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INSTITUTIONEN FÖR KULTURT
Royal Institute of Technology
Dept of Land Improvement and Drainag
Meddelande Trita-Kut **1034**

GROUND-WATER DAMS FOR RURA WATER SUPPLY IN DEVELOPING COUNTRIES

ÅKE NILSSON

RESEARCH REPORT

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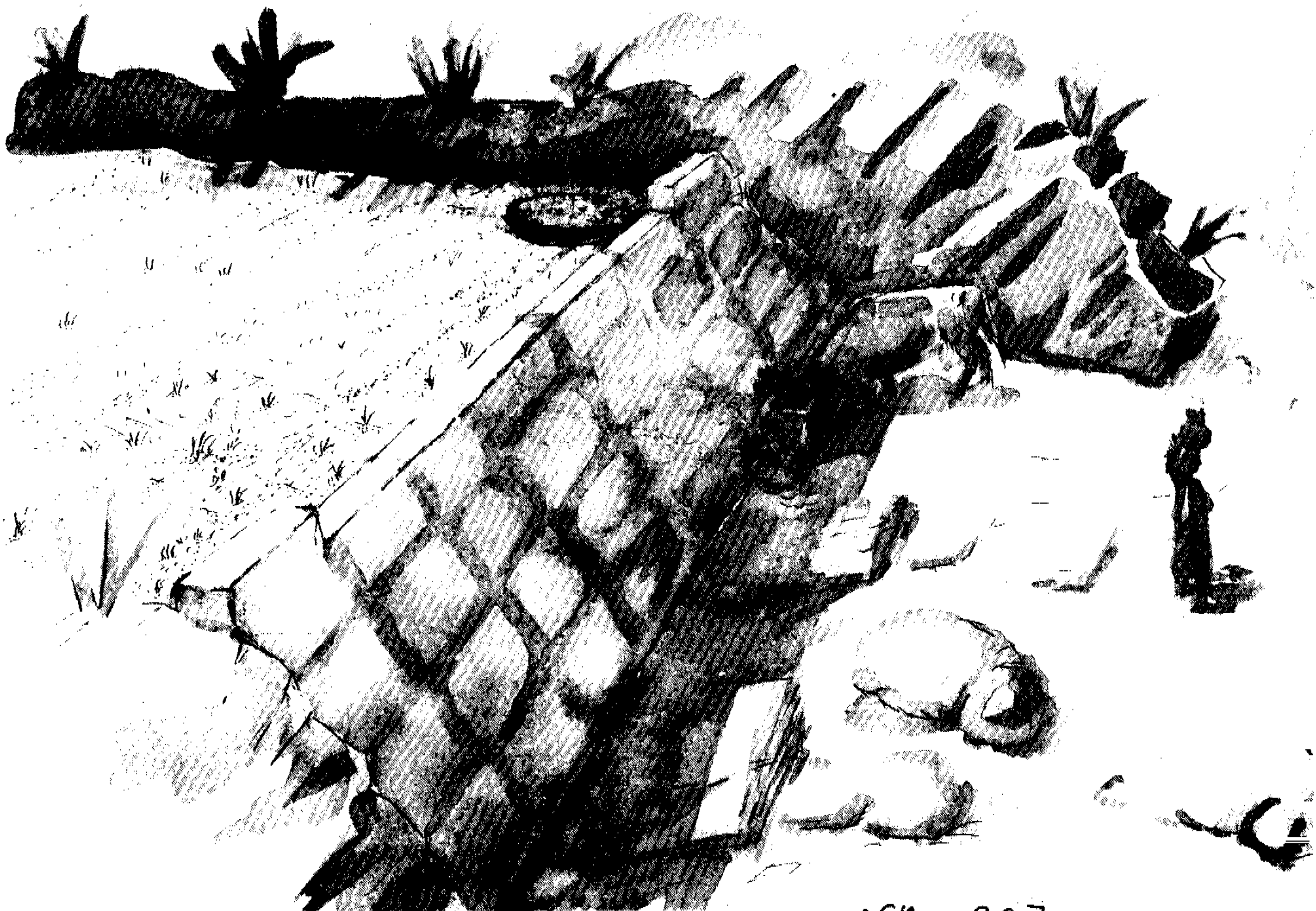

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RESEARCH REPORT

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PREFACE

This study presents the results of a literature study combined with study visits to Africa and India. The study has been financed by the Swedish Agency for Research Cooperation with Developing Countries (SAREC) to which I hereby express my gratitude.

I am grateful to Professor Gert Knutsson, Department of Land Improvement and Drainage, Royal Institute of Technology, for his support and guidance. I would also like to thank all colleagues and friends I have met in Africa and India who have so willingly supplied information and guided me in the field. In this respect I am especially indebted to staff of MAJI, Tanzania; DNA and GEOMOC, Mocambique; Ministry of Water Development and the Machakos Integrated Development Programme, Kenya; and the Central Ground Water Board, and the Tamil Nadu Agricultural University, India.

I would also like to thank colleagues in the informal ground-water dam working group formed by SIDA for valuable input to the study, and the staff of the RIT Library for finding all the strange documents I have been asking for.

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Stockholm in March, 1984.

Åke Nilsson

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PREFACE

SUMMARY

SUMMARY

Various methods for storing water in dry regions by means of damming ground water have existed for thousands of years. During the last few decades the methods have received an increased attention, and new techniques and applications are being tested in several research-oriented projects in different parts of the world.

The methods are simple and inexpensive and therefore suitable for application in connection with water supply schemes in rural areas in developing countries. This report is limited to this specific field, and presents the result of a literature survey and a field study of some projects in Africa and Asia.

Two types of ground-water dams are defined, namely sub-surface dams and sand dams. A sub-surface dam is constructed below ground level and arrests the flow in a natural aquifer, whereas a sand dam impounds water in sediments caused to accumulate by the dam itself.

A number of specific construction sites and areas where the methods have a general application were identified. A number of fairly large projects exist in Europe and north-western Africa. In certain parts of Ethiopia, East Africa and Namibia ground-water dams are used quite extensively as storage reservoirs for rural water supply. There is a long tradition of building ground-water dams in the arid south-western part of the United States and northern Mexico, and there are isolated examples of sub-surface dams in Afghanistan, India and Japan. The potential of using the method has been established and proposals for implementation put forward in reports from several dry-climate areas. A number of research projects are planned or have started in Afica and India.

The relation of the various techniques to physical conditions is discussed. The basic climatic conditions of low rainfall and high evaporation are the basic rationales for underground storage of water and topographical conditions govern to a large extent the construction alternatives and the possibilities of achieving large reservoirs with good recharge conditions. Sub-surface dams are generally built in river beds but also shallow residual-soil aquifers may have sufficiently good hydraulic characteristics. The parent rock, weathering conditions, extent of erosion and the sediment transport conditions determine the type of sediments accumulated in a sand dam.

Water stored behind sub-surface dams is generally used for drinking water and irrigation, whereas water stored in sand dams is used mostly for drinking water due to the lower quantities stored.

Only a few of the projects carried out by government agencies have resulted in new, self-sustained projects. This implies that a link is missing between the existing technology and the awareness of its benefits among the potential users. Such links could be promoted by local participation, improved health education, cooperative efforts and the realization of economic benefits. The economy of storing water by ground-water damming is discussed.

There has generally been a lack of general as well as detailed planning in the projects studied. In some cases it is evident that a more thorough planning involving the use of remote sensing, hydrogeological studies and simple geophysical methods would have resulted in better designs and more successful schemes. However, the investigations preceding construction should be kept at a level adapted to the low total costs involved. The suitability of various investigation methods is discussed.

Several design and construction alternatives are presented. The most common types of sub-surface dams are clay, concrete, stone masonry and brick walls built in excavated trenches of 3 - 6 m depth. Also ferroconcrete and sheets of polyethylene or tarfelt have been used. In deep aquifers it may be necessary to use injection screens. Sand dams are mostly built by concrete or stone masonry but there is a potential to use also gabions or blocks combined with clay layers. Water extraction from a ground-water dam is mostly by large-diameter wells, or when topography permits, by gravity.

The proper connection of ground-water dams to solid, impermeable rock or un-consolidated layers is important to avoid erosion and seepage losses. A ground-water dam may also serve the purpose of replenishing adjacent aquifers.

The risk of negative environmental impact is low, provided a scheme has been properly planned. Aspects that have to be considered are the possibility of upstream water logging, effects on downstream flow, pollution problems caused by higher ground-water levels, and salt accumulation.

A brief resumê of the identified schemes is given and case histories from Kenya, Tanzania and India are presented.

1 INTRODUCTION

The period 1981-1990 has been declared the International Drinking Water Supply and Sanitation Decade by the United Nations. The target of the Decade is the supply of safe water and sanitation for all by 1990. The target group is some 2 billion people living mainly in rural areas of the Third World. It is evident that the target can not be attained unless there is an orientation away from expensive, sophisticated techniques towards appropriate, low-cost and socially acceptable techniques that are adapted to local conditions.

Many developing countries are located in climate regions where rainfall is seasonal and highly erratic. The supply of water in such regions is to a large extent a matter of storing water from the rainy season to the dry season, and from years with high rainfall to dry years. The use of ground water is a method of overcoming the seasonal shortages, but in some areas even the ground-water resources are depleted towards the end of the dry season and in many areas there are no aquifers available, or they would require deep-drilled wells and pumps for development, a fact that makes this alternative less suitable in certain socio-economic environments.

The technical solution most commonly applied today, to solve the storage problem is surface storage by means of dams or ponds. The list of serious disadvantages related to surface storage of water is long; evaporation losses and pollution risks are high, valuable land is occupied by water, dams are often filled up by silt or covered by vegetation, mosquito breeding and spreading of snail fever is promoted etc.

An alternative method which solves most of these problems and which has received considerable attention during the last few years is the use of ground- water dams.Damming ground water for conservation purposes is certainly not a new concept. Ground-water dams were constructed on the island of Sardinia in Roman times and structures in Tunisia show that damming of ground water was practised by old civilisations in North Africa. There is a report of a sand dam built in Arizona already in the 18th century. More recently, various small-scale ground-water damming techniques have been developed and applied in many parts of the world, notably in southern and East Africa, and in India.

The most common reason for damming ground water is to store water below ground level in the reservoir upstream of the dam. A ground water dam may also serve the purpose of raising the ground-water level and thereby improving the recharge to adjacent aquifers. It may also serve to protect aquifers from pollution or sub-surface works from unwanted ground-water seepage.

In connection with water supply there are basically two types of ground water dams, namely sub-surface dams and sand dams. A sub-surface dam is constructed below ground level and arrests the flow in a natural aquifer, whereas a sand dam impounds water in sediments caused to accumulate by the dam itself.

The general principle of a sub-surface dam is shown in Figure 1.1. An aquifer consisting of fairly permeable alluvial sediments in a small valley supplies water to a village by means of a shallow dug well. Due to consumption and the natural ground-water flow, the aquifer used to be drained out during the dry season and consequently the well dried up. To prevent this, a trench was dug across the valley, reaching down to bedrock.An impervious wall was constructed in the trench, and then the trench was refilled with the excavated material. The reservoir thus built up will not be drained out and may be used throughout the dry season, provided of course that the storage volume is sufficient to meet the water demand.

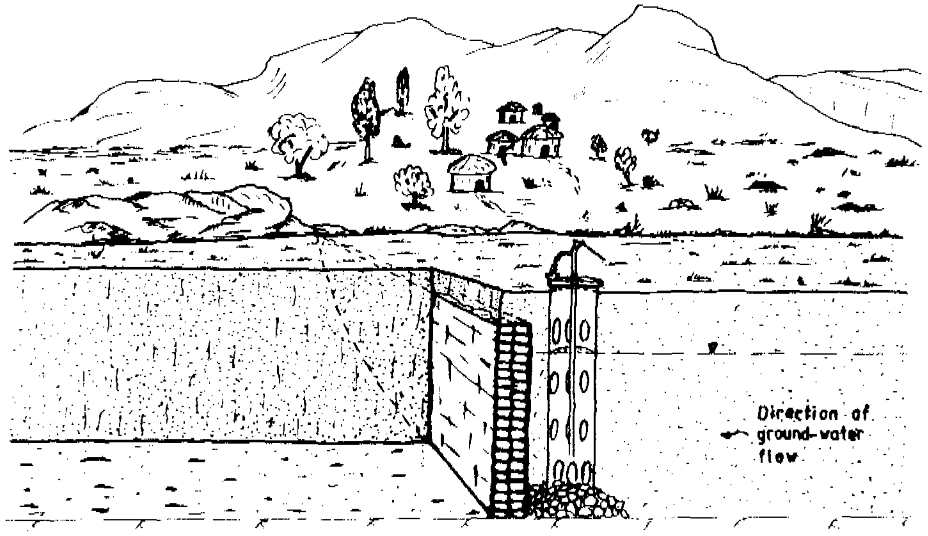

Figure 1.1 General principle of a sub-surface dam.

Sub-surface dams are often built in river beds, since these generally constitute highly permeable aquifers with good storage potential.

The general principle of a sand dam is shown by the example in Figure 1.2. The villagers used to collect their water from the small non-perennial stream at times when it carried water, or from holes dug in the shallow river bed for a short period after the rains. The quantity of water stored was not sufficient, however, to supply water to the village during the entire dry period. By the construction of a weir of suitable height across the stream bed, coarse particles carried by heavy flows during the rains were caused to settle and the reservoir was eventually filled up with sediments. This artificial aquifer will be replenished each year during the rains and if the dam has been properly sited and constructed, water will be kept in the reservoir for use during the dry season.

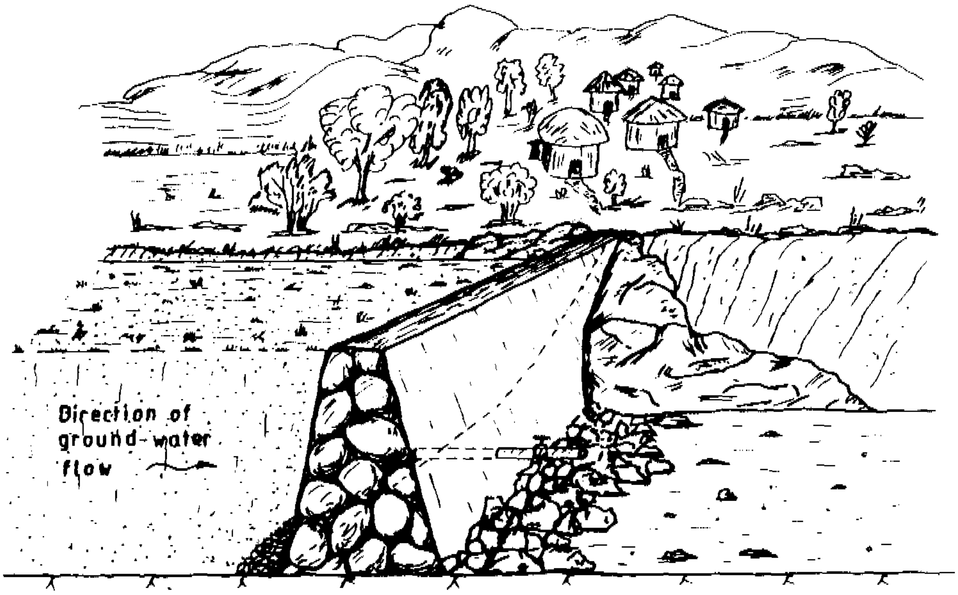

Figure 1.2 General principle of a sand dam.

By using this method it is often possible to extract water by gravity from the reservoir by using a a pipe through the dam wall, thus avoiding the construction of a well and the problem of pump installation and maintenance.

Quite often a ground-water dam is actually a combination of the two types. When constructing a sub-surface dam in a river bed, one may wish to increase the storage volume by letting the dam wall rise over the surface, thus causing additional accumulation of sediments. Similarly, when a sand dam is constructed it is usually necessary to excavate a trench in the sand bed in order to reach bedrock or a stable, impervious layer.

This study presents the result of a literature study combined with field visits to some sites in Africa and India where ground-water dams have been constructed or proposed. A general impression from working with literature collection is that quite a lot has been written, but mostly the literature consists of specific reports from isolated projects. Two exceptions from this rule are Wipplinger (1958) and BCEOM (1978), which present experience from Namibia and french-speaking Africa respectively. The present report does not, although it covers experience from many parts of the world, pretend to be exhaustive in any respect. It presents general conclusions in the introductory chapters and finally some of the field projects are described. For details, however, the reader is referred to the basic documents which are all included in the list of references.

The main subject of the report is the storage of ground water for water supply in developing countries. Ground-water dams for the protection of aquifers or sub-surface works, or such technical solutions that are developed in, and especially adapted for, climatic and technological conditions typical for industrialized countries are not treated at any depth.

Figure 1.3 shows a map of the world where all ground-water dam construction sites identified under this study have been marked. The map also shows areas where it has been proposed after preliminary investigations to implement the technique. Most of the sites and areas have been described in the following text and notably in Chapter 6.

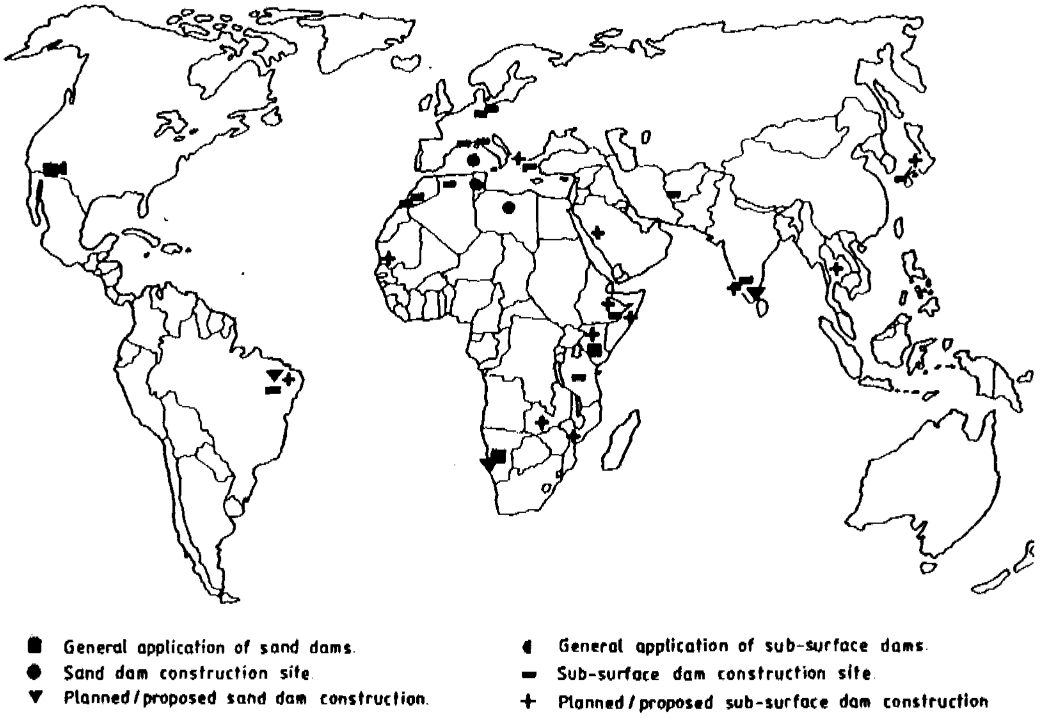

Figure 1.3 Identified ground-water dam sites and areas for proposed or planned construction.

The interest for using ground-water dams for water supply has increased during the last few years in connection with rural development projects, and several research projects are planned or have already started. In Ethiopia a project carried out by VIAK, Stockholm, 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 will site and construct a number of dams in Kerala, and a research project at the Royal Institute of Technology, Stockholm, will develop regional suitability plans and construction site recommendations for an area in south India. There has been a comprehensive study covering also socio-economic aspects regarding the possibilities of implementation in Nordeste, Brazil, by IPT, São Paulo.

2 PHYSICAL CONDITIONS

2.1 CLIMATE

The rationale of damming ground water for water supply purposes is basically the irregularity of rainfall. In arid areas of the world every drop of water is valuable and has to be saved, since nobody knows when the next rain will come. In monsoon-climate areas the total amount of rainfall would generally be sufficient to cater to the needs of people and agriculture, but here the seasonality means that during some parts of the year water is not available. Damming ground water is thus a means of bridging over the seasonal dry periods. In addition, quite often the monsoon rains also fail and this can have a disastrous effect on the water-supply situation.

Damming of`ground water may also be done in such climatic regions where water is available throughout the year, but where one wishes to increase the quantity or raise the ground-water level in the aquifer actually dammed, or through lateral or vertical seepage to surrounding or underlying aquifers.

Figure 2.1 shows a map where all dry, monsoon and tropical wet-and-dry climate areas of the world have been marked. These are the parts of the world where the rainfall conditions are most suited for damming ground water and hence it is not a surprise to notice the correspondence with the map showing the actual sites in figure 1.3.

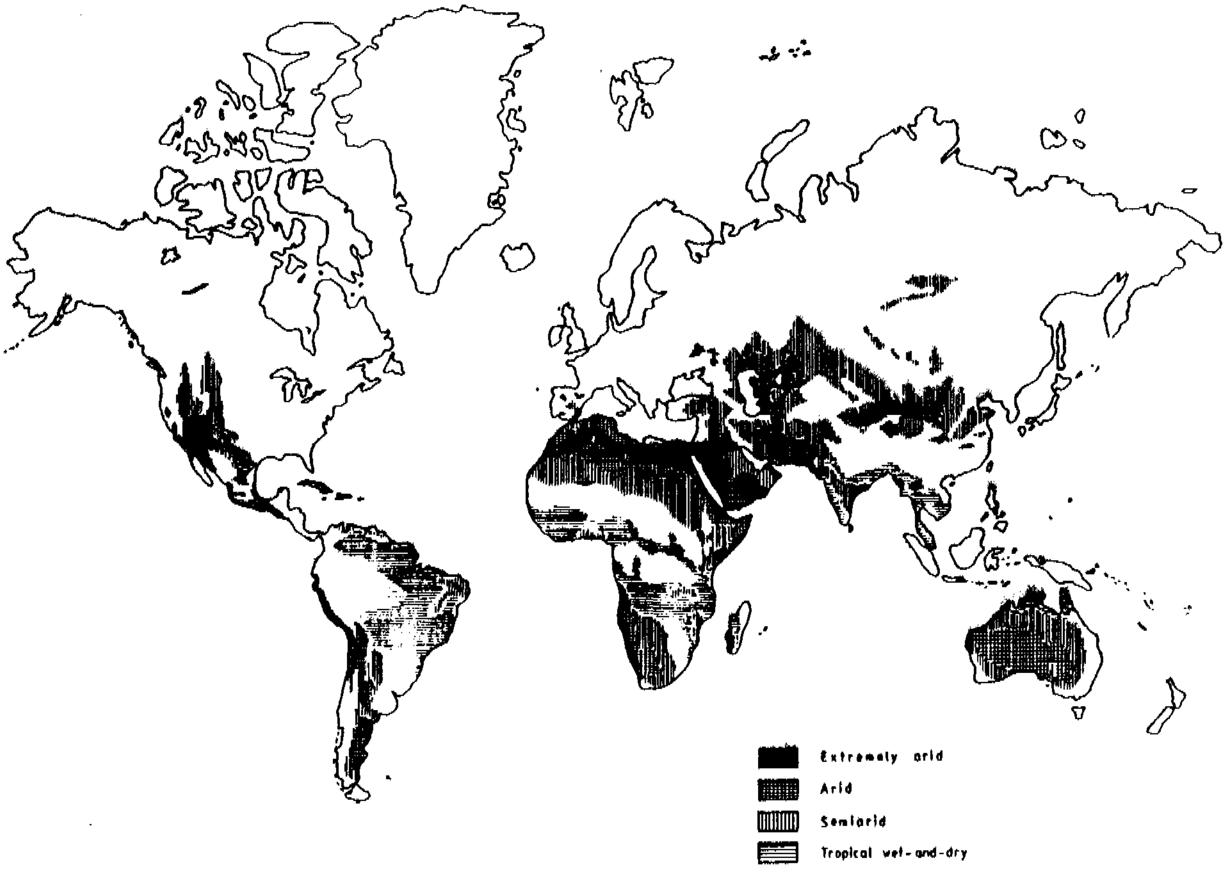

Figure 2.1 Dry, monsoon and tropical wet-and-dry climate areas (adapted from White, 1956).

The arid areas of the world are by Köppen's definition those where the potential evaporation is larger than rainfall. The relative advantage of damming ground water as compared to common surface storage depends to a large extent on the losses that would result from open-surface evaporation. Some values of potential evaporation from relevant areas where ground-water dams have been constructed or proposed are presented in Table 2.1.

Table 2.1 Rainfall and potential evaporation data from some dry areas.

Area	Average rainfall (mm/year)	Potential evaporation (mm/year)	Reference
Biskra, Algeria	180	1.330	UN, 1973
Tarfaya, Morocco	110	850	UN, 1973
Moudjēria, Mauritania	170	1.870	UN, 1973
Lugh Ferrandi, Somalia	360	2.060	UN, 1973
North Turkana, Kenya	200-600	>2.500	Sørlie, 1978
Machakos, Kenya	850	1.600-1.800	Fellows&Fridfeldt,1983
Dodoma, Tanzania	590	1.110	UN, 1973
Catuane, Moçambique	670	1.300	UN, 1973
Gross Barmen, Namibia	400	2.260	Hellwig, 1973
Palghat Gap, India	2.000-3.000	1.550	Central Ground Water Board, 1980
Bartlett Dam, Arizona	350	3.090	Skibitzke et al.,1961
Nordeste, Brasil	500-1.000	2.000	IPT, 1981

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

Hellwig (1973) has studied quantatively the evaporation of water from sand at experiments at Swakop River in Namibia. The evaporation from a saturated sand surface was found to be approximately 8% less than from an open water surface. The lowering of the water table by 0,3 meters below the sand surface reduced the evaporation from a fine sand to 50% of that from an open water surface. The corresponding figure when keeping the water level at 0.60 meters depth in medium sand was 10%. The relation between evaporation and depth of water table is shown in Figure 2.2.

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% to 0.7% in a layer of medium sand,

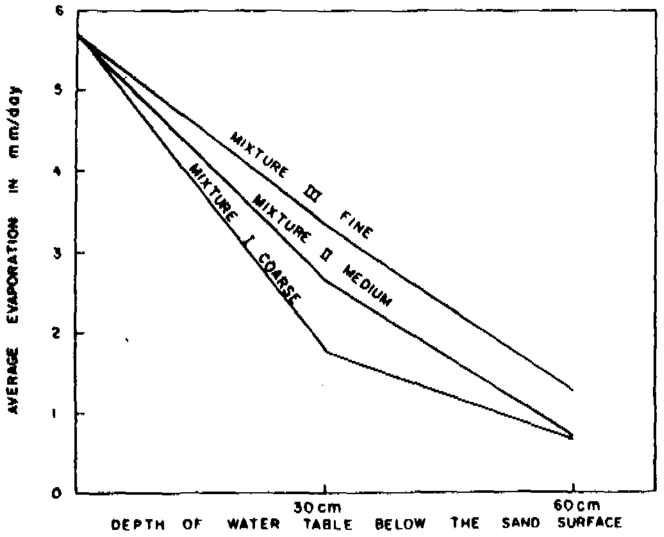

Figure 2.2 Evaporation as a function of depth to water table (Hellwig, 1973).

reduced evaporation by 25% at 0.30 meters depth to the water table. It is important therefore that the accumulation of fines at shallow depths in sand dams is avoided. Evaporation as a function of particle size is shown in Figure 2.3.

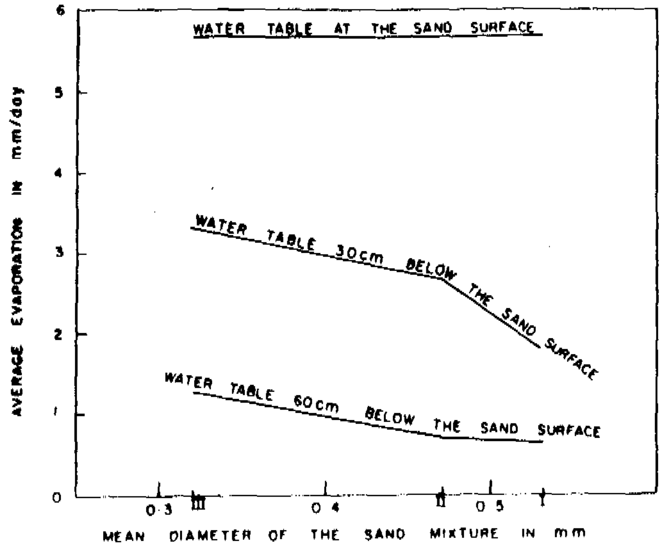

Figure 2.3 Evaporation as a function of grain size (Hellwig, 1973).

2.2 TOPOGRAPHY

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

The basin in which water is to be stored may be underlain by tight bedrock or low-permeable unconsolidated formations. It is generally preferable to site ground-water dams in well-defined and narrow valleys or river beds. This reduces costs and makes it possible to assess storage volumes and to control possible seepage losses. This is apparently difficult in areas with flat topography, where on the other hand the possibility of recharging adjacent aquifer is more obvious. On the other hand storage volumes have to be maximized keeping dam heights as small as possible. In mountainous areas with very high gradients, it might be difficult to find an acceptable relation between storage volumes and dam height.

One of the basic conditions justifying the construction of a subsurface dam is the depletion of ground-water storage through natural ground-water flow. The gradient of the ground-water table and thus the extent of flow is generally a function of the topographic gradient. This fact indicates that the construction of sub-surface dams is feasible only at a certain minimum topographical gradient, which naturally varies according to local hydro-geological conditions.

Examples of topographical gradients at some construction sites are presented in Table 2.2. Generally the gradient is between 1.5-4% but in extreme cases sand dams have been constructed in gulleys of 10-15% slope.

Table 2.2 Topographical gradients at some construction sites.

Site	Type of dam	Gradient (%)
Medenine, Tunisia	Sand dam ("jessours")	4
Machakos, Kenya		
general	Sand dam	3-4
extreme	Sand dam	10-15
Bihawana, Tanzania	Sub-surface dam	1.5
Namibia		
general	Sand dam	1.5-3
extreme	Sand dam	10-15
Ottapalam, India	Sub-surface dam	4
Ananganadi, India	Sub-surface dam	3
Arizona, USA	Sand dam	4

The particle size of sediments accumulated along streams and in river beds is generally proportional to the topographical gradient whereas on the other hand, the depth and lateral extent of such deposits is inversely proportional to the gradient. The optimum relation between these two factors, and thus the most favourable sites for sub-surface dams, is generally found on the gentle slopes in the transition zone between hills and plains.

The topography of the impermeable beds or bedrock underlying the storage reservoir determines storage efficiency and methods of dam construction. Figure 2.4 shows how the existence of natural underground dams in the form of rock bars improves the natural ground-water conditions (Skibitzke et al., 1961). They may also constitute promising locations for the construction of ground-water dams that would further increase the amount of exploitable water (Sörlie, 1978). Also natural dikes may have a damming effect that could be enhanced by the construction of ground-water dams (Newcomb, 1961). The presence of surface rock bars is generally necessary for the construction of sand dams (Werner 1982), c.f. case history from Machakos, Kenya in Chapter 6.

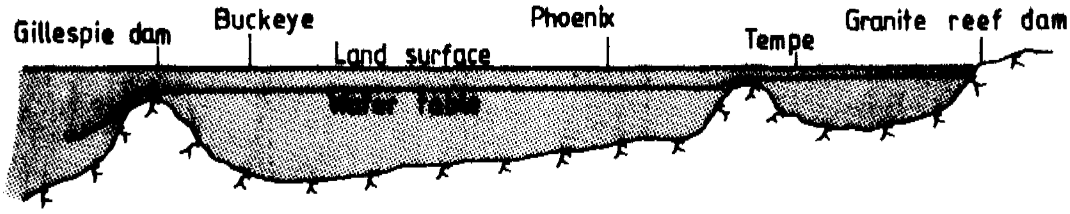

Figure 2.4 Effect of rock bars on ground-water table, Salt River valley, Arizona (from Skibitzke et al., 1961).

2.3 HYDROGEOLOGY

The most favourable type of aquifer for construction of sub-surface dams is definitely surficial river beds made up by sand or gravel. In-situ-weathered layers and deeper alluvial aquifers have also been dammed with success, even if such aquifers generally have less favourable storage and flow characteristics.

The specific yield of such water-bearing strata may vary from 5 to 50% depending on grain-size distribution, particle shape and compaction (Davis & de Wiest, 1966). Wipplinger (1958) reports a specific yield of approximately 25% from a typical river bed in Namibia, whereas the specific yield at the site of a sub-surface dam constructed in a residual-soil aquifer in south India was 7.5% (Ahnfors, 1980). These figures represent fairly well what can be expected in the two types of aquifers, and they are apparently of about the same order of magnitude.

Permeability values, however, are much more sensitive to the type of material constituting the aquifer. The permeability of coarse sand for instance, may be a hundred times higher than that of a very fine sand (Bedinger, 1961) and the presence of clay in a sand aquifer may reduce its permeability thousandfold. The problems that will be encountered when a sub-surface dam is constructed in an aquifer with fine-grained material is thus less related to available storage volumes than to extraction possibilities. The techniques that may be used to solve such problems will be treated briefly in Chapter 5.

A typical profile through a weathered layer is shown schematically in Figure 2.5. According to Taylor (1984) four zones can generally be identified within the profile. The uppermost zones (a) and (b) both have high porosity values but low permeability, whereas zone (c) has low porosity but high permeability. If such an aquifer is dammed, it would provide storage in zones (a) and (b), and zone (c) would act as a natural, and, due to its lateral extent, very effective drain transmitting the water for extraction at the dam wall.

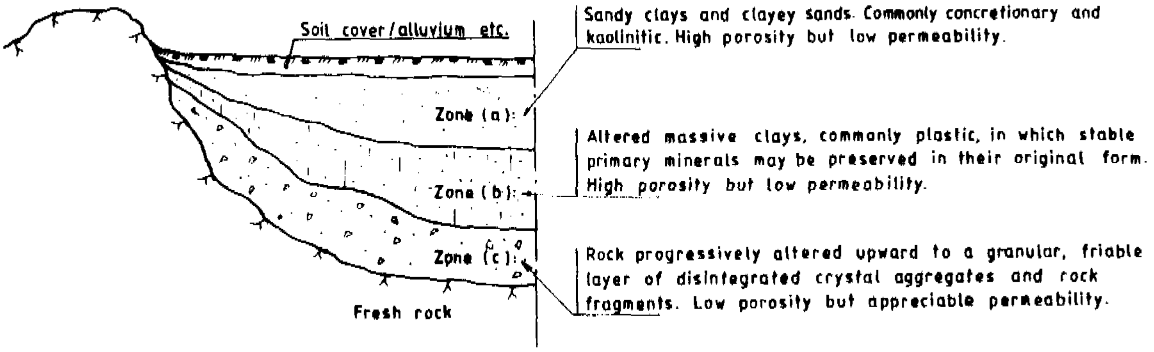

Figure 2.5 Schematical profile of a weathered layer (adapted from Taylor, 1981).

It has been proposed to construct sub-surface dams also in fractured hard-rock aquifers (Larsson & Cederwall, 1980). Such dams would consist of grout curtains cutting off the flow in deep-seated, permeable fracture zones. It would then be possible to stop the drainage effect of such zones and thereby improving the storage in over-lying aquifers. The grout injection technique involved, however, makes this method more suited for large-scale application than for the small-scale rural water supply schemes in developing countries that are within the scope of this report.

Sub-surface dams are, mainly for reasons of the excavation techniques applied, suited for shallow aquifers. The maximum depths of the two dams in residual soils in South India are 4 and 9 m respectively. The depth of sub-surface dams built in river beds is generally around 3-6 meters.

The slope stability of the excavated material, and the acceptable costs for any form work that has to be constructed, set the limit for dam depths.

The fact that aquifers dammed by sub-surface dams are generally shallow means that they are also generally un-confined. Matsuo (1975), 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. By damming a deep, confined aquifer it may be possible to control large quantities of water with a relatively small dam area, but it implies that the hydrogeological conditions must be well known through geophysical investigations. If considered for application in developing countries, it should be realized that it necessitates the application of a sophisticated and expensive technology which might not always be appropriate. For large-scale application where it is possible to accept high construction costs, however, it has certainly a high potential.

The basic idea behind constructing a sub-surface dam for storage purposes is to arrest the natural flow of ground water, and before it can be judged whether a scheme will be beneficial or not, the extent of flow has to be estimated. The permeability conditions in the aquifers in question were treated briefly above. There has rarely been any attempt in the projects studied to quantify the extent of flow by using estimated permeability values and by measuring the actual gradients of the existing ground-water table. In some cases, the seasonal fluctuations of the ground-water levels have been estimated, and this has been used to quantify the additional storage effect resulting from the dam construction.Since any cost-benefit analysis is based to a large extent on this figure, it would be desirable in future projects to put a bit more effort into making it as realistic as possible. This can be done by a fairly simple monitoring programme involving a few observation wells in the aquifer.

Sub-surface dam reservoirs are generally recharged by lateral ground-water flow and the monitoring programme will give data showing its extent and direction. When the stored water is used for irrigation upstream of the dam, there will also be a substantial recharge from return flow provided the soils are sufficiently permeable.

Most ground-water dams are founded on solid bed-rock. In order to avoid seepage losses below the dam it should be as tight as possible, since it is very difficult to stop the leakage through fractures even if they are detected during construction of the dam. The fact that ground-water dams are either constructed in narrow valleys or ~~along~~ across rivers, that is along topographical elements that may often be considered as indicators of underlying fracture zones, makes caution necessary.

Under favourable conditions it may also be possible to utilize an existing clay or other impermeable layer as bottom of the storage reservoir. Such layers may be of alluvial origin, or they may constitute the uppermost part of a weathered layer.

Such layers are generally unfractured and, if sufficiently thick, fairly impermeable but they do not always have the basin structure that is characteristic for the bedrock and this may give rise to a lateral loss of water from the reservoir. When ground-water damming is considered for aquifer recharge purposes, however, they may be excellent.

2.4 SEDIMENTS

The deposition of sediments upstream of a sand dam is the final result of a series of natural physical processes which will all have an influence on the hydraulic characteristics of the sediments. The parent rock in the catchment is the basis, weathering processes disintegrate the rock, and soil particles are detached by erosion, transported by water and finally deposited in the storage reservoir. 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, since research has been focused on total rates of erosion in the catchments and on total rates of sediment deposition in the dams, the findings are not directly applicable to this topic, since sand dams utilize only one fraction of the total sediment load.

Hydrological and hydraulic aspects of sedimentation directly relevant to the storage of water in sand dams have been treated extensively by Professor O. Wipplinger. His work is based on studies in Namibia, but the results are probably applicable also to similar parts of the world. The reader is referred to Wipplinger (1958) where detailed studies on river discharge, sediment characteristics in natural river beds and sedimentation processes in pilot sand-dam schemes have been excellently presented.

The type of parent rock in the catchment from where sediments originate determines the amount of coarse particles in the total sediment load. The most favourable rocks are coarse granite, quartzite and sandstone, but also dams constructed in gneiss and mica-schist areas have been successful. 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 basalt and rhyolite tend to be less favourable for sand dam construction.

Climate has a great influence on sediment characteristics in that it 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. Thus, contrary to what agricultural and hydraulic engineers generally would feel, an engineer planning the construction of a sand dam would be happy to find steep slopes with little vegetative cover in the catchment area.

The coarse sediments one wishes to trap in a sand dam are those generally transported as bedload. It is therefore necessary that the rainstorms producing the initial floods at the outbreak of the rainy season are sufficiently heavy to cause a bedload transport.

When surveying an area to find out whether it is suitable for the construction of sand dams, one should not be immediately discouraged by the fact that there are no sand deposits along the river. This might be the result of a high-intensity rainfall pattern causing such heavy flows that deposition is not possible under natural conditions. Such conditions prevail in parts of Kerala, India (Jacob, 1983).

3. USER ASPECTS

3.1 WATER USE ALTERNATIVES

The volumes of water which it is possible to store by ground-water dams of different types and in different physical environments determine the water use. The amounts needed for irrigation purposes are quite large whereas schemes designed for small-scale drinking water supply may involve the storage of less than a hundred m^3 and still be economically sound.

Table 3.1 shows how the water stored in existing known schemes is being used. Although the number of schemes included in the material is quite limited it is apparently possible to draw some conclusions, general as well as related to different types of dams.

Table 3.1 Main use of water and approximate volumes stored in existing known schemes.

Main water use	Sub-surface dams		Sand dams	
	Number of schemes	Appr.volumes (m^3)	Number of schemes	Appr. volumes (m^3)
Irrigation	8	$15.000\text{-}10^6$	1	6.000
Drinking water	7	400.-2.000	6	50-2.500

Generally water stored behind ground-water dams is used for drinking water or irrigation. Only exceptionally is it being used also for industrial purposes. One such example is from India where some of the water stored behind a sub-surface dam is being used in a small-scale industry. Another is a dam constructed in 1928 in Tanzania where some of the stored water was used to supply the needs of the railway.

There is a clear functional difference between sub-surface dams and sand dams in terms of water use. Only one of the sand dams is primarily used for irrigation purposes, whereas half of the sub-surface dam schemes supply water for irrigation. The reason for this is clear from the approximate figures of stored volumes. It is possible to store relatively large quantities by damming existing aquifers, and this is generally a pre-requisite when irrigation is considered. It should be mentioned, however, that in some areas of the world a fairly limited quantity of water may help bridging over occasional dry spells during the rainy season or it may prolong the cropping period by a few days and thereby making it possible to grow an extra second or third crop.

Conflicts between different groups of users may develop when the amounts of water available is limited. There is a risk that people tapping water for drinking purposes will have difficulties in claiming their rights against land-owners using the water for irrigation.

The way water is used determines which type of water extraction system can be applied. For irrigation schemes it may be economically and technically feasible to construct wells and install motor pumps, whereas for small-scale drinking water supply it may be better to use gravity extraction, or at least make do with hand pumps. The population distribution pattern will also determine the required storage volumes and the choice of extraction and distribution systems.

3.2 ORGANIZATIONAL FACTORS

Most of the schemes identified, planned and executed by government agencies have been executed as research projects with the apparent purpose of encouraging imitation. In most areas where such pilot projects have been tried, however, there has been rather a limited effect in terms of new, self-sustained projects. This has been the case for instance in Tanzania and India, for which case histories are presented in Chapter 6.

In the vicinity of Dodoma in Tanzania a number of sub-surface dams were constructed by the Geological Department and the Public Works Department in the beginning of this century. The available records are incomplete, but at least one of them seems to have been fairly successful. The area is from geographical and technical points of view excellent for the construction of sub-surface dams; the rainfall is scarce and seasonal, the terrain is gentle, thick and well defined river beds made up by coarse sediments and underlain by low-permeable layers are common features, and dam construction materials are available. In spite of this it took 40 years before another dam was constructed in 1967, this time on private initiative. The success of this dam proves that ground-water dams are technically feasible in the area, but evenso there has up to now been no new attempt. So the reason why the technique is not being used has to be found elsewhere; there is a missing link between the existing technique and its practical application. This is to a large extent an organizational problem and a matter of finding ways to combine efforts from government agencies with the participation of the local users in the planning, construction, operation and maintenance phases. It is also important that the potential users are made aware of the benefits they will get from an improved water supply, for instance by promoting health education.

In India the problem is of a different nature. Two sub-surface dams have been built in Kerala State, a part of the country which is densely populated and where the average land holdings consequently are small. Both existing dams were built on quite large farms; one on a private farm and one on a government seed farm. Since the construction of a dam generally would involve several farms, a more general introduction of the technique in the area depends on the possibilities of promoting co-operative efforts among the farmers. Another alternative would be to adapt the technique to the existing conditions by finding ways to construct smaller dams.

Namibia may serve as an example of where the introduction of the technique has worked well. A successful sand dam was built in 1908 and this example has been followed ever since. Today the method seems to be generally applied and there has been a continuous development of technical solutions. The fact that the private farmers in the country easily have realized the economic benefits they can derive from increasing the amount of water available for their cattle, has certainly been an important part of the process.

3.3 ECONOMIC FACTORS

There are basically two different ways of approaching the economic feasibility of using ground-water dam techniques. One is to relate the costs involved to the economic benefits accrued from the improved water supply, the other is to compare the cost of a ground-water dam to that of a conventional technical solution. The latter is a rather straight-forward method provided some basic data is available, whereas a conventional cost-benefit analysis of water supply for a rural community in a developing country is extremely difficult to make.

Carruthers & Browne (1977) have described the problems involved in a cost-benefit analysis of water supply projects. Estimating the costs of a project can be done by shadow pricing financial costs and discounting the stream of future costs, even if this involves problems of finding the correct shadow prices and determining an appropriate discount rate. More difficult is to valuate the future benefits; what are the benefits and how much are they worth in economic terms? When the project supplies water for irrigation it may be possible to do this, but if the water is used for domestic purposes, it is not easy to define the benefits economically even if the production and health effects are known and positive. An additional problem is that water supply alone does not improve, for instance, the health conditions in a village, but there has to be other inputs like improved sanitation, health education etc. Having this in mind, it is questionable to use a conventional cost-benefit analysis in this connection and if it is done, the results should be treated with utmost care. One method employed by the World Bank is to use expected revenues as a measure of the benefits, but this is likely to underestimate the real benefits substantially.

Comparing a ground-water dam scheme with a conventional solution is a more simple method. Burger & Beaumont (date unknown) have compared the cost of a sand dam for drinking water supply to that of a conventional surface reservoir under conditions specific to Namibia. By using depletion charts developed by Wipplinger (1958) they conclude that a conventional dam 12 m high and 80 m long will yield 20% of the impounded water or 46.000 m^3 per year, whereas a sand dam of corresponding size will yield 70% of the water stored in the sand or 41.000 m^3 per year. The astonishing similarity of these volume figures is primarily an effect of the evaporation losses involved in surface storage. The construction cost of a sand dam is a bit higher due to the fact that it has to be constructed during a period of several years with what that involves of re-establishing the construction gang etc. On the other hand the water in the surface dam has to be purified and the expected useful life of the dam will be limited due to siltation. A cash flow analysis for this example is presented in Table 3.2. Apparently the cost of using a sand dam is about 75% of that for a conventional dam under these specific conditions.

Table 3.2 Cash flow analysis for sand storage and conventional water supply projects (Burger & Beaumont, date unknown).

	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/year	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/year	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 = 96.500/391.000 = 24.7 cent/m^3

Cost of water for conventional dam = 107.200/330.000 = 32.4 cent/m^3

Cost of capital = 6%

4 PLANNING AND INVESTIGATION METHODS

4.1 EXPERIENCE FROM PREVIOUS SCHEMES

Most ground-water dam construction schemes are geographically isolated. Very few attempts have been made to make a more thorough regional physical study which would pinpoint areas where the geographical conditions would be particularly favourable for different types of dams. Present projects in Ethiopia and India are exceptions from this rule, and the study carried out by IPT (1981) gives guidelines for such a physical planning approach to be implemented in Nordeste, Brazil. The need for developing a systematic approach to site identification has been stressed by Nilsson (1983a and 1983 b) and Möller (1983).

There has also generally been a lack of over-all physical planning at the local scale, that is within actual project areas. Sites tend to have been chosen quite haphazardly from field trips more than by systematic studies. Also in this respect there are positive examples of projects where this is not so, one of them being a sand-dam project in Machakos, Kenya.

In consequence with the lack of over-all planning little use has been made of remote sensing methods like satellite imagery and air-photo interpretation. The geophysical and geotechnical methods applied in some cases have all produced site-specific data necessary for design, construction and economic analysis.

Since the construction of a ground-water dam generally is a rather straight-forward affair which should not cost much, it is understandable that the technical investigation methods used have been simple. The only technical investigations used before the construction of one of the sub-surface dams in South India, for instance, was a steel-rod sounding across the valley to find out the bedrock levels. A more research-oriented scheme in the same area involved land survey, a ground-water level monitoring programme, neutron-probe and tension-plate measurements of specific yield, hammer sounding and geo-electrical measurements.

There are unfortunately many examples of ground-water dams which have not been successful due to lack of planning and improper detailed design. This may have been caused by unforeseen seepage losses through underlying fracture zones, erosion damages due to improper bedrock foundation, etc, or it may have been the result of a total misinterpretation of the ground-water conditions at the site. In some cases it can be concluded that the use of quite simple geophysical methods combined with a proper analysis of the data could have resulted in a better design or the abolishment of a non-successful project. There is definitely a need to establish which geophysical methods would be relevant and possibly also to develop new simple investigation aids.

4.2 SUITABLE METHODS

For regional studies the most appropriate instruments are maps of various themes and satellite imagery. Topographical and geological maps are necessary for a regional study, and they generally exist in developing countries even if they may sometimes be difficult to acquire. Also thematic maps showing climatic, hydrological, hydrogeological, soil, vegetation or land-use conditions will yield valuable information. Satellite data is avalailable 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 1:200.000 is sufficient to draw general conclusions about the geological environment, ground-water conditions, surface runoff and erosion and sedimentation processes (Hansson, 1984).

It is important that reports from previous studies are collected and integrated in the analysis. Such reports will mostly cover the same themes as the maps listed above, but also more peripheral subjects may be of interest. It might for instance be possible to find relevant data on erosion and sedimentation in reports issued in connection with irrigation and hydro-power projects.

The local study following a regional analysis that has identified potential implementation areas, will involve more of field work and detailed investigations. The best instrument for finding actual groundwater dams sites is air-photo interpretation combined with map studies and field control. Also at this stage it is important to incorporate data from studies carried out previously.

Field measurements of surface water discharge and sedimentation should be done as simple as possible. If gauges are not available it is for instance possible to estimate peak flow levels from marks in the terrain or from interviewing people. Similarly the sediment transport and characteristics can be estimated to some extent from accumulation that has taken place close to existing rock bars.

A proper hydrogeological survey is essential in order to assess the benefits of the construction in terms of increased storage volumes, and in order to get a 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. 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 also include mechanical sounding or a geoelectrical survey when sub-surface dams are considered. The aquifer material should be hydraulically classified through in-situ as well as laboratory tests. Other hydrogeological methods such as chemical analyses, pumping tests, test drillings etc, should be applied only if necessary and economically feasible.

For economic reasons it is important to limit the use of sophisticated geophysical methods. One very usable method that should always be considered, however, is the VLF method which is an inexpensive and quite simple method of finding out the presence of open fractures that could drain the reservoir (Müllern, 1980; Parasnis, 1984). There are also systematic geological methods by which it is possible to use the interpretation of fracture zones in outcropping rocks in the area to predict the potential drainage effect of underlying fracture zones (Larsson, 1984).

The most common construction materials used for ground-water dams are brick walls, compacted clay, concrete and stone masonry. The dam has also in general some type of gravel filters for water extraction. To keep construction costs low it is important that as much as possible of the materials used, that is clay, sand, gravel and stones, are available locally, and this has to be established through a field survey that can run parallel to other field work.

5. DESIGN AND CONSTRUCTION

The principle designs of sub-surface dams and sand dams were shown in Chapter I. Since the two types are basically different, the presentation of design and construction alternatives has been divided into two parts, followed by a chapter on certain aspects which are common to both types.

5.1 SUB-SURFACE DAMS

The storage volumes of some existing schemes were shown in Table 3.1. The actual storage volumes of sub-surface dams range from a few hundred to several million m^3 and the designs are in consequence quite different. The following presentation concerns mainly small-scale schemes.

5.1.1 Earth works

The most common way of constructing a sub-surface dam is to build 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 3-6 meters.

The fact that the material in which the excavation is carried out generally is sandy, creates slope stability problems. Generally a slope of maximum 30^0 is acceptable for a sandy material and this means that in order to make a 4-meter deep trench in river sand, the width at ground level would be about 15 meters. This width can be greatly reduced by using formwork, but this will increase the total costs considerably. Since soil compaction is usually higher at greater depth, however, it is possible to increase the slope gradually. When earth work is carried out by manual labour it is necessary that the excavation is carried out in steps with horizontal levels every 2 or 3 m and this will further increase the width of the excavation.

The shape of a clay-dike sub-surface dam will determine the amount of earth work needed as shown in Figure 5.1. Since the second alternative means that more clay will be needed, 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 dams are generally constructed at the end of the dry season when there is little water in the aquifer. Usually there is some flow, however, and this has to be pumped out during the construction.

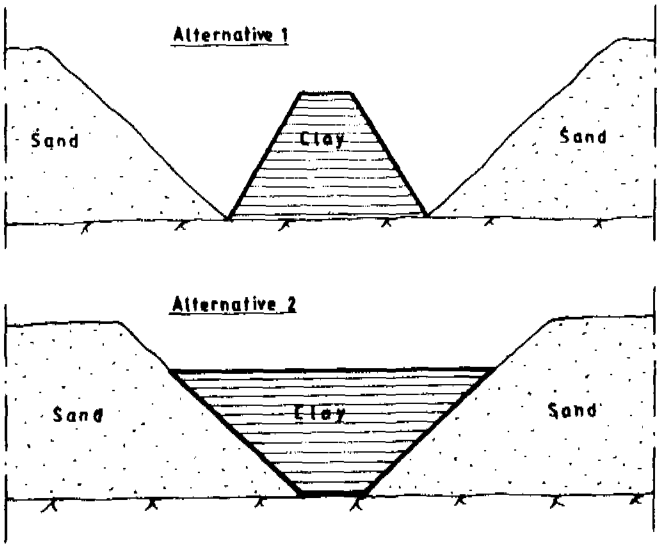

Figure 5.1 Schematic influence of clay-dike design on required earth work.

After the dam has been constructed the trench is refilled with the excavated material. It is important that the refill is properly compacted by manual compaction and watering.

5.1.2 Dam construction

Various construction materials have been used to create the impermeable screen. Some examples of materials that have been used are shown in Figures 5.2 - 5.9.

The clay dike in Figure 5.2 is an alternative 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 it can be mined and transported to the

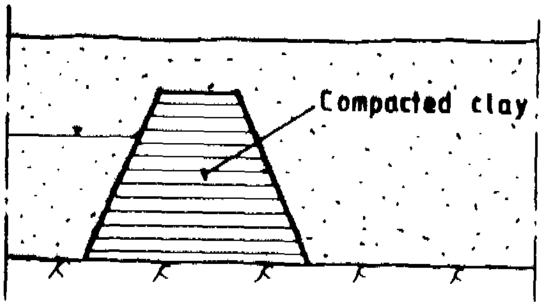

Figure 5.2 Clay dike.

site at low cost. The use of clay is a labour-intensive alternative and there is no need for skilled labour. A possible drawback is the large excavation generally needed when the dam is constructed according to alternative 1 in Figure 5.1. The clay also needs to be properly compacted. Further, there is a 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).

A concrete dam covered on both sides with block or stone masonry as shown in Figure 5.3 is an alternative involving a bit 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 it above the level of a river bed and use it for further sand accumulation.

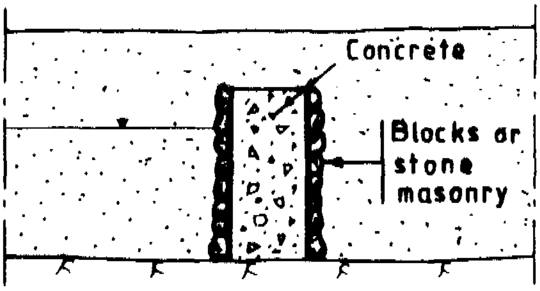

Figure 5.3 Concrete dam.

The same goes for the stone masonry dam shown in Figure 5.4 which is also an alternative necessitating the use of skilled labour and which is suited only for areas where stone masonry work is a part of the engineering tradition, which is not always the case.

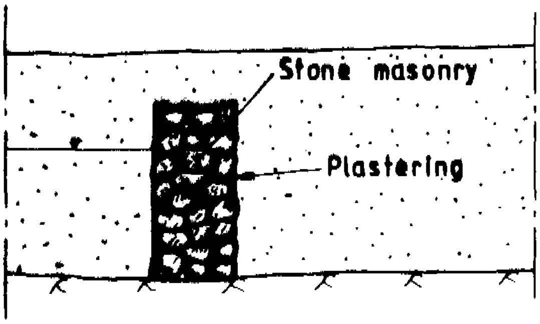

Figure 5.4 Stone masonry dam.

Using ferrocement (Figure 5.5) means that steel rods or wiremesh have to be brought in to the area, but generally such material is available at 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.

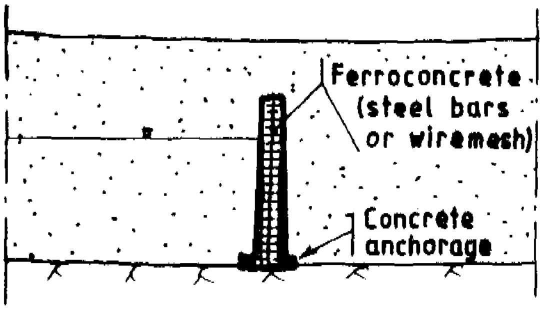

Figure 5.5 Ferroconcrete dam.

Bricks are generally available or may be manufactured from local clay. Building a brick wall as shown in Figure 5.6 and plaster it to make it water tight is a fairly simple procedure. The relatively high cost of bricks is a draw-back, however, and there are also some doubts as to the stability.

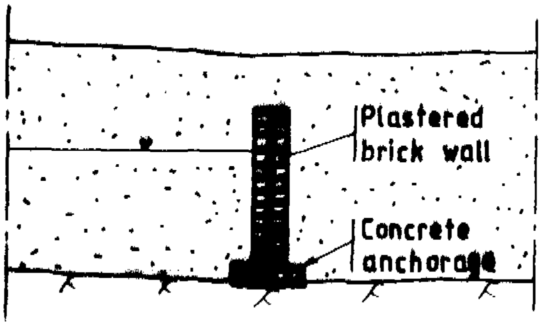

Figure 5.6 Brick wall.

Using thin sheets of impermeable materials such as tarfelt or polyethylene (Figure 5.7) is certainly the least expensive alternative as far as material cost is concerned. The mounting of the sheets to wooden frames and the erection process is a bit complicated. The material, especially the polyethylene, is highly sensitive to damage during the erection as well as during refilling of the trench, and a minor rip will cause leakage losses. There are also doubts as to whether plastic material will withstand high ground-water temperatures and the activities of micro-organisms in the soil.

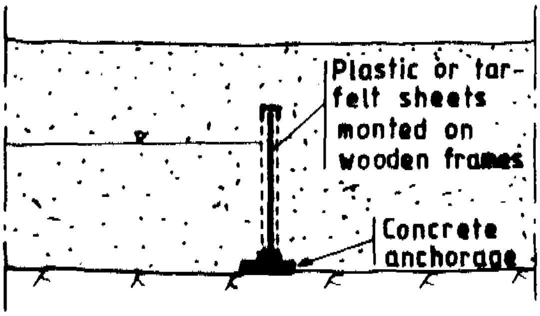

Figure 5.7 Plastic or tarfelt sheets.

Using sheets of steel, corrugated iron or PVC to build up an impermeable wall has still not been done to any large extent (Figure 5.8). 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 sturdy and definitely impermeable structure. One advantage is that the structure could extend over the surface of a river bed and accumulate additional sediments. It would also be possible to drive sheets of thick corrugated iron down into river sand from the surface and thereby raising the ground-water level in the bed. Common sheet piling has been used in connection with the construction of large sub-surface dams in North Africa.

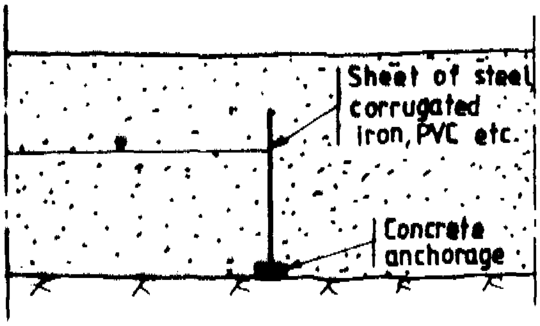

Figure 5.8 Sheets of steel, corrugated iron or PVC.

Injection screens (Figure 5.9) have been used to arrest the flow in large or deep-seated aquifers in North Africa and Japan, and to protect fresh water from pollution in Europe and USA. For very large projects and when a deep aquifer is dammed, it is certainly a feasible alternative.

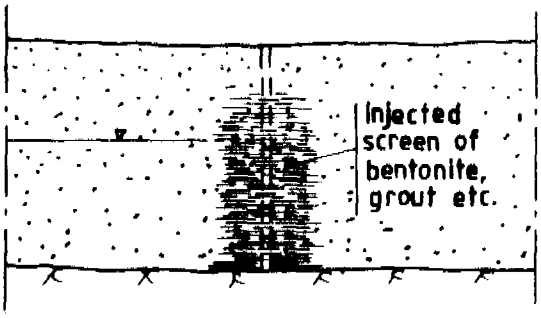

Figure 5.9 Injection screen.

The average heights of some of the dam types are shown in Table 5.1. In most cases the crest of a sub-surface dam is kept at some depth from the surface. This is partly in order to avoid water logging in the upstream area, and partly to avoid erosion damage to the dam. A common distance from dam crest to the surface is about 1 meter but it will vary according to local conditions.

Table 5.1 Heights of some sub-surface dam types - average values from studied schemes.

Dam type	Average height in meters
Injection screen	10
Brick wall	6
Concrete dam	6
Stone masonry dam	5
Ferroconcrete dam	4
Clay dike	3

5.1.3 Water extraction

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 or a 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. If the permeability of the aquifer material is very low it may be necessary to improve the flow also along the reservoir bottom by a system of collection gravel or slotted-pipe drains perpendicular to the dam. Although this method is more suitable for sand-dam reservoirs, it has been applied also in connection with sub-surface damming in river beds.

The well through which water from sub-surface dams is generally extracted may be placed in the reservoir or, for erosion protection reasons, in the river bank. 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.

If the community to be served by the scheme is located downstream of the dam site and the topographical conditions are favourable, it is possible to extract water from the reservoir by gravity. By using gravity extraction, problems with pump installation, operation and maintenance are avoided, problems which are today generally encountered in rural water supply projects in developing countries, even in such projects where shallow well and simple hand-pump technology is applied.

Figure 5.10 shows a typical sub-surface dam where both extraction alternatives have been shown.

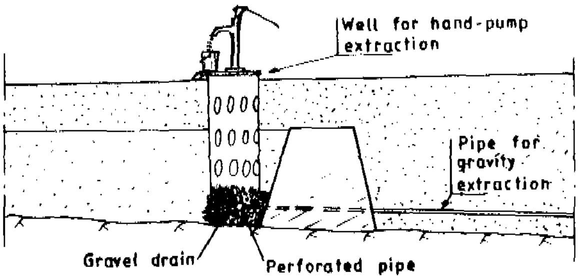

Figure 5.10 Water extraction alternatives from a sub-surface dam.

5.2 SAND DAMS

When a sub-surface dam is built it is always possible to get at least some idea of the hydraulic characteristics of the existing aquifer material. When planning the construction of a sand dam, however, the material in which the water is supposed to be stored is still lying in the catchment area waiting to be transported to the dam site by a flood of unknown intensity. The proper design of a sand dam is therefore a more complicated matter, involving more of hydrological and hydraulic calculations. Wipplinger (1958) has treated the various aspects involved more extensively and some further research has also been indicated in Burger & Beaumont (date unknown).Design instructions of a down-to-earth nature are given in Nissen-Petersen (1982).

5.2.1 Water flow

The surface flow of water in the stream under consideration will determine the design of the dam in terms of stability and height, as well as govern the sedimentation process in the reservoir.

An analysis of surface discharge data in the actual river or similar rivers in the same area would make it possible to arrive at dimensioning flows. Since such data is generally not available, simpler methods such as those mentioned in Chapter 4 may have to be used. Wipplinger (1958) has arrived at figures representative for Namibia which in turn are based upon experience from the Rocky Mountains in the USA.

The upper limit of dam construction and thus also the upper limit of storage volumes is set by the condition that the dam has to withstand the maximum peak flow. If the river banks are not made up by solid rock or if the banks cannot otherwise be safe-guarded against erosion, the peak flow has to pass between the dam crest and bank level.

5.2.2 Sedimentation

A sand dam is generally constructed in stages as shown schematically in Figure 5.12.

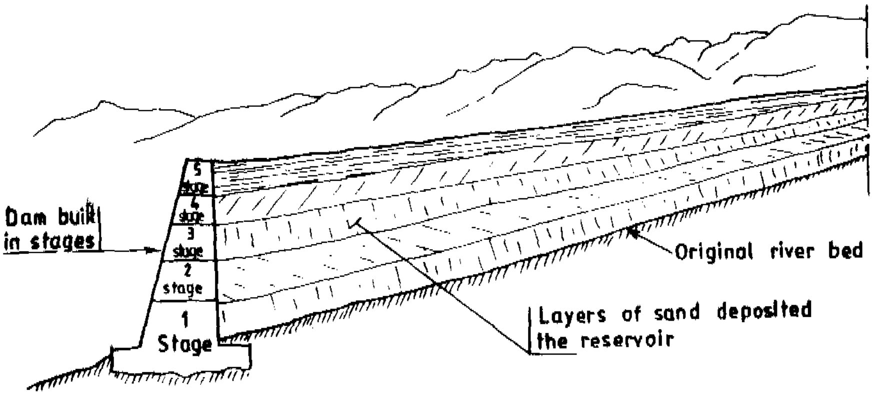

Figure 5.12 Construction principle of sand dam (from Burger & Beaumont, date unknown).

The basic idea is to limit the height of each stage in order to keep a sufficiently high velocity of the water so that fine particles are washed out from the reservoir while the coarse particles settle.

The height of each stage is determined by an estimation of the sedimentation process in the reservoir founded on experience from sedimentation in previous stages, from the extent of natural sedimentation in the stream, or calculations of water velocities in the reservoir.

When a large number of dams is constructed within the same project or by the same agency within the same area, the staff will build up an experience which will make it possible to arrive at a suitable stage height only by studying the particular site and by estimating the transport of sediments from the extent of erosion in the area (Werner & Haze, 1982). It is also possible to make quantitative analyses by arriving at limiting flow velocities from studying previous sedimentation.

There are several reasons why it is generally not possible to avoid the settling of fine particles in the reservoir, but it is for several reasons important to keep it as little as possible. The specific yield and the permeability of the whole reservoir will be lower, and the evaporation losses higher with a higher percentage of fines (Hellwig, 1973). Another factor which is very important is that fine 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 the costs will be higher than they would be if the dam were constructed to full height directly. 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 to be technically efficient and furthermore it is very costly (Burger & Beaumont, date unknown). Another method is to leave a notch in the dam which allows the settling of sediments only up to a certain height. The notch is then filled in before the next rainy season and the reservoir is allowed to be filled completely. This method has proved quite successful in Kenya (Werner & Haze, 1982).

5.2.3 Dam construction

Some dam types are shown in Figures 5.12 - 5.17.

Figures 5.12 and 5.13 show a concrete and a stone masonry dam respectively. These two types are by far the most common. They fulfill the basic requirement for a sand dam; that is they are sufficiently massive to take up the pressure from the sand and water stored in the reservoir. In addition, they are watertight. For larger reservoirs they have the form of arch dams.

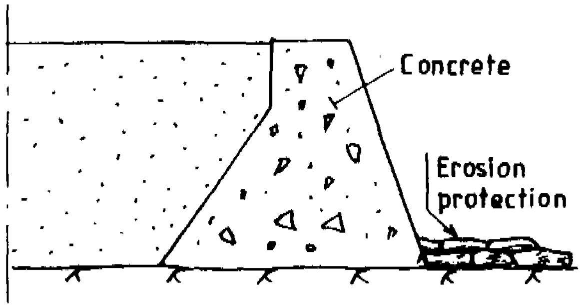

Figure 5.12 Concrete sand dam.

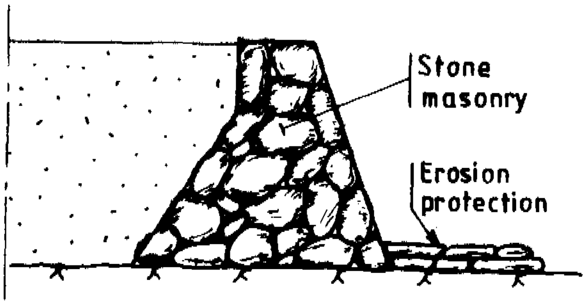

Figure 5.13 Stone masonry sand dam.

Figures 5.14 and 5.15 show two examples where the weight of the dam is made up by stone gabions or large blocks which are sufficient to withstand the pressure. In Figure 5.14 the gabion or block dam is covered on the upstream side by a thick layer of clay. In Figure 5.15 the core of the dam is made up by a clay wall.

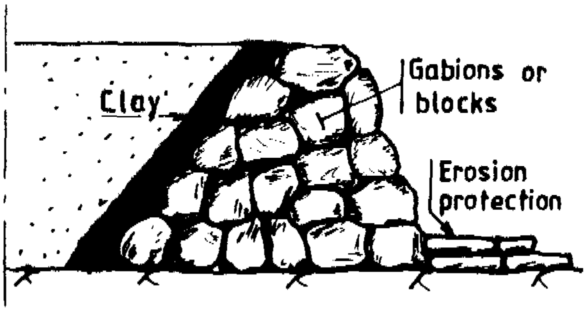

Figure 5.14 Gabion sand dam with clay cover.

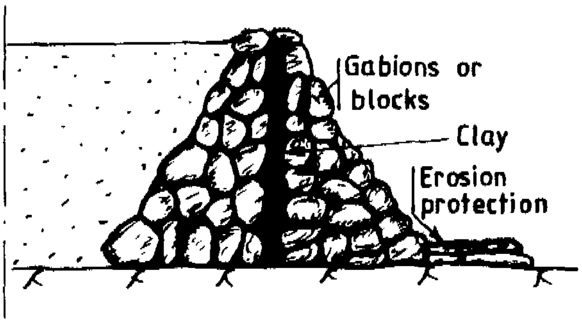

Figure 5.15 Gabion sand dam with clay core.

Figure 5.16 shows an example of a sand dam where the main dam body is made up by a heap of stones which are covered by concrete walls for stability and tightness. In reality a dam of this type serves at the same time as a bridge over a small stream in Kenya.

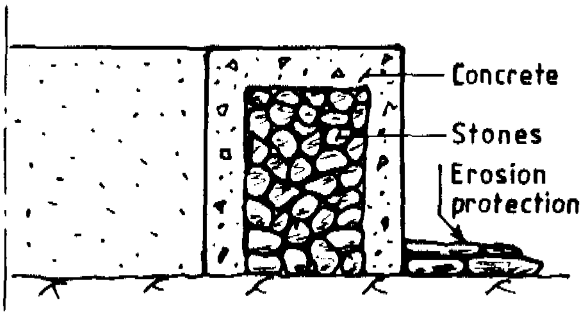

Figure 5.16 Stone-fill concrete sand dam.

A sand dam does not necessarily have to be watertight. The dam in Figure 5.17 consists of flat stones which have been piled up to form a massive dam which allows water to seep through it at a rate which is sufficient to water cattle in a trough downstream.

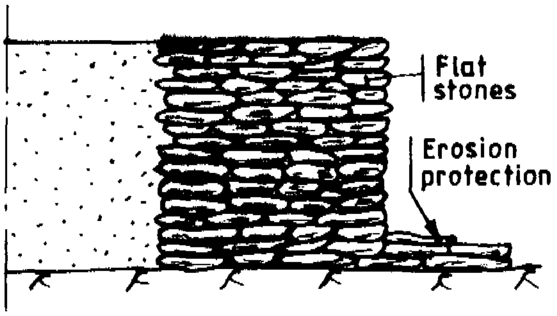

Figure 5.17 Stone sand dam.

All sand dams have to be very well protected against erosion along the banks, and evenmore so at the dam toe where the energy of water during peak flows will be extremely high. The best way of avoiding erosion is to construct the dam at natural rock bars. If such are not available it is important to extend the dam wall several meters into the river bank and to protect the dam toe by stone filling or concrete.

It is important that sand dams have spillways with sufficient capacity to take care of the overflow during peak flows.

5.2.4 Water extraction

Water extraction alternatives from a sand dam are generally the same as those for a sub-surface dam with the important difference that sand dams are even more suitable for gravity extraction.

If it can be expected that the accumulated sediments will be fine-grained, it is fairly simple to arrange a system of drains along the reservoir bottom before the sedimentation takes place. As in the case of a sub-surface dam they can be made up by slotted pipes covered by gravel. Naturally they 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 should be installed in the dam to facilitate cleaning of the reservoir as needed.

As pointed out above, one extraction alternative is to allow a seepage through the dam which can then be collected immediately at the downstream side or in a well or trough at some distance along the course of the stream.

A typical sand dam with extraction alternatives is shown in Figure 5.18.

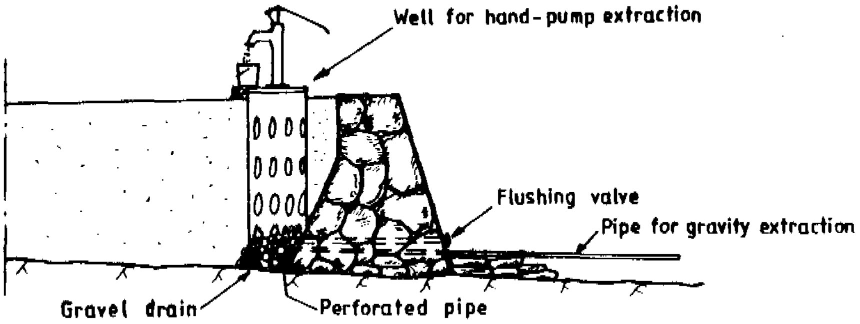

Figure 5.18 Extraction alternatives from a sand dam.

5.3 COMMON ASPECTS

5.3.1 Bedrock foundation

Ground-water dams should as far as possible be anchored in solid rock. This generally gives the best stability and fracturing of the dam can be avoided. Furthermore, it makes it possible 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 the weathered 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 after excavation it is important that it is investigated with regard to possible open fracture zones. The rock surface should be cleaned properly and simple infiltration tests carried out if it is suspected that there might be fractures. If a leakage is established it might be possible to stop it by pouring very thin mortar into the fracture system after it has been excavated as deep as possible. It is important, however, that the full length of the system is checked out and tightened if necessary. If it is not possible to stop the leakage and if it is not feasible to use the fracture system as a natural extraction system, the implementation of the scheme may have to be reconsidered.

5.3.2 Replenishment of natural aquifers

A ground-water dam may also function as a means of recharging an already existing aquifer by lateral or vertical flow.

Figure 5.19 shows an example from Namibia of how this can work (*Sauermann*, date unknown). The dike was utilized as an aquifer by means of a well supplying water to an airport. The aquifer did not carry enough water to meet the demand so it was decided to construct a sand dam which would increase the recharge.

Sometimes a ground-water dam is considered a failure because it is drained out by a fracture system. It might, however, then be possible to drill a well in the zone and utilize the ground-water dam as an artificial recharge structure (Hansson, 1984).

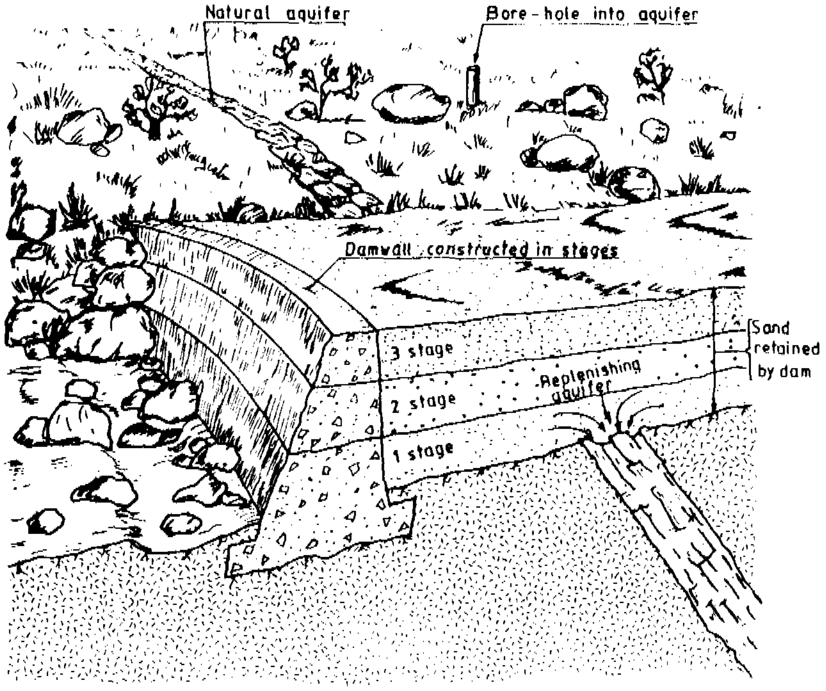

Figure 5.19 Ground-water dam for recharging purposes (from Sauermann, date unknown).

5.3.3 Recharge

When ground-water dams are constructed in areas where the top soil layers have low permeability or where gradients are high, it might be necessary to improve the recharge to the reservoir by surface flow diversion, trench digging etc. This goes also for sand dams where the upper layers have been silted.

5.3.4 Series of dams

In some areas it might be possible to construct a whole series of interconnected ground-water dams. Such potentials have been identified along sandy river beds in Kenya (Sørlie, 1978) and along narrow and very long valleys in South India (Jacob, 1983). The "jessours" of Tunisia are examples of small-scale dams that may be placed at regular intervals along alluvial valleys (El Amani, 1979). In the specific example shown in Figure 5.20 it was possible to determine the rate of siltation by comparing the level of a 50-year-old weir with the present level.

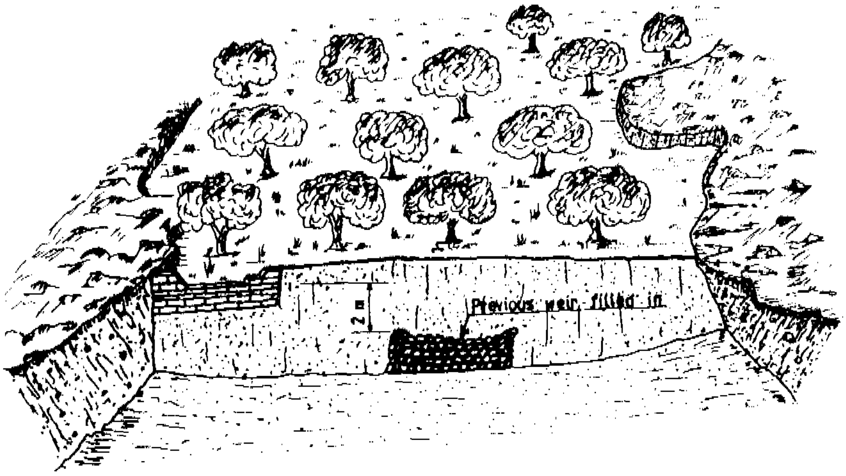

Figure 5.20 "Jessour", Tunisia (from El Amani, 1979).

5.3.5 Environmental impact

If planned and executed properly, a scheme involving damming of ground water should have no direct negative impact on the surrounding environment. It should be kept in mind, however, that the technique is implemented in a very fragile environment where even a small change may have long-term physical as well as social consequences. This calls for cautiousness in the planning of schemes.

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

There is also a risk of water logging of upstream areas. This problem can be solved by keeping the crest of sub-surface dams well below ground level. In the case of sand dams this will not be a big problem because there is generally no effective land use in the area that may be influenced.

The fact that ground-water levels will rise means that the risk of pollution increases. When the water is used for drinking purposes it may be necessary in some cases to protect the recharge areas by fencing or by soil or vegetative cover.

The water stored behind sub-surface dams may be used for irrigation in the area above the dam. In this way the return seepage is collected in the reservoir and may be used again. This re-circulation is certainly a good way of conserving water, but it may create problems with salt accumulation if the seasonal rains are not sufficiently heavy to wash out the salts accumulated in the soil.

6. CASE HISTORIES

The reader is referred to the map in Figure 1.3 where all known schemes and areas where various types of ground-water dams that have been constructed or proposed are shown. In the following a resumé of the activities in all these areas will be made, followed by more detailed descriptions from three selected areas in Kenya, Tanzania and India.

6.1 EUROPE

Ground-water dams built by the Romans still exist on Sardinia (Tröften, 1982), and several schemes in Germany, France and Italy where sub-surface dams have been used mostly to raise ground-water levels are presented in Gignoux & Barbier (1955), Guembel (1945 and 1947) and BCEOM (1978). Sand dams primarily serving as stream-flow moderators, have been constructed in mountaineous regions of Austria (Baurne, 1982). Sub-surface dams serving the purpose of containing water in existing aquifers have been constructed in Greece (Garagunis, 1981) and sub-surface dams mainly functioning as protection against sea-water intrusion into fresh-water aquifers have been proposed in Yugoslavia (Pavlin, 1973) and Greece (Garagunis, 1981).

6.2 AFRICA

Several very large sub-surface dam schemes primarily designed to increase the ground-water availability for irrigation purposes exist in north-western Africa, notably in Morocco and Algeria (Robaux, 1954; Duquesnoy, date unknown; BCEOM, 1978), and have been proposed for construction in Mauritania (Guiraud, 1980). In Tunisia the "jessours" represent a special type of "sand" dam which is very slowly filled by sediments and at the same used for growing olive trees (El Amani, 1979).

In the Hararghe Region of Ethiopia, a number of sub-surface dams for drinking water supply have been constructed in river beds during the last few years (Hansson, 1982 and 1984) and several are proposed for construction within the near future. A large sub-surface dam scheme involving jet injection has been proposed in Nogal District, Somalia (Pozzi & Benvenuti, 1979).

Ground-water dams are quite frequently used for water supply in East Africa. Detailed examples of sand dams in Machakos Region, Kenya and sub-surface dams close to Dodoma, Tanzania, are presented below. Sub-surface dams in river beds are quite frequent in the area east of Nairobi (Pettersson, 1981) and have been proposed for construction in North Turkana (Sørlie, 1978). In Tanzania the known schemes are concentrated around Dodoma, but some are also reported to exist in the southern parts of the country (Mitchell, 1954).

There is a mention of sub-surface dams in Zambia (Verboom, date unknown; Hapwaya, 1981). The potential of using ground-water dams in northern Mocambique has been reported by de Sonneville (1982) and Ferro (1982).

Increasing the water available for domestic supply and for watering of cattle by means of building sand dams is a generally applied technique in arid parts of Namibia. Numerous examples exist and have been described by Wipplinger (1958 & 1974), Aubroeck (1971), Burger & Beaumont (date unknown) and Sauermann (date unknown).

6.2.1 Machakos, Kenya

The following account is based on a study visit made by the author in 1982, which was guided by Messrs Werner and Haze of the Machakos Integrated Development Programme.

The climate in the Machakos area is semi-arid with an average, and highly seasonal, rainfall of about 850 mm/year, and a potential evaporation of about 1.600 - 1.800 mm/year. The bedrock is mostly Pre-Cambrian and the topography is hilly.

Old sub-surface dams in river beds and sand dams in gullies are quite common in the area. One such old dam is shown in Figure 6.1. The dam was built in 1961 but without extending the abutments properly into the river banks. Sediments have been trapped upstream of the dam, but due to erosion the river has taken a new course around the dam thus making the dam useless for water storage purposes.

Figure 6.1 Old eroded sand dam, Machakos.

Under the present programme a large number of sand dams have been built. The siting of the dams as well as the estimation of erosion and sediment transport was made mainly by using air-photo interpretation with field check.

The basic criteria used for a dam site were the availability of rock bars and the existence of natural basins for sand accumulation. All dams were of gravity type and built by stone masonry.

Figures 6.2 and 6.3 show a dam built in Mukio. The dam is built on top of an already existing "bridge" across a river. The additional height is about 2 meters. The area above the dam is almost completely filled up with sand. The dam is constructed in three parts: two dam walls of about 50 cm width surrounding a fill of stones, covered by a cement layer constituting the road surface. It took 10 months to construct the dam.

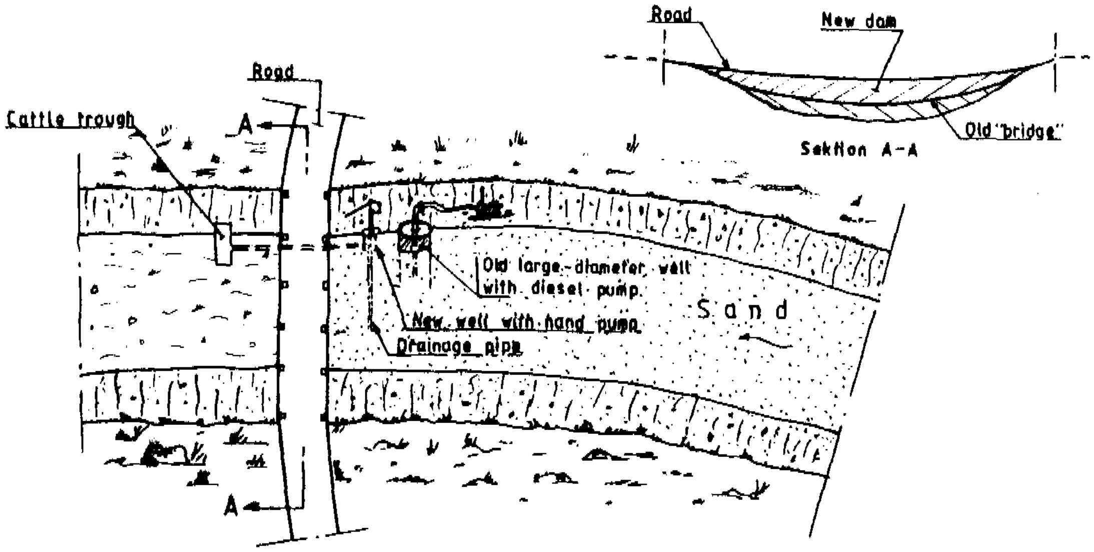

Figure 6.2 Plan and section of Mukio sand-dam site, Machakos.

Figure 6.3 Mukio sand dam, Machakos.

Figures 6.4 and 6.5 show a sand dam built in Kyandili. This quite large dam was built with the V-notch method. This means that instead of building the dam in sections each year, the whole dam is built at one occasion but a notch is left in the centre to allow silt outflow. In this way the dam was filled-up with coarse sand after two seasons. The notch can be seen in Figure 6.6.

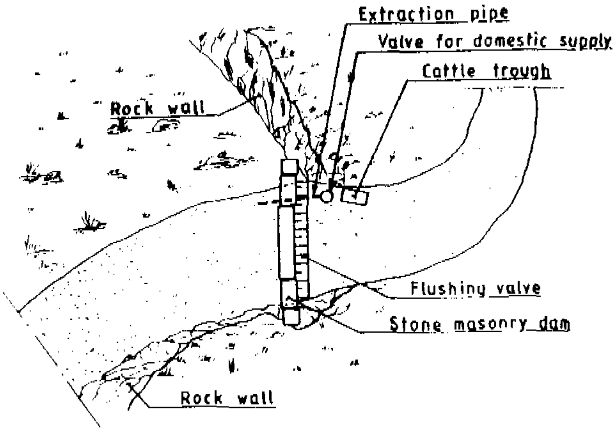

Figure 6.4 Plan of Kyandili sand-dam site, Machakos.

Figure 6.5 Kyandili sand dam, Machakos.

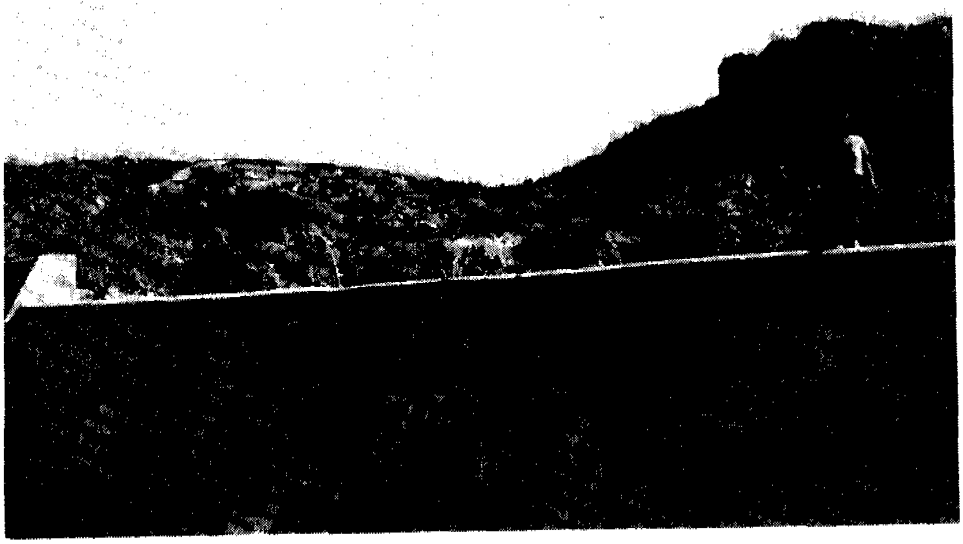

Figure 6.6 Filled-in notch, Kyandili sand dam, Machakos.

The dam height is about 3 meters and the total cost of construction was 35.000 Kenyan Shs. It was at the time of the visit supplied with a pipe outlet and valve. A shallow well would be installed only after the possible failure of the present system. At the bottom of the dam there is a pipe which may be used for flushing the reservoir.

A special type of sand dam is shown in Figures 6.7 and 6.8. The idea behind this scheme is to store the water in the main surface dam but let water for drinking purposes in a pipe down to a sand dam where it is extracted from a well equipped with a hand pump. The dam had been constructed at the time of the visit but no sedimentation had yet

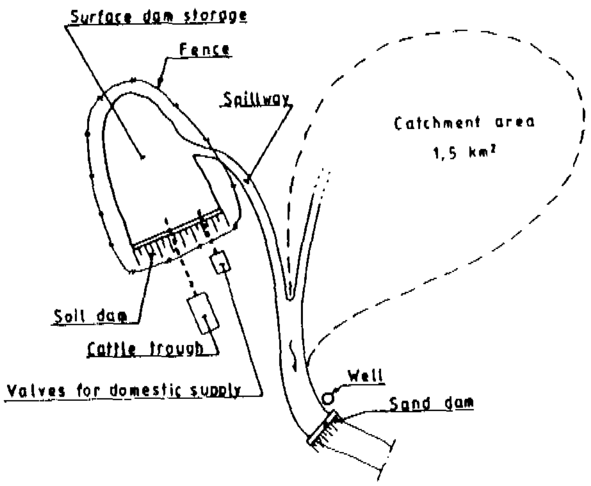

Figure 6.7 Plan of Kalusi dam site, Machakos.

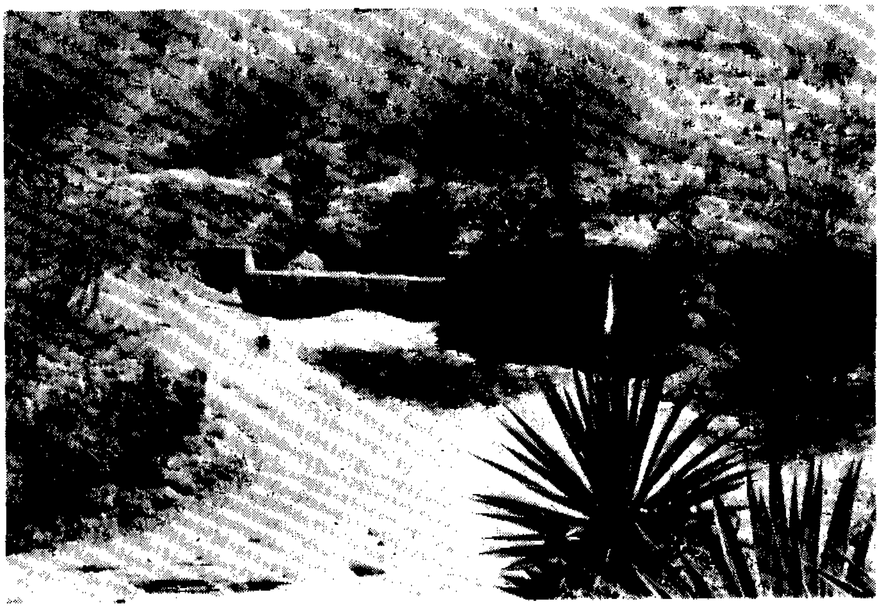

Figure 6.8 Kalusi sand dam, Machakos.

taken place since the rains had not started. It was believed that the sediments carried in the small tributary to the main stream would be enough to fill the dam. The drainage area of the tributary is about 1.5 km^2. The purpose of this sand dam is thus to serve as a slow sand filter and not to store water. The flow to the dam will be automatically regulated by a ball valve. The sand storage volume will be about 150 m^3.

A general impression of the sand dam project in Machakos is that the schemes have been fairly successful. There are some problems with operation and maintenance of the schemes, but they seem to be less than for water supply projects of conventional types.

6.2.2 Dodoma, Tanzania

The following account of existing ground-water dams identified in the Dodoma area is based on Fawley (1956) and Tanganyika Territory Geological Survey Annual Report (1928). The author visited the area in 1982, guided by Mr George Kifua of the Ministry of Water and Energy. The account of the Bihawana Scheme is based on an interview with Father I. Maggioni. The scheme was also discussed with Mr D.S. Bushaijabwe of the Ministry of Water and Energy, Dar es Salaam.

The earliest reference to a sub-surface dam in Tanzania is that of a dam built in 1912 near Dodoma. The dam is referred to very briefly in Fawley (1956), but there are no records available on the type of construction or the exact location.

In 1927 a masonry wall with a concrete core was built across the sand bed of a river, the name of which is not mentioned in the reference (Tanganyika Territory Geological Survey Annual Report, 1928). The objective was to provide water for cattle as well as human consumption during the dry period. No detailed description of the construction is given, but apparently the dam was a combination of a subsurface dam and a dam projecting over the surface in order to trap sediments during the floods. This latter objective was fulfilled during the rains of late 1927 when the dam was completely filled with sand. Unfortunately the rains were so heavy that they destroyed some of the piping that had been installed for conveyance of stored water to a cattle trough on the down-stream side. For this reason some alterations aiming at protecting the piping were made during 1928 and apparently it then functioned properly, at least during the rains of 1928.

It was calculated that the total effective storage volume behind the dam would be 410 m^3 which would provide for a daily supply of 2.3 m^3 during the dry season. During 1928, which apparently was an abnormally dry year, stock were watered for two months of the dry period until grazing in the vicinity of the dam was exhausted. Calves and small stock were watered throughout the dry period. No further records about the dam have been found.

In 1928 another sub-surface water conservation scheme was constructed at a place called Kikuyu. The scheme involved the construction of some type of sub-surface dam, but there are no construction details available. Since the objective was to supply water for town, stock and railway requirements, 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. This was in spite of failure of the rains and the fact that some 27.000 m^3 of water had to be pumped to waste for drainage purposes during construction.

A more recent scheme was constructed in the Bihawana area about 15 km south-west of Dodoma. The river in which the dam was built is intermittent and flows to the west about 500 meters north of the Bihawana Roman Catholic Mission which is situated on a high hill (Figure 6.9). The river bed consists of coarse sand and has at this particular site a width of about 20 meters. The banks rise about 1 meter above the sand level and are covered by dense bush vegetation. Women collect water from holes dug in the sand above the dam site.

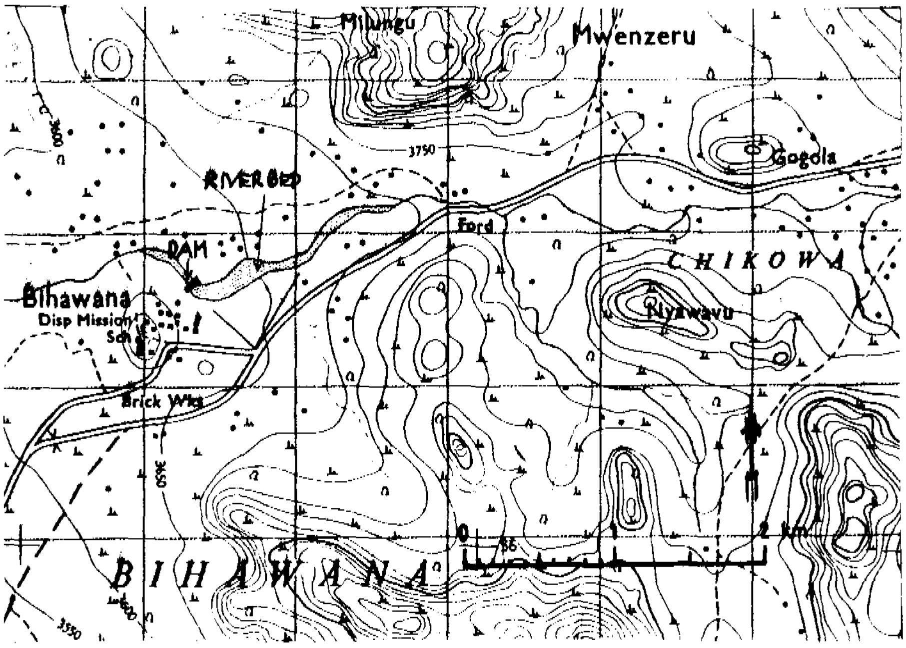

Figure 6.9 Map of Bihawana area, Dodoma.

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 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 across the river down to a layer of calcrete, probably the upper part of the weathered profile. This layer was encountered at about three meters depth. The excavation was done by manpower only. A clay dam was built in the trench. The clay was brought in by truck from somewhere in 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 of six meters depth constructed in the river bank. (Figure 6.10). The sump 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.

Figure 6.10 Site of sub-surface dam at Bihawana, Dodoma.

The system has been in function since the year of construction and today supplies water to some 25 people, 100 pigs and irrigation of a vegetable garden of 1/4 acre. The sump never dries out but maintains a level of about 1 - 1.5 meters above the bottom even at the end of the dry season.

6.3 ASIA

Large-scale sub-surface dam projects have been proposed in western Saudi-Arabia by Basmaci (1983). The construction of a relatively small sub-surface structure damming an extensive aquifer in Charuli, Afghanistan, has been reported by Guembel (1945 and 1947).

Sub-surface dams have been proposed for construction in Thailand and at several sites in Japan by Matsuo (1975 and 1977), who also reports of a sub-surface dam constructed by means of jet injection on the island of Kaba in western Japan.

6.3.1 South India

The following account is based on Kittu (1979), Ahnfors (1980), Raju (1983), Skoglund (1981) and Raman (1983). The author has visited the sites in Kerala on several occasions, guided by Professor R.K. Sivanappan and Mr S.V. Kottiswaran of the Tamil Nadu Agricultural University and Messsrs P. Subramanian and J. Kurien of the Central Ground Water Board

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 rainfall averages 2.400 mm, the main part of which comes in June-October.

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 2 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.

One factor restricting the possibility of constructing ground-water dams in this area is that land holdings are generally small, and it is difficult to organize the co-operative effort needed when several farmers are involved. 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 down to bedrock was built across a narrow valley, surrounded by out-cropping rocks (Figure 6.11).

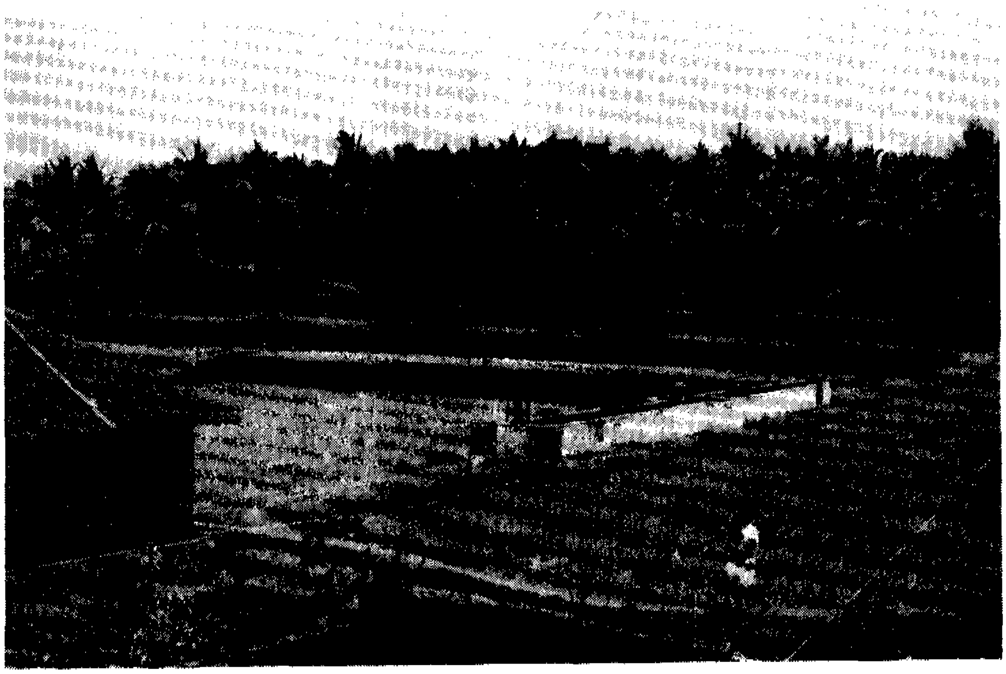

Figure 6.11 Sub-surface dam at Ottapalam, Kerala.

The depth to bedrock, which was established prior to excavation by steel-rod sounding, is on the average 5 m and reaches a maximum of 9 m 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.

The dike consists of a 4-inch plastered brick wall (Figure 6.12). Water is extracted from the aquifer through a gravel drain along the dike, to a series of infiltration 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 1 ha of coconut trees.

Figure 6.12 Brick wall of Ottapalam sub-surface dam, Kerala.

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. In consequence, a scientific approach was used at the hydrogeological investigations as well as the construction.

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 in-situ 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%. 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 4 m.

The total length of the dam is about 150 m and the crest was kept one m below ground level in order to avoid water logging in the upstream area. The main part of the dam is made up by a plastered brick wall but there are also sections consisting of tarfelt and plastic sheets. Two wells, connected to each other by drill holes through an unexpected rock bar, were constructed along the dike (Figure 6.13).

Figure 6.13 Site of sub-surface dam at Ananganadi, Kerala.

The dam took three months to complete at a total cost of 7.500 dollars, including pumping equipment. One third of this cost was for earth work and the rest for equipment and construction materials. The storage volume of the reservoir was estimated to 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 benefit/cost ratio at 8% interest rate was calculated to 1.06.

A sub-surface dam was proposed in Ooty, Tamil Nadu in 1976 (Skoglund, 1981), and also reportedly constructed (Raman, 1983). The dam, made of plastic sheets, was built in a weathered layer and supplies water for irrigation purposes.

The "ani-cuts" of the large rivers in Tamil Nadu (Figure 6.14) are basically irrigation water diversion structures, but are extended to some depth below surface, thus causing a substantial rise of ground-water levels which benefits nearby wells (Kandaswamy, 1983).

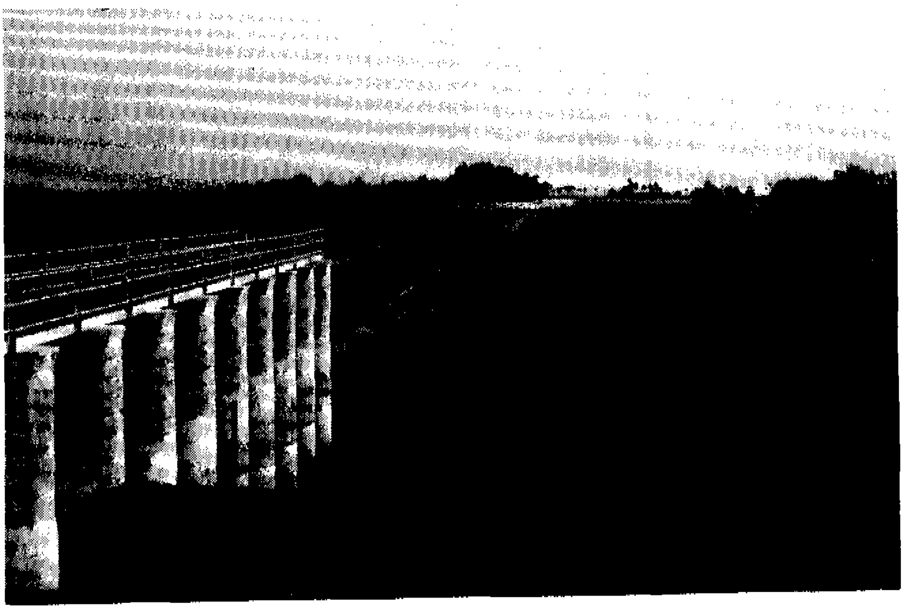

Figure 6.14 Ani-cut at Vellore, Tamil Nadu.

6.4 AMERICA

There is a long tradition of building ground-water dams in the arid south-western parts of the United States and northern Mexico. Sub-surface dams called "tapoons" have been constructed in sandy river beds in Arizona (Lowdermilk, 1953), and sand dams have been built in semi-desert regions of Arizona and Sonora, the oldest one already 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 2-feet-thick concrete wall (Dixey, 1931). Helweg & Smith (1978) report a type of artificial aquifer built in New Mexico and elsewhere, which involves a small basin being excavated, covered with PVC or clay and then refilled with sand. The excavated material is used for a dam which retains water in the reservoir.

The suitability of ground-water dams for rural water supply in the dry Nordeste Region of Brazil has been established by Pompeu dos Santos & Frangipani (1978) and IPT (1981), and there are also examples of old dams in that region (Dixey, 1931; IPT, 1981).

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