. In most cases it is necessary to excavate a test shaft in order to check up the underlying bedrock so that no leakage can arise. The fracture zone can also be checked while excavating the trench to construct the dam. After the bedrock has been reached it is important to clean the trench and pour water into it to check wheather leakage can occur or not. VLF (Very Low Frequency) is one simple and inexpensive geophysical method which can be used to find out the presence of fractures that could drain the reservoir. Resistivity and seismic tests can be used in large projects.

The aquifer material has to be hydraulically classified through in situ as well as laboratory tests. Samples should be taken and examined for:

- porosity
- specific yield or permeability.

Parameters of major importance when investigating new dam sites are:

- bed rock conditions as regards fractures and weathering
- size and shape of the catchment area in order to determine runoff and recharge rates
- depth of the sediment deposit, width and slope of the river bed in order to find out the storage volume of sand
- porosity in order to estimate water storage capacity in the sand deposit
- specific yield to estimate the amount of water that can be extracted.

The main loads to which sub-surface flow dams can be exposed are soil and hydraulic loads. Sub-surface dam can be designed to resist only hydraulic loads, whereas sand-storage dam should be designed to withstand sliding and overturning forces which can be caused by active soil pressure and hydraulic loads.

The most common types of sub-surface dams are clay, stone masonry and concrete walls built in excavated trenches of three to six meters depth. Bricks, ferroconcrete and corrugated iron sheets have been used. Sand storage dams are usually constructed by concrete and stone masonry.

Gabions or blocks combined with clay layers can be used. Water is extracted mostly by hand pumps from large diameter wells or when topography permits, by gravity.

Construction should be planned in such a way that it can be accomplished during the dry seasons, in order to keep costs down and to avoid damage caused by high floods.

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