INTERNATIONAL REFERENCE CENTRE
FOR
COMMUNITY WATER SUPPLY AND SANITATION

RAINWATER HARVESTING FOR DRINKING WATER SUPPLY

Draft

August 1981

E.H. Hofkes

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CONTENTS

1. INTRODUCTION

In some parts of the world, rainwater catchment and storage has been traditionally practiced providing drinking water supplies, and in some areas they continue to be used for this purpose up to the present time. In other regions, rainwater harvesting for drinking water supply is less common. Yet, in view of the pressing need for adequate supplies of drinking water in many arid and semi-arid areas, the catchment, storage and use of rainwater should receive more or renewed attention.

In arid and semi-arid areas the rate of evaporation is frequently very high, so that open storage of surface water for late use is an unreliable source of supply. Surface water in open storage also is liable to contamination with the associated health hazards when it is used for drinking and domestic purposes. Groundwater generally is an attractive source of drinking water, because of its bacteriological safety and constant temperature, but it may be unavailable or too difficult to reach. Frequently, exploitation of groundwater resources requires the use of expensive drilling equipment for making boreholes or tubewells. Thus, collecting and storing rainwater for drinking water supply in some areas may be a highly relevant option.

Rainwater is collected as it runs from roofs, or as surface runoff flowing of natural ground, roads, yards, or specially prepared surface catchments. Rainwater harvesting involves the catchment, collection and storage of rainwater for ready use for drinking and domestic purposes. Historical sources mention the existence of such rainwater harvesting systems some 4000 years ago in the Middle East region. Roman villages and cities were planned to take advantage of rainwater for drinking water supply. In the hills near Bombay in India, the early Buddhist monastic communities had an intricate series of gutters and cisterns cut into the rock to provide domestic water on a year round basis. In the Mediterranean area and the surrounding arid belt, rainwater use for drinking water supply is traditionally widespread and preserved to this day.

In many countries of Europe, rainwater was extensively used for the provision of drinking water, particularly in the rural areas. With the advent of piped water supplies, the importance of rainwater as a source of water supply has, however, diminished in those countries.

On several tropical islands and in some coastal areas, where the groundwater is brackish or salty, rainwater continues to be the only source of drinking water supply. In other countries, rainwater is sometimes used to supplement the piped water supply.

Depending on the circumstances, rainwater is collected from roofs, or while running over ground surfaces. A tank standing at the corner of a house, with the water running to it from the roof gutters, surely is a quite familiar sight. Larger tanks for storing water collected from ground surface catchments are frequently made underground by excavating holes and lining them, or by other construction methods using various building materials.

Whichever rainwater harvesting system is used, it is important to note that such systems when provided for drinking water supply, are more likely to serve a need which the users are keenly aware of, than when they are provided for small plot irrigation or similar purposes. Tanks designed to store and provide water for micro-irrigation too often have been a complete failure. In Botswana, for example, during a survey in 1972, one out of nine tanks for irrigating school gardens were found holding water, and some of these tanks were so completely destroyed that it was difficult to find the site where they had been. In this instance, the damage was done by goats as the fencing round the tanks had not been kept in repair. Apparently, irrigation for gardening was seen by the people concerned as a rather marginal activity. In contrast, rainwater harvesting systems for drinking water supply have been proved to be quite often well-kept and preserved for long years, and even centuries.

2. RAINWATER COLLECTION AND STORAGE

2.1. ROOF CATCHMENTS

Reasonably pure rainwater can be collected from house roofs made of tiles, slates, (corrugated) galvanised iron, aluminium or asbestos cement sheeting. Thatched or lead roofs are not suitable because of health hazards. With very corrosive rainwater, the use of asbestos cement sheeting for roof catchment requires some caution. Asbestos fibers may be leached from the roof material leading to relatively high asbestos concentrations in the collected rainwater. Plastic sheeting is economic but often not durable. Newly developed roofing materials are bituminous felt and sisal-reinforced paper. Painting the roof for water-proofing may impart taste or colour to the collected rainwater, and should be avoided. Fig. 2.1 shows a simple roof catchment.

Fig. 2.1 Simple Roof Catchment

The roof guttering should slope evenly towards the downpipe, because if it sags, pools will form that can provide breeding places for mosquitoes.

Dust, dead leaves and bird droppings will accumulate on the roof during dry periods. These will be washed off by the first new rains. It is helpful to arrange the downpipe so that the first water fom each shower (the "foul flush") can be diverted from the clear water container and allowed to run to waste.

To safeguard the quality of the collected rainwater, the roof and guttering should be cleaned regularly*. A wire mesh should be placed over the top of the downpipe to prevent it from becoming clogged with washed-off material.

An arrangement for diverting the first rainwater running from the roof is shown in Fig. 2.2 and 2.3.

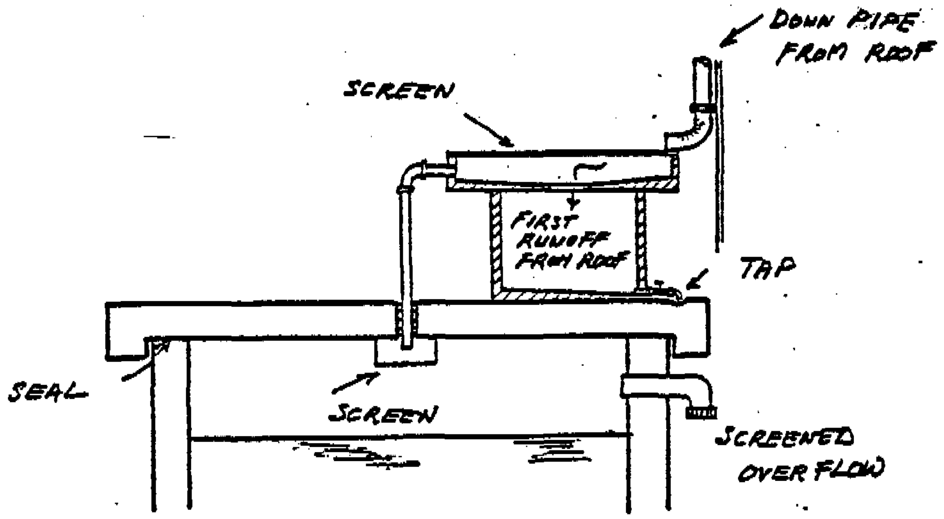

Fig. 2.2 Arrangement for diverting the 'First foul flush'

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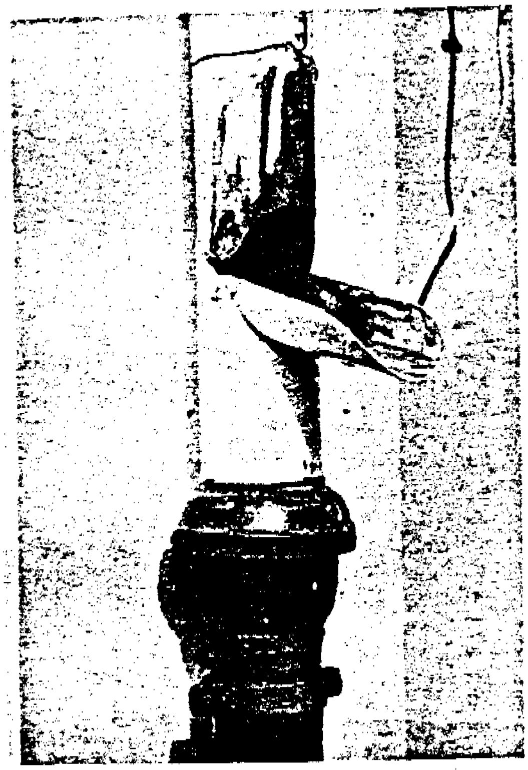
* Bird dropping have been reported to cause health hazards (salmonellosis) in Jamaica.



Fg. 2.3 Clap Switch

Another arrangement is a below-ground storage tank receiving rainwater that overflows from a vessel placed above the ground (Fig. 2.4). The surface vessel thus occasionally contributes water to the underground tank.

The size of the roof will depend on the size of the house. The quantity of rainwater that can be collected through roof catchment, will be largely determined by the effective area of the roof and the local annual rainfall. One millimetre of rainfall on one square metre of roof will yield about 0.8 litres of water, allowing for evaporation and other losses.

For a roof measuring 5m x 8m (in plan), and assuming an average annual rainfall of 750 mm, the amount of rainwater which can be collected in a year may be estimated as:

$5 \times 8 \times 750 \times 0.8 = 24{,}000$ litres/year

or: $\frac{24{,}000}{365} = 66$ litres/day on average.

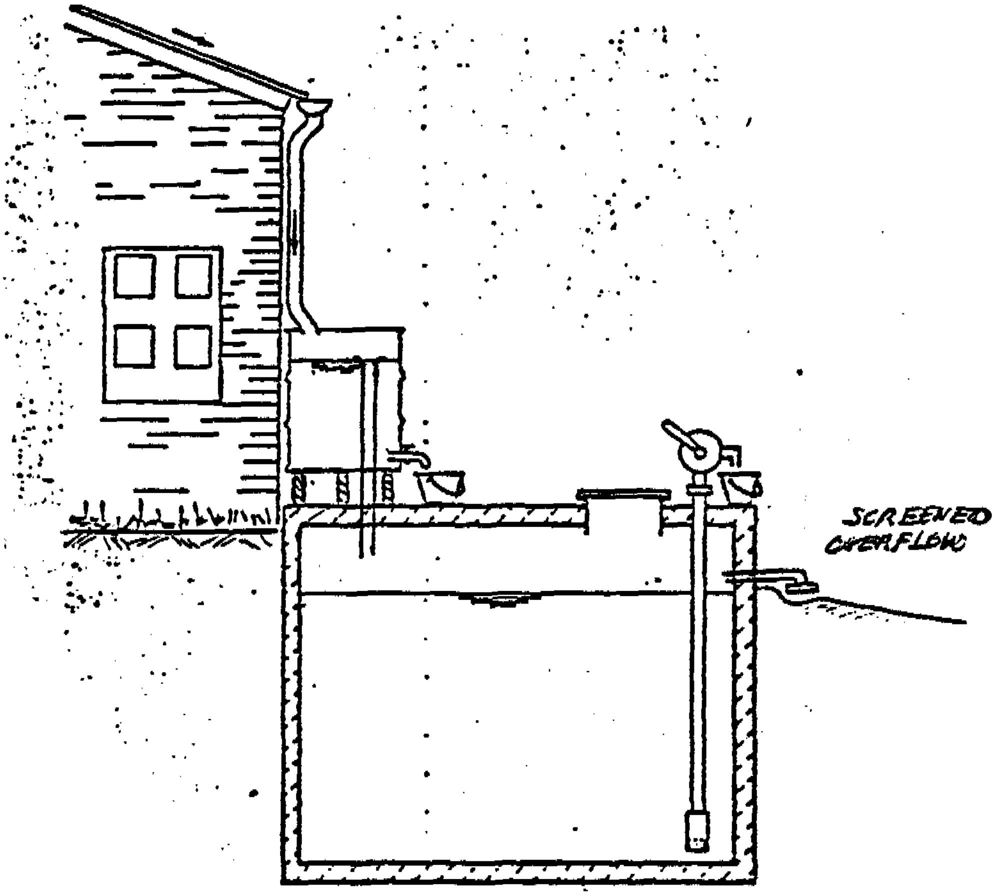


Fig. 2.4 Roof Catchment and Storage of Rainwater (withdrawal by handpump)

To allow for conditions in years that are drier than average and also for dry seasons of exceptional duration, the roof and storage should have about 50% surplus yield over the basic water requirements of the people who will be dependent on the supply. With a sufficient storage, the roof catchment could in a dry year still provide some 40 litres/day which is the basic drinking and domestic water requirement of a family of 6 persons.

One can estimate the required storage volume by working out the amounts of water that will be used by the family household in the longest season which may pass without rainfall. For short dry periods the needed storage volume will be small and can probably be provided in the form of a simple wooden vessel, an oil drum or an other suitable container. Where rainfall varies widely during the year, dry seasons of considerable duration need to be anticipated.

For an average dry season of 3 months the storage volume required would be: 3 x 30 x 40 = 3600 litres. To allow for longer periods without rainfall in extremely dry years, a 50% surplus should be provided and the storage volume would thus have to be 5400 litres.

Example

In the Gusii Highlands (Kenya) the average annual rainfall is 1,800 mm. Rain storm intensity can be as high as 0.2 mm/minute (= 12 mm/hr), but a rainfall of 4 mm/hr is more usual. Family housing in the Gusii area would provide a roof catchment of some 120 m^2. The amount of rainfall collected, may be estimated at 120 x 4 x 0.8 $\approx$ 400 l/hr. A tank of some 5,000 litres would thus be filled in about 12 hours of rainfall. The stored quantity of 5,000 litres could serve a family of 6 persons adequately for a period of 40-45 days. In the Gusii there are, on average 150 rainy days annually, so the water would be in surplus during a considerable part of the year.

2.2. GROUND CATCHMENTS

Ground catchments are used for collecting rainwater runoff. Part of the rainfall will serve to wet the ground, is stored in depressions, or is lost through evaporation or infiltration into the ground. A considerable reduction of such water losses can be obtained by laying tiles, concrete, asphalt or plastic sheeting to form a smooth impervious surface on the ground. Another method involves chemical treatment of the soil surface. Sometimes simply compacting the surface is adequate.

The amount of rainwater that can be collected in ground catchments will be dependent on whether the catchment is flat or sloping, and the watertightness of the top layer. Through preparation of the ground surface, a sufficiently rapid flow of the water to the point of collection and storage can be assured in order to reduce evaporation and infiltration losses.

In some areas, natural cisterns exist that receive and store the rainwater runoff (Fig. 2.5). The cistern should be underground, covered or at least shaded, to protect the water from heat and sunlight, and to reduce the evaporation losses. The cistern should be sited at a place that is not affected by floods. The northern slope of a hill may be a suitable place for a cistern.

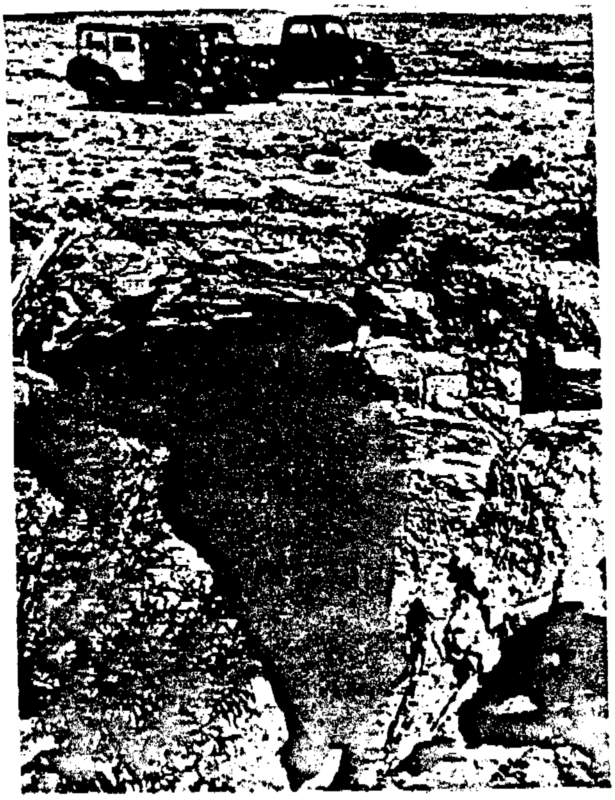


Fig. 2.5 Natural Cistern in Niger Desert

For rainwater surface catchments, terraces, smooth rock or other suitably prepared ground surfaces can be used (Fig. 2.6). Sometimes, it is necessary to file crevices for water tightness of the catchment. An example of a graded catchment area is shown in Fig. 2.7.

Fig. 2.6 Catchment area and inlet of storage tank (Yugoslavia)

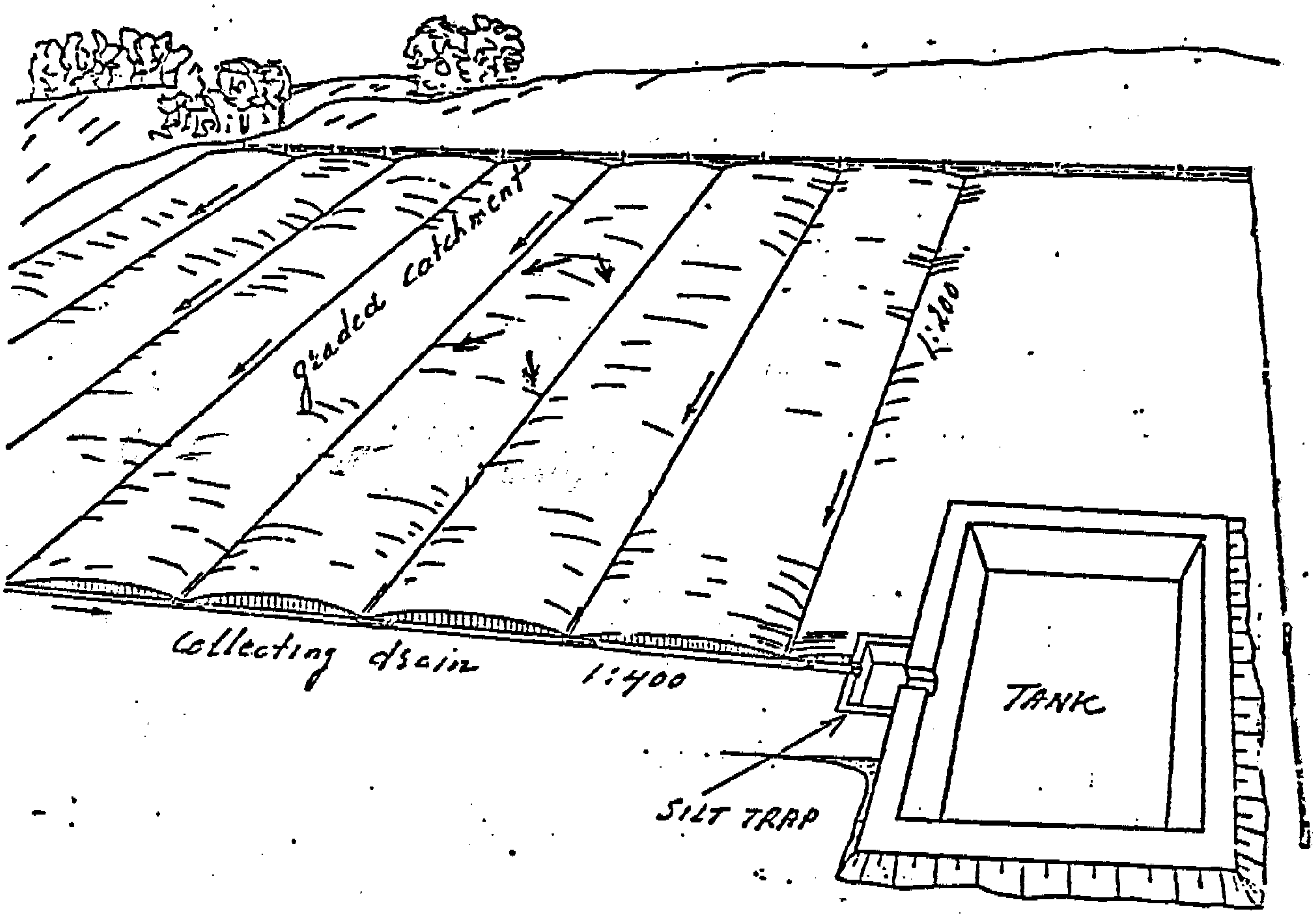


Fig. 2.7 Graded ground catchment area

The portion of rainfall that can be harvested ranges widely from about 30% for pervious, flat ground catchments, to over 90% for sloping strip catchments covered with impervious materials.

Land alteration involves the construction of ditches along contours, the clearing of rocks and vegetation, and simple soil compaction. Attempts are often made to achieve reduced infiltration losses of rainwater in the ground catchment area. In rolling hills careful soil compaction may be sufficient to attain good catchment efficiency. In flat terrain a subdivision in small, sloping strips will be needed with such special preparation of the ground surface as appropriate. Puddles must be avoided as these provide breeding places for insects.

Where the surface of the ground catchment is to be covered, various materials may be used. Tiles, corrugated iron sheets, asphalt, cement, or even materials such as heavy butyl rubber or thick plastic sheets may be considered. When properly applied, these materials can give good water catchment efficiency with a yield as high as 90% of the rainfall runoff from the catchment area. Additional advantages are low maintenance and long useful life. However, these materials are generally too expensive for use over large ground catchment areas. Catchment surface coating methods that may save costs, are being tested. These include:

- Asphalt in two coats (sealant and protection); reinforcement with plastic or fibreglass and covered with gravel; and,
- Paraffin wax spread as granules which melt in the sun.

Thin plastic membranes covered with 1-2 cm gravel or bonded to the ground surface by a bitumen tar are much cheaper but they are easily damaged by sharp stones, plant roots, or animals, and repairs are difficult to make. The water yield of such membrane-lined ground catchment sometimes proves disappointing (not higher that 30-50% of the rainfall). Good results can probably be obtained by treating the top soil layer of the ground catchment area with chemicals. Sodium salts may be applied converting clay particles to form an impervious layer, or a bitumen or tar coating may be sprayed over the ground to block the soil pores. Such a treatment need not be expensive and can be repeated at regular intervals (once every few years) in order to maintain the watertightness of the ground catchment.

Treated ground catchments of sufficient size can provide a domestic water supply for a number of families or even a whole village community but they need proper management and maintenance, and protection against damage and contamination. It may be necessary to provide fencing or hedging. An intercepting drainage ditch at the upper end of the catchment area, and a raised curb around the circumference would be needed to avoid the inflow of polluted surface runoff. A grass cover may be used to reduce erosion of the ground catchment although this will result in a lower yield. Trees and shrubs surrounding the catchment area can be planted to limit the entry of wind blown materials and dust into the ground catchment area.

2.3. CONJUNCTIVE USE OF ROOF AND GROUND CATCHMENTS

It can be quite advantageous for people to use roof and ground catchment side by side for rainwater collection. The rationale of this arrangement is that the water collected by a roof catchment by itself is rarely sufficient to provide all the water a family or small community needs. If the roof collected water would have to suffice for the whole year, the amount used each day would have to be rationed strictly, probably to an unacceptable low level. Any additional water must then be fetched from some other source (Fig. 2.8).

As rainwater from roofs is usually quite clean, this water is best used for drinking and cooking. Additional water needed for washing and watering a vegetable garden can be taken from less clean sources such as an underground tank collecting surface runoff. For water taken from these, there will be not the same need for strictly rational use.

The success of conjunctive use of roof and ground catchments greatly depends on the distance people will have to go to fetch water from the surface runoff collecting tank. If it is a long distance away, the family will probably take all its water from the roof water tank until that supply is exhausted. If the ground catchment tank is within a few metres of the house, then the family mambers will distinguish their water requirement in a clean water part, for which they will use roof tank water, and a less clean, lower-quality part for which they will take water from the ground catchment tank.

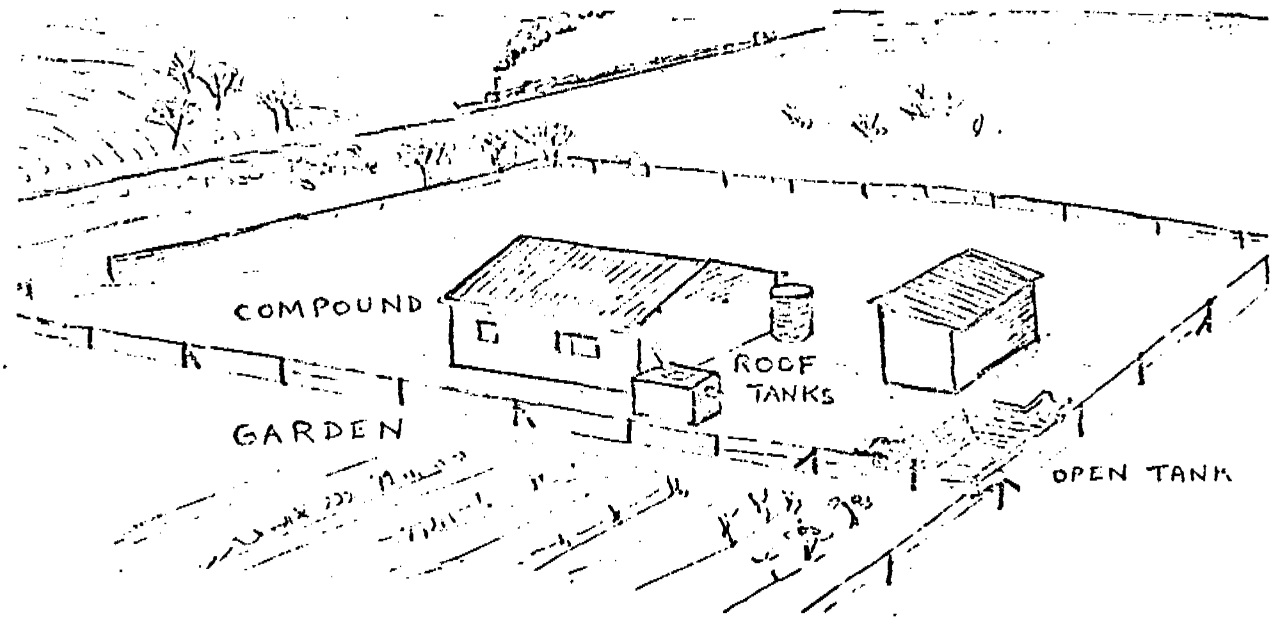


Fig. 2.8 Conjunctive use of roof and ground catchments (Botswana)

These points are well-illustrated by the small farm house situation shown in Fig. 2.8. The large roof is of corrugated iron and measures 9 x 10 m, it feeds rainwater to a 2,200 litre galvanised iron tank, and to an 18,000 litre square tank, built of concrete and partly sunk in the ground. The roof area yields about 30,000 litres in a typical year. There is also a 40,000 litre open tank situated at the edge of the compound which collects runoff from most of the compound, including any overflow from the two roof water tanks. The small roof tank provides water for cooking and drinking; the square concrete tank, from which water is drawn by lowering a bucket from the top, provides washing water; and water from the "open" tank, of relatively poor quality, is used mainly for watering the adjacent garden. Because this tank loses a lot of water by evaporation, the most logical way of using it is to take water from it for all uses apart from drinking for so long as its contents last.

2.4. STORAGE OF RAINWATER

Storage facilities can be above-ground or below-ground. Whichever type of storage is selected, adequate enclosure should be provided to prevent any contamination from humans or animals, leaves, dust or other pollutants entering the storage container. A tight cover should ensure dark storage conditions so as to prevent algal growth and the breeding of mosquito larvae. Open tanks or storage ponds are generally unsuitable as sources of drinking water.

Underground tanks have the advantage of keeping the water cool due to the isolating effect of the walls and surrounding ground; they will suffer practically no loss of water due to evaporation. Fig. 2.9 shows a typical rainwater storage arrangement.

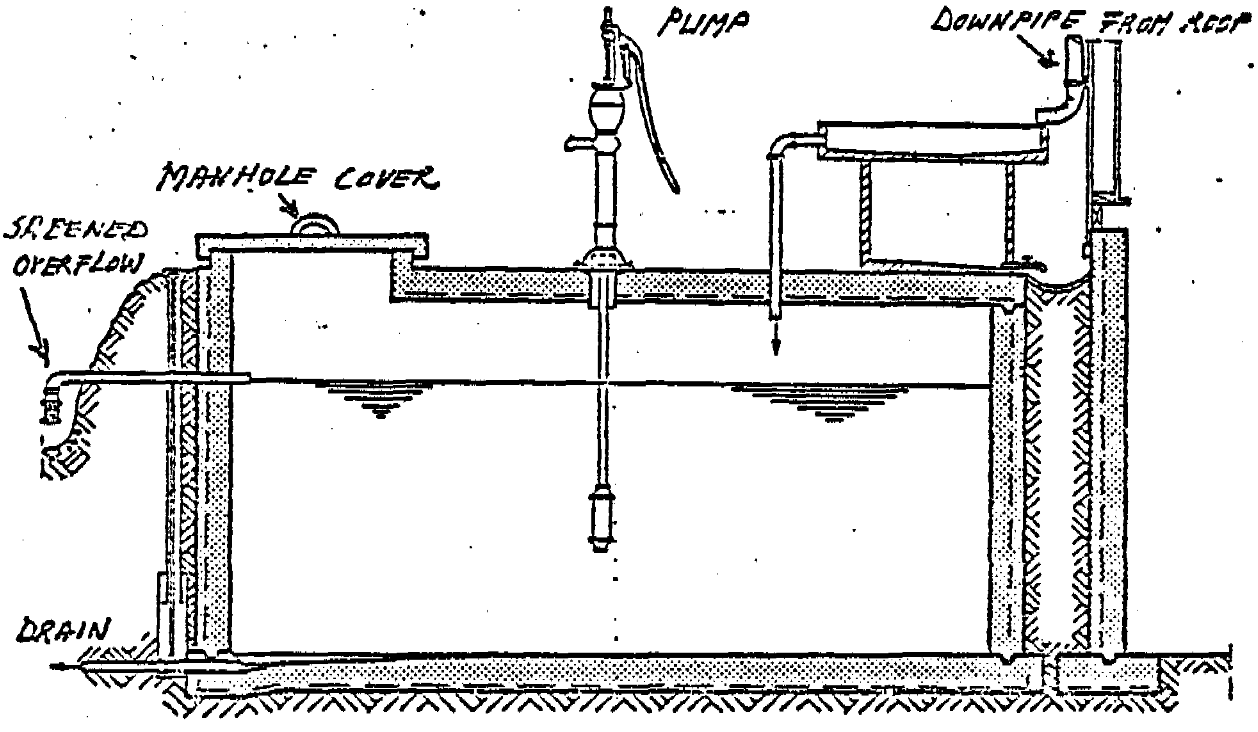


Fig. 2.9 Rainwater Storage Arrangement.

The bottom of a rainwater storage tank should be slightly sloping up towards the outlet. This allows particles that settle from the water near the tank inlet, to accumulate at the tank bottom. The water drawn at the outlet will then be substantially free from suspended solids (Fig. 2.10).

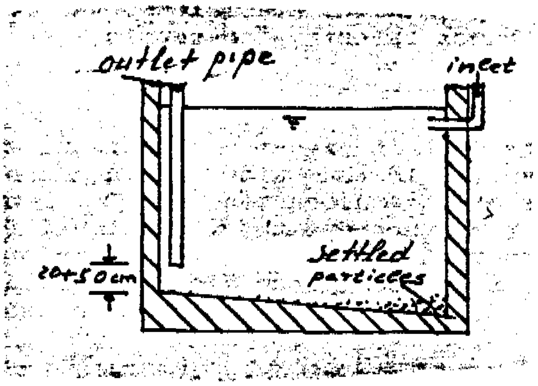


Fig. 2.10 Components of Rainwater Storage Tank

The inlet and outlet are also situated at the opposite sides of the tank. This helps ensure that only cool, settled water which has been in storage for some time, will be withdrawn.

There is a wide choice of materials for the construction of water storage tanks and containers. For small storage volumes, vessels made of wood, cement, clay or water-proofed frameworks may be used.

A saving in space and cost of construction may be obtained if the tank is moulded directly in the ground by simply compacting the earth. An example of a bottle-shaped rainwater storage well is shown in Fig. 2.11. A silt trap must be provided for depositing the larger sediments before the water flows into the well.

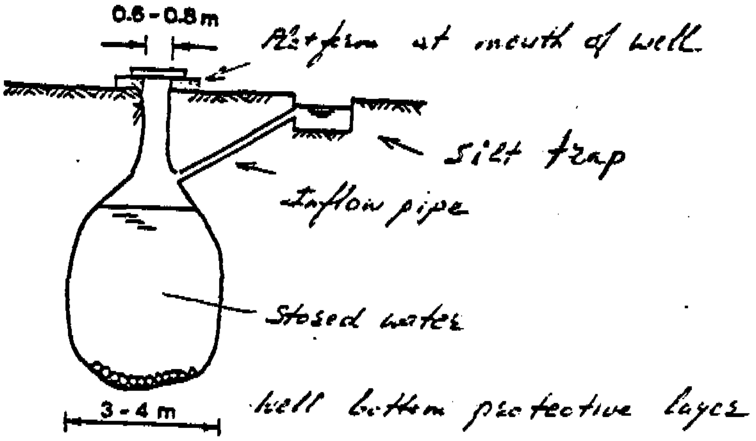


Fig. 2.11 Underground rainwater storage well
(as used in Northwestern China)

Cement applied by hand may be used for plastering the walls of the excavation, or simple plastic sheeting. Storage tanks consisting of bee-hive structures (Fig. 2.12) have been built in various countries (e.g. Sudan, Botswana, Swaziland, Brazil, Jamaica) to volumes of 10,000 litres. Polythene tubes filled with a weak cement mixture and sealed at the ends, are laid in place before the mixture sets; this will allow them to readily take up the required shape. The sides of these tanks are polythene-lined.

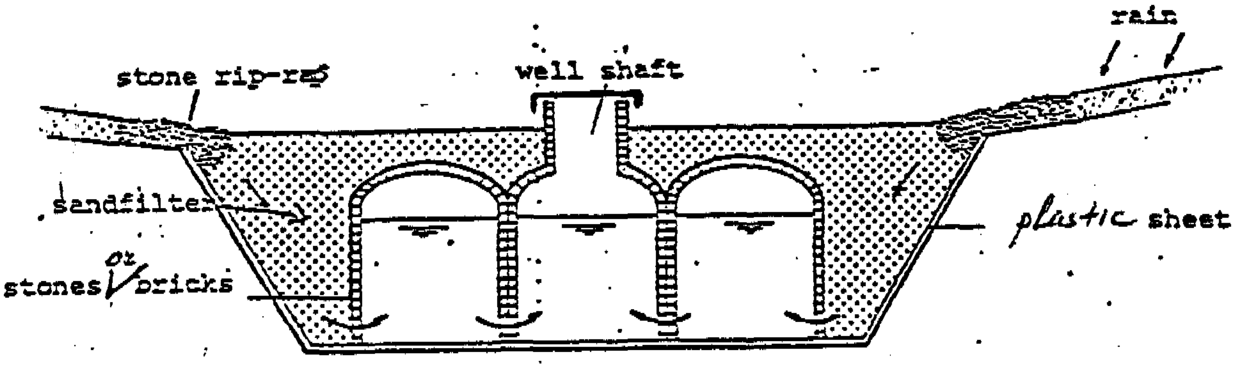


Fig. 2.12 Cistern built of Polythene Tubes

For large storage volumes, tanks or cisterns constructed of brick or stone masonry are used most. Typically the walls are cylindrical and bonded by cheap lime mortar or more expensive cement mix. Where large storage volumes are built, and certainly for tank heights exceeding 2 m, reinforcement along the outside edges becomes necessary. This can be conveniently provided by means of one or more tightened steel bands around the outer circumference of the tank. The roofing of this type of tank is commonly provided by placing some suitable cover (e.g. galvanized iron sheets) over a supporting framework (Fig. 2.13).

When built of brick or stone masonry, the vault span of a tank should be small, in order to reduce the risks of cracks forming in the walls. If a large storage volume is required, it should be preferably provided in the form of a number of separate units.

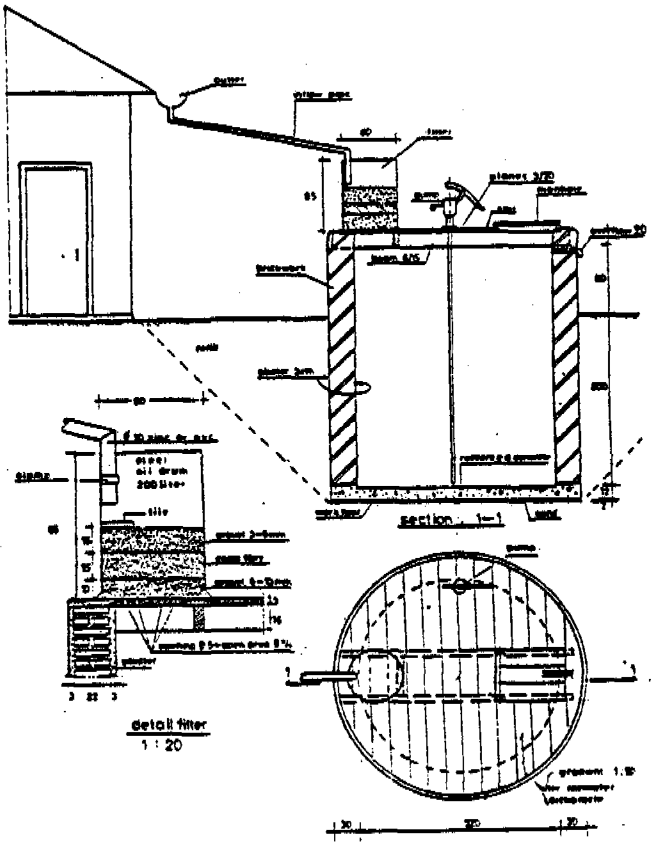


Fig. 2.13 Brick Masonry Rainwater Storage Tank (10,000 litres)

Relatively <u>thin-walled cement containers</u> can be built for moderate rainwater storage volumes (up to 1,500 - 2,000 litres). A tapered form has been developed by UNICEF, in Kenya, in which a simple cloth bag is used as the basis for a wall 3 cm thick or even less. Containers providing up to 2,500 litres storage volume can be built in this way.

In many parts of Africa, Asia and Latin America, <u>clay</u> is available. Clay can be used to build suitable rainwater storage containers of limited volume (Fig. 2.14). Hard-baked tiles, of course, are to be preferred as a building material for water storage tanks.

A simple glazing technique should be useful in improving the impermeability of the clay pot or barrel walls.

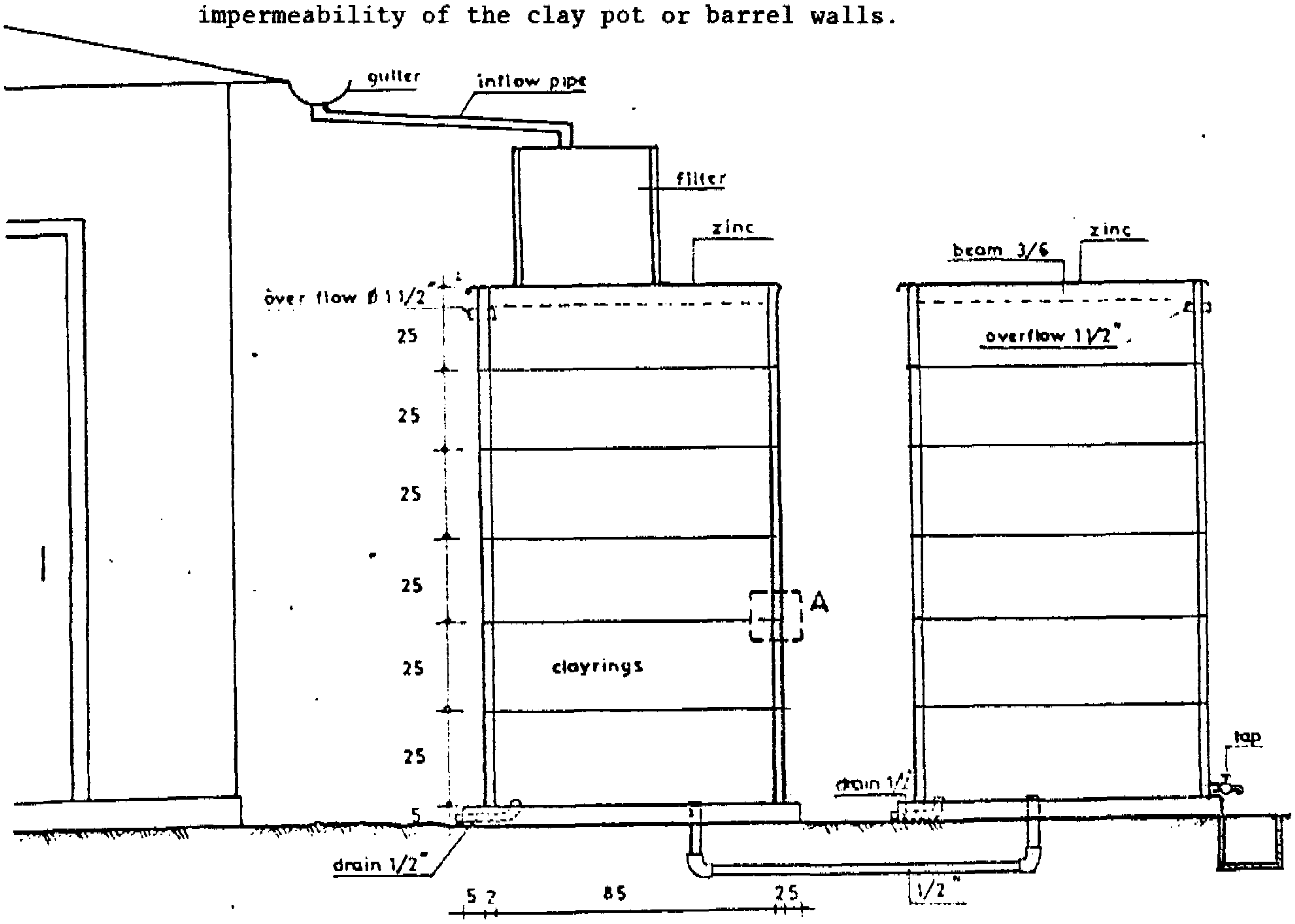


Fig. 2.14 Storage Tanks built of Clay Rings (850 litres)

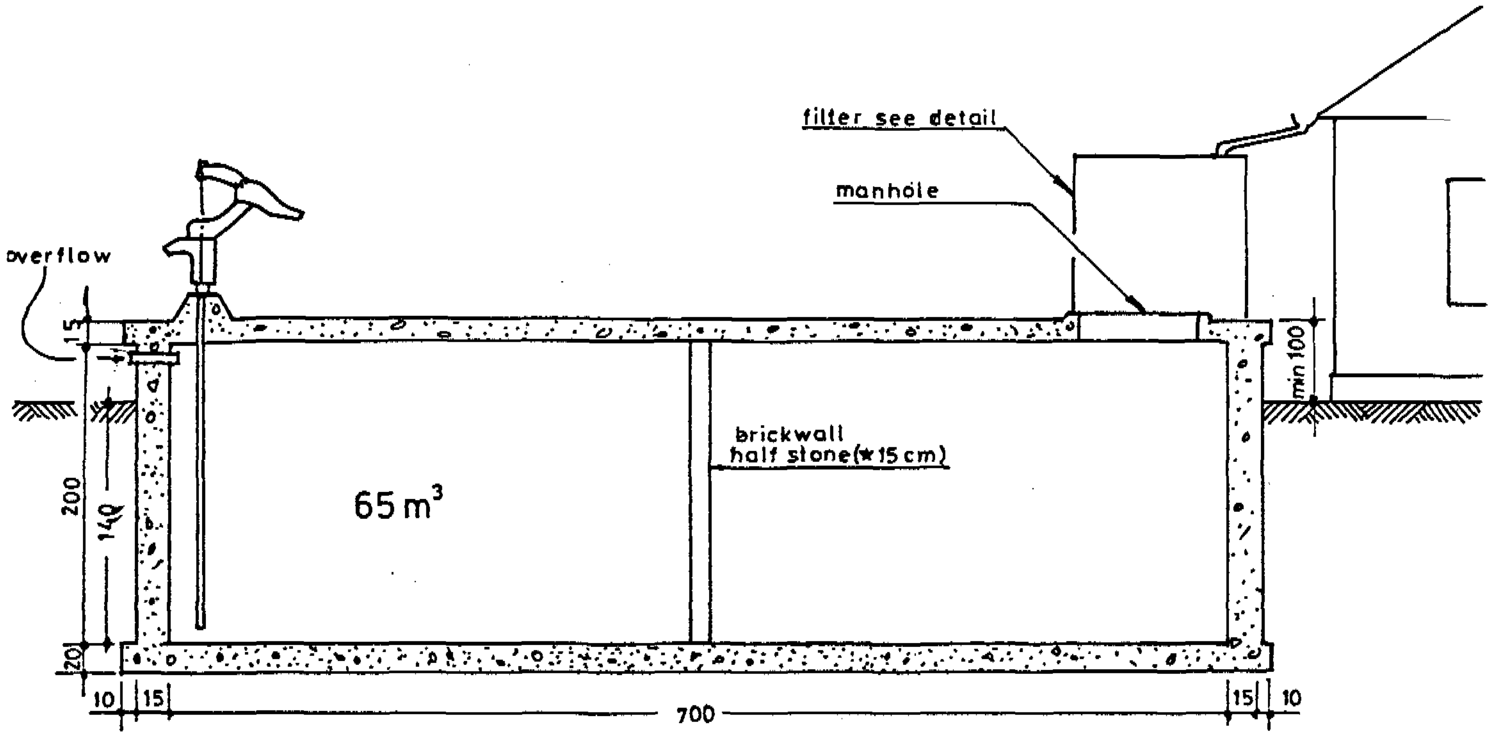
Water-proofed frameworks (e.g., from bamboo, or twigs) can be built by lining woven baskets with cement, mortar or plastic. Using a tapered form, full enclosure of the storage vessels should be accomplished easily.

In the construction of metal storage tanks, the most common material is galvenized iron sheets which are readily riveted and softsoldered. To avoid deformation of the tank when filled, a framework (wood, steel etc.) is required. These tanks can, in some instances, be incorporated as part of the wall structure or foundation of buildings.

Corrugated iron tanks have the advantage of being self-supporting. Tanks of this type for storage volumes up to 10,000 litres are found in Africa and Australia. Their construction is not difficult but a special 'roller' machine is required unless the corrugated iron sheets can be prepared manually. Local craftsmen can be trained to build these tanks in sizes suitable to the local requirements

Reinforced concrete tanks are used in many areas. Mainly for large storage volumes. An example is shown in Fig. 2.15.

Double-walled formwork is used in their construction. Reinforced material, usually steel mesh or bars, are positioned in the space and the concrete mix is poured in. The formwork can be removed when the concrete has hardened enough, usually after one full day or so. The formwork should then be deployed again for building another tank. This is necessary because the formwork represents a substantial initial investment; it must be economically utilized several times for which organisational measures are required. Reinforced concrete tanks have the advantage of great durability and they can, in principle, be built to any desired size. Because of their structural strength such tanks can be used as part of the walls or foundation of a building.



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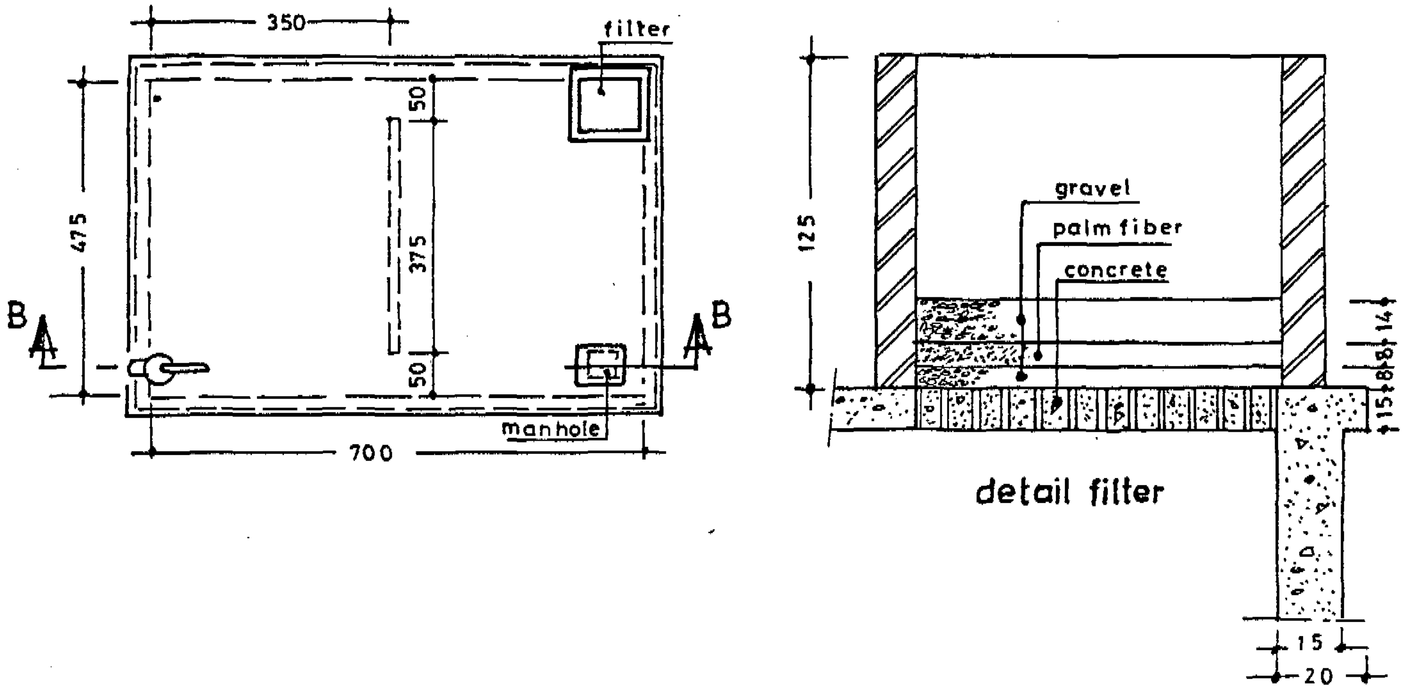


detail filter

Fig. 12.15 Reinforced concrete storage tank (65,000 litres)

Bamboo reinforced concrete tanks have been successfully built in countries where bamboo is available in suitable lenght, size and strenght (e.g. China, Indonesia, Thailand). Increasingly popular are ferro-cement tanks in which wire is used for the reinforcement of walls and bottom that are formed by plastering cement. Such tanks are quite economical. Typical designs of bamboo-cement and ferro-cement tanks are given in Figs. 2.16 and 2.17.

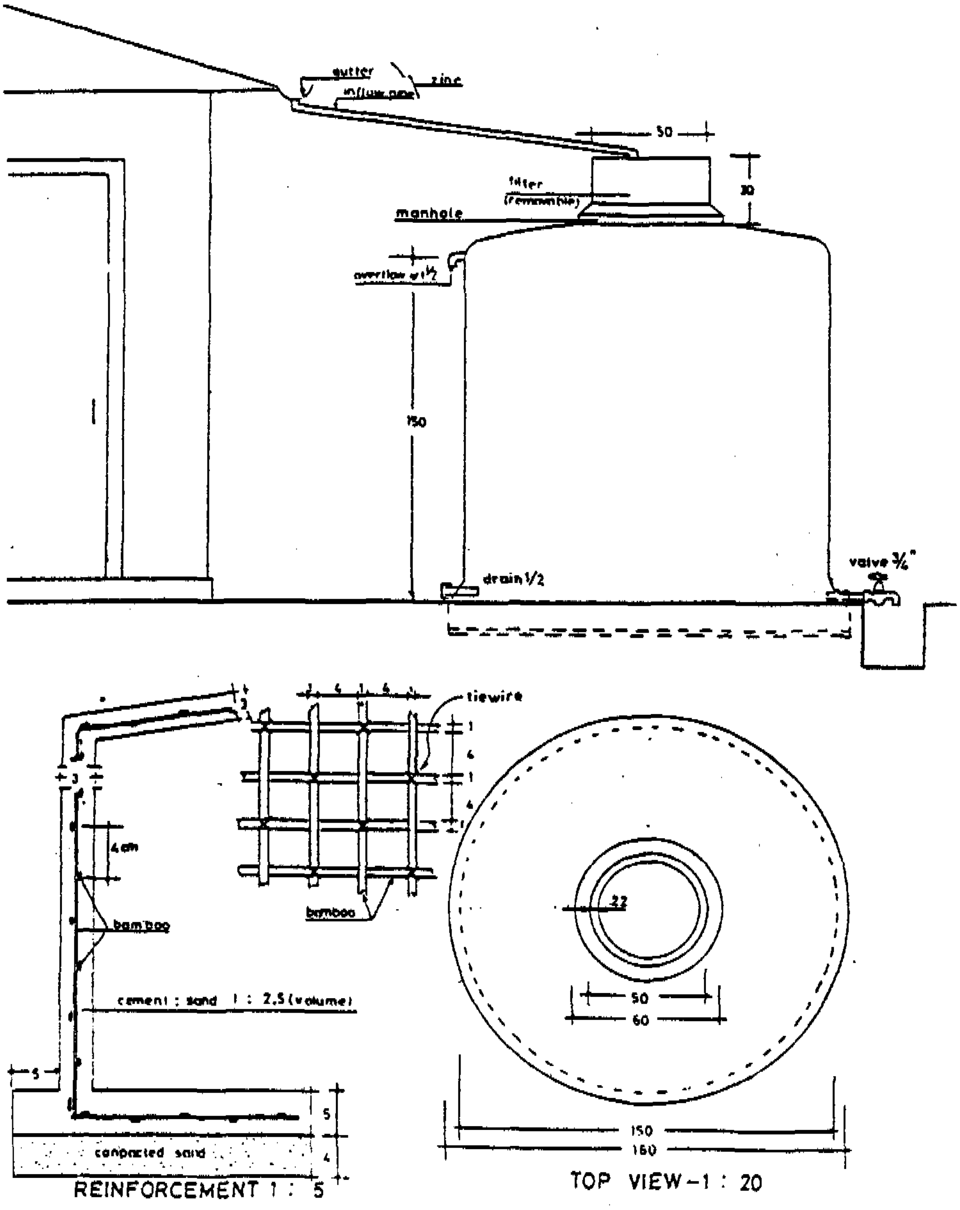
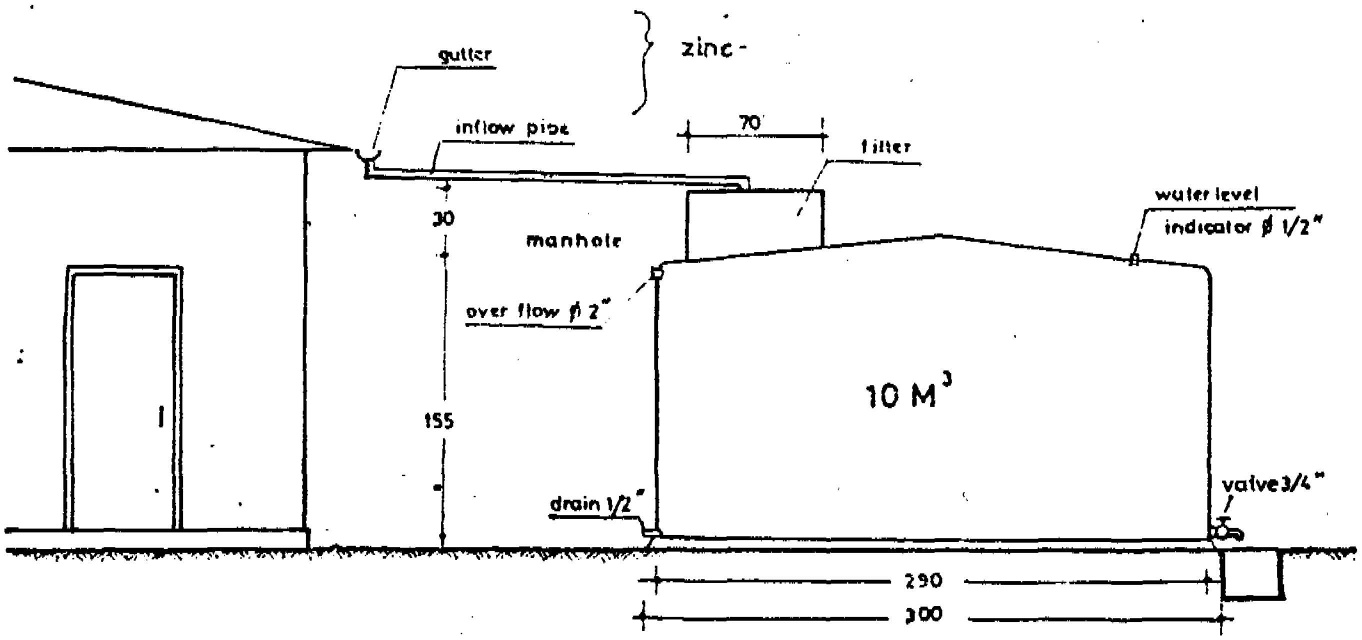
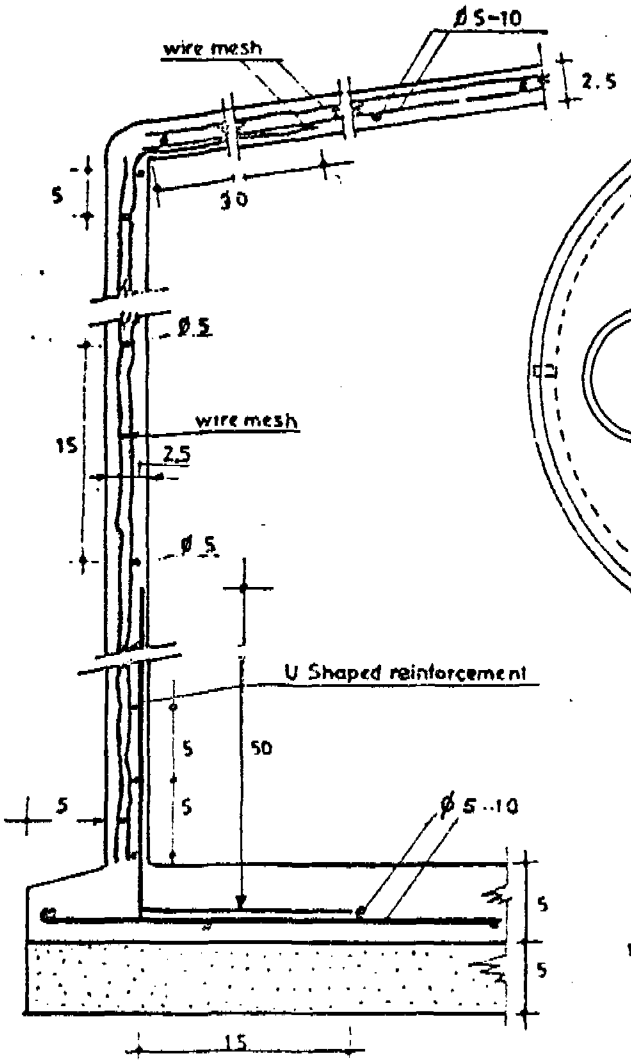


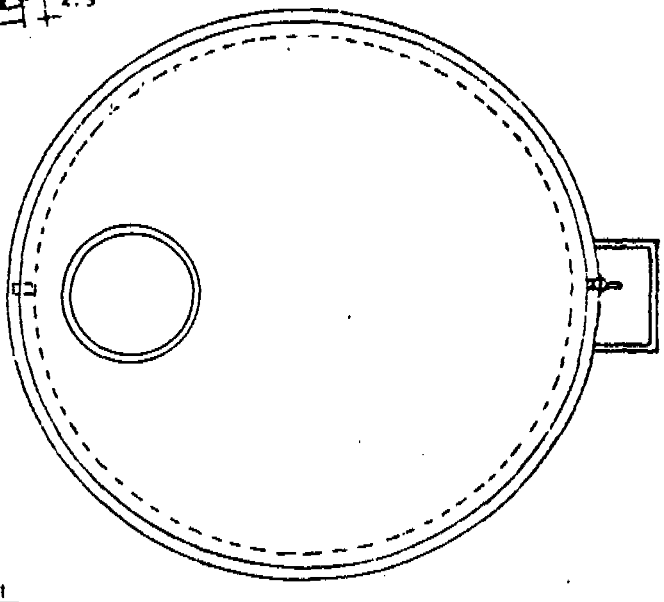
Fig. 2.16 Bamboo-cement storage tank (2,500 litres)

all dimensions in cm (unless otherwise indicated)
steel diameters in mm

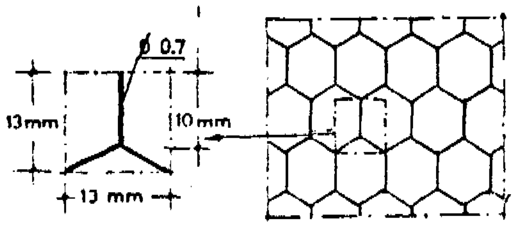




VERTICAL SECTION



TOP VIEW 1:40



DETAIL WIRE MESH

2.5. WATER QUALITY PRESERVATION

Where storage tanks or cisterns are built below ground, special provision must be made to prevent dust, sand, leaves, insects or other pollutants from entering. For the same reason, the inlet and outlet opening and any air vents should be fitted with screens.

An intercepting ditch should be provided to drain off any excess surface runoff.

Rainwater generally is rich in oxygen and it contains carbon dioxide, these gases being dissolved in the rain drops during their fall through the atmosphere. Rainwater frequently is acidic.

During storage, the quality of the rainwater collected from the roof or ground catchment may deteriorate through the putrefaction of organic material in the water, or through growth of bacteria and other micro-organisms. Measures to protect the quality of the stored water include the exclusion of light from the stored water, cool storage conditions, and regular cleaning. Simple disinfection devices such as the pot chlorinator may be very useful in rainwater storage tanks.

There are recorded cases, where cleaning of storage tanks has proved to be unnecessary. Apparently, micro-biological processes may provide for a self-cleaning effect. A large one-chamber tank was opened after 30 years of continuous use. A rigid layer of 5 cm depth was found consisting of black silt. Analysis of the silt material under the microscope shows very little bacterial presence and hardly any algal growth.

The silt layer seemed to perform a cleaning effect by biological processes, and it was decided to re-introduce part of the silt material after cleaning the tank.

Where necessary, treatment of the rainwater may be provided prior to its flowing into the storage tank, i.e. pre-filtration (Fig. 2.18). The water may also be treated before it is drawn from the tank. In theory, pre-filtration of the collected rainwater (coupled with sedimentation) is to be preferred, but in practice it is very difficult to ensure an effective functioning of the filters due to the fact that they operate only intermittently. The settling of particles from the stored water (sedimentation process), of course, will be more effective as the water is kept longer in the storage tank.

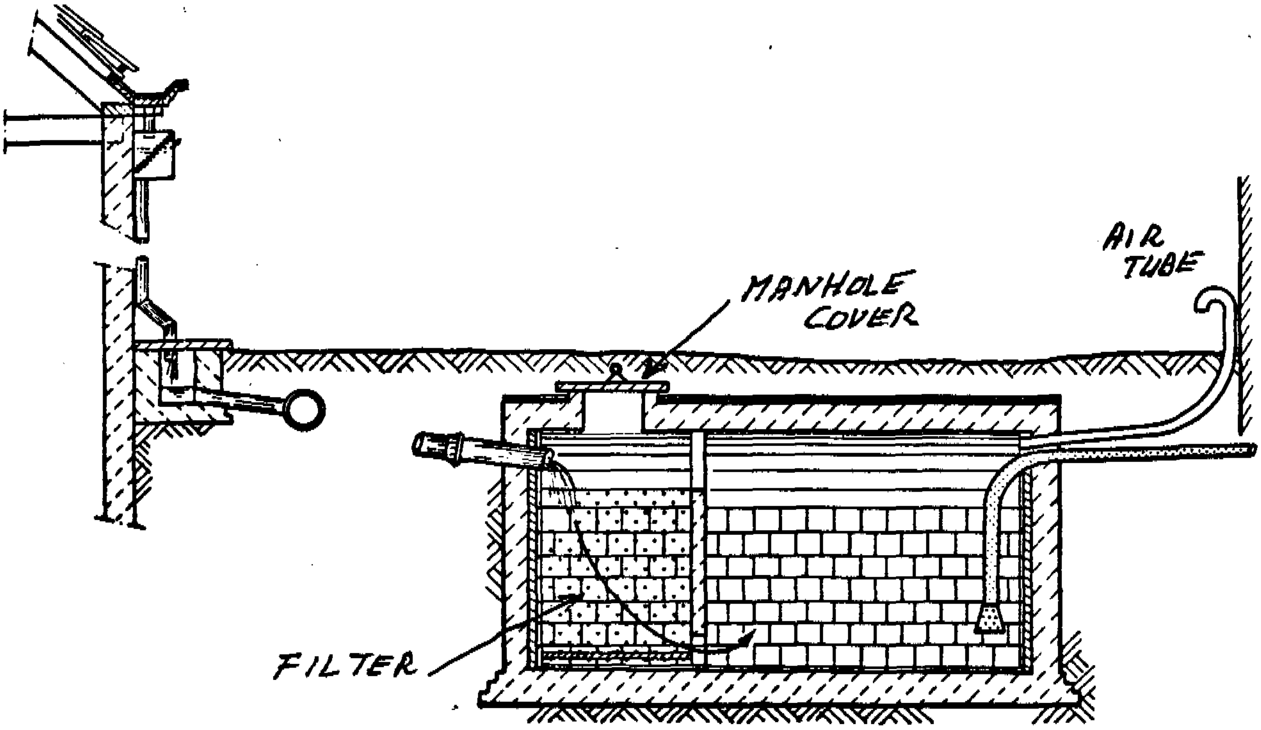


Fig. 2.18 Pre-filtration of Rainwater before its Storage

It is also possible to filter the water during its withdrawal from the storage tank (Fig. 2.19).

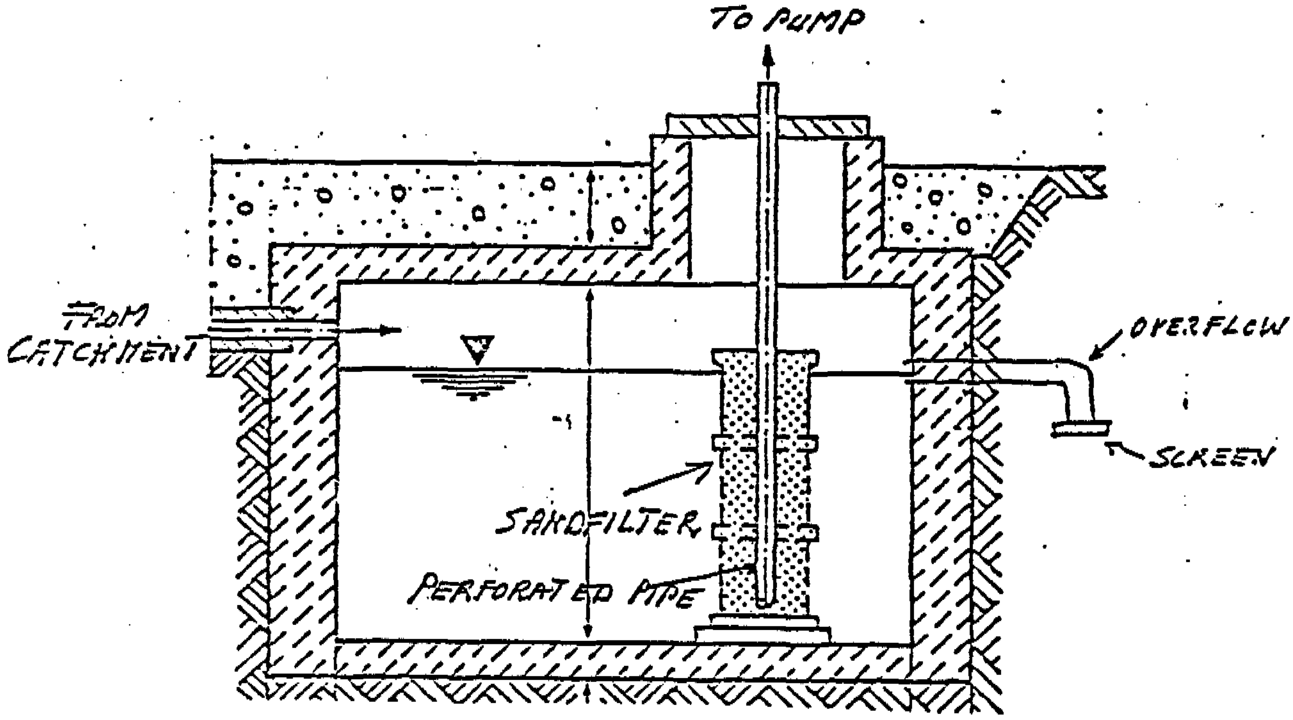


Fig. 2.19 Filtration of water during its withdrawal from storage tank ("American Cistern")

The boiling of water drawn from the storage before it is used for drinking or food preparation, would be desirable but it is often not practicable. In some places, a little bag containing a coagulant is suspended in the storage tank to flocculate the suspended solids in the water. The water drawn from the storage tank has a clear appearance, but its bacteriological safety is not assured.

2.6. TYPICAL RAINWATER SYSTEMS

Venetian Cistern

The "Venetian Cistern" (Fig. 2.10) was widely used in Venice and other places before the advent of piped water supply. The collected rainwater is fed into an inlet channel running around the cistern. The channel must be generously sized to hold the collected rainwater, even during heavy rain storms. From the channel, the water infiltrates through a sand filter for purification. The clean water is drawn from a well shaft (about 4 m deep) with rope-and-bucket or by pumping. The water can enter the well only at the bottom; hence it is forced to follow the longest stream path through the sand filter.

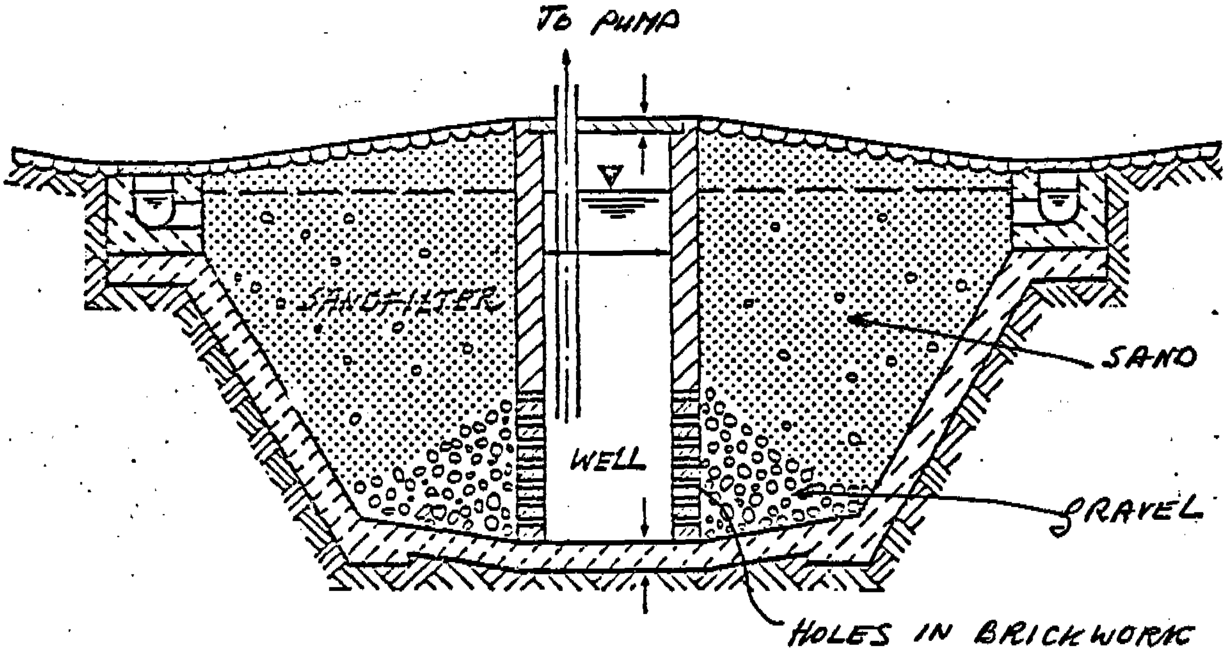


Fig. 2.20 Venetian Cistern

Re-contamination of the filtered water in the well shaft is possible; therefore, some final disinfection of the water prior to its consumption is to be recommended. These cisterns can have a substantial capacity, so that one or more may provide an adequate supply of water for a whole village. They are worth considering, if suitable sand and the other required materials for construction are available.

Siphon Cistern

This type has separate filters and storage chambers (Fig. 2.21)

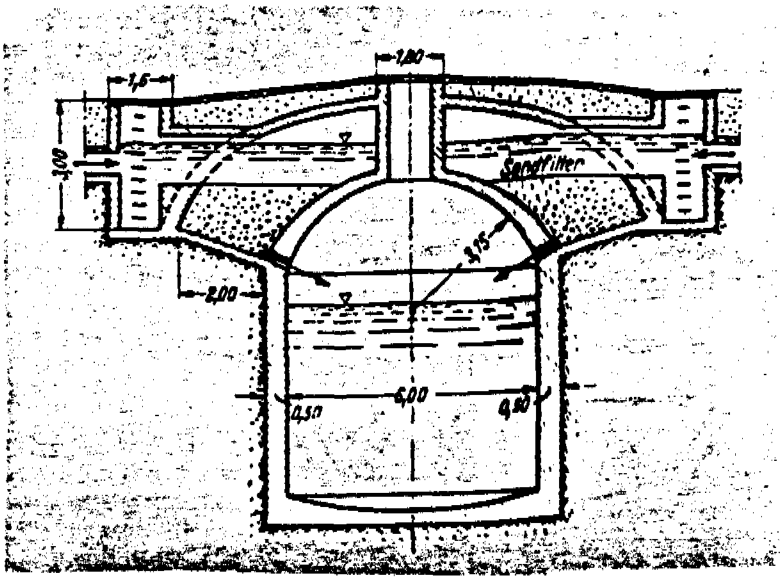


Fig. 2.21 Siphon Cistern

The "Siphon Cistern" provides for mechanical straining of the water, and possibly some biological filtration in the sand filter. However, if the filter top stands dry during periods without rain, the biological filter skin will die off. The biological filtration effect, therefore, is not assured.

The construction of the storage chamber roof is not easy, as the vault must be strong enough to support the heavy sand filter on top of it. With the construction materials and equipment normally available in rural areas of developing countries, this may be difficult to build.

German Cistern

The "German Cistern" uses the two-chamber operating principle (Fig. 2.22).

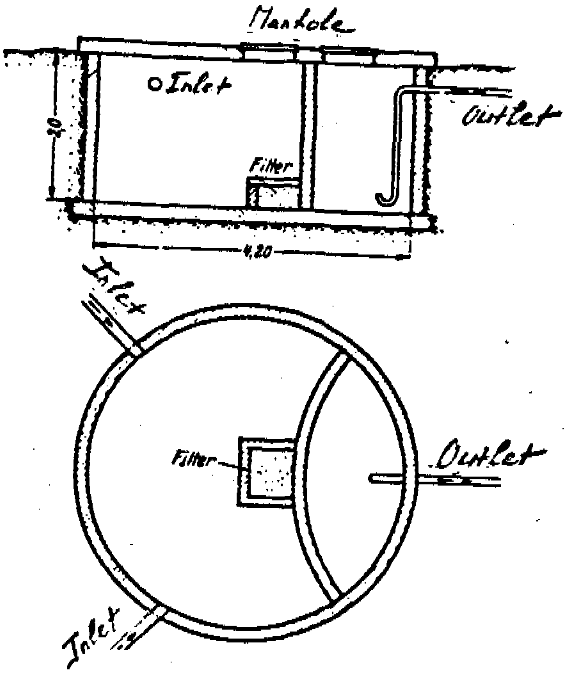


Fig. 2.22 German Cistern

The collected rainwater first flows into the storage chamber. Suspended solids are removed by sedimentation during the storage period. The second chamber holds the quantity of water which is needed for immediate consumption. The wall separating the two chambers is porous, and water is continuously passing the filter and thus purified. In Germany, gravel and charcoal are used as the filter materials.

The filter material will need to be replaced with new material after some period of operation (about 4-6 years), when the old filter material has become clogged with the impurities retained from the water. This is a difficult operation which requires the cistern to be completely emptied.

3. RAINWATER QUANTITY AND QUALITY

3.1. HYDROLOGY

Rainfall forms part of the hydrological cycle. This is the never-ending recycling of the water on earth and in the atmosphere (Fig. 3.1).

While rainfall is, by far, the most important form of precipitation, there are also other forms such as hail, sleet, dew and snow.

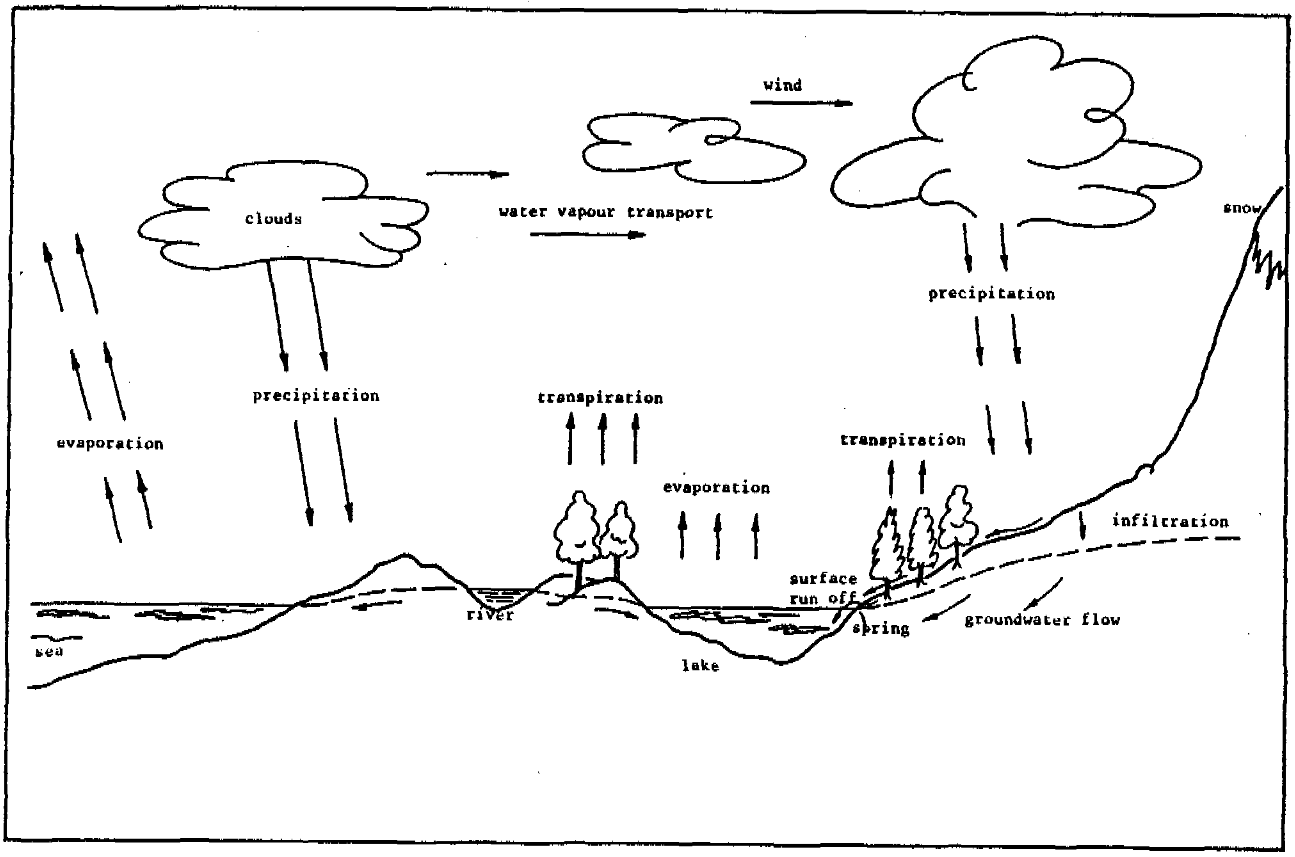


Fig. 3.1 Hydrological Cycle

In general, annual rainfall is highest in the equatorial zones, and less in the northern regions (Fig. 3.2). However, rainfall data shows that annual rainfall distribution is influenced by many more factors than geographical location alone.

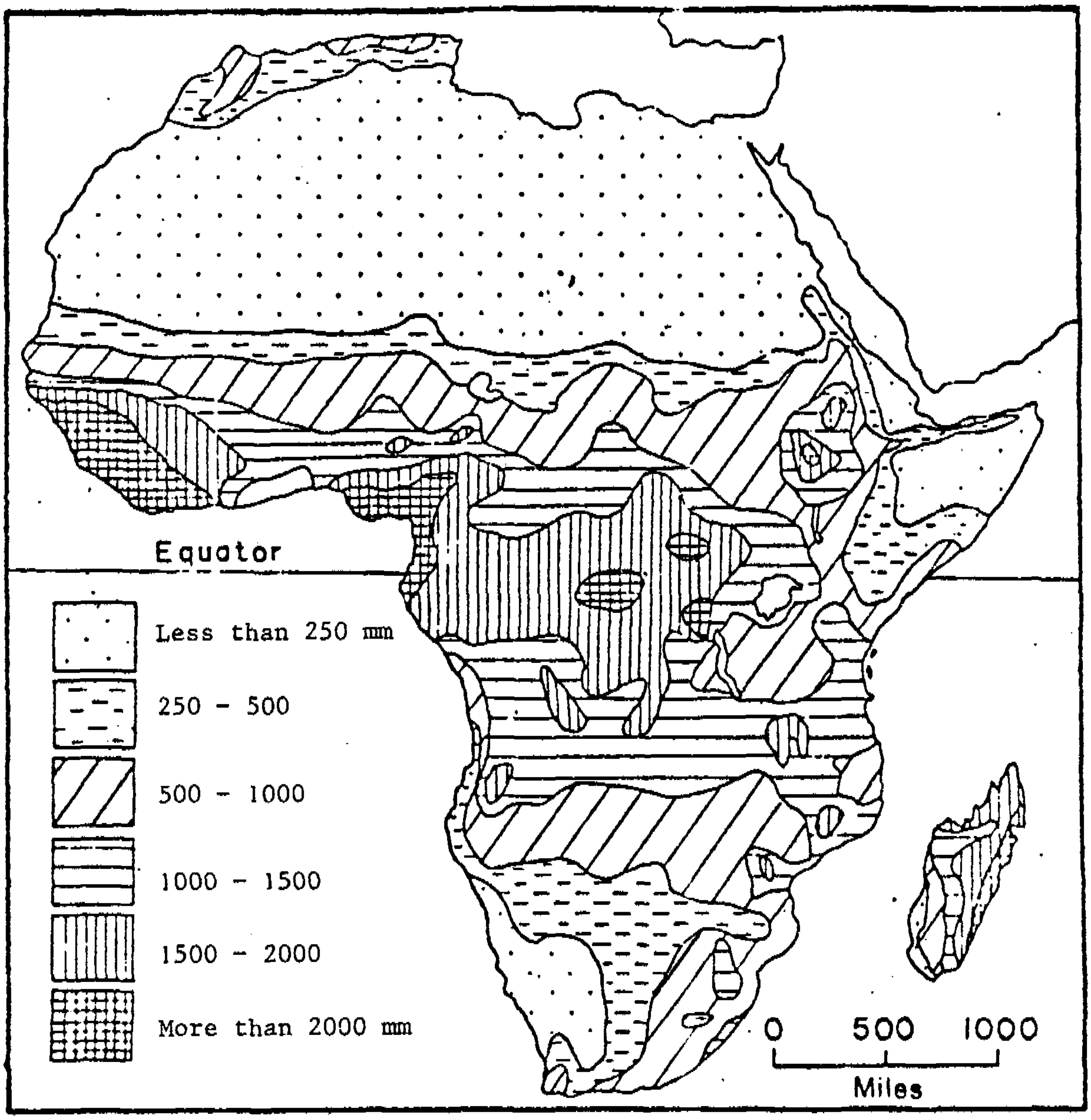
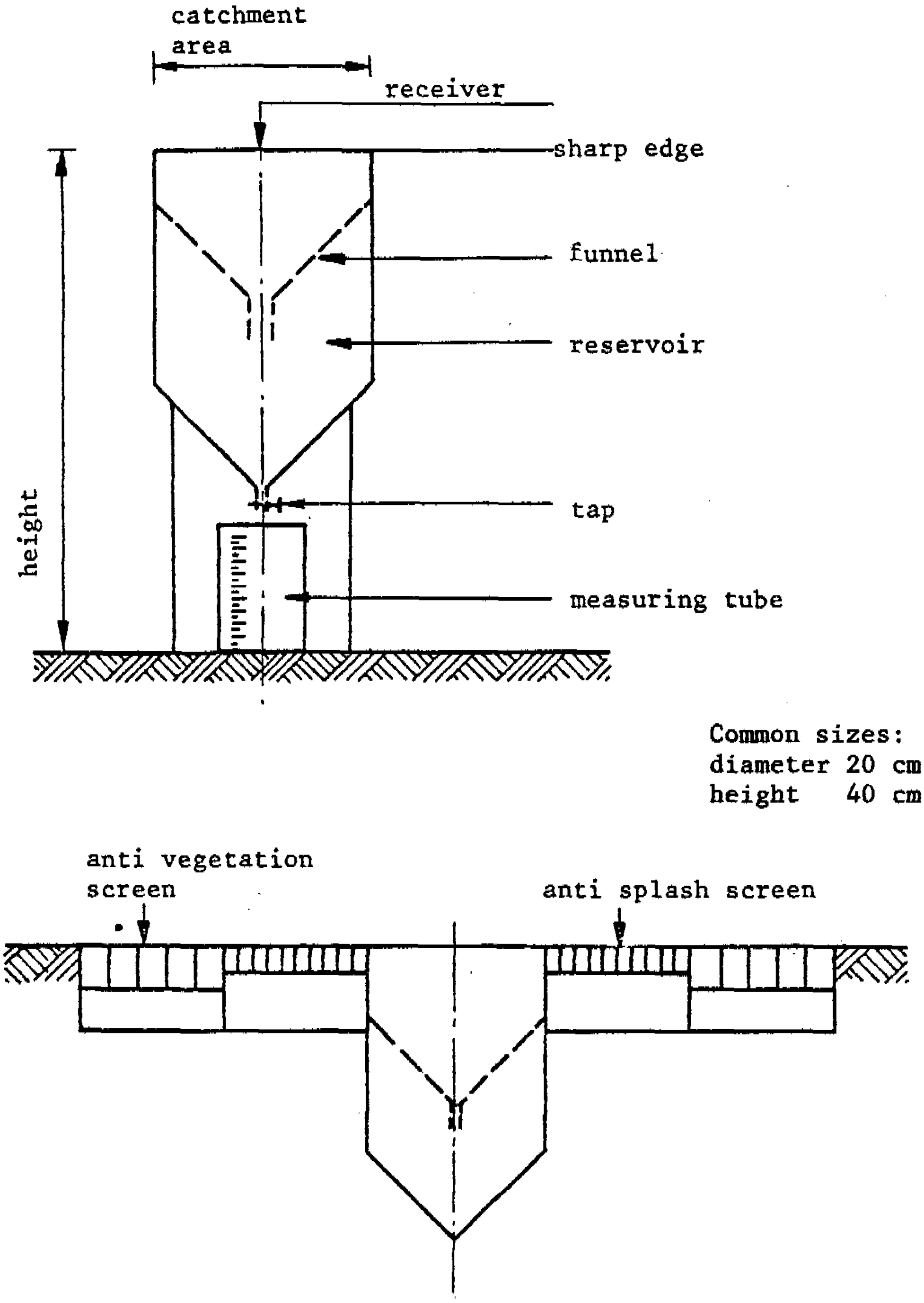


Fig. 3.2 Average Annual Rainfall (Africa)

3.2. MEASURING RAINFALL

The instrument used most widely for measuring rainfall is the raingauge device of which two typical models are shown in Fig. 3.3.



Common sizes:
diameter 20 cm
height 40 cm

Fig. 3.3 Rain Gauges

A ground-level gauge, in general, is capable of measuring rainfall with a higher degree of accuracy than a gauge positioned at a height above the ground, but a ground-level gauge requires more maintenance attention and careful handling.

These rainfall gauges are usually read once a day by pouring the water collected in the reservoir, into a measuring tube. There are also ram gauges that provide for automatic registration of daily rainfall quantities. These gauges with a water storage facility are probably more suited for use in remote areas where they are left unattended to record rainfall during longer periods; they are read regularly, e.g. once a month. The collected rain fills a reservoir which, when full, tops over with the water flowing in a separate standpipe of adequate holding capacity. An oil filter on top of the standpipe is provided for reducing any evaporation losses of water.

Rain records can be presented in tables (Fig. 3.4) or in diagrams giving the annual distribution for a number of years, and the monthly distribution within the year (Fig. 3.5). It depends on the purpose for which the rainfall data are to be used, how any records can be worked out best and presented. For designing rain harvesting systems for drinking water supply, monthly rainfall data probably provides the best basis.

RAINFALL RECORD

Lat.N. 08° 10'
Long.E. 35° 33'

Station at Gore REGION Baro Basin ELEVATION 2002

Detail 10-days total precipitation Unit mm

Year	Jan.	Feb.	Mar.	Apr.	May.	June	July.	Aug.	Sept.	Oct.	Nov.	Dec	ANNUAL Total
1971													
1-10	5.9	0.0	0.0	44.0	100.5	43.7	137.5	98.5	112.1	58.2	0.5	0.0	
11-20	16.9	0.0	52.1	0.0	95.2	100.3	98.3	47.7	154.6	64.8	96.8	0.0	
21-31	22.8	0.0	14.5	42.4	155.3	71.3	90.7	53.0	93.4	97.2	10.4	41.1	2039
1972													
1-10	24.5	0.0	0.0	86.7	78.3	79.6	88.9	104.5	77.2	38.9	72.4	0.0	
11-20	20.0	39.2	0.8	16.6	13.2	62.3	87.2	70.5	102.4	42.0	0.0	12.5	
21-31	52.5	3.3	33.7	35.3	63.1	103.1	93.5	97.9	28.9	50.6	14.4	24.4	1720
1973													
1-10	3.2	0.0	15.7	122.0	82.6	79.4	111.4	98.5	135.4	112.2	28.9	0.0	
11-20	45.0	0.0	5.5	59.1	134.5	55.8	98.4	236.5	121.0	32.5	0.8	0.0	
21-31	48.1	26.4	26.7	33.6	65.9	100.4	128.1	110.9	99.6	40.1	28.4	7.8	2310
1974													
1-10	8.4	10.8	11.5	0.0	160.8	131.2	95.3	51.9	170.5	76.7	2.7	1.1	
11-20	21.4	20.2	15.8	4.4	90.7	142.7	122.6	138.0	138.9	1.6	44.6	50.0	
21-31	40.8	11.9	26.0	19.5	112.2	73.5	117.5	123.7	84.4	63.7	0.0	10.7	2236
1975													
1-10	0.0	40.3	0.0	25.0	26.9	151.6	100.2	57.5	71.7	73.1	73.8	12.1	
11-20	2.6	41.5	4.6	89.3	123.4	86.3	85.5	21.1	125.7	32.5	46.7	30.4	
21-31	39.0	17.9	20.1	52.7	65.6	117.9	108.3	114.9	89.2	27.7	0.0	31.3	2048

Fig. 3.4 Rainfall Record

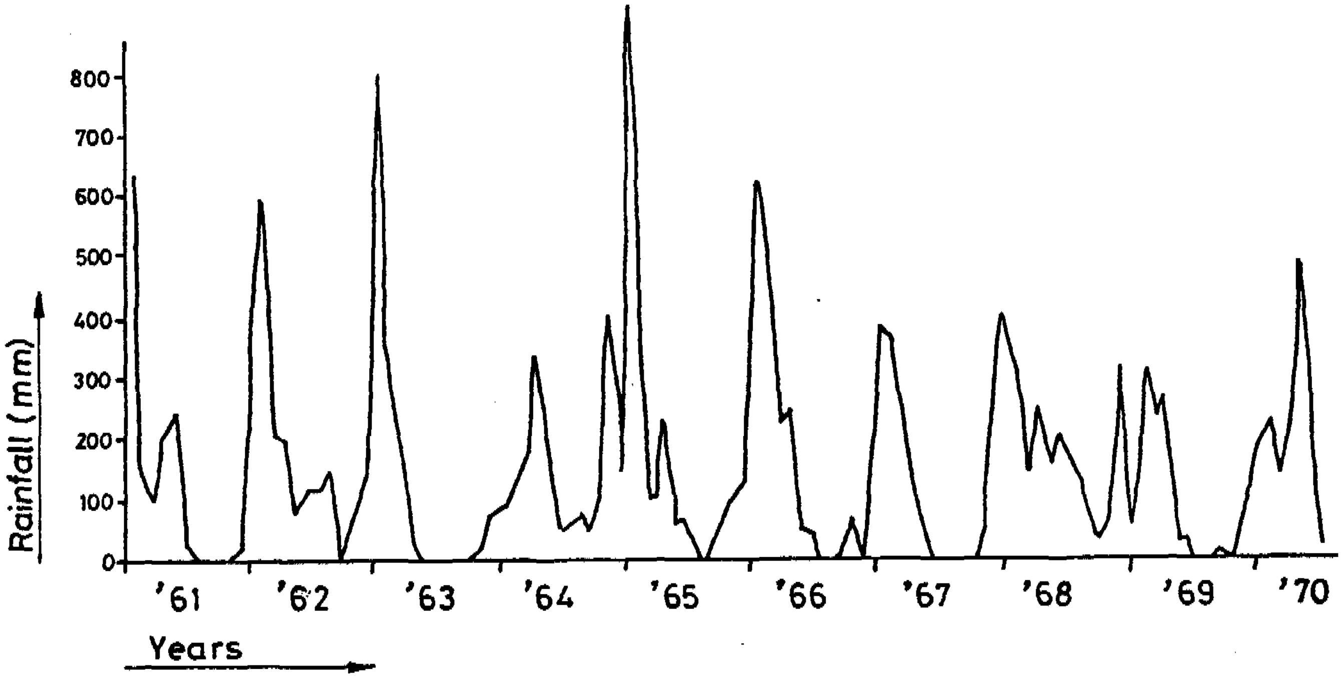


Fig. 3.5 Rainfall Records (Juntinyat, West Java, Indonesia)

It will be seen that annual rainfall exhibits a considerable variation, but from the records of a series of years a seasonal pattern usually can be recognized. The monthly rainfall distribution averaged out of the 10 years record, reflects the seasonal pattern quite clearly.

If possible, a network of gauges should be established to cover the variation of rainfall over the entire area for which rainwater harvesting systems are planned to be provided. They should be spread more or less evenly. The density of rainfall gauge stations differs wide from country to country. Great Britain has one gauge on every 40 square kilometre on average. Israel even has a higher density of rainfall stations.

The altitude frequently has a considerable effect on rainfall, and the distribution of rain gauge stations should cover the range of altitudes relevant for the area concerned. One way of checking whether a planned distribution of the gauges would be proper, is by calculating the cumulative percentage of area for a number of elevation intervals. Table 3.1 presents an example.

Table 3.1 Cumulative percentage of area for elevation intervals

Elevation m	Area km^2	E Area km^2	% of total area exceeded
1000 800	6	6	$\frac{6}{38}$ = 16%
600	10	10	$\frac{10}{38}$ = 26%
400	12	22	$\frac{22}{38}$ = 58%
200	16	38	$\frac{38}{38}$ = 100%

Thus, in the example, 16% of the area lies above 800 m, 26% above 600 m, 58% above 400 m, and all of it has an elevation higher than 200 m.

The sites of the rain gauges to be installed should cover the various elevation ranges more or less proportional to the calculated distribution.

3.3. RAINWATER QUALITY

All rainwater contains constituents that are taken up or washed out from the atmosphere. Atmospheric gases are dissolved in the rainfall droplets. Above oceans and seas, salts are taken up from the fine spray over the water surface. Over land areas, particularly in dry regions, dust particles are washed out.

Rainwater is usually slightly acidic due to its reaction with carbon dioxide (CO_2) in the atmosphere to form carbonic acid. Water having a low Calcium content will contain CO_2 which reacts with $CaCO_3$ from cement. When rainwater contacts gaseous pollutants in the atmosphere like sulphur dioxide (e.g. from volcanoes, industry), it may become quite acidic causing problems of corrosion and bitterness of taste. In rural areas, however, this is not a common problem.

After reaching the ground surface, rainwater forms surface runoff or groundwater flow. It will pick up considerable amounts of mineral compounds and of organic matter, debris from vegetation and animal origin, soil particles and micro-organisms. Fertilizers and pesticides may be picked up in areas where they are used in agriculture.

Some typical examples of the composition of rainwater are given in Table 3.2. A general characteristic of rainwater is its low content of dissolved solids.

Table 3.2 Typical Examples of Rainwater Composition

	Obibos in Amazone area; Brazil	North Carolina USA	Juntinyat, West Java Indonesia
Specific conductivity (S/cm)	40		25
pH	6.5		5.6
chloride Cl^- (mg/l)	1.9	0.6	3
nitrate NO_3^- (mg/l)	0.1	0.6	1
sulphate SO_4^{--} (mg/l)	3	2.2	4
iron Fe (mg/l)	0.6		nil
manganese Mn (mg/l)			nil
calcium Ca^{++} (mg/l)	4.3	0.65	2
magnesium Mg^{++} (mg/l)	1.1	0.15	1

From the figures in the table, it may be judged that rainwater in its composition is not likely to exceed the guidelines for drinking water quality which can be derived from recommendations made by the World Health Organization. However, in using rainwater for drinking water supplies, it is not so much the quality of the rainwater itself that is important, but rather the quality of the water as drawn from the storage tank in which the water is collected and stored for later consumption.

4. DESIGN OF RAINWATER HARVESTING SYSTEMS

4.1. GENERAL

A rainwater harvesting system basically provides for the catchment and collection, and the storage of rainwater (Fig. 4.1). In designing such a system the objective should be to arrive at the most economical combination of storage tank volume and catchment area. There are cases where the available catchment area is fixed (e.g. roof and surface of the housing, land allocation by government), and then the most suitable size of storage tank may have to be determined on that basis. Sometimes, a degree of standardization as regards the rainwater storage tanks to be constructed in a particular area, is sought by the authorities in view of the reduction in construction costs that can be obtained by repititious use of designs, building materials and labour. In those cases, the required catchment area may be determined for each of the available sizes of storage tank.

In other instances, the conditions for determining the most economical combination of catchment and storage volume will be more open. Sometimes, experience with rainwater harvesting systems in the area may be wide enough to serve as a basis for decision. However, more often than not this is not the case, and then the proper method to establish the optimal tank volume, in conjunction with the required size of catchment area, should be based on a systematic analysis of rainfall records, and construction cost and other data.

The systematic analysis as here proposed, uses monthly rainfall data. Verification of results has shown that the use of daily rainfall data, if available at all (which is not very likely for rural areas of less developed countries), does not substantially add to the accuracy of analysis.

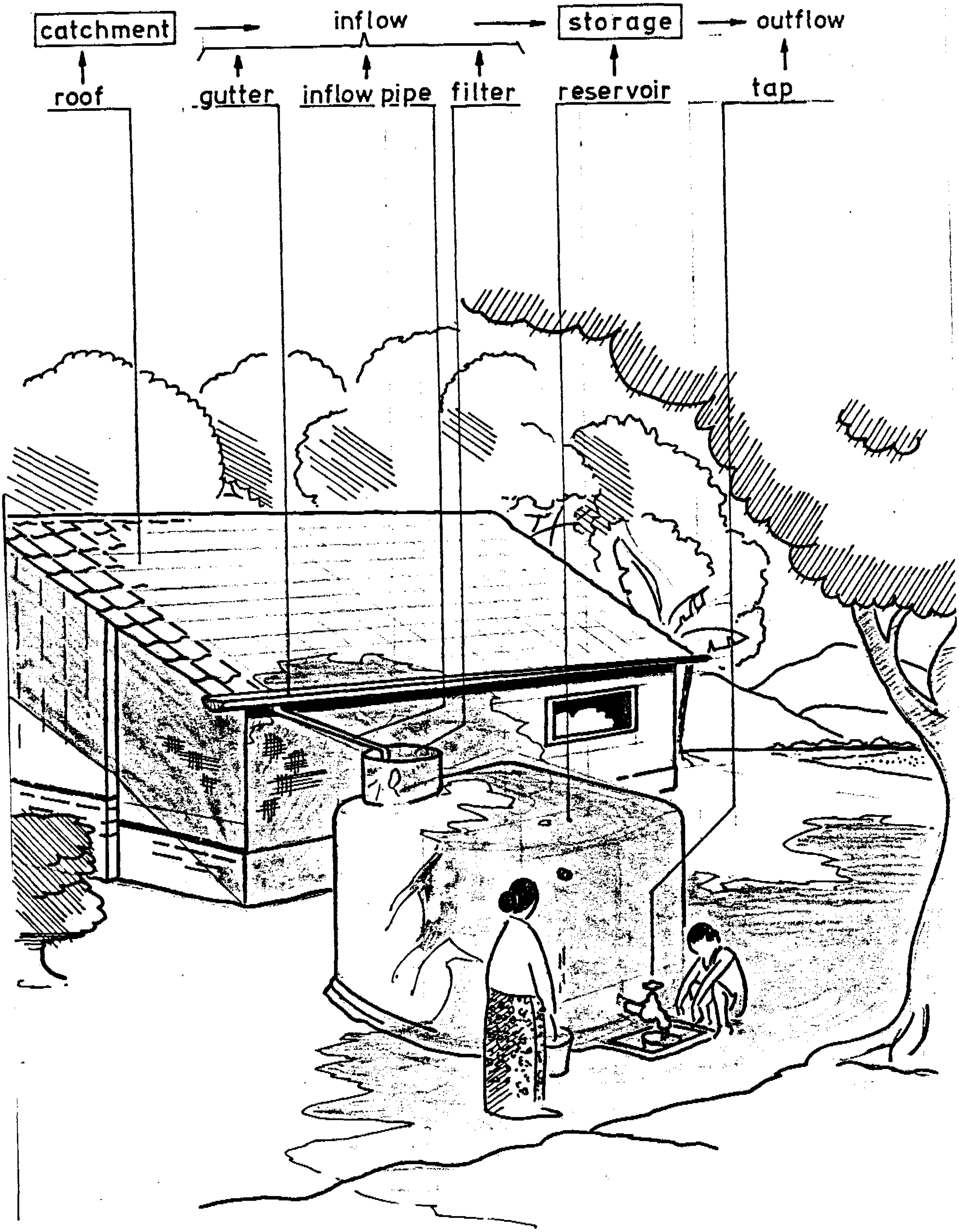


Fig. 4.1 Rain Water Harvesting System

4.2. DESIGN PROCEDURE

The basis of the design is provided by any records of monthly rainfall measured at one or more rain gauge stations which can be regarded as representative of the area under consideration (Fig. 4.2). If no such rainfall records are available, either because there are no gauge stations in the area or because the rainfall records are too short or unreliable, then it may be possible to use records from existing stations outside the area. This, however, may introduce serious errors in the analysis. As soon as possible, rainfall stations should be erected in the area, and observations started.

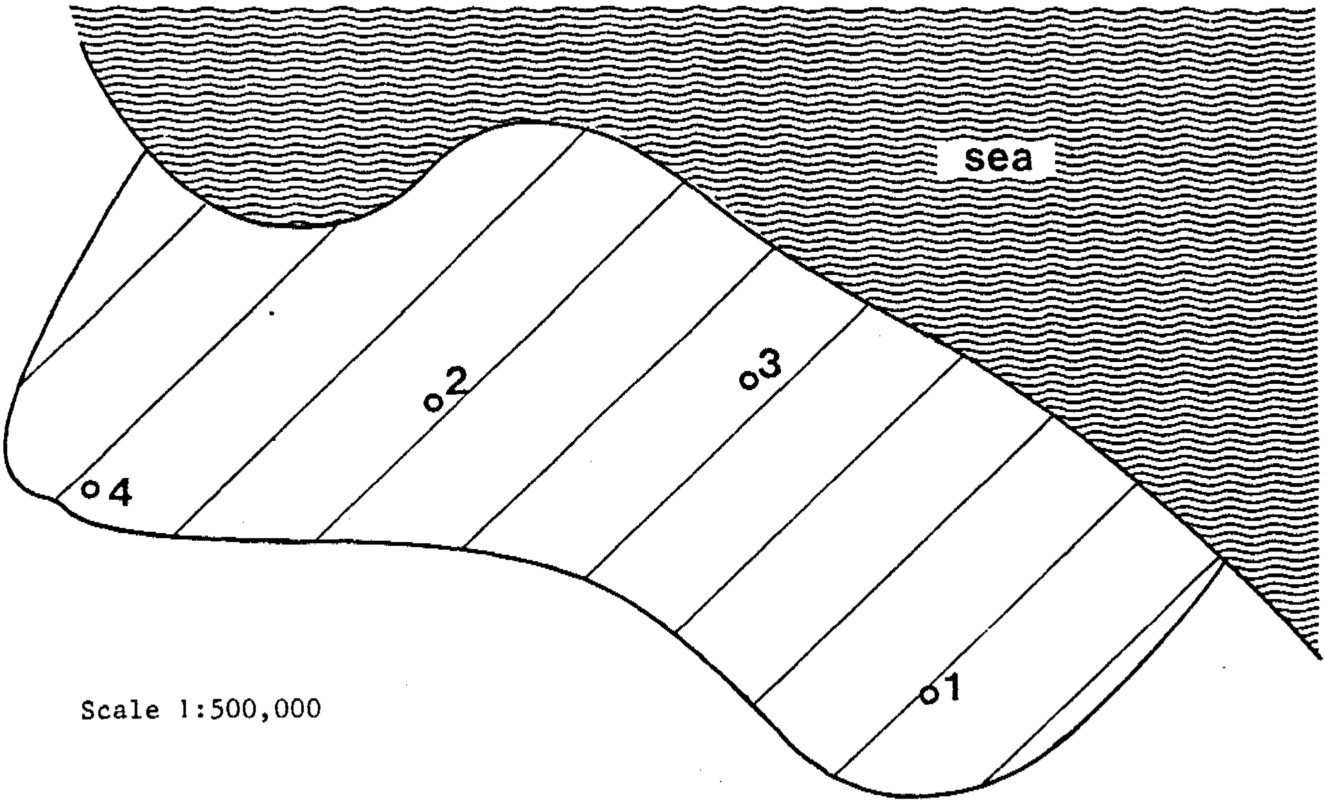


Fig. 4.2 Area under consideration, with locations of rainfall observation stations indicated

On the basis of the rainfall data, as availbale, a schematisation of the annual rainfall pattern may be made (Fig. 4.3).

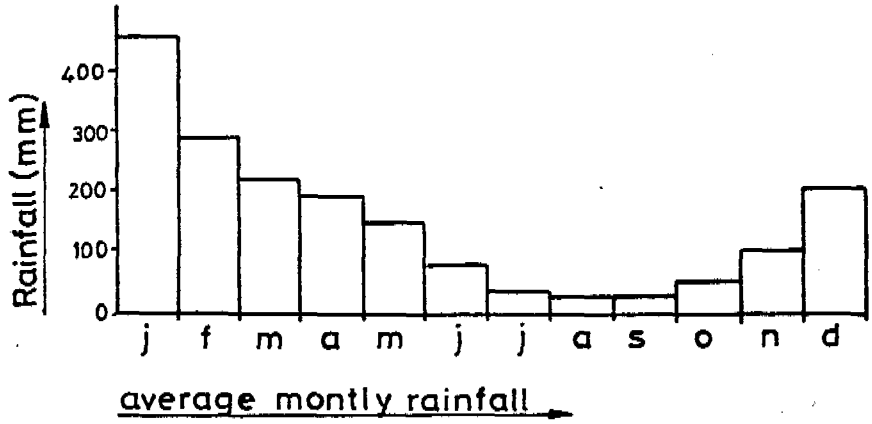


Fig. 4.3 Schematisized Annual Rainfall Pattern

The rainfall received by a catchment area (whether a roof or ground surface) is only partly discharged toward the storage tank. A portion of the rainwater serving to wet the surface of the catchment area, is held in depressions and then lost by evaporation or infiltration in the ground.

The amount of rainwater that can be collected in ground catchments will be dependent on whether the catchment is flat or sloping, and the watertightness of the top layer. Through preparation of the ground surface, a sufficiently rapid flow of the water to the point of collection and storage can be assured in order to reduce evaporation and infiltration losses.

With a catchment area of A m^2 in size, receiving a rainfall of R mm in a particular month, the amount of water yielded by the catchment, may be computed as:

$$\text{Yield of catchment} = \frac{f \times A \times R}{1000} \quad m^3/\text{month}$$

<u>in which</u>: A = catchment area (m^2)
R = monthly rainfall (mm)
f = catchment efficiency factor or runoff coefficient

Admittedly, a short low-intensity rain storm after a long dry period is likely to evaporate for the greater part, so that the useful runoff would be very small. Conversely, during a long period of heavy rain, the runoff coefficient might be very high. For reasons of simplicity, however, in this analysis the catchment efficiency is taken constant.

Field measurements indicate that the portion of rainfall that is actually harvested, ranges from about 30% for pervious, flat ground catchments to over 90% for covered, sloping-strip ground catchments and roofs of suitable material. The factor f, thus, ranges between 0.3 and 0.9. Table 4.1 is provided for general guidance.

Table 4.1 Run-off Coefficient

Type of Catchment	f
Uncovered Catchment Surface	
completely flat terrain	0.3
sloping 0 - 5%	0.4
sloping 5 -10%	0.5
sloping more than 10%	0.5 and more
Covered Catchment Surface	
- (roof) tiles	0.8 - 0.9
- corrugated sheets	0.7 - 0.9
- concreted bitumen	0.7 - 0.8
- plastic sheets	0.7 - 0.8
Brick Pavement	0.5 - 0.6
Compacted Soil	0.4 - 0.5

For each size of catchment area, a certain storage volume will be required for the rainwater harvesting system to be able to supply the selected ration of water daily and without interruption even at the end of the dry period (i.e. without the storage tank running dry).

Assuming that the daily ration available from the systems for consumption is constant, then the required catchment area will be large if the available storage volume is small, and, conversely, if a generous storage volume is provided, the size of the needed catchment area will be relatively small.

It appears that there is a range of combinations of catchment area and storage volume each of which will be capable of supplying the required daily ration. The optimal combination is the one that results in the lowest overall costs.

The catchment area can be expressed in terms of m^2 per person serviced (A_c), and the storage volume in m^3 per person serviced (V_c). The relationship between A_c and V_c takes the form illustrated in Fig. 4.4.

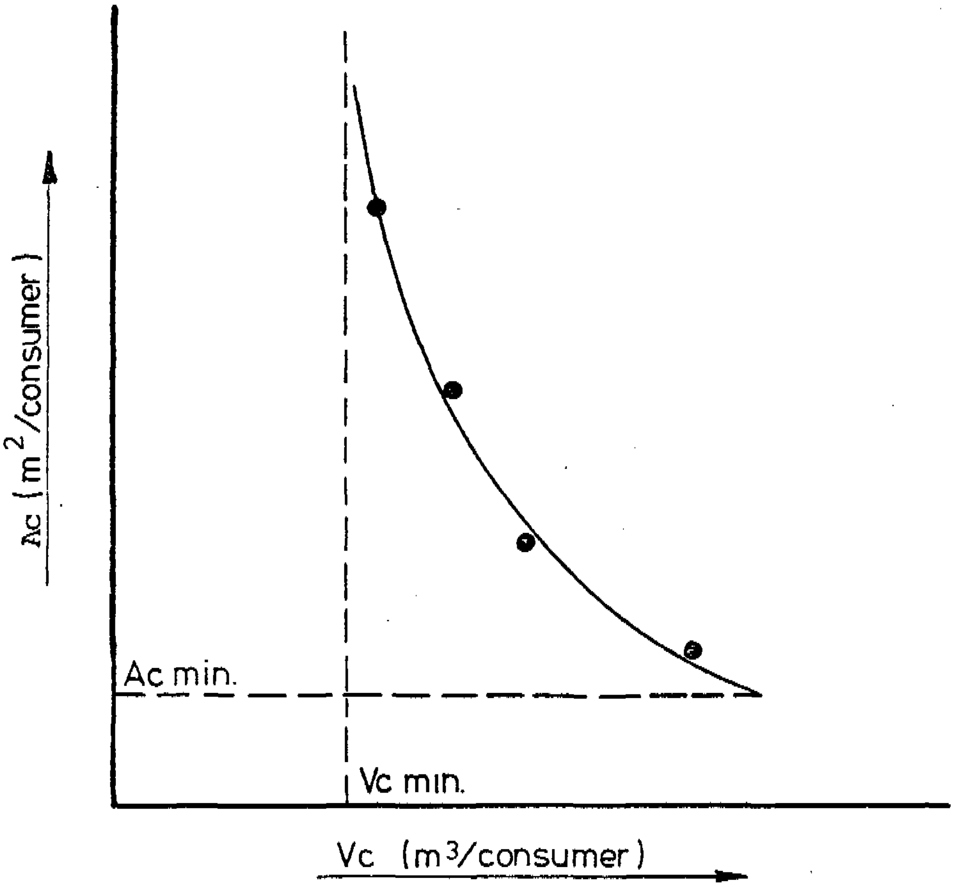


Fig. 4.4 Relationship A_c - V_c

The optimal A_c - V_c combination is dependent on the relative cost of catchment area, and construction of storage tanks. Before proceeding to the determination of the optimal A_c - V_c combination, it is useful to explain the two boundary conditions, i.e. the minimal catchment area per person (A_c mm) and the minimal storage volume per person (V_c min).

Determination A_c min

If a certain number of people (N) is to be serviced with drinking water form a rainwater system, with each of them being supplied with a daily ration of C litres/day, the amount of water to be supplied per month will be:

$$Q = \frac{N \times 30 \times C}{1000} \quad m^3/\text{month}$$

in which: Q = Amount of water to be supplied per month (m^3/month)
N = Number of people serviced by the rainwater system
C = Daily ration per person (litres/day)

A catchment area A m^2 in size, and receiving a rainfall of R mm in a particular month, will in that month have a yield of:

$$Y = \frac{f \times A \times R}{1000} \quad m^3/\text{month}$$

in which: Y = Yield of catchment (m^3/month)
A = Catchment Area (m^2)
R = Rainfall (mm/month)
f = Runoff Coefficient

The above formula is based on the assumption that there is an adequate storage volume to accumulate any surplus of rainfall over consumption, for later use by the people serviced.

For a period of sufficient length (e.g. one full year), it may be assumed that there will be neither a nett withdrawal of water from the storage volume, nor a nett accumulation. That is: over such a long period the water received by the storage tank would be equal to the amount taken from it by the people serviced.

The minimum catchment area required (A min) then follows from the equation:

$$\frac{N \times 30 \times C \times 12}{1000} = f \times \frac{A\ min \times (R1 + R2 \ldots\ldots R12)}{1000}$$

So that: $A \text{ min} = \frac{N \times 30 \times C \times 12}{f(R1 + R2 \ldots R12)}$

which expressed in terms of the minimum catchment area required per consumer (A_c min) leads to:

$$A_c \text{ min} = \frac{30 \times C \times 12}{f(R1 + R2 \ldots\ldots R12)}$$

in which: A_c min = Minimum catchment area required per person services (m^2)

C = Daily ration per person (l/day)

R1, R2, ...R12 = Rainfall in month 1, 2,......12 (mm/month)

f = Runoff coefficient

Determination of V_c min

Monthly rainfall distribution shows a wide variation. The length of the periods with very little or no rainfall are critical for the minimal storage volume that must be provided. The variation of the length of these dry periods is considerable. Inspection of the figures shows that an average dry period of about 2 months, but longer dry periods of up to 5 months have occurred in individual years. It is basically impossible to provide a guaranteed adequate supply under all conditions using a rainwater harvesting system. It must be accepted that such a system will, under exceptional conditions, not be able to supply the adopted ration at all times.

Selecting, on the basis of the rainfall records as available, a design (or "critical") dry period (e.g. 4 months) the minimum storage volume per person serviced (V_c min) can be computed as:

$$V_c \text{ min} = \frac{30 \times C \times T}{1000}$$

in which: V_c min = minimum storage volume provided per person serviced (m^3/person)
C = daily ration per person (litres/person)
T = design (or "critical") dry period.

Selection of the critical dry period should be related to the question how any periods of reduced supply of drinking water would affect the people dependent on the rainwater system. An assessment must be made on the points:

- whether the people could temporarily curtail water use, to cope with the reduced supply during a period of limited duration;
- whether the people would have to use alternative, possibly unsafe sources.

This must be balanced against the relatively high costs of raising the capacity of the rainwater systems to a level which would only be needed under exceptional conditions. A careful survey in the area, with full consultation with the prospective users of the rainwater system, should be made to provide a basis for these design decisions.

Determination of Optimal A_c - V_c Combination

For the determination of the optimal A_c - V_c combination, it is necessary to establish, for the area under consideration, the A_c - V_c relationship as represented by the curve in Fig. 4.4. The curve can be drawn when a sufficient number of points is computed and plotted in the diagram.

Fist, a starting value of A_c must be selected. It is recommended to take the A_c value as calculated for the year with the lowest annual rainfall on record. This value is computed as:

$$A_c = \frac{30 \times C \times 12}{f \times P_{min}}$$

in which: P_{min} = minimum annual rainfall on record (R1 + R2........R12) in that year

The year with the lowest annual rainfall on record, can be selected from the available monthly rainfall data. It is easiest done from a diagram of which Fig. 4.5 is an example.

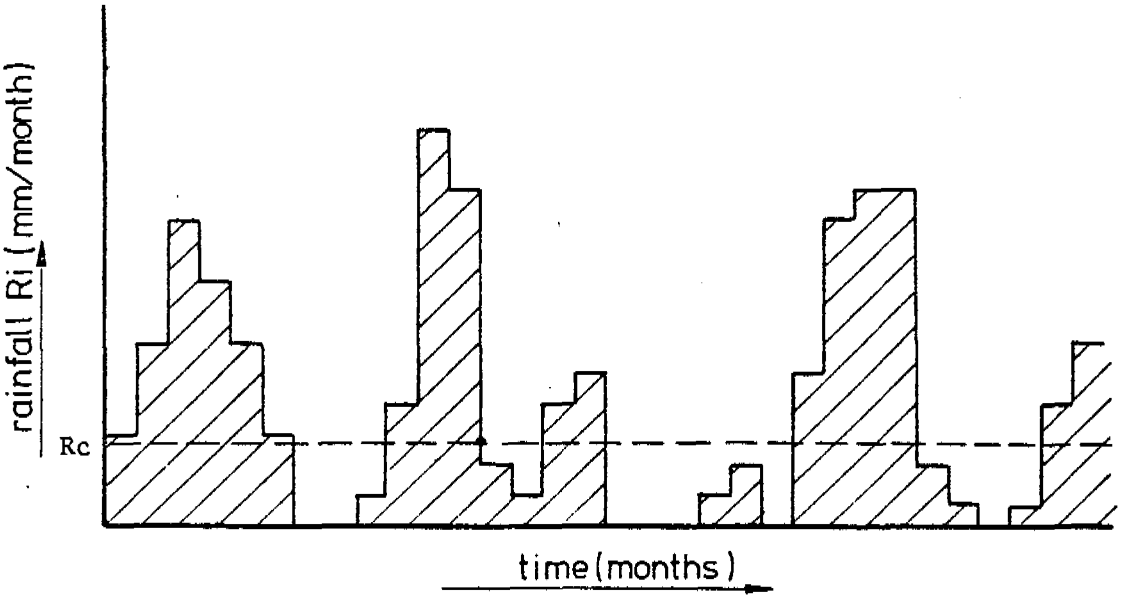


Fig. 4.5 Rainfall Record Diagram

The amount of rainfall which just balances the water requirements of the people using water from the rainwater system, is:

$$R_c = \frac{C \times 30}{f \times A_c}$$

in which: R_c = amount of rainfall which just balances consumption (mm/month)

C = daily ration per person (litre/day)

f = runoff coefficient

A_c = catchment area per person (m^2/person)

In each month (rainfall R_i), one of two situations will apply:

(1) The amount of rainfall R_i exceeds or is equal to R_c

(2) The amount of rainfall R_i covers only part of the requirements as expressed by R_i; the balance is supplied from the storage volume.

See Fig. 4.6.

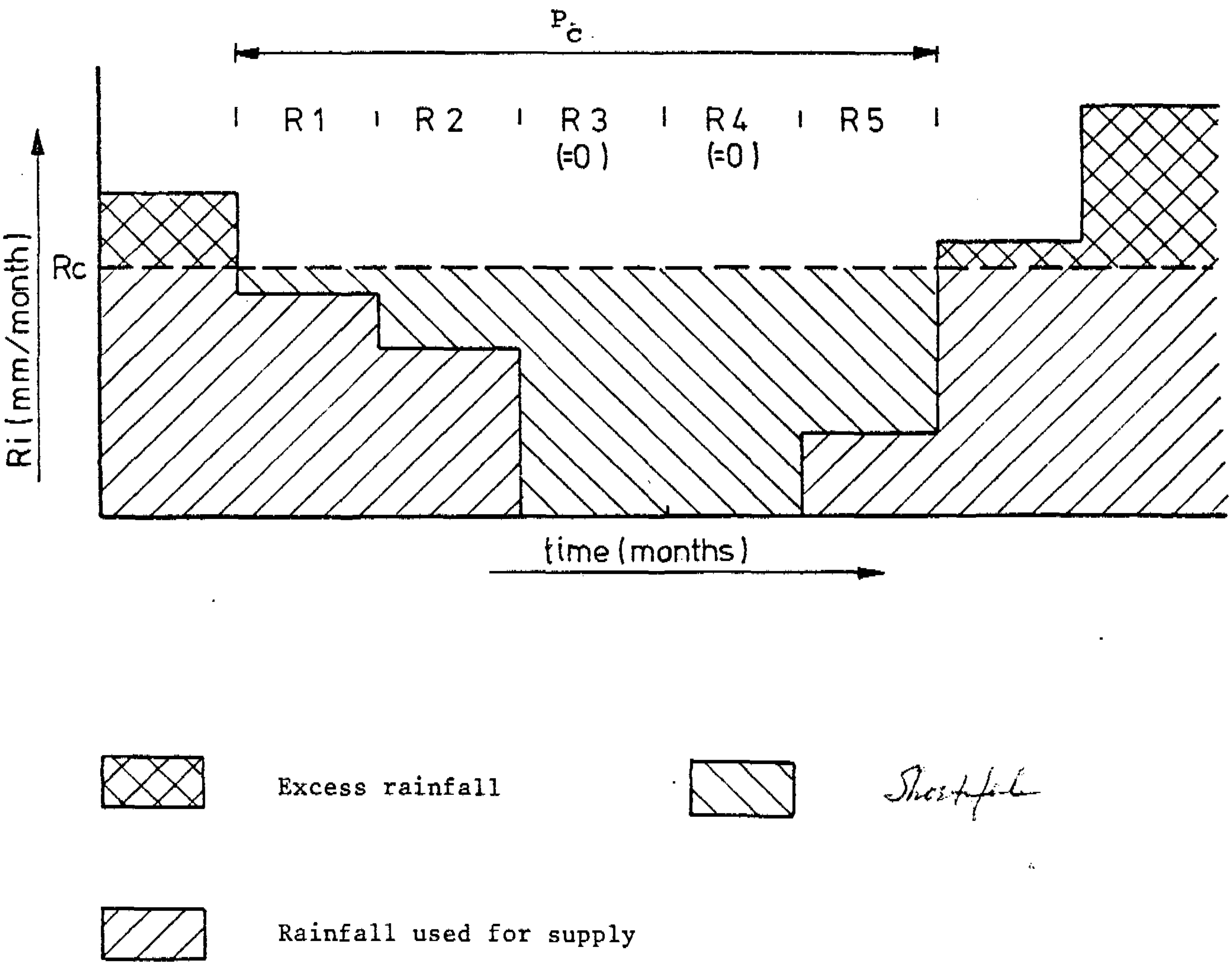


Fig. 4.6 Rainfall Collection and Use Analysis

Starting at the beginning of the dry period ($R_i < R_c$), with the storage volume assumed to be full, the amount of water used in excess of the rainfall collection is deducted from the storage volume. This is done on the basis of the available monthly rainfall data from the record. The highest accumulated deduction of the storage volume represents the storage volume required.

A graphical determination of the required storage volume is presented in Fig. 4.7.

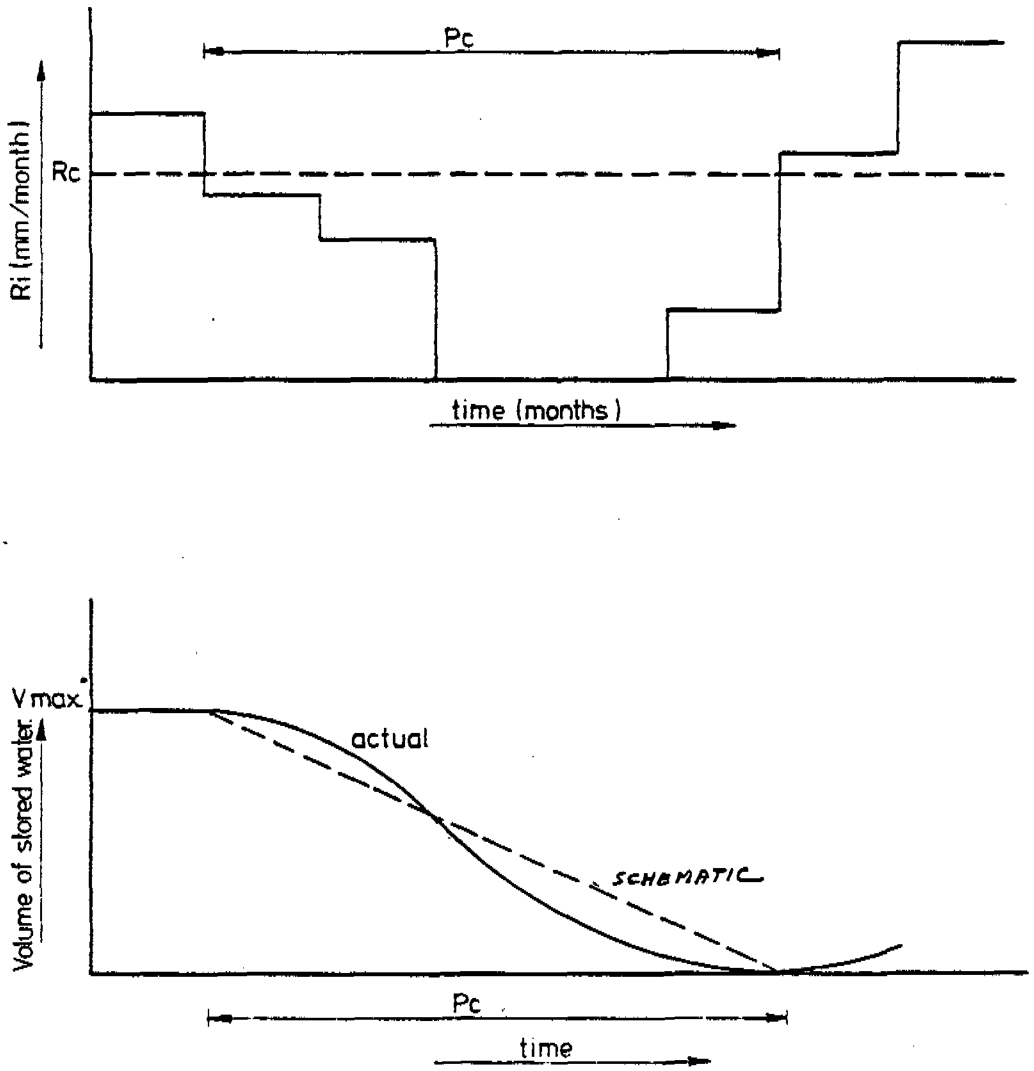


Fig. 4.7 Graphical Determination of Required Storage Volume

This calculation can be carried out for the starting value of the catchment area per person, A_c, so this is A_c1.

Similar calculations are then carried out for:

$A_c2 = A_c1 + 1$ m2/consumer, and
$A_c3 = A_c2 + 1$
$A_c4 = A_c3 + 1$
and so on, until a sufficient number of V_c values have been computed, each of them for the corresponding A_c value.

The curve of the A_c - V_c relationship can now be drawn in the diagram as a "best fit" for the computed A_c - V_c points.

The catchment area required is calculated as N x A_c m^2, and the corresponding storage volume as N x V_c m^3.

Using per unit costs of catchment area e.g. (US $\$/m^2$) and per unit costs of storage volume (e.g. US $\$/m^3$) the various combinations of catchment area and storage volume can be costed, to establish the combination with the lowest overall cost using the method of interpolation, if required.

To the storage volume, as computed, an additional volume must be added to provide for any losses of water due to evaporation and leakage. Evaporation losses from a coverage storage tank will be small. Leakage losses may be assumed to be proportioned to the amount of stored water (this is a measure of the pressure of the water against the walls and bottom of the tank), and the length of period the water remains in storage. Measurements on existing storage tanks (of ferrocement) show leakage losses of the order of 0.05 l/month per 10 m^3 storage volume. To the storage volume computed in the above design procedures, a small addition should be made which also will allow for any storage volume taken up by deposits.

4.4. DISCUSSION

The design procedure as introduced in section 4.3, is based on monthly rainfall data. Clearly, the amount of work involved in the calculations, would vastly increase if daily rainfall data would be used (provided these are available, which is not very likely for rural areas of less-developed countries).

Verification has shown that the use of daily rainfall data would not substantially add to the accuracy of analysis. It should be recognised that apart from the rainfall data many more factors influence the results of the calculations. Using daily rainfall data for greater accuracy of results would, therefore, neglect the limited accuracy of the other factors which are included in the analysis.

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