Chapter 19
Water supply and sanitation

Water, along with food, is one of the essentials of life. Perhaps because of its importance and scarcity in many locations, in most societies the use of water is encompassed by very strong cultural/social precepts. The success of projects aiming to improve water supply and water quality therefore depends on the full participation of the village population, in particular the women, as they are the main users of water.

While relatively small quantities will sustain human life, much more is needed for cooking, personal hygiene, laundry and cleaning. Water for a sanitary system is desirable, although not essential if it is scarce. Water is also required for livestock and perhaps for irrigating crops. Types of water required for the farmstead include: (a) clean water for use in the home; (b) reasonably clean water for livestock; and (c) water for irrigation.

WATER REQUIREMENTS: QUANTITY AND QUALITY

Quantity for domestic use

Location and convenience are significant factors in determining the volume of clean water for domestic use, as Table 19.1 below shows.

TABLE 19.1
Domestic water consumption per person

Water source several kilometres away	2–4 litres per day
Water source up to 1 kilometre away	4–8 litres per day
Water next to the house	10–20 litres per day
Water in the home for toilet, tap and shower	60–100 litres per day
Water in the home for toilet, bath, kitchen and laundry	100–250 litres per day

The range of consumption given in Table 19.1 varies by a factor of over 100. It seems obvious that people adapt their needs to the supply. At the low extreme, the bare minimum is used for cooking and drinking, while at the upper extreme water is used with abandon. When there is a shortage, much lower quality water may be used for personal hygiene and for washing clothes. The suggestions that follow are intended to improve both the supply and the quality of water.

Quantity for livestock

Table 19.2 gives the estimated water requirements for various classes of livestock. This can be used to determine the total requirements.

TABLE 19.2
Water requirements for livestock

Type and number		Daily needs in litres	Total for each type
Upgraded dairy cow	....	× 70 =	....
Upgraded beef cows	....	× 50 =	....
Local cattle	....	× 20 =	....
Sheep	....	× 5 =	....
Goats	....	× 3 =	....
Poultry, dipping, biogas, etc.			....

If water for dipping livestock is to be drawn from the same source, 3 litres per head of livestock per week must be added to the estimated amount needed.

Fish can be raised in a reservoir without any additional volume of water. Although chickens, pigeons and turkeys can live on used water from the house, ducks and geese need approximately 1 litre of fresh water a day per bird.

For the production of biogas, a weekly consumption of around 100 litres must be included in the total requirement of water for livestock.

Quality of water

Water from a protected well is nearly free from harmful bacteria although it may contain dissolved salts that make it less than desirable for drinking. A protected well is located upgrade from sources of pollution such as animal yards and privies. Twenty metres is an adequate distance in areas with fairly heavy type soils, while double that distance is necessary for light soils and even more in areas with limestone formations. “Protected” also implies a well head that extends high enough above the ground level to prevent anything from washing or blowing into the well mouth and narrow enough to discourage the users from standing on it. The other essential feature is a concrete apron sloping away from the well on all sides. A sanitary means of lifting the water is also necessary.

Water from roof catchments is generally safe for drinking and other domestic purposes. The dust and bird droppings that accumulate on the roof during dry times are usually carried away at the start of the first rain and should be diverted away from the storage tank. A paved catchment to collect water for domestic use must be fenced to restrict animals and people. It should also be allowed to clean itself before the water is saved. Water that is stored for a week or more in a catchment tank will generally be free of any harmful bacteria such as those causing cholera, typhoid and diarrhea in children as these bacteria cannot live for long outside the human body.

Streams and ponds, whether artificial or natural, are very likely to be contaminated and should be used for domestic purposes only as a last resort.

When the only water available is turbid (cloudy) and suspected of being polluted, it should be filtered through a well-designed sand filter. Even then, the safety of the water for drinking is questionable and boiling or other purification is recommended for complete safety.

WATER STORAGE

Long-term storage of drinking water may give rise to contamination because the tank may not always have been cleaned properly before the start of the rains, and because it not possible to block entry to the tank by small animals and microroganisms altogether. The use of chemicals, cooking or biological treatment of the water may be necessary to obtain good quality drinking water.

Catchment areas

The success of rain catchment depends on two factors:

1. The amount of rainfall.
2. The area and character of the catchment surface.

The type of surface determines both the quality and quantity of water saved.

Types of catchment area include:

Total runoff areas such as a hard roof surface or a protected paved area, which allows the collection of nearly all the rain that falls on them. If surface dust and impurities are flushed away first, the water collected should be good for domestic use.

Partial runoff areas are hard surfaces such as rocky outcrops, roads and pavements, which allow the collection of up to half the rain falling on the area. Obviously the water will not be as clean as water from total runoff surfaces but, if stored properly, it should be satisfactory for livestock requirements.

Other surfaces include open land surfaces, road drains and ends of ridges. Water from these sources is likely to carry a considerable amount of sediment into the storage, making the water suitable only for crop irrigation.

If wells are dug close to surface water storages they can provide high quality water.

Roof catchments

The advantage of roof catchment systems is that even light rain showers will supply clean water, and the total runoff is easily stored in a tank situated next to the house.

Types of storage for roof catchments

A *granary basket tank* (design by the United Nations International Children's Emergency Fund [UNICEF]) is a type of tank that uses a granary basket of woven sticks as a built-in framework for a cement–mortar plastered tank. The cost of the framework is only the labour of cutting and weaving sticks into an open weave basket. To improve strength and allow the construction of larger tanks, the outside of the basket can be covered with a layer of chicken wire, after which barbed wire is wrapped around with 150 mm spacing before the basket is plastered inside and out.

A rich mortar of approximately 1:3 portland cement-to-sand ratio should be used and mixed with just enough water to make the plaster easy to apply. Without wire reinforcement, the tank size should not exceed a diameter of 1.5 metres and a depth of 2 metres. If it is reinforced with barbed wire, it should not exceed a diameter of 2.5 metres and a depth of 2 metres. A cover is desirable and can be made of mortar reinforced with chicken wire.

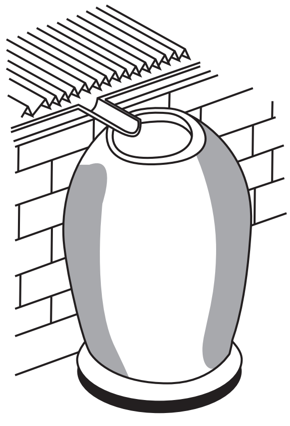

Figure 19.1 **Reinforced mortar tank (courtesy of Erik Nissen-Petersen)**

A *large cement jar* tank is a large bag with a framework made of cloth or sacks and stuffed with sawdust, sand or rice hulls. Mortar is then plastered onto the bag, after which chicken wire and barbed wire are tied onto the plaster, and another layer of plaster is applied. The bag is removed from the inside of the jar after 24 hours, and plaster is applied to the inside to make it waterproof.

The bag can be used to make many water jars, with the result that the cost per tank is minimal. A 1:3 portland cement to sand mortar is essential. The same size restrictions apply as for the granary basket tank. In both the large cement jar tank and the granary basket tank, the curved sides contribute to the strength and life of the tank. A cover is desirable.

Concrete ring tank sections can be used to form water tanks with a capacity of around 2 000 litres. The small tank volumes are suitable for rain catchment from small roofs scattered around a compound and for areas with relatively even annual distribution of rainfall. A reinforced concrete cover should be installed. Concrete ring tanks are particularly suitable where a form can be obtained for community use. When the casting is carried out on site, expensive transportation is avoided.

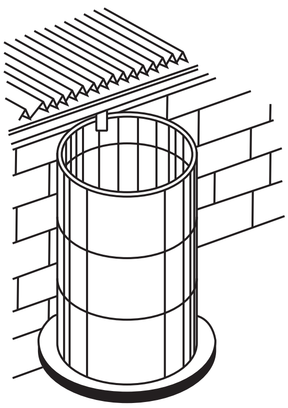

Figure 19.2 **Concrete ring tank (courtesy of Erik Nissen-Petersen)**

A *concrete block tank* must have steel reinforcing incorporated into the walls. Two barbed wires woven completely around the tank and embedded in the mortar between each course of blocks are adequate. The blocks must be of good quality to be relatively impermeable to keep leakage and evaporation to a minimum. The site for a tank of this size must be on firm ground with a reinforced concrete base. If the original ground is sloping, it is necessary to dig out the high area but not to fill in the low side.

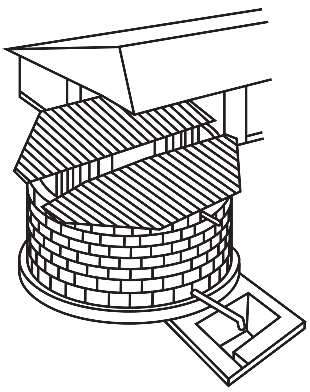

Figure 19.3 **Roof catchment (courtesy of Erik Nissen-Petersen)**

Corrugated galvanized steel tank: The quickest and easiest way of providing roof catchment storage is to buy and install a corrugated steel tank. Although the steel sheets are rather easily damaged, if they are handled carefully and protected from corrosion by coating them both inside and out with bitumen and then installing them on a concrete base, corrugated galvanized steel tanks provide very good storage.

Partial run-off catchments

In areas with heavy rainfall during relatively short periods, the runoff can be considerable if the ground-level catchment areas are well sloped and hard surfaced. While as much as three-quarters of the annual rainfall may be collected from sloping areas, where there is little slope and a permeable surface, only approximately one-quarter can be saved.

To compensate for a gentle slope, a soft surface, or to meet the need for additional water, the catchment area can be extended or covered with a hard surface material. For a small group of farmers, a compound catchment tank can be enough, while dammed reservoirs are more suitable for communal use. Table 19.3 compares different storage systems.

TABLE 19.3
Storage tank selection and sizes

Type	Range of capacity (litres)	Relative cost	Notes
Water jar	< 1 000	Low	No reinforcement needed, filled sack used as form.
Water jar	< 5 000	Low	Reinforced, sack form.
Granary basket tank	< 10 000	Low	Woven stick form, reinforced with chickenwire and barbed wire.
Precast concrete rings	2 000–3 000	Medium	Simple to install. Less expensive if cast on site.
Concrete block	< 20 000	Medium	Requires good base and reinforcing.
Corrugated steel	> 1 000	High	Simple to build, needs good base and corrosion protection.

Storage requirements

If a dependable, continuous source of water is available, no storage facilities are required. However, with an intermittent supply, storage is absolutely essential. The theoretical size of the storage required is determined by multiplying the total daily needs, for the family, livestock and irrigation, by the forecast number of days without rain.

Selection of tank size

This section describes four methods of rainwater roof tank sizing, to answer the question: “What tank size do I need to satisfy my water needs?”

To illustrate these methods, it is assumed that a person uses a minimum of 15 litres of water per day for drinking and cooking. Therefore assuming a family of 8 people:

Daily demand = 8 × 15 = 120 litres

The roof water supply for a given building is estimated by:

Supply (litres) = roof area (m^2) × rainfall (mm) × 90 percent (loss factor)

1. Balance method

This method balances the supply of water with the demand at the end of each month and calculates the storage left in the tank. Assuming that the storage at the end of each month can never be less than zero, this method can be used to determine the minimum tank size needed to satisfy the family's water requirements. Table 19.4 presents the result of using this method, given the data above and the following additional information:

annual rainfall	731 mm
roof area	75 m^2

The basic formula (balance equation) is

$$S_E = S_P + R_M - D_W$$

where:
S_E = Storage at the end of the month
S_P = The amount stored at the end of the previous month
R_M = Monthly rainfall × roof area × loss factor
D_W = Amount of water used by a family in a given period

Using this method, the supply and demand are calculated and the cumulative supply and demand for each month is also calculated. The maximum difference between the cumulative supply and demand is determined either graphically or by calculation. This difference is the optimum tank size. For the balance method, the optimum tank size is 18 060 litres. This can be seen in the column labelled 'cumulative (R_M - D_W)' in Table 19.4.

2. Dry-season storage method

This is perhaps the simplest method for determining the size of a roof catchment tank. First, estimate the longest period during the year without rain. For example: November, December, January and February constitute the dry period in some parts of eastern Africa. This is approximately 120 days without rain.

Secondly, estimate the daily water use. For example, for a family of eight people using 200 litres per day (one drum per day is an average use), the size of storage tank can be determined as follows:

Tank size = Number of dry days × daily water use
= 120 days × 200 litres
= 24 000 litres (24 m^3)

If the annual yield is less than the dry-season storage tank size, the tank will have to be reduced to the value of the annual rainfall yield. For example, if the rainfall is 500 mm per annum and the effective roof area is 40 m^2, a maximum yield of 18 m^3 (500 mm × 40 m^2 × 0.9 = 18 m^3) is obtained. This is less than the ideal tank size, so the tank size would be reduced to 18 m^3.

Using as input the data from Table 19.4, the tank size for this method would be:

TABLE 19.4
Balance method for sizing a roof tank

Month	Average rainfall (mm)	Rainfall supply, R_M (litres)	Demand, D_W (litres)	R_M - D_W (litres)	Cumulative (R_M - D_W) (litres)	Calculated Storage at end month, S_E (litres)
January	45	3 038	3 720	-683	-683	0
February	60	4 050	3 360	690	7	690
March	77	5 198	3 720	1 478	1 485	2 168
April	198	13 365	3 600	9 765	11 250	11 933
May	156	10 530	3 720	6 810	18 060	18 743
June	40	2 700	3 600	-900	17 160	17 843
July	0	0	3 720	-3 720	13 440	14 123
August	0	0	3 720	-3 720	9 720	10 403
September	0	0	3 600	-3 600	6 120	6 803
October	50	3 375	3 720	-345	5 775	6 458
November	45	3 038	3 600	-563	5 212	5 895
December	60	4 050	3 720	330	5 542	6 225
	731	**49 343**	**43 800**	**5 543**		

Dry days = 3 months (July to September) = 92 days.
Tank size = 92 days × 120 litres/day = 11 040 litres = 11.04 m^3

3. Collecting and storing all the rainfall

This involves collecting all the rainfall from the roof and storing it until there is an acute shortage. This implies that the tank size will be equal to the total supply for the year.

Tank size = Annual rainfall × roof area × 90 percent
= 49 343 litres (refer to Table 19.4 in the column labelled 'Rainfall supply, ')

This method is common in arid and semi-arid land (ASAL) areas, where it may rain only once a year.

4. Graphical method

Figure 19.4 illustrates a method for determining the maximum potential storage capacity using the graphical procedure:

1. Plot the mean monthly rainfall for the area.
2. Calculate the amount of rainfall that can be collected each month. This is determined by the amount of rain that falls and the area of the roof. (For a rectangular roof the area is the length of the roof times the width between the eaves.) Thus the amount of water collected each month is the product of the amount of rainfall and the area of the roof.
3. Starting with the first month after the dry season in which there is a chance to accumulate water in the tank, plot the amount of water that can be collected each month, without regard to the amounts used. In the example, the first month is November.
4. Draw a line from zero on the left to the highest point on the right, making sure the line never goes above the amount of water accumulated to date. The slope of the line represents the average number of litres that can be used daily.
5. Finally, the maximum difference in litres between the water usage line and the water accumulation line indicates the theoretical size of the storage tank required, which in the example is a little over 16 000 litres. It should be noted that these calculations are based on average rainfall records. There will be dry years when the tank will not come close to filling, and other years when water runs to waste from an overflowing tank.

The accuracy of the first two methods depends on the accuracy of the rainfall data. Mean monthly data is used in most cases. However, as there is wide variation in rainfall (mostly in the ASAL area), both geographically and over time, mean monthly data may not reflect the actual rainfall distribution.

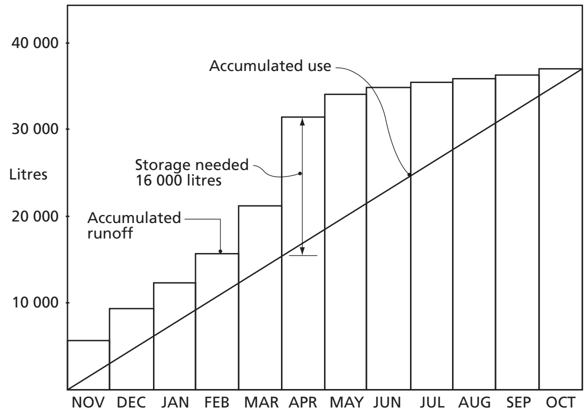

Figure 19.4 **Estimating storage tank size**

The balance method allows for a minimum tank size to be determined to satisfy daily needs and will be of great use in a situation where money for building tanks is limited. It is suitable for the majority of rural people who are interested in rainwater as a clean and safe (and possibly the only) source of water.

The cumulative supply/demand method enables the ideal tank size to be determined, especially where funds are not limited. The dry-days method is quick and easy but does not reflect rainfall patterns accurately. Any method works well only if the following key points for the management of a successful rainwater catchment system are adhered to:

- Install gutters on the maximum roof area.
- Maintain the gutters to collect the maximum amount of rainfall.
- Use the water carefully (economically), especially towards the end of the rainy season when the tank is full, to conserve water for the dry season.
- Clean the gutter and the tank at regular intervals and maintain proper standards of sanitation. If possible, install a foul-flush system or self-cleaning gutters (inlets).

Calculation of tank and reservoir volumes

Roof catchment tank

One of the strongest and least expensive tank shapes for a roof catchment is cylindrical, with a diameter greater than its height. The height is usually determined by the distance between the surface of the tank foundation and the lowest point of the gutters.

The formula for calculating the volume of a cylindrical tank, using interior dimensions, is as follows:

$$V = \pi \times r^2 \times h \times 1\,000$$

where:
V = volume, litres
r = radius, metres
h = height, metres

Example:
Calculate the volume of the tank shown in Figure 19.5

$V = 3.14 \times 2.25^2 \times 2.0 \times 1\,000 = 31\,792.5$ litres

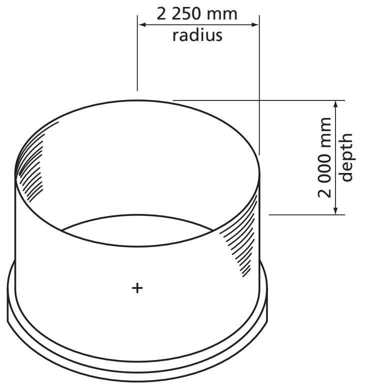

Figure 19.5 **Capacity of a cylindrical tank**

TABLE 19.5
Cylindrical tank capacities in thousands of litres (interior dimensions)

Diameter	Height			
(m)	1 metre	2 metres	3 metres	4 metres
1.0	0.785	1.570	2.356	3.142
1.5	1.767	3.534	5.300	7.068
2.0	3.141	6.283	9.425	12.566
2.5	4.910	9.817	14.726	19.635
3.0	7.070	14.137	21.206	28.275
3.5	9.621	19.242	28.863	38.485
4.0	12.566	25.132	37.700	50.265

Catchment tank for the compound

Where a storage tank must be dug into a relatively level area of ground, an approximate half-sphere shape is easiest. The volume of a half sphere can be found by using its radius in the following formula:

$$V = \frac{2}{3} \times \pi \times r^3 \times 1\,000$$

where:
V = volume, litres
r = radius of half sphere, metres

Example:
Calculate the volume of the half sphere tank shown in Figure 19.6.

$$V = \frac{2}{3} \times \pi \times 2.13^3 \times 1\,000$$
= 20 239.4 litres

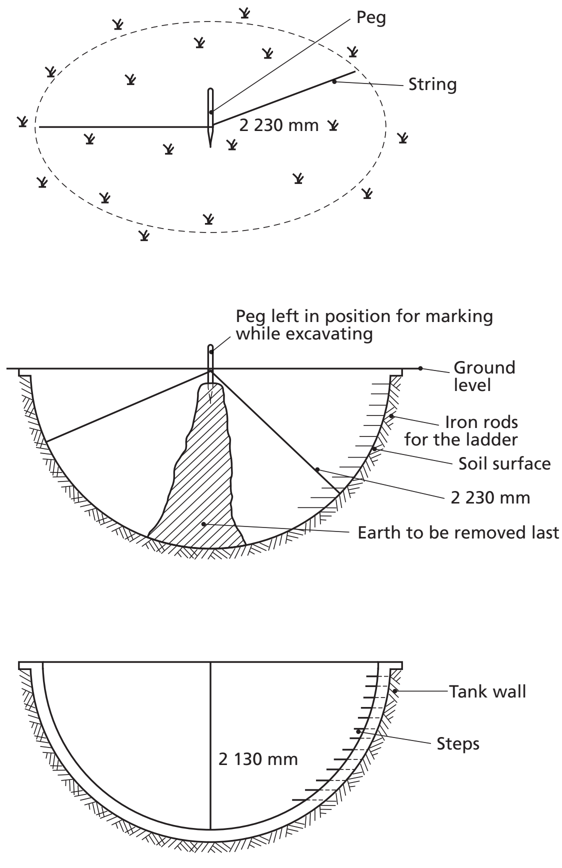

Figure 19.6 **Half sphere tank**

Dammed reservoir

Water that drains from the compound, or from a large area, may be stored in a pond or reservoir behind a dam. It is difficult to estimate the quantity of water behind a dam because of the uneven topography below the water level. Two formulas that will help to make a rough estimate are as follows:

For a long, narrow pond, perhaps a dammed-up stream:

$$V = \left(l \times w \times \frac{d}{8} \right) \times 1\,000$$

where:
V = volume (litres)
l = length of pond (metres)
w = width of pond at dam (metres)
d = depth of pond at dam (metres)

For a circular pond with an area in the middle that is quite uniform in depth, the volume is determined in two steps, and the results are combined.

$V_1 = \pi \times r^2 \times d$

where:
V_1 = volume in uniform depth area (m^3)
r = radius of the area of uniform depth (metres)
d = depth of the uniform area (metres)

$$V_2 = \frac{1}{2} \times w \times d \times c$$

where:
V_2 = volume of sloping edges of pond (m^3)
w = width of sloping edges (metres)
d = depth (metres)
c = circumference or length of sloping edge (metres) (3 × the diameter is a good approximation)

$$V_t = (V_1 + V_2) \times 1\,000$$

where:
V_t = total volume (litres)

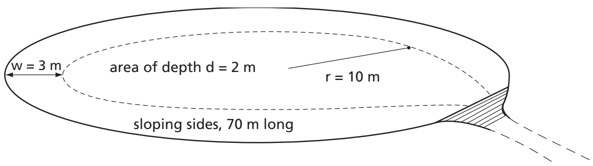

Figure 19.7 **Volume in a circular reservoir**

Example:
Assume a pond roughly 26 metres in diameter with a uniform depth of 2 metres in the centre covering an area estimated to have a radius of 10 metres. The approximate volume can be found using the method described above.

$$V_1 = \pi \times 10 \times 10 \times 2 = 629 \text{ m}^3$$

$$V_2 = \frac{1}{2} \times 3 \times 2 \times 70 = 210 \text{ m}^3$$

$$V_t = (629 + 210) \times 1\,000 = 839\,000 \text{ litres}$$

Plastic-lined reservoirs

One of the easiest and cheapest methods of water storage is a plastic-lined reservoir. It involves excavation of a hole on the ground of a size equivalent to the storage required. Care must be taken to have sloping sides to avoid landslides. Once the reservoir has been levelled smooth to avoid stones and other sharp objects, the plastic lining material is placed in the excavation with a 10 percent allowance for shrinkage.

The plastic is normally 0.5 mm–1.2 mm in thickness and the most common type of material used is high density polyethylene (HDPE). Water can then be stored in the reservoir from roof catchment or ground runoff. To avoid people and animals falling accidentally into the reservoir, it should be covered with an iron sheet roof (which also minimises evaporation) the reservoir must be fenced. When water is diverted from road runoff, a siltation tank as well as a filtration mechanism must be included in the path of the water before it enters the reservoir.

SAND DAMS

The terms 'sand dams', 'subsurface dams' and sometimes 'sand weirs' are often used interchangeably to refer to the same, or different, kinds of structure. In a sand dam, the dam wall protrudes above the surface of the sand, while in a subsurface dam, the dam wall is level with the sand surface. It should be noted that these structures are feasible only in certain areas. The type of soil in an area is important because it determines the types of sediment deposited in a dam and consequently its water storage capacity.

Subsurface dams are used in many parts of the world, including Thailand, Japan, southern India, Arizona, California, Morocco, Algeria and Ethiopia. In the past, people in the Machakos district of Kenya have been known to obtain water from holes dug in dry river beds, usually at a depth of 60–100 cm below the sand surface. They are able to do so because water has been deposited in sand under natural conditions, where there are large natural rock barriers across riverbeds and where the channel gradient is low. This natural phenomenon provides water storage, albeit in limited quantities.

Development of sand dams

Site selection for sand dams
Suitable sites have the following features:

- The river is naturally confined between banks, even when flooding.
- There is a rock bar through the river bed that is not fractured. The rock bar provides the best foundation and reduces the risk of failure.
- The size and shape of catchment should be such that reasonable runoff and recharge rates are obtainable.
- The bedrock should be free from fractures, especially major ones, which may be difficult to seal.
- The width and slope of the river bed should be able to provide adequate sand storage volume.

The design and construction procedure of sand dams is variable because virtually no two sites are the same. Rivers vary in width and discharge, while rock foundations vary in depth and susceptibility to leakage. Riverbanks vary in height, and the need for wing walls has to be carefully assessed. There are predesigned standard cross-sections to be used in the construction of sand dams. However, the dimensions of a sand dam have to be adjusted to suit the specific site conditions. Provision for a draw-off pipe is made at the bottom of the dam wall. Construction in multiple stages along the river has no significant effect on the quality of the deposits.

Structural design criteria

The conditions prevailing at a selected site for a sand/subsurface dam determine which type of dam and which materials will be most suitable. The criteria include such factors as the height of the river banks, the depth of sand and the cost implications.The height of the dam wall, or crest, for a sand dam is determined by the maximum height of flash floods. The maximum allowable height of the crest of a dam wall is the difference between the maximum flood level and the height of the lowest bank.

Before a choice is made between two sites, the economic viability of a sand/subsurface dam should be assessed based on the expected water yield. For a subsurface dam built of clay, the following specifications must be determined:

- quality of clay;
- location of clay soil;
- thickness of dam wall and its key;
- depth of dam wall into river floor;
- length of key;
- crest of dam wall;
- spillway;
- reinforcements.

Sand dams built of stone masonry are more complicated than subsurface dams in terms of hydraulics, and structural aspects such as structural stability are a major consideration. The dam must have sufficient own weight and a wide enough base to counteract the overturning moments and sliding pressures exerted by water and sand.

The gravity design has proved itself over a period of 40 years. In the design:

Base width = 0.75 × height of dam wall from its base
Crest width = 0.2 × height of dam from its base

Estimating the yield of water from a sand dam

The extractable yield of water can be estimated using the following procedure:

1. Volume of sand in reservoir.
This is given by: (length × maximum width × maximum depth) divided by 3.

2. Porosity or water-holding capacity of sand.
The test procedure is as follows:

(a) dry the sand until all moisture is removed;
(b) fill a container of known volume with the dried sand;
(c) pour a measured volume of water into the sand until the sand is fully saturated;
(d) upon full saturation of the sand, record the total volume of water poured into the sand.

Then porosity = volume of water required for full saturation of sand (litres) × 100 percent total volume of dried sand sample in the container (litres)

3. Extractability of water from sand

This is given by:

Total volume of water flowing out of container (litres) × 100 percent
Total volume of dried sand sample in container (litres).

Methods for abstracting water from sand dams

Scoop holes

The most common and simplest method of extracting water from sand dams is to use scoop holes. Separate holes are dug for people and livestock. As the water level goes down during the dry season, wider holes are required to avoid the risk of sand caving in. This method of water extraction is risky to both people and livestock, inefficient and encourages contamination of the sand-dam water.

Shallow wells

The shallow-well abstraction method is an improvement on the scoop-hole method above. The well should be sited high enough to prevent river water from entering during peak flow. The location should be on one side of the river, and between 10–20 metres upstream of the dam wall. Scoop holes near the dam wall can serve as livestock watering points without any danger of polluting the shallow well-water source. Water can be abstracted from wells using a simple rope and bucket, a windlass or a hand pump.

Draw-off pipes

Draw-off pipes are passed through the bottom of the dam wall. They have been largely unsuccessful because of poor operation and management of the tap and intake components.

Quality status of water from sand dams

Water stored in sand dams is assumed to be of suitable quality for drinking because of the filtration process it undergoes in the sand reservoir. However, the chemical quality is usually localised and more dependent on hydrological factors. Sand filters are capable of purifying the water bacteriologically, as well as physically. Slow sand filtration has proven efficient in improving the physical, chemical and bacteriological quality of surface waters and in removing turbidity, tastes and odours.

How to ensure that the quality of water in sand dams is maintained

River barrages increase the quantity of water available, but other measures are needed to improve the quality of water. Although water drawn from scoop holes may look reasonably clean, it is likely to contain pathogenic micro-organisms. The following measures are suggested to protect against contamination:

- Keep the places where livestock come to drink separate from places where people extract their water.
- Construct pit latrines at all homesteads so that runoff water does not carry human waste into the river during rainy periods.
- Boil water for drinking.

ROCK CATCHMENT DAMS

A rock catchment is a reservoir located on a bare rock surface with sufficient surface area to capture enough rainwater in the rainy season for use during the dry season. The rock catchments may be natural or artificial. Natural rock catchments are formed when weak rocks are embedded in resistant rock.

When weathering occurs, the weak rock is removed, leaving a depression in the resistant rock. These depressions act as reservoirs. It is important for the base of the reservoir to be free from cracks or permeable rocks. Essentially, the only way in which rocks can act as natural reservoirs is where there are depressions in the rock.

There are three types of artificial rock dam. All types of artificial rock dam have a water trapping/ diversion mechanism, a route through which water flows to the storage and a storage tank. The methods used to trap water depend on the shape and orientation of the rock catchment.

When the rock has a flat, sloping surface similar to a roof or is dome shaped, water may be harvested using flat stone gutters constructed around the surface. As there is no large storage surface behind the stone gutters, it is usually necessary to construct a storage tank for the harvested water. When the rock has a valley or funnel-shaped depression, a long wall may be built across the valley to trap water. It may be necessary to include a spillway in the design, which will guide any overflow into a tank.

The third type of artificial rock dam is similar to the second type, apart from the fact that it has a ferrocement roof above the dammed water. The purpose of this roof is to minimize evaporation (as these dams are usually constructed in arid areas) and to prevent the entry of dust, insects and birds.

WELLS

A properly constructed and protected well can provide an excellent source for domestic water needs. The terms *borehole well*, *dug well* and *tube well* describe the manner in which water is reached. A borehole well is drilled with a cable or rotary drill. It is small in diameter and can be 200 metres or more in depth. A dug well is a hole dug with a diameter large enough to allow a man to work, usually to a maximum depth of approximately 30 metres. A tube well is a perforated pipe with a pointed end, which is either hammered or jetted into the ground.

When a well is less than 7 metres deep, it is called a shallow well, and when it is more than 7 metres deep, it is called a deep well. An earth well is unlined; a masonry well is lined with concrete blocks or stone; and a sinking well casing is constructed and sunk in stages from the ground level as the well is being excavated.

Location of well site

Water may often be found in one of the following locations:

1. Near a pond or reservoir.
2. In the foothills near mountains, and especially near green trees or holes dug by animals.
3. In areas of green vegetation during drought.
4. Near existing wells or waterholes.
5. In sandy river beds, especially upstream from bedrock, where temporary wells may be dug.

Types of well casing

There are several methods of constructing well casings; the choice depends on the purpose, soil structure, water source and local skills.

An *oil barrel* can be used to form an inexpensive well casing. The barrels are perforated to allow the entry of water. The life of this casing will be shorter than with other materials, and the residue in the barrels may pollute the water, making it unfit for domestic use.

A *ferrocement* well is a type of earth-wall well that is excavated to a straight and smooth surface, which is then plastered with a layer of mortar, reinforced with chicken wire, and finally plastered a second time. A wellhead is built above ground level to limit the risk of children and animals falling into the well. To prevent contamination of the well, a concrete apron sloping away from the wellhead is constructed on the surrounding ground.

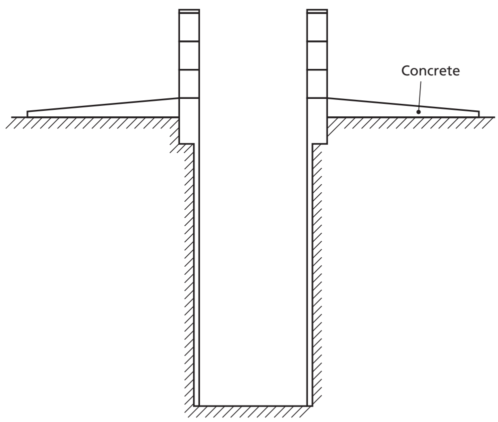

Figure 19.8 **Ferrocement well (courtesy of Erik Nissen-Petersen)**

Sinking wells are so named because the casing is sunk into place. The method works well in sandy soils. Figures 19.9 and 19.10 show casings that can be sunk into place.

A *concrete ring well* is a method that requires either a steel casing ring mould for casting the concrete rings on site, or precast rings purchased and transported from the factory to the construction site. While both these alternatives are expensive for a single well, they are feasible when a number of wells are being constructed in a local area. The rings, measuring 0.9 metres in diameter and 0.5 metres in height, are stacked on top of each other in an excavated well hole, or they can be used for sinking wells, or for a combination of the two procedures.

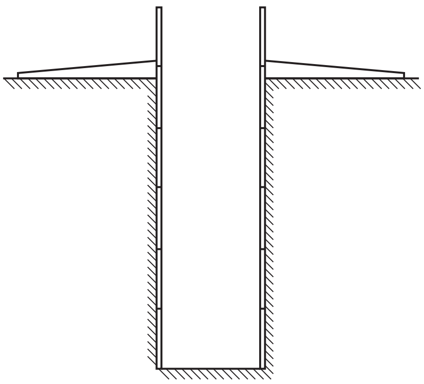

Figure 19.9 **Concrete ring well (sinking well)**

A *concrete block well* is a less expensive alternative to concrete rings, using concrete blocks that have been shaped in a wooden form. These blocks are stacked on a concrete foundation ring, which can be cast in a wooden form or, more cheaply, in a hole in the ground at the construction site.

With either type of casing, the whole structure will be allowed to settle by digging out soil from under the bottom of the casing. When the top of the well casing has reached the surface of the surrounding soil, another section is added to the top. Thereafter, digging is repeated until another section can be added onto the well at ground level, and so on until a satisfactory depth has been reached. The blocks must be tied together with vertical reinforcing rods to ensure that the casing sinks as a single unit.

Lift for wells

The simplest means of lifting water from dug wells, such as a rope and calabash or a bucket and windlass, have been used for centuries and, unfortunately, they continue to be used today in many parts of the world. The objection to their use is that, all too often, they are a source of pollution because the top of the well is open and the water vessel is frequently set down on a badly polluted surface. An improvement on these methods uses a bucket with a hose attached to the bottom and to an outlet at the wellhead, as shown in Figure 19.11. When the bucket is lifted, water is discharged from the outlet while the top of the well remains covered.

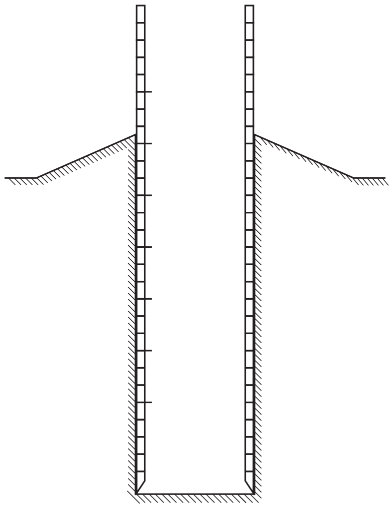

Figure 19.10a **Concrete block well (sinking well)**

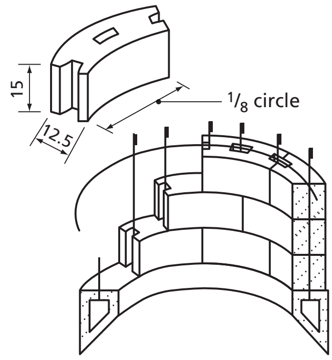

Figure 19.10b **Section of foundation and reinforcement (courtesy of Erik Nissen-Petersen)**

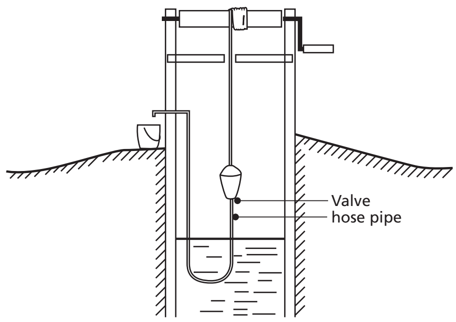

Figure 19.11 **Bucket lift in closed well (courtesy of Erik Nissen-Petersen)**

PUMPS

A pump is the most convenient and sanitary means of lifting water from a well or any other low-level water supply. Pumps may be hand- or power-operated, designed to lift only, or to lift and discharge against pressure, and to lift from either shallow or deep wells.

As mentioned earlier, shallow wells are those in which the low water level is 7 metres or less below the pump. In deep wells, the water level may drop well below the 7-metre mark. The maximum suction lift for shallow-well pumps of any type is reduced by approximately 1 metre for every 1 000 metres of site elevation.

Hand pumps

The simplest hand pump, often referred to as a pitcher pump, is satisfactory for use on wells or cisterns in which the water never needs to be lifted more than around 6 metres. A cross-section of a pitcher pump is shown in Figure 19.12. If pitcher pumps are maintained in good condition, they are easily primed and will hold their prime from one use to the next. However, if the valves leak, the pump will need to be primed each time it is used. Not only is this a nuisance, it can also be a source of pollution from the priming water.

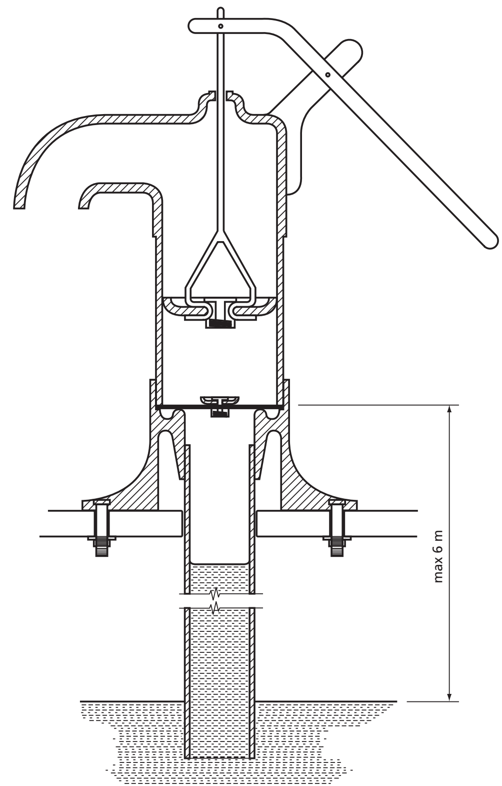

Figure 19.12 **Shallow-well handpump**

Water from deep wells is lifted with a similar plunger-type pump in which the cylinder, including the plunger and valves, is supported on the discharge pipe deep enough in the well to be submerged in water at all times. The pump handle is connected to the plunger by means of a long rod. While this type of pump is self-priming because the cylinder is submerged in the water, it must nevertheless be maintained in good condition to work effectively. Figure 19.13 illustrates a deep-well pump. Both of these pumps allow the well top to be completely covered for maximum protection against pollution.

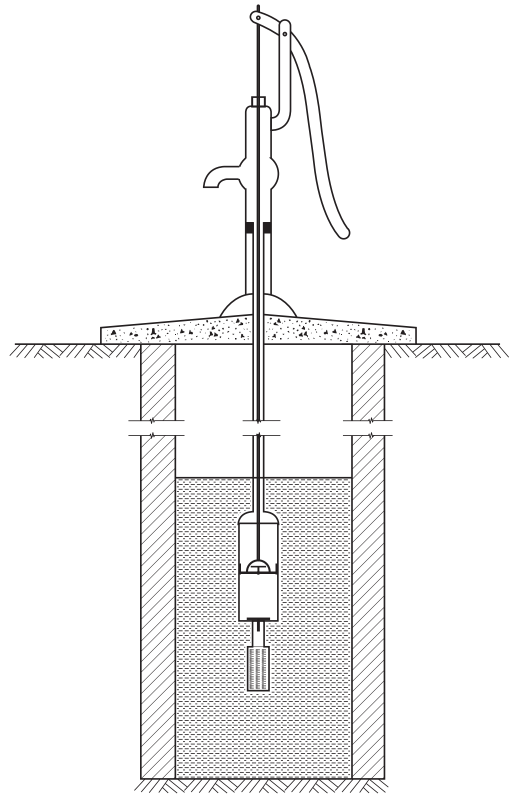

Figure 19.13 **Deep-well handpump**

Occasionally it is necessary to use a hand pump to force water above the level of the pump. Models are available with packing around the lift rod and a pipe connection at the point of discharge, enabling them to force water to a tank higher than the pump. An even more sophisticated model is equipped with a small 'differential' cylinder that causes the pump to discharge on both the up- and down-strokes.

Power-driven pumps

There is a selection of pumps on the market to suit different applications. They all have characteristics that influence their suitability for a specific water supply, as well as the volume and pressure required.

Centrifugal pumps are simple (with only one moving part), durable and relatively inexpensive for a given capacity. However, they are suitable only for low lifts of 3–4 metres and are prone to losing their prime unless the suction pipe is equipped with a good foot valve (check valve). They will not discharge against a very high head (pressure).

There are several centrifugal pumps designs that further complicate the choice. The impeller may be an open type with a relatively large clearance between it and the casing, or it may be a closed type with very small clearances. The open type will tolerate sand or silt in the water much better than the closed-impeller type (see Figure 19.14 and Figure 19.15).

A centrifugal pump may have an integral electric motor or a petrol-powered engine, which the manufacturer will have sized correctly, or it may have a belt drive. If it has a belt drive, great care must be taken to drive the pump at a suitable speed and with a motor or engine of adequate power.

As with the propeller fans described in Chapter 13, centrifugal pumps have volume, pressure and power requirement characteristics that vary with speed, as follows:

- The volume changes directly with the speed.
- The maximum pressure changes directly as the square of the change in speed.
- The power required changes directly as the cube of the change in speed.

This means that, for a pump designed to run at 2 000 rpm and to be operated by a 1 000 W motor, if the motor pulley is exchanged for one that is 1.5 times the original diameter, the pump will then turn at 3 000 rpm. The corresponding changes in volume, maximum pressure and power required will be:

- Volume = 1.5 times greater.
- Maximum pressure $(1.5)^2 = 2.25$ times greater.
- Power $(1.5)^3 = 3.375$ times greater.

Consequently, the motor will be badly overloaded and may be damaged.

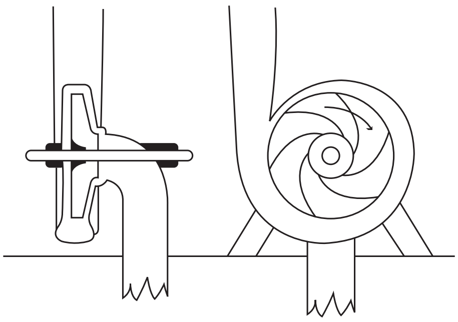

Figure 19.14 **Open impeller**

Jet pumps are centrifugal pumps for a shallow well that may have a jet (ejector) built into the pump housing. This will improve both the lifting and discharge efficiency. Shallow-well jet pumps are suitable for lifting up to approximately 6 metres.

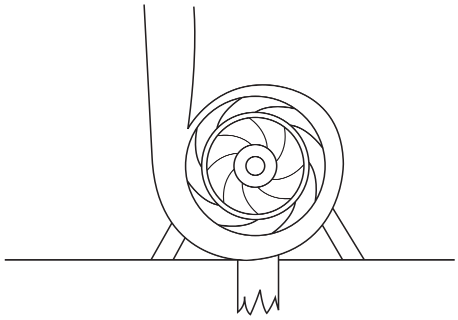

Figure 19.15 **Closed impeller**

A deep-well jet pump will have the ejector installed below the low-water level in the well. Two pipes of different dimensions connect it to the pump, which may be located at the top of the well or even some distance to one side. The smaller of the two pipes carries water to the ejector, while the larger one delivers water to the pump housing, where most of the water is discharged, but some is returned to the ejector. These deep-well jet pumps are suitable for wells in which the water level drops to 30 metres. The correct ejector for maximum efficiency is chosen on the basis of the lowest expected water level in the well (see Figure 19.16).

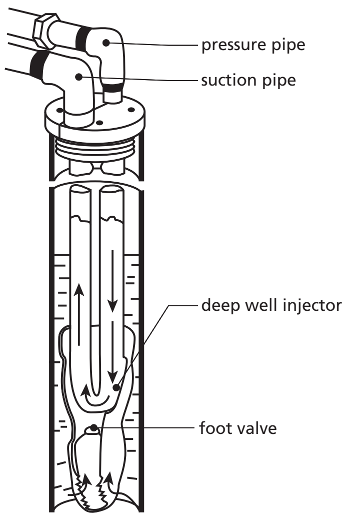

Figure 19.16 **Deep-well jet**

Deep-well turbine pumps are multistage centrifugal pumps that may be driven either by a long vertical shaft from a drive head at the top of the well or by a submersible motor below the pump in the well. These shaft-driven units are large, expensive pumps designed to supply sizeable volumes of water for irrigation or community use.

On the other hand, the submersible pump is available in a range of sizes and is an efficient, trouble-free design for medium-sized installations. Obviously it is a major operation to remove the pump from the well if something goes wrong. It should be noted that the motor is installed below the pump to ensure that, if the water level is reduced to the pump level, the motor will still be submerged in water, which is essential for cooling.

Reciprocating pumps are available for both shallow wells and deep wells. They are capable of delivering water at quite high pressures. The shallow-well type is usually reasonable in cost, but the deep-well type tends to be expensive and must be installed over the top of the well.

In *diaphragm pumps*, the piston and cylinder are replaced by a diaphragm. As there are no sliding parts to wear, diaphragm pumps are suitable for pumping muddy water or high-moisture slurries, such as the waste from a biogas generator (see Figure 19.17). These pumps may be either hand- or power-operated.

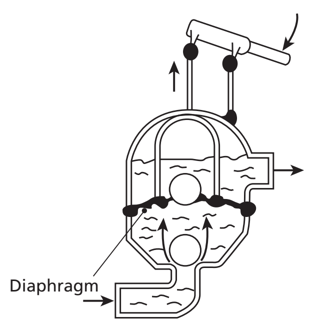

Figure 19.17 **Diaphragm pump**

Hydraulic rams require no electricity or human power to operate, relying instead on the energy from flowing water. A minimum flow of 10 litres per minute, with a head of at least 1 metre, is required. As water flows through the ram, the waste valve opens and closes alternately. Each time the valve closes, water is forced up the delivery pipe by the inertia developed in the flowing water, which is abruptly stopped when the waste valve closes. Small quantities of water are thus lifted well above the original source. A ram can be useful for pumping domestic or livestock water to a storage reservoir.

Commercial rams are available in a number of sizes, with supply-flow rates of 10–400 litres per minute, and can discharge to maximum heights of 100–150 metres. Although a ram will operate with as little as 1 metre of head, larger heads will increase discharge rates considerably, e.g. increasing the supply head from 1 metre to 10 metres can increase delivery by a factor of 20. Before purchasing a ram it is necessary to know the flow rate of the water supply and the head available. Although the initial cost is substantial, maintenance is low, life is long and the operating cost is nil so, if suitable natural conditions are available, a hydraulic ram can be a very good investment.

Choosing a pump

Five main factors must be considered when selecting a pump:

1. The total water required per day.
2. The maximum rate of flow desired.
3. The maximum flow from the water source.
4. The vertical distance the water must be lifted to the pump.
5. The total head against which the pump must operate.

The terms 'head' and 'pressure' are used interchangeably. The unit of measurement for pressure is the pascal (Pa) while the unit of measurement for head is the metre (m). One metre of water column equals

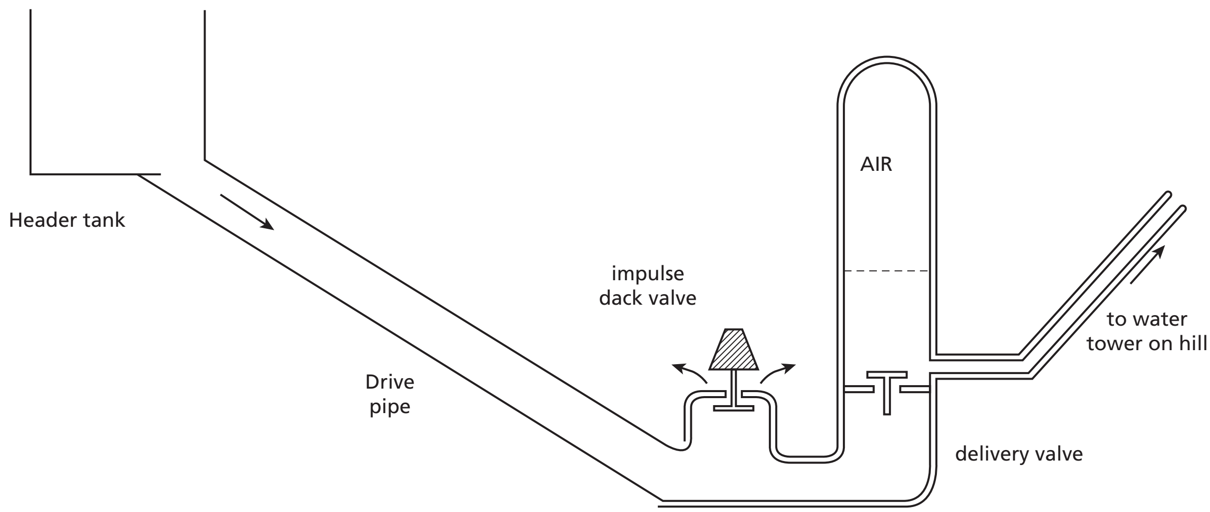

Figure 19.18 **Hydraulic ram**

9.8 kPa. Head is frequently used in discussing pump installations because there will be vertical distances from water level to pump, and from pump to point of discharge. Pipe friction tables are often given in terms of loss of head per unit of pipe length.

The daily water requirement influences pump size, as it is desirable for the pump to operate no more than 25 percent of the time.

The maximum rate of flow is determined by totalling suitable flow rates from all the discharge openings that may be operating at one time. If the source of water is a dug well, pond or stream, the desired flow rate can be used when choosing a pump. However, if the source is a borehole or driven well with very low storage capacity, there is no alternative but to choose a pump with a capacity that does not exceed the flow rate of the well.

The vertical distance between low-water level and the location of the pump is the primary factor governing the type of pump chosen, although the total head is also significant. Total head is made up of: (a) lifting head from well to pump; (b) vertical discharge head from pump to point of use; (c) working head or pressure at the point of use; and (d) friction losses from the flow through pipe and fittings.

Pump storage tanks

Regardless of the type of pump chosen, it must either discharge into a tank or have an open-pipe discharge into an irrigation channel. Operating any of the centrifugal pumps against a closed line results in overheating and damaged shaft seals. Operating a reciprocating pump against a closed line will result in a stalled motor or the physical breakage of some part of the pump.

Hydropneumatic systems

Hydropneumatic systems consist of an enclosed tank combined with an automatic pressure switch that turns on the pump motor when tank pressure drops to a preset level. As the tank is approximately half full of air, several litres of water can be pumped into the tank before the air is compressed and the stock cut-off pressure is reached. The amount of water pumped into the tank can then be used as required before the pump needs to operate again. There are several advantages to the hydropneumatic system:

(a) The tank can be located in any convenient place.
(b) Optimum discharge pressure is available at all times.
(c) The system is completely automatic.
(d) The tank may be relatively small.

As air is soluble in water, a small, continuous supply of air is required to prevent the tank from becoming waterlogged. Each type of pressure pump discussed will have an air-volume control suitable for its mode of operation to provide the necessary supply of air. Alternatively, tanks may be equipped with rubber air bags or foam plastic floats for permanent air retention.

The operation of a pressure tank is governed by the universal gas law, which states that:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

where:
P = absolute pressure (Pa)
V = volume (litres)
T = absolute temperature (K)

Although it is the water charge and discharge that is of interest, it is the pressure and volume of air that must be considered. Although the operation of the tank is essentially an isothermal process (constant temperature), as fresh water is pumped into the tank the temperature is likely to change a little. For optimum operation, the tank should be approximately half full at the cut-in pressure. Water-system problems are discussed later.

TABLE 19.6
Pump applications

Type of pump	Vertical distance from pump to water	Quantity of water required	Operating pressure	Applications
Centrifugal	Up to 4 metres	Large	Low	Stock or irrigation
Shallow-well jet	Up to 6 metres	Medium	Medium	Domestic or stock
Deep-well jet	6–30 metres	Medium	Medium	Domestic or stock
Shaft-driven deep-well turbine	4–40 metres	Large	Low to high	Irrigation
Submersible deep-well turbine	6–40 metres	Medium	Medium	Domestic, stock, irrigation
Reciprocating shallow-well	Up to 7 metres	Low to medium	Medium	Domestic, stock
Reciprocating deep-well	6–40 metres	Medium	Medium to high	Domestic, stock
Diaphragm	Up to 5 metres	Medium	Low	Slurries
Hydraulic ram	(- 1 metre)	Small	Medium	domestic

Gravity system

A second system for storing pumped water is a gravity tank, with the pump operation controlled either manually or by a float switch. The tank must be elevated above the highest point of water use, frequently on the roof of the building where the water is used. The tank is usually considerably larger than a pressure tank. This is an advantage in that, in the event of a power failure or pump breakdown, there will be a larger reserve of water available for use. However, the need to support a large tank on the roof requires strong structural supports that will add to the cost of the installation. Finally, water pressure is seldom very high and may be barely adequate near the level of the tank.

Pipe flow

If the rate of water flow in a pipe system remains constant, the equation of continuity of flow applies:

$Q = A \times V$

where:
Q = flow (m^3/s)
A = cross-section area (m^2)
V = velocity (m/s)

If the area of the pipe is halved, the velocity of flow will double, and so on. Although the velocity is not uniform across a cross-section of the pipe because of the friction affect of the pipe walls, average velocity is used for calculations.

Friction losses occur when water flows through a pipe. The amount of loss is related principally to pipe size, velocity of flow and the roughness of the interior pipe surface – and to a lesser extent to temperature. As the friction is proportional to the square of the velocity, the resistance, which is small at low velocities, builds up quickly as the velocity increases.

Roughness in pipes can change with age. Galvanized steel pipes may form rust or scale with age, increasing the roughness and friction and reducing the rate of flow. A smooth pipe, such as one made from plastic,

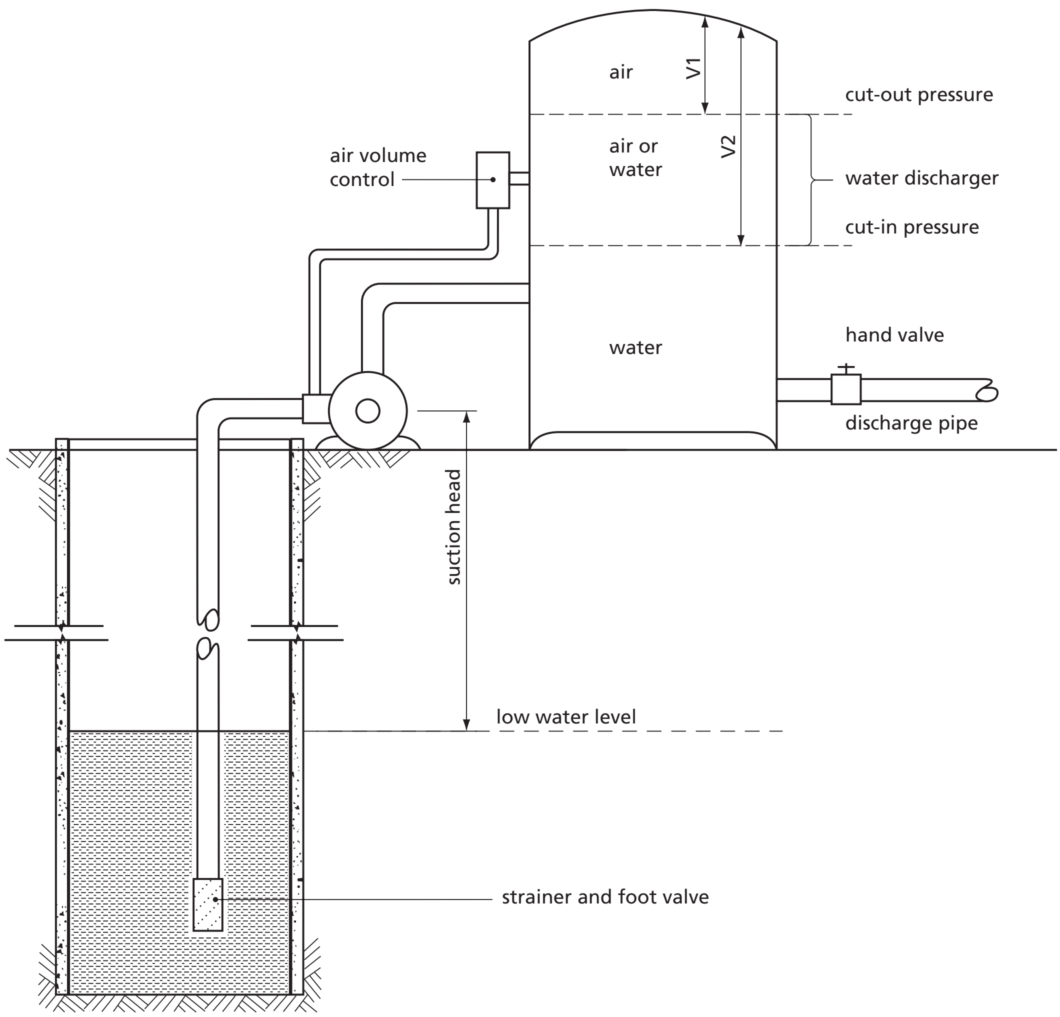

Figure 19.19 **Hydropneumatic water system**

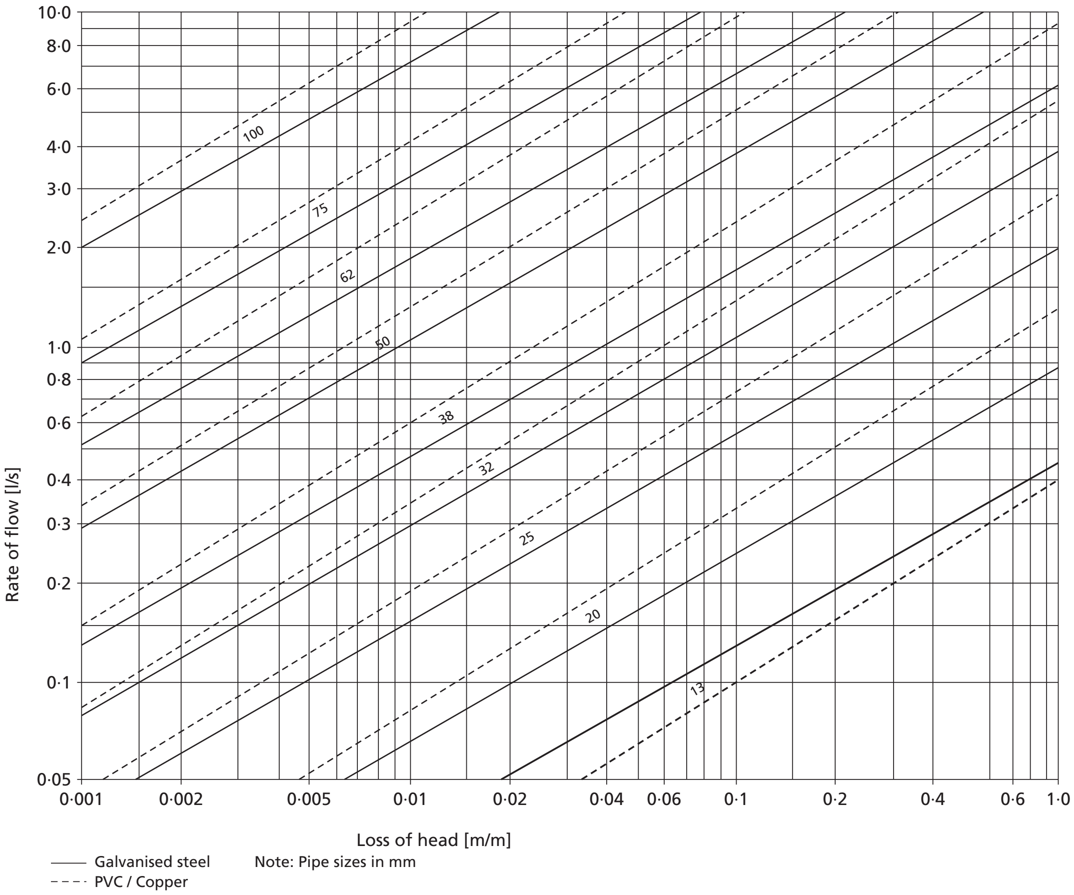

Figure 19.20 **Friction losses in pipes**

generates less friction than a pipe with a rough surface, such as concrete.

The length is directly proportional to the friction head in pipes. Figure 19.20 gives the loss of head for both smooth and rough pipes of several sizes and for a range of flow rates.

Other losses can occur when water flow in a pipe is interrupted by passing through fittings, or from one pipe size to another, where there will be a friction loss. This results from turbulence in the flow, which uses up energy, with the result that more energy must be used to produce a higher pressure at the start of the pipelines. As friction loss is proportional to the square of the velocity of flow, it can be ignored at low velocities, such as in drainage pipes.

However, friction loss can be significant in high-pressure irrigation lines or water-supply systems, especially if there are a large number of fittings. It is common practice to add 10 percent to the friction loss of the pipes to allow for all the various fittings.

Water-system problem

Example:

It is necessary to design the water system for domestic and stock watering for a family of five people who keep 3 zebu cows and 10 goats. The water will be pumped from a dug well that is 3 metres below and 5 metres away from where the pump will be located. The pump will need to discharge into the storage tank at a minimum of 300 kPa of pressure. The discharge from the tank between cut-out and cut-in pressure should be approximately one-twelfth of daily water consumption, so that the pump will operate no more than 12 times per day.

Water will be discharged from the tank at a distance of 50 metres to a single tap, and the head loss at a flow of 1 litre/second should not exceed 10 percent of the average pressure. The pump dealer has advised that the pumps are approximately 75 percent efficient in terms of power demand, and the electric motors are 85 percent efficient.

Determine the following:

1. Total daily water consumption (maximum flow 1 litre/second)
2. A suitable type and capacity of pump
3. A suction pipe sized to have a friction head of 8 percent or less of the suction head
4. An adequate tank size
5. A suitable discharge pipe size
6. A motor size capable of driving the pump.

1. From Table 19.1, a single water tap supply indicates 10–20 litres/day per person. Choose 20 litres.
   From Table 19.2, local cattle require 20 litres/day and goats require 3 litres/day.

   5 people × 20 = 100 litres
   3 cows × 20 = 60 litres
   10 goats × 3 = 30 litres

   Total daily needs are 190 litres at 1 litre/second maximum flow

2. The lift from well to pump is low (3 metres) and the water demand is low. Choose a shallow-well jet pump with a 1.2 litres/second capacity. The extra capacity will allow for some loss of capacity caused by wear over the life of the pump.

3. Calculate the loss of head per metre of suction pipe.

   3 m × 0.08 = 0.24 m/8 m of pipe = 0.03 m/m. From Figure 19.20, the intersection of 1.2 litres/second and 0.03 m/m head loss is 38 mm plastic pipe. Choose a 38 mm PVC suction line.

4. Tank size: 190/12 = 16 litres discharge/cycle. Choose a pressure range of 200–300 kPa; atmospheric pressure equals 100 kPa.

   $P_1V_1/T_1 = P_2V_2/T_2$, but assume $T_1 = T_2$

   $V_2 = V_1 + 16$ as P_1 drops to P_2
   $400 \times V_1 = 300 \times (V_1 + 16)$
   $100 \times V_1 = 4\,800$
   $V_1 = 48$ litres
   $V_2 = V_1 + 16 = 48 + 16 = 64$ litres
   V_2 = should be around half of the tank size
   Approximate tank size = 2 × 64 = 128 litres.

5. Average pressure at the tank is (200 + 300) / 2 = 250 kPa (1 metre of head = 9.8 kPa), therefore 250 kPa = 25.5 metres of head 25.5 × 10 percent = 2.55. Which gives:

   2.55/50 m/m = 0.5 m/m allowable loss at 1 litre/second flow.

   From Figure 19.20, 20 mm PVC pipe is small but 25 mm PVC pipe is satisfactory.

6. Power to lift water from the well and overcome all head at a flow rate of 1 litre/second is as follows:

   Total head = 3 + 0.24 + (300 / 9.8) + 2.55 = 36.4 metres of head

   1 litre water = 1 kilogram mass and gravitational force = l kg × 9.8 m/s^2
   Force required = 1 kg × 9.8 m/s^2 = 9.8 N
   Work done = 9.8 N × 36.4 m = 357 Nm

   As this amount of work is done each second,

   power = work/second = 357 Nm/s or watts (W)
   356 / 0.75 pump efficiency = 475 W input required by pump
   475 / 0.85 motor efficiency = 560 W input to motor
   560 / 220 V = 2.5 amp running current, which gives:

   2.5 × 2 = 5 amp starting current.

Summary of requirements

1. Total daily water consumption: 190 litres at 1 litre/second.
2. Jet pump with minimum capacity of 1.2 litres/second at 36 metres total head.
3. 38 mm suction pipe (PVC).
4. Tank size: approximately 128 litres.
5. 25 mm discharge pipe (PVC).
6. Motor of 560 W minimum input.

Water system design features

1. Even if the home water system consists of only one tap near the house, a complementary drainage system is essential. A pit 1 metre square and 0.5 metres deep, filled with stones or gravel, should be constructed under the tap to carry off leakage and spillage without creating a muddy area.
2. Perhaps the second step in the development of a rural home water system is the installation of a solar water heater. This can be as simple as a black 208-litre oil drum installed on the roof, either refilled periodically from the tap or connected permanently by a branch pipe from the water supply line. A combination of a check valve in the supply line to the water heater and a pressure safety valve at the tank is advisable. Although the check valve will prevent warm water from draining back into the cold-water line when pressure is low, a safety valve is absolutely essential when the check valve is used to prevent excessive pressure build-up from hot water.
3. If an extensive home water system is planned, complete with toilet, shower and sinks, it is prudent to plan a good drainage system at the same time. Soakaways are necessary for disposing of shower and sink water, unless the water must be saved for irrigation or stock watering, in which case a collection tank should be constructed. It is best to treat waste from a toilet in a septic tank, with the effluent allowed

to soak away into a pit or drainage field. These systems will be discussed later.

4. Pipe materials for cold water may be either plastic (PVC or high-density polythene) or galvanized steel. Although steel is more expensive and difficult to work with, it is not easily damaged. Galvanized pipe has a relatively short life when exposed to acid water, but lasts very well when the water is neutral or slightly alkaline.
5. Pipe of 20–25 millimetres in diameter should be used as a main supply line, but 13 mm will be adequate for branches to sinks, shower and water closet. Each branch should have a shut off valve to facilitate repair work.
6. Tropical areas are normally an ideal place in which to make use of solar water heating. Two square metres of properly positioned collector should heat 20 litres or more to 45–50 °C on most sunny days. Solar heaters are discussed in greater detail in Chapter 20.

WATER TREATMENT

The preferred way to obtain pure water is a safe water source that is well protected from pollution. A good example would be a tube well 20–30 metres uphill from any pollution, and equipped with a pump, a tight-fitting cap and a well designed apron. Unfortunately, good sources of water are not always available, and some treatment will be advisable. Four methods are discussed briefly.

Boiling

A 208-litre oil drum may be cleaned and then mounted horizontally over a brick fire box, as shown in Figure 19.21. A tap should be fitted at the bottom of one end and the tank should be set at a height to allow enough clearance to place a bucket under the tap. The tank should not be filled completely and the filler plug should never be installed tightly. Water should be boiled for 15–20 minutes and 1–2 litres should be drawn from the tap during the boiling process. Once cooled, the 200 litres should provide enough drinking water for several days.

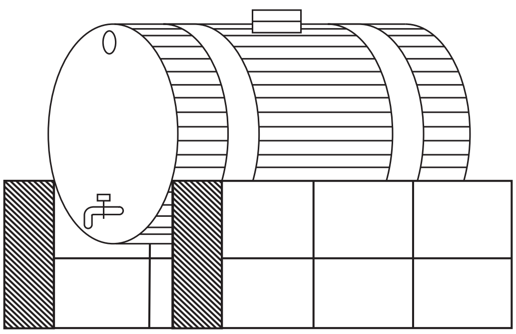

Figure 19.21 **Water boiler**

There are a number of filter designs that will clarify water and remove some bacteria. They all require periodic cleaning, the difficulty of which depends on the size and type of filter.

A medium-sized upward-flow sand filter can be effective in reducing suspended solids, and is easy to clean and maintain. The filter containers can be made either from either 208-litre drums, or from 175–200-litre concrete tanks made by using a hessian bag filled with sand or sawdust as a form and applying mortar over it. If good quality mortar is used, small tanks will not need reinforcing.

A filter cross-section is shown in Figure 19.22. Successive layers, first of stones then gravel, coarse sand and fine sand, are placed in the tank until it is around half full. A layer of charcoal, crushed to approximately 5 mm in size, is desirable, as it will trap bacteria, which is helpful in removing disease-carrying micro-organisms from the water. The charcoal bed is enclosed with thin cloth and weighted down by a top layer of sand.

Water poured into the top tank flows through the tube to the bottom, where it percolates up through the gravel, sand and charcoal and out through the hose to a water jar. Before being used, some water should be passed through the filter to make sure that the filter is working properly. The drain plug at the bottom should be large so that, when it is removed, water will flow back through the sand rapidly and flush away all accumulated sediment. Experience will indicate when back-flushing is necessary.

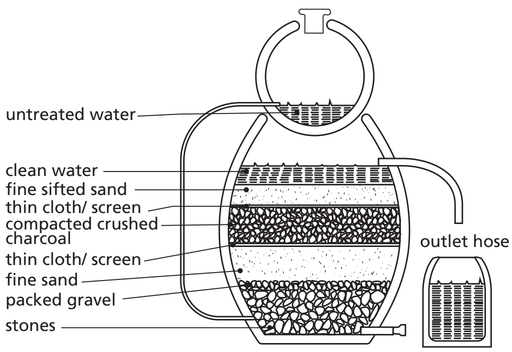

Figure 19.22 **Upward-flow water filter for filtering up to 40 litres per day**

Chlorination

Proper attention to detail is needed to make a satisfactory job of chlorination. However, proper chlorination can make drinking water much safer. After adding the correct amount of chlorine material, thoroughly mix it into the water and allow it to stand for at least 30 minutes.

Treatment levels are given in parts per million (ppm): 1 mg/m^3 equals 1 ppm. Water that is clear and not suspected of dangerous contamination can be treated with 5 ppm of active chlorine. If the water is a

TABLE 19.7
Sources of chlorine for water treatment

Compound	Active chlorine percentage by weight	Quantity of chlorine to add to 100 litres to obtain the following concentration (grams)			
		5 ppm	10 ppm	15 ppm	50 ppm
HTH $Ca(OCl)_1$	70	8	15	23	80
Chlorinated lime	25	20	40	60	200
Sodium hypochlorite (NaOCl)	14	38	75	113	380
Sodium hypochlorite	10	48	95	143	480
Laundry bleach	5.25	95	190	285	950

little cloudy, 10 ppm is safer. Sources of chlorine vary considerably in terms of the amount of active chlorine available. Table 19.7 gives information about several materials.

While these quantities may be reduced proportionally for smaller quantities of water, measurements become more critical for amounts under 100 litres, and it is advisable to ask a pharmacist to weigh out several packages of treatment material in quantities appropriate for the quantity of water to be treated each time.

The 50 ppm column in Table 7 is the level at which to treat a new or repaired well or cistern. This dosage is left to stand for 24 hours before flushing out.

Water treatment by solar disinfection (SODIS)

This is by far the cheapest and most effective means of water treatment in tropical rural areas. It involves placing water in a transparent bottle, painted black on one side, and exposing it to tropical sunlight for several hours. It is more environmentally friendly than boiling because boiling involves the use of energy from burning wood.

SODIS (or SOlar DISinfection) is a treatment method used to eliminate the pathogenic micro-organisms that cause waterborne diseases. It is ideal for disinfecting the small quantities of water used for consumption and depends on solar energy alone.

The treatment process is a simple technology using solar radiation to inactivate and destroy the pathogenic micro-organisms present in the water. The best use of solar energy is the combined application of two treatment processes. First, boiling water to kill micro-organisms; second, using the UV radiation from the sun to kill micro-organisms. In combination, they are sufficient to sterilize the water.

Basically the treatment consists of filling transparent plastic (PET) or glass bottles with water and exposing them to full sunlight for approximately five hours. To absorb more heat and raise the water temperature, the bottle is painted black on one side and placed on a black surface, in the sun, with the clear side facing the sun. The recommended exposure time is 5 hours under bright sunlight or a 50 percent cloudy sky, or two consecutive days under a 100 percent overcast sky.

OPEN CHANNEL FLOW

A knowledge of the principles of open channel flow is necessary when designing ditches to carry water into grade-level storage and channels to carry away storm water without causing erosion. The same principles apply to the design of irrigation canals, road splashes and drifts. The most common problems are:

1. Estimating the flow in a channel when the cross-section, gradient, depth, etc. are known or can be measured. This is useful in planning irrigation canals, ditches, and natural watercourses.
2. Estimating the depth of flow at which a given channel will carry a given rate of flow. This can be useful in estimating how high a river flood crest will rise, or how deep the flow will be in an irrigation channel or over a drift.
3. Designing a channel to carry a given rate of flow. This is useful in designing channels to carry storm runoff away from buildings or other structures.
4. Designing a channel to carry an estimated maximum flow, when the velocity must not exceed a given maximum value. This is a problem of designing stormwater diversion drains or other unlined channels when the velocity must be low enough to avoid scouring of the channel. A suitable cross-section and gradient must be chosen.

The quantity of water flowing in an open drainage channel is the product of the cross-section area of the channel and the speed of flow.

$$Q = A \times V$$

where:
Q = flow in cubic metres per second (m^3/s)
A = cross-section area of the channel (m^2)
V = average velocity of flow (m/s)

If the velocity is measured at any cross-section in a channel, the water will be found to flow more slowly along the sides and bottom. This is caused by frictional resistance, and is more pronounced in vegetated channels than in paved channels. However, in practice a theoretical average velocity is used.

The equation of continuity shows that, for a constant discharge Q, the velocity must change inversely with the section area of the channel.

$$Q = A_1 \times V_1 = A_2 \times V_2 = A_3 \times V_3$$

There are two types of flow in a channel, which may give the same discharge but at different velocities and depths. A rapid, shallow flow is called a *supercritical* or shooting flow. A deeper, slower flow is called a *subcritical* flow. An example of each type of flow is found on a dam spillway. The thin layer rushing down the spillway surface is supercritical flow. After hitting the standing wave at the bottom, the water moves away much more slowly in a subcritical flow. In general, supercritical flow should be avoided, as erosion will occur in all channels that are not lined with concrete.

The velocity of flow in a channel is determined by the gradient, the shape and size of the cross-section and the roughness of the surfaces. Obviously, the velocity will be greater in steep, smooth channels. Not so obvious is the fact that two channels with the same cross-section area, but with different shapes, can have different velocities. This results from the different amounts of surface contact and frictional resistance.

The effect of cross-section shape is measured by the hydraulic radius of the channel (R). It is found by the equation:

$$R = A / P$$

where:
R = hydraulic radius (metres)
A = cross-section area (m²)
P = wetted perimeter (metres)

The wetted perimeter is the length of the cross-section in contact with the water. Figure 19.23 illustrates the effect of shape on the hydraulic radius. While both channels have an area of 24, the upper channel has a larger hydraulic radius.

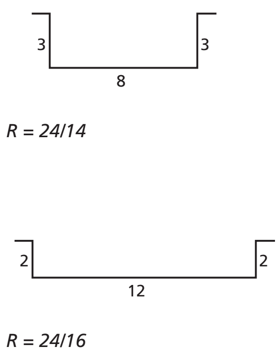

Figure 19.23 **Channels of equal area but with different hydraulic radii**

When other factors are equal, the channel with the larger hydraulic radius will have the higher channel velocity.

The two most common shapes for earth channels are shown in Figure 19.24. The trapezoidal shape has a tendency to gradually change to the parabolic shape over a period of time.

The variables that affect the velocity of flow are related, as shown, in the empirical equation called the Manning formula for open channel flow.

$$V = \frac{1}{n} \times R^{2/3} \times S^{1/2}$$

where:
V = velocity (m/s)
R = hydraulic radius (m)
S = gradient (m/m)
n = Manning's roughness coefficient

$$R = A/P$$

where:
A = cross-sectional area (m²)
P = wetted perimeter (m)

TABLE 19.8
Value of Manning's roughness coefficient (*n*)

(a)	*Channels free from vegetation*	(*n*)
	Uniform cross-section, regular alignment, free from pebbles and vegetation, in fine sedimentary soils	0.016
	Uniform cross-section, regular alignment, few pebbles, little vegetation, in clay loam	0.020
	Irregular alignment, ripples on bottom, in gravelly soil or shale, with jagged banks or vegetation	0.025
	Irregular section and alignment, scattered rocks and loose gravel on bottom, or considerable weed on sloping banks, or in gravelly material up to 150 mm diameter	0.030
(b)	*Vegetated channels*	
	Short grass (50–150 mm)	0.030–0.060
	Medium grass (150–250 mm)	0.030–0.085
	Long grass (250–600 mm)	0.040–0.150
(c)	*Natural stream channels*	
	Clean and straight	0.025–0.030
	Winding, with pools and shoals	0.033–0.040
	Very weedy, winding, and overgrown	0.075–0.150

Extracted from *Field Engineering for Agriculture Development* by Hudson.

With the Manning formula, any three variables can be used to find the fourth variable. When, for example, R, S and n can be measured or estimated, it is possible to calculate velocity.

While open-channel problems may vary in detail, the principle is usually the same. The designer has some fixed quantities, such as a given discharge to be carried, and some variables, such as gradient and velocity, which have restricted ranges. These can be used to determine a size and shape. Usually there is no single solution but a range of satisfactory alternatives.

TABLE 19.9
Maximum channel velocities in metres per second (cover after two seasons)

	Vegetative cover		
Soil	**Bare**	**Medium grass**	**Long grass**
Light, silty sand	0.3	0.75	1.5
Coarse sand	0.75	1.25	1.7
Firm clay loam	1.0	1.7	2.3
Coarse gravel	1.5	1.8	-
Shale, hardpan	1.8	2.1	-
Rock	2.5	-	-

TABLE 19.10
Design velocities for grass waterways (m/s)

	Slope		
Soil	**0–5%**	**5–l0%**	**10%**
Erosion-resistant veils	2.0	1.75	1.50
Erosion-prone soils	1.75	1.50	1.25

Source: Department of Conservation, Government of Zimbabwe

Example:
An earth- or grass-lined channel should be designed with a flow velocity fast enough to avoid sediment deposits. but not so fast that erosion will occur. Table 19.9 suggests maximum velocities for various channel soils and vegetative covers.

For convenience, Figure 19.25 may be used to solve open channel flow problems. For example, assume a channel is to be designed for a firm clay–loam soil with a medium grass cover (200 mm) to be established. The maximum expected flow is 2.0 m^3/s and the gradient is approximately 0.025 m/m. Choose a channel shape and determine a satisfactory size from Table 19.8; read a value for roughness coefficient (n) of 0.030–0.085; choose 0.04.

From Table 19.10, read 1.7 m/s acceptable velocity.

From Figure 19.25, read 0.30 metres hydraulic radius.

Choose a parabolic shape arbitrarily.

$A = Q/V = 2 / 1.7 = 1.18\ m^2$
$P = A/R = 1.18 / 0.30 = 3.93$ m
$P = t + (8d^2 / 3t)$, (assume a value for t of 3.75 metres)
$d^2 = (P - t) \times 3t / 8$
$d^2 = (3.93 - 3.75) \times 3 \times 3.75 / 8 = 0.25$
$d = 0.5$ m
$A = (2 / 3)\ td$
$A = (2 / 3) \times 3.75 \times 0.5 = 1.25\ m^2$

which is close to the previous $A = 1.18\ m^2$

In summary, a parabolic-shape channel 3.75 metres wide and 0.5 metres deep will be satisfactory.

RURAL SANITATION

When dealing with the problems of poor sanitation in the rural areas of developing countries, it might be tempting to assume that improved technology is the answer, e.g. the assumption that new latrines will provide the required ‘technological fix’. However, technology alone does not solve everything, for it has been found that newly built latrines may not be fully utilized and, when used, may not reduce significantly the diseases caused by poor sanitation.

Good sanitation depends on people and how they organize hygiene-related activities. It depends on a large ‘package’ of hygiene measures, and latrines are

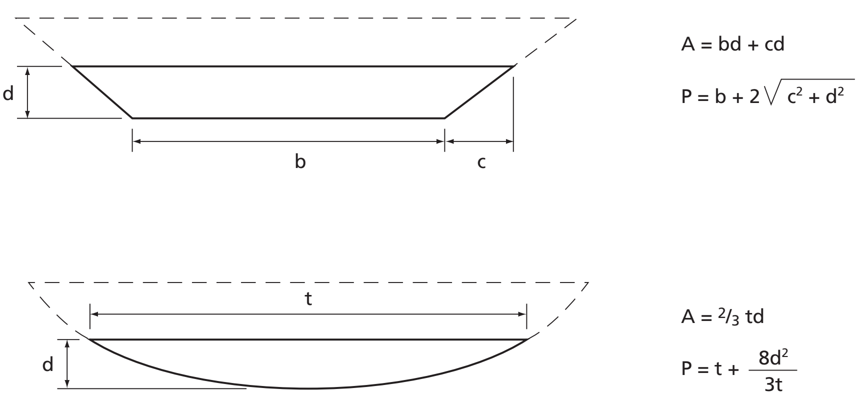

Figure 19.24 **Basic dimensions of common channel sections**

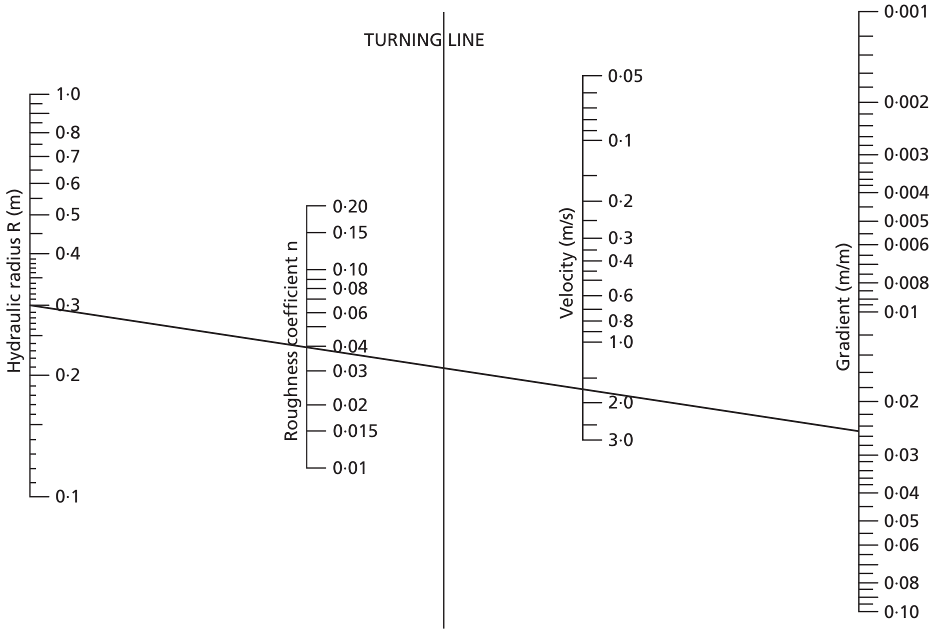

Figure 19.25 **Nomograph for Manning's formula**

only a part of this package. Technology does have a part to play, and many rural communities need basic technical assistance. While latrines may not always be a practical solution, if they are, they must be designed carefully to suit local cultural patterns.

Wastewater treatment and sanitation

A rainbow of water

It is common practice in in the field of water and sanitation to refer to different types of water as different colours:

- Green water refers to the direct use of rainwater by plants after it has been stored in the soil's unsaturated zone.
- Blue water refers to the combination of surface water and renewable groundwater. Blue water is the water that can be managed by engineering interventions and that can be allocated, reallocated and measured by traditional monitoring.
- White water is either the part of the rainfall that feeds back directly to the atmosphere through evaporation from bare soil, or rainfall that is intercepted for human use, such as from roof catchments. Together, white and green water form the vertical component of the water cycle, as opposed to blue water, which is horizontal.
- Black water is wastewater from the toilet.
- Grey water is wastewater from washing, bathing, washing of clothes and from the kitchen, which can be reused in agriculture or industry. It can also be processed into drinking water, often after mixing with blue water.
- Ultraviolet water represents 'virtual water', which is invisible but detectable. It is the amount of water used in the production of water-consuming products, in its widest sense. Grains, produced under proper conditions, use approximately 1–2 m^3 of (often green) water per kilogram. The trade in grain is a trade in 'virtual' water.

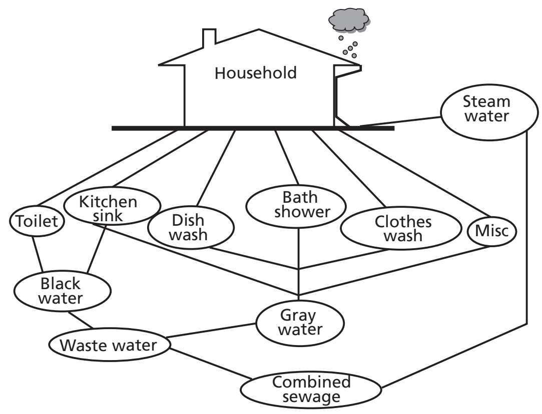

Figure 19.26 **Sources of household wastewater (International Environmental Technology Centre of the United Nations Environment Programme [UNEP–IETC], 2000)**

Wastewater can be divided into grey water and black water. Grey water consists of the wastewater from washing/bathing, washing of clothes and from the kitchen, while wastewater from the toilet is called black water. Storm water also contains solids and pollutants that have been picked up from the surfaces it flows over, and therefore also requires treatment. Storm water collection is important from the standpoint of flood control. If wastewater is combined with storm water it is called combined sewage.

The main aim of wastewater treatment is to reduce the Biological Oxygen Demand (BOD) and Suspended Solids (SS) to acceptable levels. Normally BOD is reduced to less than 20 mg/litre, and SS to less than 30 mg/litre. SS is removed by filtration and sedimentation. BOD is mainly reduced by aerating the water. However, anaerobic treatment may also be used to recover energy. If the wastewater is discharged into bodies of water that are sensitive to nutrients, the nutrients should also be removed. Pathogenic and faecal indicator micro-organisms need to be reduced to acceptable levels to ensure that they will not pose any threat to human health.

Different treatment techniques can be adopted, depending on land availability and on the quantity and characteristics of the wastewater. Treatment plants, which are used for treating sewage, usually employ biological processes. The process is dependent on natural micro-organisms that utilize oxygen and organic contaminants in wastewater to generate CO_2, sludge and treated water.

The following guidelines should be followed for rural treatment systems:

1. Do not mix different kinds of waste. Collect solid wastes, wastewater and storm water separately, but have an integrated plan to deal with them.
2. Promote a low-cost, decentralized wastewater treatment system.
3. Develop norms based on existing standards for reuse of treated water for non-potable applications.
4. Water under or near a pit or septic tank can become polluted. To prevent this, septic tanks should be located 15–20 metres away from the nearest water supply point, and 3 metres from the nearest house.
5. Kitchen waste should be separated from animal and toilet waste to ensure hygiene.

Classification of wastewater treatment methods

Wastewater can be treated on-site or off-site. The common on-site treatments are:

- pit latrines and pour-flush latrines;
- composting toilets;
- septic tanks and Imhoff tanks.

Common off-site treatment systems include:

- activated sludge treatment;
- trickling filtration;
- constructed wetlands;
- simple anaerobic systems;
- upflow anaerobic sludge blanket (UASB);
- lagoons or ponds;
- decentralised wastewater treatment systems (DEWATS).

Pit latrines

Many latrine designs can be built in areas where more sophisticated sanitary systems are not possible. The simplest design is the pit latrine, with certain characteristics that are common to the many variations of this design. A latrine should always be dug at least 30 metres downhill from a well, if the well is the source of the family water supply. However, in areas where the water table is very high, the distance should be increased to 200 metres or more. The latrine should also be at least 10 metres from the nearest house or kitchen.

While a pit a little less than 1 metre in diameter is sufficient, an oval pit measuring 0.7 metres by 1.5 metres will provide more convenient space for the person digging. The depth is at least partially dependent on the stability of the soil, and therefore on how deep the hole can be dug without danger of a cave-in. While a depth of 4–5 metres is normal in stable soil, an increase to 7 metres will reduce the problem of flies. In areas with a high water table, the depth may have to be decreased because, in order to avoid pollution, the bottom of the pit should be no less than 1 metre above the highest groundwater level. A pit with a diameter of 90 cm that is 5 metres deep will last for around five years if used by a family of six people.

The desired depth and the character of the soil will determine whether a stabilizing liner is necessary. Most latrines should have a block or brick liner for at least the top 1 metre. To install a stabilizing liner, a hole is dug a little less than 1 metre deep and approximately 1 metre in diameter, and lined with concrete blocks or bricks. After curing for a few days, the balance of the pit can be dug out, taking care not to make the diameter too large, allowing the blocks to sink. If the soil is sandy, a complete liner may be necessary. Bamboo is one possibility for lining the remainder of the pit sides.

A simple floor to cover the pit can be made of bamboo or timber. However, cast concrete provides a much more durable and sanitary slab. See Figure 19.28 and the accompanying paragraphs for the design and construction of a two-piece cast concrete slab that includes footpads and a slope toward the hole. The type of structure built above the slab to give privacy is largely a matter of personal preference. Bamboo, offcuts, concrete blocks or corrugated steel are all possibilities for wall construction. Corrugated iron sheets or thatch may be used for roofing.

A desirable feature to include is a vent pipe. A vent will not only reduce odours but, if screened at the top, it will catch numerous flies. The vent hole can be cast in the slab so that the vent is just outside the toilet hut. For optimum effectiveness, the vent should be located on the side facing the prevailing sunshine, should be as large in diameter as possible, should be painted black and should have a screen over the top. This combination of design features tends to produce a significant air current that carries off odours and traps flies. Figure 9.27 shows a latrine of this type.

The vent pipe can be made at low cost using hollowed bamboo, but alternative materials, such as masonry, cement/sisal, reeds/mud, PVC or galvanised iron, can also be used. A piece of glass fitted at the base of the vent pipe will provide light to attract flies away from the squatting hole and will trap them in the vent pipe.

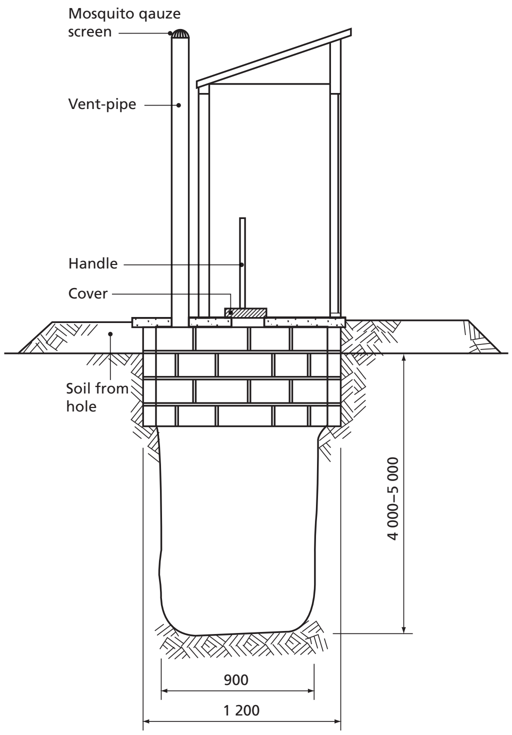

Figure 19.27 **Pit latrine with vent pipe**

Latrine slab

The latrine slab can be cast to provide a perfectly satisfactory two-piece slab that is easy to handle. First, a small mould is constructed to cast the footpads, which should be approximately 10 cm by 30 cm by 2 cm, with rounded corners. The footpads are cast a few days prior to casting the slab and are stored in a bucket of water to cure. The form for the slab is then built using four boards measuring 7 cm by 120 cm and any convenient thickness. A round block 5 cm thick and 10–12 cm in diameter, and a rectangular block measuring 10 cm by 20 cm by 5 cm, are needed for the hole. If a vent pipe is to be installed, another 7 cm thick round block will be needed, with a diameter to match that of the pipe.

Two screeds are required: one straight and the other curved enough to be 1–2 cm lower in the middle. Three pieces of polythene are cut to the lengths required to serve as separators between the two halves of the slab (See Figure 19.28, section B–B). Six pieces of 8 mm reinforcing rod, cut to fit tightly into the form, are also needed. Find a flat surface (a floor or levelled earth), spread a piece of polythene and position the form and the wood blocks on it. Mix a 1:3 cement-to-sand concrete (or 1:2:2 cement–sand–small gravel), using just enough water to obtain a workable mixture.

The polythene separators are then positioned, and a uniform 2.5 cm layer of concrete is placed on either side. The reinforcing bars are then fitted, as shown in Figure 19.28, section A–A. Next, the form is filled, and the concrete is compacted and levelled with the straight screed. Then, using the curved screed in the middle one-third of the form, work out from the centre of the concrete in both directions to give the sloping surface. Smooth lightly with a steel trowel. Place the dampened footpads in place, working them into the surface slightly. Use any excess concrete to cast a pad to be laid just outside the privy entrance.

After all signs of free water have disappeared from the surface, finish the concrete with a steel trowel. Cover and keep damp for several days. Handle with care. A number of variations and refinements in latrine use and design may be considered.

Placing a thick pad of grass in the bottom of a newly dug latrine and then adding some vegetable waste regularly will turn the latrine into a compost pit, with a substantial reduction in odour. When the pit is full, it is necessary to dig a new latrine hole and move the slab and hut. The full hole is covered and left for at least six months, after which the compost may be removed and used as fertilizer.

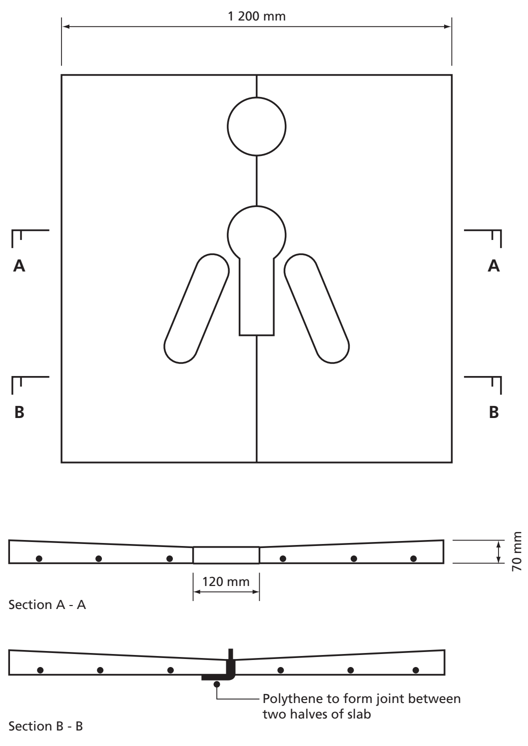

Figure 19.28 **Concrete slab cast in two pieces**

Aqua privies

Aqua privies are usually equipped with either a water-trap hole or a discharge below water level. Either of these alternatives will reduce odours considerably. However, some water must be added daily for complete decomposition of the waste, and a soakaway pit is essential to dispose of the effluent that is discharged (see Figure 19.29).

One way to ensure that extra water is added each day is to combine a bath house with the privy. Figure 19.30 shows the plans for such a combination. In the illustration, a separate soakaway is shown for the bath, as it is combined with a pit latrine. However, if it were combined with an aqua privy, the water would be directed into the privy tank.

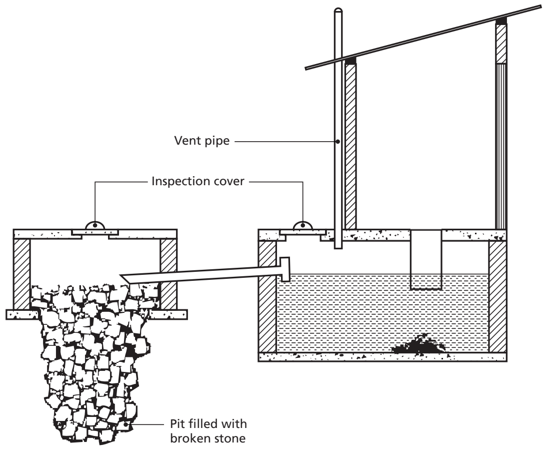

Figure 19.29 **Aqua privy with soakaway pit**

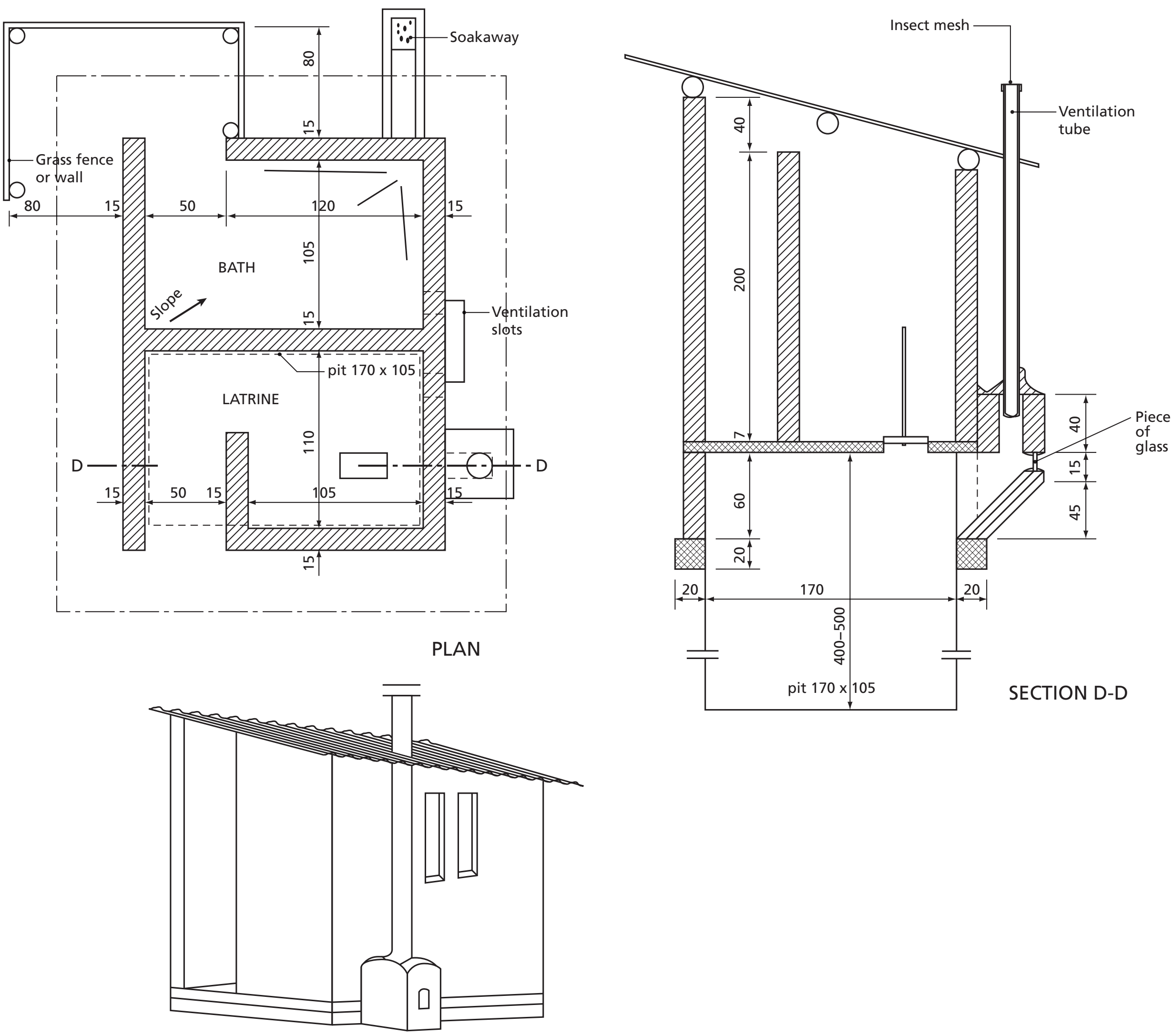

Figure 19.30 **Bath house and latrine (all dimensions in centimetres)**

A bath house is an inexpensive but convenient additional facility for a family, either with or without piped water.

A farm home with an adequate and continuous water supply can be equipped with a water closet toilet. A water closet system uses a much larger quantity of water than the other systems mentioned, and requires the installation of a septic tank, plus a large soakaway or drainage field, to handle the considerable amount of effluent.

Septic tanks

The septic tank is a large concrete or concrete-block tank, the base of which is at least 150 cm below the inlet and outlet level. The raw sewage flows into the tank through an open tee, and the effluent leaves the tank through a similar tee. The tank is divided by a wooden baffle that extends from 50 cm above the bottom to 25 cm above the sewage level. A heavy scum forms on the surface and all digestive action is by anaerobic bacteria, i.e. bacteria that live and multiply without the presence of air. Figure 19.31 shows a cross-section of a septic tank.

Soakaway trenches

The effluent from a properly operating septic tank will be almost free of solids, and further biological activity in the soakaway trench, or pit, will be aerobic in nature, i.e. some air needs to be present. Therefore, trenches with a depth of approximately 50 cm are preferred over deep pits. Before a tank and soakaway system are installed, it is important to check with the local authorities concerning design specifications. If there are no specific rules, the information given in Table 19.11 may be used. Percolation time is found by digging a hole 30 cm square and 60 cm deep. Fill the hole with water and let it drain completely. Refill the hole and then measure the seconds per millimetre rate at which the water level falls.

The outlet from the septic tank should be approximately 50 cm below ground level. However, sometimes this is made difficult by site gradients and the need to install the tank low enough to ensure that the sewerage lines will drain into it. Although the soakaway field is usually close to the tank, it may need to be located some distance away because of site conditions. The soakaway trench should be approximately 100 cm wide and 50 cm deep and with very little slope. A layer of gravel or broken stone is placed in the bottom of the trench, and then 100 mm clay tile or 100 mm perforated PVC pipe is laid in the trench.

The maximum slope of the soakaway lines is 1:200. If lines have to be installed at different levels because of

TABLE 19.11
Septic tank and soakaway trench sizes

Number of people regularly in the home	Tank interior dimensions (centimetres below drain level)	Soakaway trench (metres)* with percolation rates (seconds per millimetre)			
	Length × width × depth	10–30	30–60	60–100	100–140
2–4	200 × 100 × 150	10	30	60	100
6	250 × 125 × 150	15	45	90	150
8	250 × 125 × 150	20	60	120	200
10	250 × 150 × 150	25	75	150	250

*Trenches should be 100 cm wide and 50 cm deep

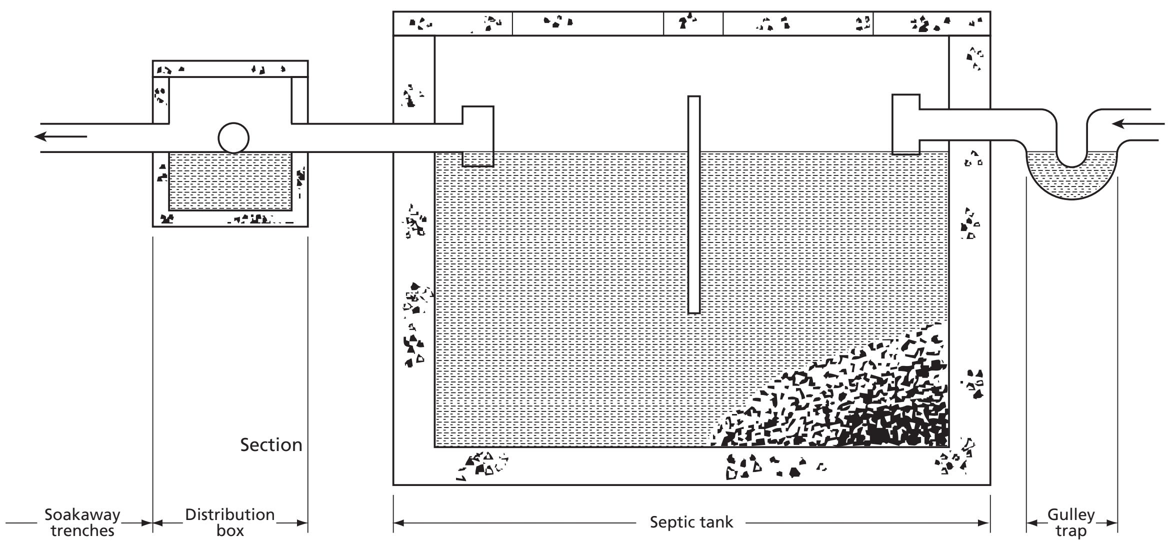

Figure 19.31 **Septic tank and distribution box**

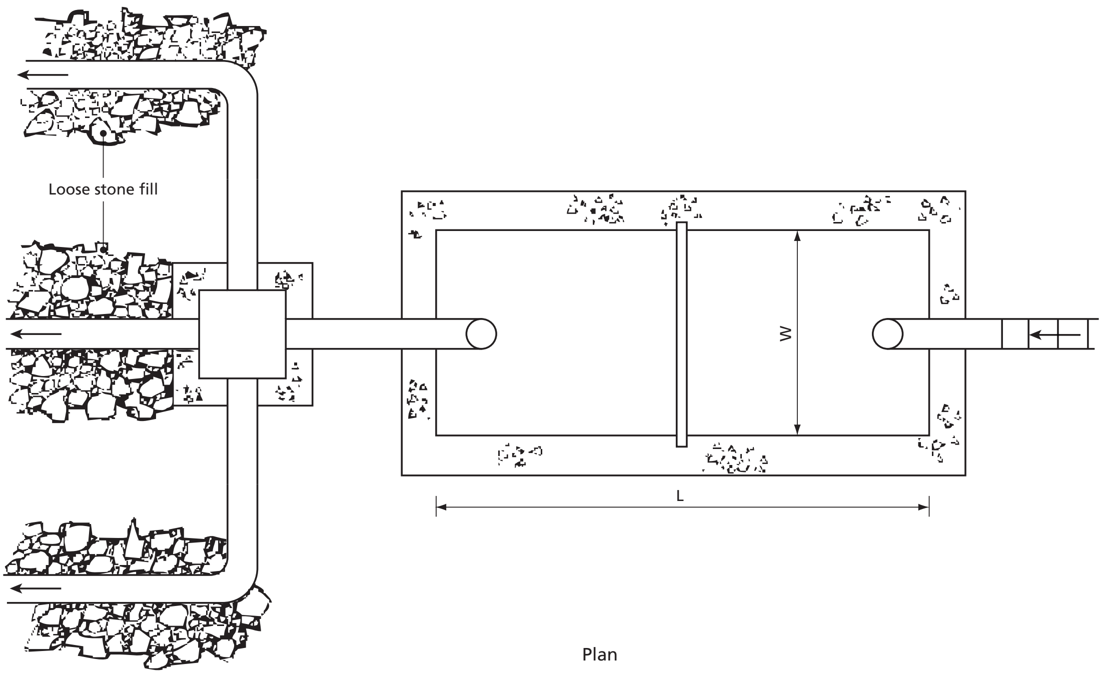

Figure 19.32 **Tank and soakaway field**

a sloping site, leakproof pipe or tile should be used to carry the effluent from one level to the other, but the seepage lines themselves should always be nearly level. Gravel or stone is added until the lines are covered. Hay, grass or newspapers can be laid over the stones before backfilling, to prevent the soil from filling the open spaces between the stones (see Figure 19.32). Although both aqua privies and septic tanks need to be cleaned out periodically, if they are built large enough, the period between clean-outs can be as much as two to three years, depending on how heavily the system is used.

WASTE MANAGEMENT

Waste management may be defined as the practice and procedure, or the administration, of activities that provide for the collection, separation, storage, transportation, transfer, processing, treatment and disposal of waste. In rural areas, the majority of waste takes the form of crop residues, animal manure and human excreta, which must be managed effectively to minimise their effects on people and the environment. However, most rural areas in tropical Africa often face the added burden of poverty, geographic isolation, limited local government resources, and financial and other constraints, making it difficult to manage the waste generated.

In the rural areas, the majority of the waste is produced from agriculture, and such wastes vary in quantity and quality. Wastes from on-farm processing are low-strength, high-volume liquid wastes, while those from livestock operations tend to be high-strength, low-volume wastes. As liquid and solid waste result from on-farm processing and livestock production, both liquid- and solid-waste management strategies must be implemented. The waste from crop residues tends to be much easier to manage than waste from livestock facilities.

The discussion of waste management will focus mainly on agricultural waste, particularly livestock waste, as livestock production is the main agricultural activity in rural areas. The discussion will cover sources, collection, storage, transportation, treatment and utilization of the waste.

Sources of waste

In rural areas, waste comes primarily from agriculture (crop and livestock production) and non-agricultural activities. Agricultural wastes consist of on-farm processing wastes, liquid and solid animal wastes, used packaging materials, agricultural chemicals, crop and field residues, greenhouse and nursery wastes, dead livestock and obsolescent vehicles, equipment, and buildings. Non-agricultural sources include waste from industry, clinical waste and other waste generated by human activity.

Agricultural wastes

On-farm processing

On-farm processing waste is generally low in nitrogen, high in biological oxygen demand (BOD) and suspended solids, and undergoes rapid decomposition. Fresh waste has a pH close to neutral, which decreases in storage. Waste from on-farm processing includes waste generated from washing and blanching raw materials, cleaning processing equipment and cooling the finished product. Such processing facilities include those for processing fruit and vegetables, meat and poultry and dairy products. In many cases, these operations are not very large compared with those in urban and periurban areas.

Livestock production

A large quantity of manure is produced each year from livestock facilities. While part of the total livestock waste production remains in the pastureland and rangelands, large volumes accumulate in feedlots and buildings, and must be collected, transported and disposed of economically. Livestock manure includes fresh excreta (solid and liquid), bedding material, the material remaining after liquid drainage and water evaporation, and material resulting from aerobic or anaerobic storage. Among livestock production operations, beef cattle, poultry, pigs and dairy cattle generate the largest volumes of manure.

The characteristics of livestock wastes depend on the digestibility and composition of the feed. The characteristics of the manure of various animals may be found in numerous sources in the literature, such as the handbooks of the American Society of Agricultural and Biological Engineers (ASABE). Livestock faeces consist mainly of undigested feed, mostly cellulose fibre, which has escaped bacterial action.

Undigested proteins are excreted in the faeces, and the excess nitrogen from the digested protein is excreted in the urine as uric acid (in the case of poultry) and urea (in the case of animals). Faeces also contain residues from the digestive fluids, waste mineral matter, worn-out cells from the intestinal linings, mucus, bacteria and foreign matter, such as dirt, that has been consumed along with the food.

Chemical wastes

Chemical wastes come mainly from fertilizers and pesticides. Continuous fertilizer application often results in excessive amounts of nutrients in the soil, particularly nitrogen and phosphorus compounds. Excessive amounts of these nutrients can end up in surface waters, resulting in overfertilization and acceleration of the eutrophication process in aquatic systems, particularly by phosphorus.

Chemicals used to control crop pests (pesticides) may also remain in the soil, enter water streams or percolate and contaminate underground water. This results in pollution of the environment, disturbing ecosystems, as some fauna may be killed (unintentionally) by these chemicals. Pesticides are categorized according to their use as insecticides, herbicides, fungicides, rodenticides, fumigants, etc.

Crop and field residues

Crop residues are useful wastes because they are:

- good sources of plant nutrients;
- the primary source of organic material added to the soil;
- important components for the stability of agricultural ecosystems.

The potential uses of crop residues include livestock feed, bedding for animals, composting, biogas generation, mushroom culture and raw material for industry.

Non-agricultural wastes

Packaging materials

The requirements of consumers and supermarkets have forced the food industry to package products in a wide range of different packaging materials. There is also a health requirement to keep products safe and hygienic for consumers. Some of these packaging materials are biodegradable and can be recycled by composting, while others are not and may be burnt or disposed of in landfills. A proper and suitable solid waste management system should be in place to cater for this waste, otherwise it results in pollution of the environment and destroys the aesthetic value of the locality. The methods used to dispose of such waste include recycling and burning.

Special wastes

Special wastes are those that need special handling, treatment and disposal because of their hazardous potential or large volumes. Although these wastes should not enter the solid waste stream, they frequently do, particularly in developing countries. Special wastes include hazardous waste in the household waste stream (e.g. oil-based paints, wood preservatives, household cleaners, used motor oil and batteries), tyres, used oils, and construction and demolition debris. Such wastes are often hard to dispose of safely in rural areas. Burning in a pit is an option that is frequently employed.

Household waste

Household waste should be collected, treated and disposed of to ensure that it does not endanger the environment. In scattered households, liquid human waste is managed through the use of pit latrines. Liquid wastes from the kitchen and laundry are best disposed off in soak pits, as described in earlier in this chapter.

For large farms and agro-industries, such as sugar mills, household waste management problems can be immense. Up to 10 000 workers and their dependants may be living close to these establishments. In this case, household wastes are collected and treated in line with practices in the municipality. This may involve manual or vehicle collection of wastes, transportation, disposal at landfills or incineration. Liquid wastes are collected by sewage systems and treated in municipal waste systems.

Waste collection

Waste collection refers to the initial capture and gathering of the waste from the point of origin or deposition at a collection point. Different collection systems exist, depending on the source and type of waste concerned.

Dairy: The collection methods for dairy waste vary depending on the management of the dairy operation. Dairy animals may be partially, totally or seasonally confined. Manure accumulates in confinement areas and in the areas where the dairy animals are concentrated before and after milking. The curbs at the edge of the paved lots and reception pits where the runoff exits the lots can be used to collect the manure. The runoff from rain and flushing may then be controlled by diversions and sediment basins. The manure and associated bedding accumulated in roofed confinement areas can be collected and stored as a solid.

Beef: Beef cattle can be confined on unpaved lots (see Figure 19.33), or on partially paved or totally paved lots. As most of the waste is deposited around watering and feeding facilities, it is advisable to pave these areas to make scraping of manure easy.

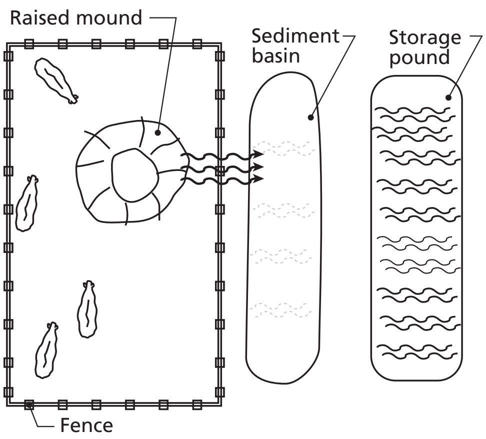

Figure 19.33 **Waste collection from an unpaved beef feedlot**

Pigs: Pig manure can be collected by scraping (solid or slurry manure) or flushing (liquid manure).

Poultry: The manure from broiler and turkey operations is allowed to accumulate on the floor, where it is mixed with the litter. Near the waterers or drinkers, the manure-litter pack forms a 'cake' that is generally removed between flocks. The rest of the litter pack generally has low moisture content and may be removed once a year, or more frequently, depending on the litter condition and management practice. For laying hens, manure accumulates under the cages and is removed by scraping between the flocks, or more frequently, depending on the manure condition and indoor air quality.

Waste storage

Storage is the temporary containment of waste. The storage period should be determined by the utilization schedule. The waste management system should identify the storage period; the required storage volume; the type, estimated size, location and installation cost of the storage facility; the management cost of the storage process; and the impact of storage on the consistency of the waste.

Dairy & Beef: Milking-house waste and contaminated runoff must be stored as a liquid or slurry in a waste storage pond or structural tank. For beef cattle, manure can be stored as a bedded pack in the confinement area, if bedding is added in sufficient quantities. In areas of high rainfall, dry-stacking facilities should be roofed.

Pigs: Pig manure can be stored as a solid, a slurry or a liquid. If stored as a solid, it should be protected from precipitation. Above- or below-ground tanks or an earthen waste storage pond can be used to store slurries or liquid waste.

Poultry: Litter from broiler, turkey and laying-hen operations is stored on the floor of the housing facility. When it is removed, it can be transported directly to the field for land application. If the spreading is to be delayed for an extended period of time, the litter should be stored in a roofed facility. If it is wet, it should be stored in a structural tank or an earthen storage pond.

Transportation of waste

Transportation of waste involves the transfer of waste from the collection point to the storage facility and onwards to the treatment facility, and finally to the utilization site. Livestock waste may be transferred as a solid, a liquid or a slurry, depending on the total solids concentration or consistency of the waste.

Livestock waste from dairy, beef and pig units can be in liquid or slurry form and can be transferred through open channels or pipes, or in portable liquid tanks. Solid and semi-solid waste can be transferred by mechanical conveyers or by sweeping down curbed concrete alleys using hand-held equipment. Semi-solid waste can be transferred in large pipes by gravity, or using piston pumps where warranted.

For poultry, liquid waste can be transferred in pipes or tank wagons, while dried litter can be scraped, loaded and hauled as a solid, using wheelbarrows, animal-drawn carts, trailers, etc. If the poultry houses are a long way from the fields where the litter is to be applied, it may be transported in a truck.

Waste treatment

Treatment is any function designed to reduce the pollution potential of the waste, including physical, biological and chemical treatment. Designing a waste treatment plant involves:

- an analysis of the characteristics of the waste before treatment;
- determination of the desired characteristics of the waste following treatment;
- selection of the type, estimated size, location and installation cost of the treatment facility;
- determination of the management cost of the treatment process.

Dried livestock manure may also be composted. Composting stabilizes the manure into a relatively odourless mass that is easier to market, and also helps to kill disease organisms, so that the manure can be reused as bedding or supplemental feed to livestock. Dead livestock, such as pigs and poultry, may also be composted.

Both livestock and municipal waste are usually treated in their liquid form using lagoons (anaerobic and aerobic). An anaerobic lagoon is commonly used for treating liquid livestock waste. For pigs, an aerobic lagoon or oxidation ditch, where methane gas would be produced, may also be used. Methane may then be harvested and used for household cooking.

Lagoons

Lagoons are earthen basins or ponds constructed for the biological treatment and long-term storage of livestock waste. The waste in the lagoon is diluted with water from rainfall, building wash water, or wastewater from livestock drinking systems. While in the lagoon, the manure is stabilized by bacterial action before eventually being applied on the land as fertilizer.

The waste-stabilizing bacteria involved are: (i) anaerobic bacteria (inhibited by oxygen); (ii) aerobic bacteria (requiring oxygen), or (iii) facultative bacteria (maintained with or without oxygen). Anaerobic lagoons are much smaller than aerobic ones, and decompose more organic matter per unit volume than aerobic lagoons. Therefore, most livestock facilities use anaerobic lagoons to treat livestock waste.

Anaerobic lagoon

The surface area of an anaerobic lagoon should be small, and it should be as deep as possible to promote anaerobic conditions and decrease the land area required. An anaerobic lagoon is loaded in such a way that surface re-aeration and photosynthetic activity cannot maintain aerobic conditions. The rate of accumulation of the solids depends on the solids loading rate, the characteristics of the raw waste and the rate of solids stabilization. The biodegradable fraction of the solids undergoes anaerobic decomposition. Considerabe quantities of gas may be generated, with a resultant decrease in the biological oxygen demand (BOD) and chemical oxygen demand (COD) of the lagoon contents.

TABLE 19.12
Advantages and disadvantages of anaerobic lagoons

Advantages	Disadvantages
• Manure can be handled with water-flushing systems, sewer lines, pumps and irrigation equipment. • The high degree of stabilization reduces odours during land application. • High nitrogen reduction minimizes the land area required for liquid effluent disposal. • Long-term storage is provided at low cost.	• Public perception that a lagoon is an open container of manure. • Offensive odours if improperly designed and maintained. • Limited nitrogen availability if manure is used as a fertilizer.

Anaerobic lagoon design

The design of anaerobic lagoons involves sizing the lagoon to ensure that sufficient volume is available for the treatment and storage of manure or effluent before pumping out. Usually, the storage period is one year (365 days).

The total volume of the lagoon is determined by the sum of the:

- minimum design volume;
- manure storage volume between periods of disposal;
- dilution volume (not less than 50 percent of the minimum design volume);
- sludge accumulation volume between periods of sludge removal.

Figure 19.34 and Figure 19.35 give illustrations of these volumes for both single-stage systems (using only one cell for waste treatment) and multi-stage systems (using two or more cells connected together for waste treatment). In multi-stage lagoons, the effluent produced in the first cell is transferred to the secondary cells, where further biological treatment occurs, resulting in effluent with far less odour than in the preceding cells.

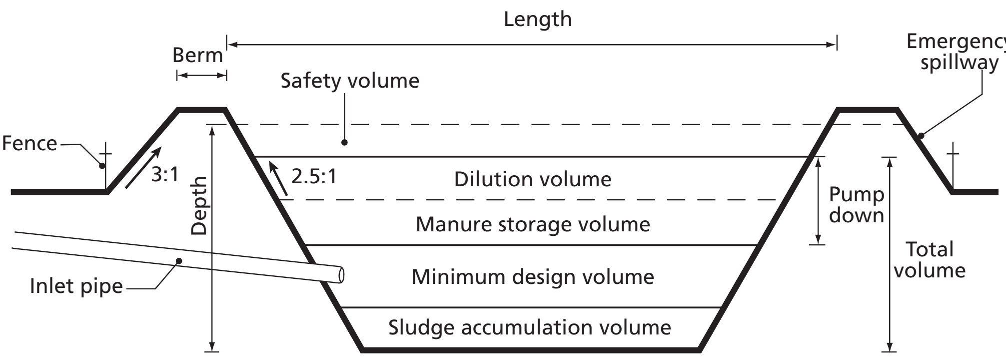

Figure 19.34 **Schematic of a single-stage anaerobic lagoon**

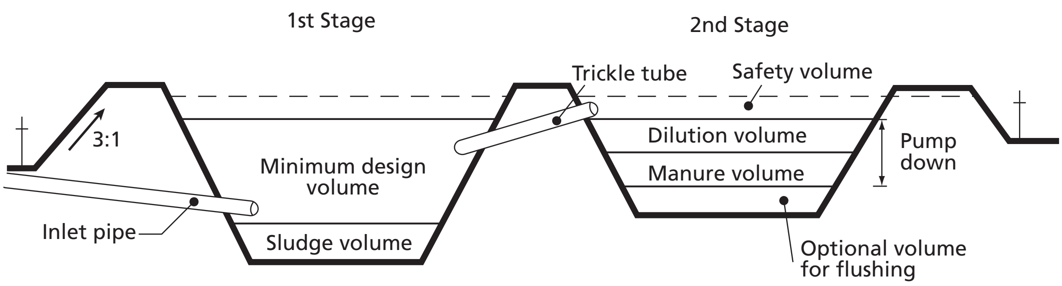

Figure 19.35 **Schematic of a two-stage anaerobic lagoon**

Minimum design volume: This is the volume required to ensure sufficient bacterial degradation of volatile solids. The liquid level should never drop below the minimum design volume, otherwise decomposition will be incomplete and odour problems may occur. The minimum design volume is determined from the maximum loading rate of volatile solids (set by the local authorities) and the production of volatile solids on the farm.

Manure storage volume: This is the amount of manure the lagoon will receive during the projected storage period. If solids are partially removed from the liquid manure before it enters the lagoon, the total lagoon design volume can be reduced by up to 25 percent. Solids can be removed from the manure by a settling tank or a mechanical separator, and then applied to the land or composted before land application.

Dilution volume: This includes all extra water, such as building wash water, spillage from animal watering systems, feedlot runoff or direct precipitation. Usually, it should not be less than 50 percent of the minimum design volume.

Sludge accumulation volume: This accounts for the manure solids that cannot be liquefied by bacteria and gradually accumulate at the bottom of the lagoon as sludge. Fractions of total solids that are assumed to stay as sludge are 50 percent volatile solids plus all the fixed solids. To maintain the minimum design volume for manure treatment, the volume of sludge accumulation over the time between sludge removals must be considered.

When a lagoon is located below the source of liquid manure, it is possible to drain the manure into the lagoon by gravity, using PVC pipes 15–25 cm in diameter with clean-outs and rigid joints. The inlet to the lagoon can be either above or below the liquid surface in the lagoon. The inlet should project at least 600 cm into the lagoon, should be supported every 240 cm, and should discharge into at least 90–150 cm depth of liquid. The last section of pipe, which extends below the liquid surface, should be laid with a slope of 1:48. Figure 19.36 and Figure 19.37 show the above- and below-surface lagoon inlets.

In a multi-stage lagoon system, an overflow pipe transports the supernatant liquid from one cell to the next. The typical pipe is a 15 cm diameter pipe (trickle tube) through the first cell's berm, tilted 30 cm on an uphill slope (Figure 19.38). The pipe should be as far as possible from the main inlet, to ensure that no untreated raw manure is transported.

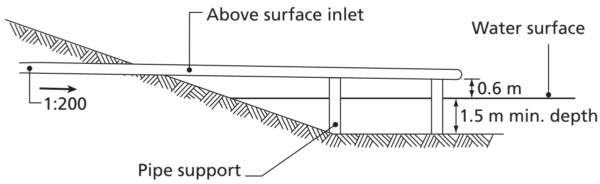

Figure 19.36 **An above-surface lagoon inlet**

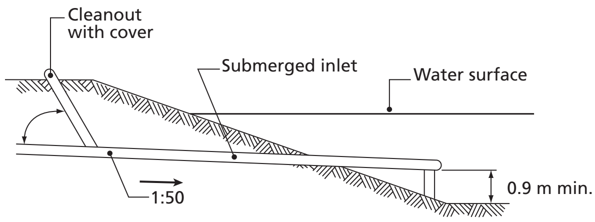

Figure 19.37 **A below-surface lagoon inlet**

Designing an earth embankment

The top width of the berm (Figure 19.39) around the lagoon should be at least 240 cm. When building the berm, allow an extra 10 percent height for settling. If possible, the berm should be capped with topsoil and seeded with grass. The outside slope of the lagoon berm should have a minimum slope of 3:1 (the horizontal run as a ratio of the vertical rise). The slope should be 5:1 if the area is to be mowed by tractor.

Lagoon sealing

The main reason for sealing the lagoon is to prevent seepage, which can pollute underground water and affect treatment performance by causing fluctuations in the water depth. Sealing methods can be grouped into three categories:

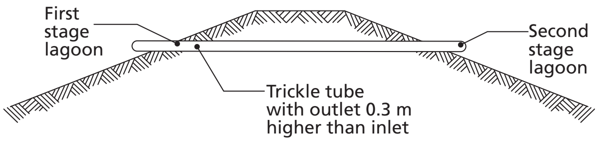

Figure 19.38 **Suggested overflow of a two-stage lagoon**

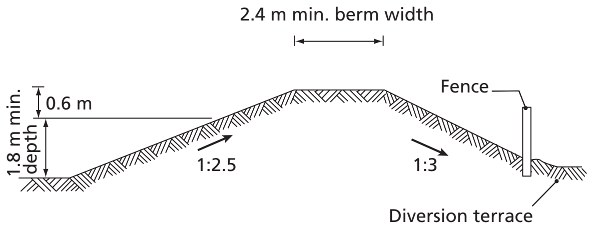

Figure 19.39 **Suggested design of a lagoon berm**

- synthetic and rubber liners;
- compacted earth or soil cement liners;
- natural and chemical treatment liners.

Choosing the appropriate lining for a specific site is a critical factor in lagoon design and seepage control. Seepage rates range from 0.003 cm/day for synthetic membranes to approximately 10 cm/day for soil cement liners. Detailed information about liners is available from manufacturers.

Locating the lagoon

The following factors should be considered when selecting the site for a lagoon:

- It should be located at a safe distance from residential areas, as the odours generated can be a nuisance.
- The site should be at least 120 metres from water wells or watercourses.
- Lagoons should be hidden from public view by landscaping or buildings because sight and smell are intimately interlinked in public perceptions.
- Lagoons should be built on low-permeability soils to minimize the seepage of effluent that could contaminate underground water. If necessary, plastic liners or a layer of compacted clay may be used to seal the lagoons.

REVIEW QUESTIONS

1. Outline six sources of water in a rural setting.
2. What are the likely contiminants of water sources in a rural setting?
3. Describe four methods you would use to determine the optimum size of a water storage tank for rainwater harvesting.
4. Outline four methods of treating water that you would use in a rural setting.
5. Briefly describe two types of well casing.
6. Name and describe two types of handpump and two types of power driven pump.
7. Describe the merits and demerits of using the earth (ground) as a water storage medium.
8. Briefly describe two types of pit latrines that may be used in a rural setting.
9. Discuss the required conditions necessary for composting process to take place effectively.
10. Consider a livestock production facility near you, gather the necessary information, and design a single stage lagoon for it.
11. Discuss the various animal waste utilization means around your area.
12. Discuss and critique the existing animal waste management strategy of a particular livestock operation near you. Formulate an improved waste management plan for the operation.
13. Outline and discuss the major waste sources in your locality and how such waste is handled to reduce its pollution effects.

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Chapter 20
Rural energy

INTRODUCTION

Rural development and transformation can only take place if there is an adequate supply of energy for crop and animal production, processing of agricultural produce, transport, education and domestic use, among other things. For expanded modern production, reliable and adequate sources of energy need to be developed.

Energy is the capacity to perform work. Energy comes in different forms or types. The energy forms are equivalent – any form of energy can be transformed to another form without changes in magnitude, i.e. energy is neither created nor destroyed. This ability of energy to transform from one form to another defines the basis on which we interact with energy in our daily activities.

Energy is a scalar physical quantity conventionally measured in joules (J). One kilojoule (1 000 J) is the amount of energy required to raise the temperature of one litre of water by ¼ °C. The rate at which a process uses energy defines its power rating. Power is the rate of doing work (i.e. the rate at which energy in one form is transformed to another form) and is measured in watts (W/s).

Energy can be categorized into two main groups, i.e. kinetic energy and potential energy. Kinetic energy is energy in motion and includes: electrical, gravitational, spring, magnetic, mechanical, light and heat energies. Potential energy is stored energy and includes forms such as nuclear energy and chemical energies.

Energy is an important ingredient in the life of a human being. Apart from the human body needing energy in various forms around the clock, civilization is defined by how much we are able to convert the energy from one form to another to suit our needs. Thus we have improvised ways to produce energy in forms that suit our needs.

Trends in our world have shown that there is a strong correlation between the per capita energy consumption and level of development in a country. For example, countries that have high electrical energy consumption per capita are generally more developed than countries with low per capita consumption. It is therefore important in the development and design of rural structures that energy requirements be taken into consideration.

ENERGY SOURCES

In order to generate energy, sources must be identified from which it can be produced efficiently. There are several natural sources that can provide energy in various forms of which some have been used extensively while others are used as alternatives.

Chemical form of energy has been obtained extensively from wood, coal, natural gas and hydrogen. These sources are extensively used in the production of heat energy for everyday use or for transformation into the electrical form of energy.

Gravitational form of energy has been harnessed from waterfalls (hydropower). This has seen the development of huge hydropower plants. The current technology has even enabled development of microplants.

Heat form of energy has been sourced from geothermal plants and burning of fuels. Kinetic form of energy in contrast to chemical form of energy cannot be stored and must be used immediately or be transformed into a form suitable for storage. The sources of this energy to humankind are wind and ocean waves. Nuclear energy is sourced from fission of uranium. The light form of energy has been sourced from solar, which is actually the mother of all forms of energy.

The energy resources are usually categorized as renewable and non-renewable. Renewable energy resources are those that can be replenished quickly, e.g. solar power, biomass, geothermal, hydroelectric, wind power and fast-reaction nuclear power. Non-renewable energy resources include fossil fuels and uranium, which are used to fuel slow-reaction nuclear power. Projections of how long a non-renewable energy resource will last depend on many changeable factors. The availability of non-renewable energy will depend on the growth rate of consumption and economic recovery of remaining resources.

Fossil energy resources are currently the most affordable and easier to store and transport than renewable sources. For renewable energy sources to become more widely used, many difficulties will have to be overcome, mostly relating to economic production and distribution. However, it should be noted that renewable choices may just be the best choice in some situations, especially in rural settings.

Rural energy choices

The sustainability of any particular energy resource is an important consideration in determining where to invest in energy technology and infrastructure. All energy resources, whether renewable or non-renewable, must be used efficiently and sustainably in order to safeguard the future use.

In a rural setting, the best energy sources will depend on answering a variety of questions including: What is to be the intended use of the energy, how it is to be used, where it is being used and what energy sources are available. One should also consider the convenience of use and reliability of the source, costs, safety, health and the environment.

For sustainable development the energy resource used should be:

- Appropriate for local needs and resources.
- Cost-effective.
- As far as possible, generate income in the rural setting.
- Minimize negative impact on the productive capacity of the land.
- Must take into account the fact that in future there will be need for expansion and therefore emission standards must be adhered to and thus need to consider the environmental impact of the choice.
- Must provide a secure supply of energy that will not be interrupted by international crisis.

Rural energy supply routes

There are several mature energy supply routes that can be adopted for use in a rural setting. Deciding on a given route requires an understanding of resources at one's disposal and their relative costs and benefits. Technologies that have been found appropriate for rural areas include the electricity supply via the national grid, electricity generation via diesel generators, biomass energy, solar energy, biogas, and small and minihydro and hybrid systems.

BIOMASS ENERGY

Biomass refers to all organic matter produced by plants through the process of photosynthesis. Biomass is available everywhere. Biomass provides food, construction materials, fibers and energy. To provide energy, biomass is burned or fermented in order to make use of the chemical energy stored within it. Biomass is basically solar energy stored in chemical bonds of organic matter. It is therefore an inexhaustible fuel source if harnessed properly.

During combustion, oxygen from the atmosphere combines with the carbon in biomass to produce CO_2 and water that may be allowed to escape to the atmosphere to start a new cycle. Use of biomass as a source of energy is therefore a friendly way of managing municipal, agricultural and industrial waste.

The amount of heat produced in the combustion is directly propositional to moisture content of the biomass used. Moisture content also influences thermo chemical processes. The energy content, lower calorific value (LCV), of nearly all kinds of anhydrous biomass feed stocks when combusted fall in the range 15–19 MJ/kg. The values for most woody materials are 18–19 MJ/kg, while for most agricultural residues, the heating values are in the region of 15–17 MJ/kg.

Conversion process

There are four basic technologies that are used to convert biomass into energy: direct combustion, thermo-chemical conversion processes, physicochemical and biochemical processes.

Biomass is used directly in combustion as in wood stoves and furnaces. The heat produced in this process can be used for cooking, space heating or production of electricity, which may be centralized or decentralized. Through thermochemical processes (pyrolysis and gasification), biomass can be processed into intermediate products, such as charcoal and producer gas, before final use. Physicochemical processes as used in production of vegetable oil and its eventual conversion to biodiesel, which can then be used for generation of electricity or as source of energy for transport vehicles. Biochemical conversion involves use of micro-organisms. For example, enzymes of bacteria are used in production of biogas discussed in the section, "biogas".

In rural areas of the tropics, biomass still remains the dominant source of energy. Most used sources of biomass include wood fuel, charcoal, crop residue, vegetable oil and animal waste. These are used to provide energy for cooking meals, firing kilns, lighting (as in oil lamps) and electricity cogeneration in rural-based agricultural factories.

Major advantage of biomass in comparison to solar or wind energy as a renewable source of energy is that the stored bioenergy can be used on demand. Therefore, it can be used to smoothen the fluctuation in their supplies.

However, unsustainable use of biomass can lead to environmental degradation. Also, cost of technical use of biomass is higher than that of fossil fuels. The low concentration of energy in biomass is a disadvantage when compared to fossil fuels because these are easily transported and stored given that they occupy less space. However, burning of biomass results in lesser emissions of pollutants, such as sulfur, nitrogen oxides, and carbon dioxide, to the surroundings.

ELECTRICITY

Electrical form of energy is currently the most important form of energy. Electrical energy is not found alone as a source of energy in nature. Electricity, therefore, must be produced from some other energy source, e.g. petroleum. Electricity is used extensively all over the world because it is easy to transport over wires from where it is produced to destination of use including industries, farms and homes. However, electricity must be used as soon as it has been produced because it is kinetic energy and thus cannot be stored.

Generation of electrical energy is a big industry all over the world. Electricity has been conventionally generated from sources such as hydropower, heat, geothermal and nuclear. The generation in this case involves building of huge power plants. The generated electricity from these sources is fed into the national grid.

Mechanization of agriculture demands that high density energy sources such as electrical energy be used. This is necessitated by the fact that most of production structures, machines and appliances can efficiently be run with electricity. Therefore, availability of electrical energy supply in a rural setting promotes agricultural mechanization.

For energy audit purposes a basic understanding of units of measurement of electricity might be necessary. The most important electrical energy parameters that should be understood by the user include: voltage, current and resistance.

Voltage (measured in volts) is the rate at which energy is drawn from a source of electricity. The movement of energy produces a flow of electricity in a circuit. Current (measured in amperes) is the flow of electricity through an electrical circuit. This flow is dependent on the supply voltage and the load connected to it; the bigger the load the lower the current. Resistance (measured in ohms) is a measure of the load in the electrical circuit. A material that is a good conductor of electricity offers low resistance to the electrical current flow, whereas that which is a poor conductor hinders flow of the current.

The mathematical relationships between these three parameters are given as: Current = Voltage/Resistance; Voltage = Current × Resistance; and Resistance = Voltage/Current. The electrical power is expressed as: Power (watts) = Voltage (volts) × Current (amperes). When one kilowatt flows for an hour, one kilowatt-hour (kWh) of energy is transferred. Power usage is commonly billed in kWh.

Rural electrification

Most rural areas are off the national grid. Therefore, governments all over the world, especially in developing countries put up policies to facilitate rural electrification, while ensuring that this supply is of high quality, affordable and sustainable.

To supply electricity to the rural settings off-grid, the technology that has been used most is the use of isolated diesel power stations. However, current trend has seen adaptation of renewable energy technologies because of their suitability and environmental friendliness.

Decentralized rural electrification involves installation of standalone systems, e.g. photovoltaic (PV), wind and biogas or minigrids that use mixed sources e.g. renewable/diesel ministations. The advantage of such systems are that they allow for optimal of use of natural resources. They reduce energy distribution losses as energy is supplied directly. Also standardization and modularization of the technology has provided high degree of flexibility. It is thus easy to install, maintain and scale up the systems without advanced training.

On grid electricity

The electricity can be sourced from the national grid, where this is available. The grid is usually extended to the rural areas through rural electrification programs. Depending on the needs of the customers, electricity is usually delivered to the farmsteads by single phase or three phase secondary distributions.

During the design and construction phase of a rural structure, it is important that such structures be made electricity ready. This usually involves electrical wiring of the premises with the help of a licensed electrician, as is usually demanded by the utility supplier.

The factors taken into consideration during the construction of rural structures that may require on-grid electricity are discussed in Chapter 8. Figure 8.85 shows a typical electrical distribution system.

Electricity from diesel generators

A diesel generator is a combination of a diesel engine and an alternator used to produce electrical energy. They can be used in areas far from grid or as a back-up to grid supply in the event that power fails. As a backup to grid supply, the system is usually fitted with automatic changeover switches.

A generator must be capable of delivering the power required for the hours per year anticipated by the user to allow reliable operation and prevent damage. The manufactures must give a generator a rating based on internationally agreed definitions. These standard rating definitions are designed to allow correct machine selection and valid comparisons between manufacturers to prevent them from misinforming the customers about the performance of their machines, and to guide designers.

Though the ratings are an important factor on whether a particular generator size is good for a particular use, choice is usually based on the maximum load that has to be connected and the acceptable maximum voltage drop. If the generator is required to start motors, then it will have to be at least three times the largest motor, which is normally started first. This means that it will be unlikely to operate at anywhere near its ratings.

Generators must be installed correctly to ensure that they function correctly and reliably and at low maintenance costs. Usually, the manufacturers will provide detailed installation guidelines covering important factors such as: sizing and selection, electrical factors, cooling, ventilation, fuel storage, noise, exhaust and starting systems.

Advantage of diesel generators is that they can be improvised to use other sources of fuels such as biodiesel and biogas. This promotes a combination of different but complementary energy systems. Some disadvantages of diesel generators include: high operation and maintenance costs, the geographical difficulties of delivering the fuel to rural areas and environmental pollution.

FOSSIL FUELS

Fossil fuels are formed by natural resources, such as anaerobic decomposition of buried dead organisms.

Fossil fuels include peat, lignite, coal, petroleum, shale oil and natural gas. Fossil fuels are non-renewable resources because they take millions of years to form.

The fossil fuels burn to release energy. This energy can then be converted to mechanical-kinetic-thermal energy in many systems, such as steam plants, internal combustion engines, gas turbines and rockets. The heat energy produced can also be used directly.

Compared to competing energy sources, such as solar energy and wind energy, energy from fossil fuels is currently still cheaper. However, because of non-renewability of the fossil fuels, prices are expected to rise in the future as supplies diminish. Also, the renewable energy processing technologies will improve. This is expected to lead to increased use of alternative energy sources.

Fossil fuels are currently very important in agricultural production. Almost all field machineries are powered by petroleum products such as diesel and petrol. Petroleum products such as kerosene and natural gas, are also used intensively in lighting and cooking.

The disadvantages of the use of fossil fuel include:

- Probable contributor to global warming through greenhouse gas emissions
- Pollutes air through emission of nitrogen oxides, sulfur dioxide, volatile organic compounds and heavy metals
- Cause of acid rain because emission of sulfuric, carbonic and nitric acids
- Offshore oil drilling poses danger to aquatic life
- Oil refineries pollute air and water
- Fossil fuels prices are influenced by world politics of oil regions

HYDROELECTRIC POWER

In the generation of hydroelectric power, a weir creates a potential difference (head) between the water before and after the weir. This potential difference can be utilized by a power plant. The water flows through a turbine, which transforms the potential energy into mechanical energy. An electric generator converts this into electricity. A transformer converts the generator voltage to the grid voltage. The power output, P, is expressed as:

$$P = \eta_G \, \eta_T \, \rho_w \, gHQ$$

where η_G is the efficiency of the generator, η_T the efficiency of the turbine, ρ_w the density of the water (kg/m^3), g the gravitation constant (m/s^2), H the head (m) and Q is the flow rate (m^3/s).

Small hydro and micro hydropower

In mountainous areas where there are many rivers and streams, the power of flowing water can be harnessed and used to generate electricity. The hydropower from this source can be particularly beneficial in rural areas, where electricity from other sources may be unavailable or very expensive.

Small hydro is the development of hydroelectric power on a scale serving a small community or industrial plant. Small hydro has a generation capacity of up to 10 MW. Small hydro can be further subdivided into mini hydro, usually defined as less than 1 000 kW, and micro hydro, which is less than 100 kW.

Small hydroplants may be connected to conventional electrical distribution networks as a source of low-cost renewable energy. Alternatively, small hydroprojects may be built in isolated areas that would be uneconomic to serve from a network, or in areas where there is no national electricity distribution network. As small hydroprojects usually have minimal reservoirs and involve negligible civil construction work, they are regarded as having a relatively low negative environmental impact compared with large hydro projects.

Micro hydro systems consisting of a propeller turbine, a generator, wires and switches can be built in mountain streams or rivers and used to generate electricity for individual households. Such very small-scale systems could supply power to remote mountain communities more cheaply and reliably than either diesel generators or high-voltage grids. In addition to using hydroelectricity in their homes, people living in remote rural communities can use it to power a wide range of small-scale agricultural and industrial activities, from which they can derive income.

The advantage of hydropower is that it is an inexhaustible energy source that has minimal environmental impact and can be used for electricity supply throughout the world. The disadvantages are that microscale types depend on availability of fast flowing streams or rivers that may not be available everywhere and that hydroelectric power may interfere with mobility of fish and impact negatively on the plants.

COGENERATION FROM AGRICULTURAL INDUSTRY

Cogeneration is the simultaneous production of heat and electricity from one fuel source. Power plants and heat engines, in general, waste more than half the available energy that can be put into useful use. This helps in reducing the amount of fuel used resulting in less pollution.

Cogeneration can be employed in rurally set agricultural factories. For example, sugar factories do have excess biomass that can be used for this purpose. With adaptation of relevant technologies these factories can generate electricity for their use and the excess can be used to power surrounding villages and towns or sold to utility companies.

SOLAR ENERGY

The use of solar energy dates back to before recorded history and has been, and is being, used by all farmers in the production of their crops. Agriculture is essentially an energy conversion process in which solar energy is converted through photosynthesis into food for humans and feed for animals. Solar energy can also be captured and used for a variety of functions on the farm and in rural areas in general. The purpose of this section is to describe the nature of solar energy, and to relate it to some applications.

Solar flux

The energy reaching the earth from the sun is referred to as solar flux. The energy approaching the earth's atmosphere perpendicular to the surface is 1.27 kW/m². As it has to travel through the earth's atmosphere, only about l kW/m² reaches the earth under optimum conditions and, for practical purposes, a value of 0.9 kW/m² is often used for latitudes where the altitude (angle of the sun's rays to the earth) is close to 90 degrees.

Factors that affect the actual amount of energy available in a particular area include:

1. *Latitude and season*: As the axis of rotation of the earth is inclined 23.5°, the angle at which the sun strikes the earth is continually changing throughout the year. Between latitudes 23.5° north and 23.5° south, the sun will be perpendicular for two days each year and its noon altitude never drops below 43°. However, farther north or south, the sun never reaches 90° and, in winter, the angle may be very low (only 16.5° in winter at latitude 50° north or south).
2. *Weather:* The frequency of cloudy days is an important factor in the amount of radiation received over a period of time. Although the belts around the earth between latitudes 20° and 30°, north and south, receive nearly 90 percent of the total solar radiation, there are huge regional variations. Consequently, for design work it is imperative to have solar information for the local area, including seasonal variations.

Application of solar energy

Increasing the use of solar energy depends largely on the cost of alternative sources of energy and improved designs of solar energy equipment. Although solar energy is free, the equipment used to capture it is not. This means that applications that can be used throughout the year, and those that are simple enough to be low in cost, are likely to be the most practical.

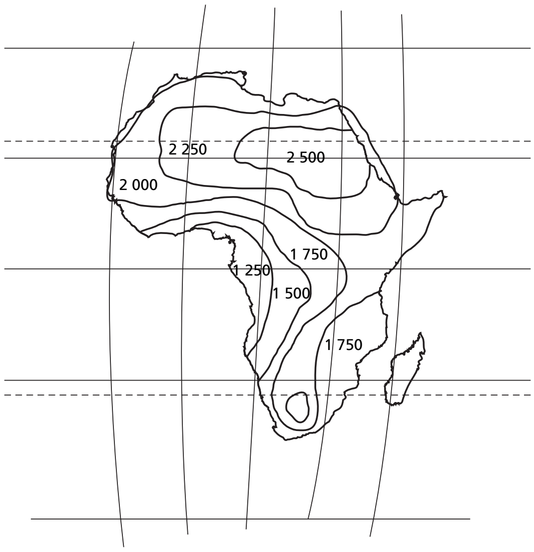

Figure 20.1 **Mean annual solar radiation on a horizontal surface kWh/m²**

Some possible applications in rural areas are:

1. Open-sided buildings facing north, to warm and dry the interior (most practical in latitudes south of 25° S).
2. Crop-drying in thin layers in the sun.
3. Food-drying in small solar dehydrators.
4. Water-heating (see Figure 20.4).
5. Solar cooking.
6. Forced-air drying of grain by blowing air through a long plastic duct before it enters the drying bin.
7. Electricity generation using photovoltaic plates.

TABLE 20.1
Mean daily solar radiation on a horizontal surface (kWh/m²)

Place	Latitude (°)	Elevation (m)	January	April	July	October	Annual
Kenya							
Kericho	0	2 070	6.14	5.16	4.95	5.19	5.46
Mombasa	4	55	6.53	6.66	4.45	6.28	5.84
Nairobi	1	1 890	6.34	5.31	3.72	5.47	5.24
Tanzania							
Arusha	3.5	700	7.24	5.74	4.81	6.49	6.04
Dar es Salaam	7	55	5.42	3.89	4.27	5.22	4.86
Mbeya	9	2 400	4.46	4.58	6.13	5.93	5.23
Zambia							
Bulawayo*	20	1 358	9.01	7.00	5.81	8.40	9.04

* Maximum daily values

Solar collectors

There are several types of solar collectors, including:

1. parabolic focusing collectors that concentrate the sun's energy for high-temperature applications;
2. parabolic cylinders for medium temperatures;
3. flat-plate collectors for relatively low-temperature applications. This type is the simplest and least expensive and has the most applications for rural areas.

A flat-plate collector can be as simple as a water tank painted black, or it can be considerably more complex, e.g. a collector surface painted black, with one or more transparent layers that allow the sun's rays to enter while reducing the reradiation of heat, all mounted in a sealed frame with insulation on the back (see Figure 20.2). In most cases, the heat collected is removed using either air or water. Which of these is used depends on the purpose of the collector; for drying products, air would be used; for heating water, water would be used.

Collector plates may be made of metal with water tubes bonded to the plate. Copper has high conductivity and is easily soldered to the plate. Aluminium also has good conductivity but is difficult to bond to the plate. Manufactured aluminium plates have the water lines pressed into the surface. Glass, glass-reinforced plastic and plastic films may be used to cover the collector.

Glass allows more than 90 percent of the solar energy to pass, fibreglass allows about 80 percent, if kept clean, and polythene film, around 90 percent. However, polythene loses a great deal of heat through reradiation. Glass has the longest life; fibreglass can be expected to last 10 years, and polythene only 1–2 years.

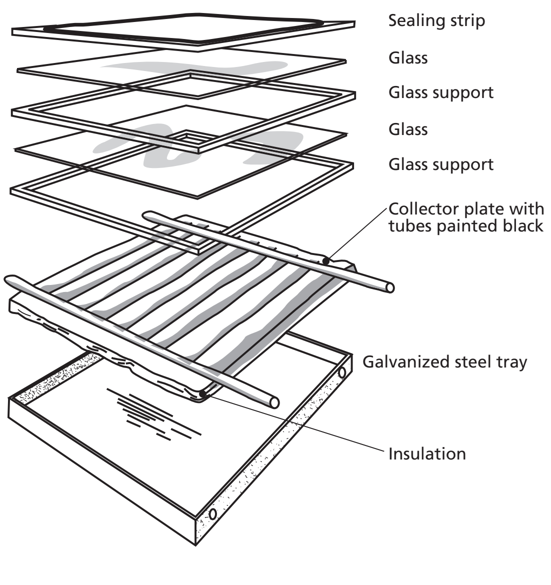

Figure 20.2 **Exploded view of typical flat-plate collector (by courtesy of Cooperative Extension Service, Cornell University)**

The efficiency of collectors varies greatly. The parabolic units mentioned earlier may reach an efficiency of 50–75 percent. Flat-plate units operate in the range of 25–50 percent, depending on the design and mounting position. Some simple designs may be even less efficient. In many cases, an inexpensive, simple design is the most practical. Low efficiency can often be offset by increasing the size of the collector. It is important to remember that no matter which type of collector is used or how efficient it is, it can never collect more energy than the product of the local flux rate and the collector area. In fact, it could be said that the size (area) of a collector is its most important characteristic.

Orientation of flat-plate collectors

Collectors of any type are more effective if they are moved continually to ensure that they remain perpendicular to the sun's rays. However, controls to accomplish this are expensive and impractical for rural operations. Instead, an effort is made to locate the collector in the best average position. This requires an understanding of two angles: azimuth and altitude (see Figure 20.3).

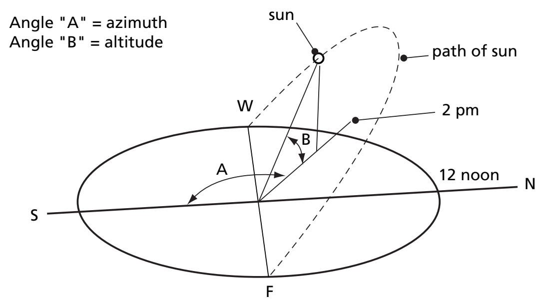

Figure 20.3 **Azimuth and altitude (southern hemisphere)**

The *azimuth* is the horizontal angle of the sun in relation to the true south meridian. It will be measured in an easterly direction in the morning and in a westerly direction in the afternoon. The *altitude* is the vertical angle the sun makes with the horizontal plane at the earth's surface. At the equator, the sun's altitude will be to the north from March to September, and to the south from September to March. Further south, the sun has a north altitude for an increasing length of time; until south of latitude 23.5° S the altitude is always to the north.

As the sun's altitude is so high in the low latitudes, it is fairly effective to place a collector horizontally. However, some angling of the collector will improve the average performance. The following angles from the horizontal are suggested:

Year-round operation:	the latitude angle
Summer operation only:	latitude minus 10°
Winter operation only:	latitude plus 10°

For example, a collector to be installed in Lusaka, latitude 15° S, for all-year use should be tipped 15° to the north and face within 10° east or west of north.

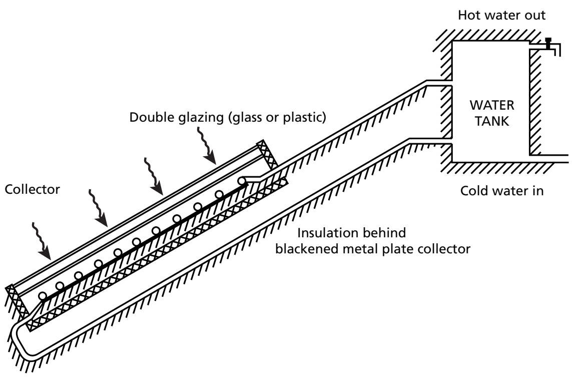

Figure 20.4 **Solar water heater**

Photovoltaic cells

A photovoltaic (PV) solar cell is an electronic device that converts sunlight directly into electricity at an atomic level. The concept used in the PV cell is the photoelectric effect shown by some materials that causes them to absorb photons of light and release electrons. These free electrons are captured to create electricity. A cross-section of a basic PV cell is shown in the Figure 20.5.

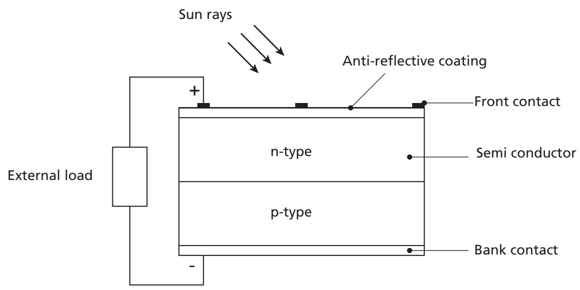

Figure 20.5 **A cross-section of a basic PV cell (solar cell)**

The semiconductor in a PV cell is usually made of silicon. A small amount of impurities, dopants, is introduced to the silicon to produce desired electrical properties. In a solar cell, phosphorus and boron dopants are used. The elements establish an N-type side and a P-type side.

The negative type side is doped with phosphorus. This results in the silicon having an excess of electrons. The positive type side is doped with boron, resulting in holes that carry a positive charge in the silicon. A junction is the result when N-type side and P-type side are combined to form an electric field. The junction creates a barrier, which only allows electrons to flow to the N-side.

When light energy strikes a PV cell in the form of photons, some of the photons are absorbed near the junction and in the process free the electrons and holes in the silicon and supply them with enough energy that enables them to cross the junction. The electrons can then be picked up on the metal contacts on the surface of the solar cell. This forms an electrical current, in an external circuit, which can be used to power an external load, e.g. a lamp.

The amount of current formed in a PV cell is dependent on the intensity of the light incident on the cell and the wavelength of the incident ray. A PV cell usually absorbs a combination of direct solar radiation and diffuse light bounced off the surrounding surfaces. To maximize amount of radiation absorbed, the solar cells are usually coated with anti-reflective material.

Individual PV cells produce low voltage. Therefore, the cells are usually electrically connected in series, parallel or series-parallel combinations to build up a PV system. Parallel connections are usually limited because the associated increase in the current results in higher transmission losses.

Solar cells connected in a series configuration form a module. Usually, modules are designed for operation with 12-V lead-acid rechargeable batteries where a series connection of 32–40 solar cells is optimal. Modules can then be electrically connected in parallel-series configurations to form arrays (see Figure 20.6). The cells or modules connected in series must have the same current rating to produce an additive voltage output. Similarly, modules must have the same voltage rating when connected in parallel to produce larger currents.

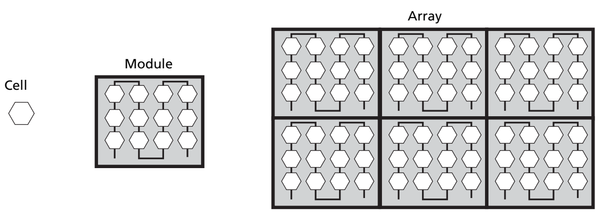

Figure 20.6 **Solar panel configurations**

PV systems have an important use in rural areas where they provide power for such applications as pumping water, lighting, vaccine refrigeration and electrified livestock fencing. They are also becoming increasingly important in rural areas for telecommunications – especially for charging mobile phones.

A basic PV installation consists of four main components: the *solar panel*, the *batteries*, the *regulator* and the *load* (see Figure 20.7). The panels are responsible for collecting the energy of the sun and for generating the electricity. The battery stores electrical energy for later use. The regulator ensures that the panel and battery are working together in an optimal fashion. The load refers to any device that requires electrical power, and is the sum of the consumption of all electrical equipment connected to the system.

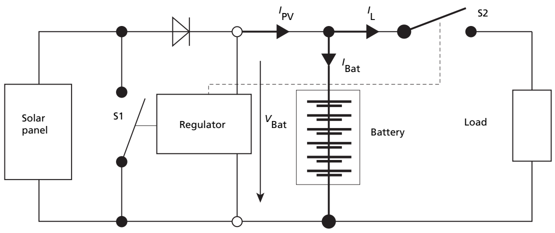

Figure 20.7 **PV battery system with parallel charge**

The electricity generated by the panel is direct current (DC) and may require a *DC/AC inverter* if some of the equipment contributing to the load requires alternating current (AC). Every electrical system should also incorporate various safety devices in case something goes wrong. These devices include proper wiring, circuit breakers, surge protectors, fuses, ground rods and lightning arresters. Figure 20.8 shows the schematics of a basic installation in a house.

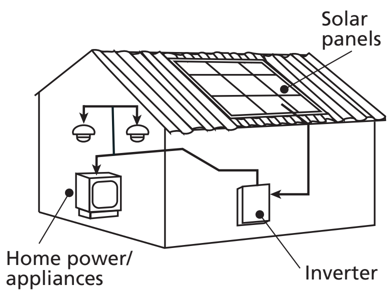

Figure 20.8 **Stand alone PV system**

Apart from the advantage of being a renewable source of energy, use of PV systems have other benefits. The fact that they are modular, allows them to be used at any scale, micro or large and the system easily can be expanded. Once installed, PV systems require minimal maintenance because there are no moving parts that wear off frequently. No fuel is required by this system, thus transportation costs are eliminated. The PV systems are also quiet during operations.

The major disadvantage of a PV system is the relatively high capital required to install the system, though this is fast coming down because of improvement in technologies and large-scale production of PV panels. Other disadvantages include the inefficient utilization of incident solar rays, the need to maintain a system of batteries and the intermittent supply because of the influence of cloudy conditions.

BIOGAS

Biogas is the gas produced through the biological breakdown of organic matter in the absence of oxygen. Biogas originates from biogenic material, and is a type of biofuel.

One type of biogas is produced by anaerobic digestion, or fermentation of biodegradable materials, such as biomass, manure, sewage, municipal waste, green waste and energy crops. This type of biogas comprises primarily methane and carbon dioxide. The other principal type of biogas is wood gas created by the gasification of wood or other biomass. This type of biogas comprises primarily nitrogen, hydrogen and carbon monoxide, with trace amounts of methane.

The gases methane, hydrogen and carbon monoxide can be combusted or oxidized with oxygen. Air contains 21 percent oxygen. This energy release allows biogas to be used as a fuel. Biogas can be used as a low-cost fuel in rural setting for any heating purpose, including cooking. It can also be used in modern waste-management facilities, where it can be used to run any type of heat engine and to generate either mechanical or electrical power. As biogas is a renewable fuel, it qualifies for renewable energy subsidies in some parts of the world.

Biogas is used in several countries around the world on a small or large scale. In countries such as China and India, waste from factories is used to generate biogas. Apart from the disadvantage that the initial cost of a biogas plant is high, the use of biogas has several advantages, including:

1. Use in place of fuelwood to reduce deforestation.
2. Utilization for lighting.
3. If produced in large quantities, it can be used to drive engines.
4. It provides a cheap way of managing waste.
5. Digested slurry is a high-quality fertilizer.

At the very basic level of production, biogas generation involves slurrying together the waste stream in a homestead and allowing it to ferment to produce methane gas. After the gas has been completely extracted, the remainder can be used as fertilizer. On an industrial scale, apart from employing the natural fermentation method, biogas can be produced using advanced waste processing systems, such as mechanical biological treatment.

Designing a small-scale biogas system is not complicated and can easily be implemented at rural level. For large-scale production involving the use of huge amounts of waste from factories and sewerage systems, more expertise is required.

Biogas digesters

Biogas systems recover the recyclable elements of household waste and process the biodegradable fraction in anaerobic digesters. There are three digester designs in common use: Chinese, Indian and Sri Lankan digesters.

The Indian biogas digester has an expandable gas cylinder or dome. As shown in Figure 20.9, the waste is collected and fed into the digester from drains on either side. The digester walls are constructed using bricks and cement. The cylindrical dome is made of sheet metal and moves freely up and down as biogas is produced and drawn from it for use.

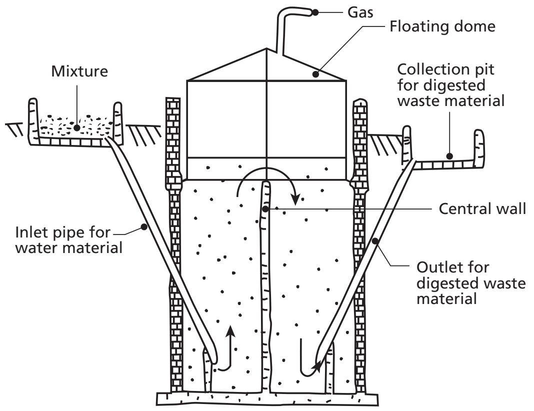

Figure 20.9 **Indian biogas digester** (adapted from Munasinghe, 2007)

In the Chinese design, the biodigester and the composter are a single permanent structure constructed using cement and bricks (see Figure 20.10). The biogas is collected in the upper chamber and the waste decomposes in the lower chamber. It has some similarities with the Indian digester in that it has two drains to feed in waste and to collect the composted waste.

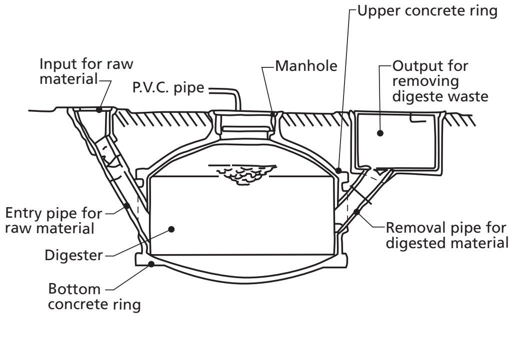

Figure 20.10 **Chinese biogas digester** (adapted from Munasinghe, 2007)

In the Sri Lankan design, the cylinder is constructed using brick and cement, while the chambers used to collect the biogas are made of low-cost 45-gallon barrels, which can be bought from a normal market. These barrels are kept separately and connected with air pipes. The raw material is added and waste is collected by removing the cap on the top (see Figure 20.11).

One of the special advantages of the Sri Lankan biodigester is that there is no need to add the raw material daily, as it can use straw, hay and other agricultural wastes. Therefore, when filled, biogas can be obtained for about 5–6 months.

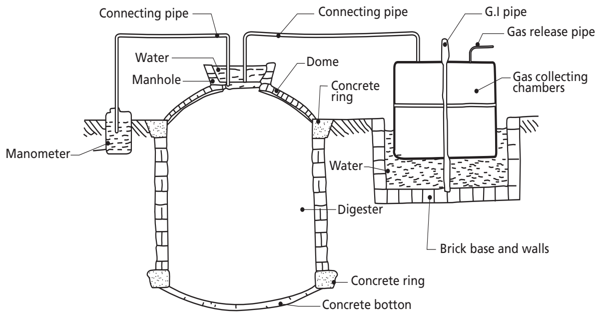

Figure 20.11 **Sri Lankan digester** (adapted from Munasinghe, 2007)

In both the Indian and Chinese digesters, the waste needs to be fed in daily and therefore the best option is to connect the digester to the cattle shed or pigsty. In both cases, toilets that are used on a daily basis can also be used to produce biogas. This gives additional sanitation advantages.

Table 20.2 provides information concerning the amount of waste required and the output.

TABLE 20.2
Amount of waste needed and output

The capacity of a digester (square metre)	Raw material (cow dung) kg (per day)	For cooking (number of people)	The number of lamps that can be supported
1	25	3–4	2
2	50	4–7	3
3	75	7–10	6
4	100	10–12	8

Source: Munasinghe, 2007.

The use of biogas systems will require thorough feasibility study of a given setting. As it is a chemical process, maintaining optimal production could be a hard task to the rural dweller. It should also be noted that already fabricated digesters are available in the market. Because these are optimally designed by experts, who are also ready to install them, buying a prefabricated system may be a quicker and sustainable solution.

WIND POWER

Wind is air moving from an area of high pressure to an area of low pressure. These pressure differences are as a result of solar radiation on the surface of earth. Moving wind contains energy in the form of kinetic energy. Wind therefore, is an indirect form of solar energy. While the maximum solar irradiance is about 1 kW/m^2, wind can have high power density. For example, a violent storm has energy content as high as 10 kW/m^2. Hurricanes go as high as 25 kW/m^2, while a gentle breeze of 5 m/s has a power density of only 0.075 kW/m^2.

Rural dwellers in the tropical climates have benefited from wind energy for centuries using it mostly in grain cleaning. However, current technology allows more to be done with the wind. Wind power derived from wind energy can be converted into a usable form of energy, such as electricity, using wind turbines.

At the end of 2010, the worldwide capacity of wind-powered generators was 194.4 gigawatts (GW). Globally, the long-term technical potential of wind energy is believed to be five times total current global energy production, or 40 times current electricity demand. This would require large amounts of land to be used for wind turbines, particularly in areas with the best wind resources.

Wind energy, as a power source, is attractive as an alternative to fossil fuels, because it is plentiful, renewable, widely distributed, clean and produces no greenhouse gas emissions. However, wind power is non-dispatchable, therefore, for economic operation all of the available output must be used as and when it is available – otherwise battery storage systems have to be used to store it.

Power content of wind

Moving air molecules have mass and speed and therefore have kinetic energy. This energy can be extracted by the blades or rotor of a wind turbine. The power content of wind, P_w (W) that the wind contains is calculated by differentiating its kinetic energy content with respect to time and thus can be expressed by:

$$P_w = \frac{1}{2}\dot{m}v^2 \qquad (20.1)$$

where $\dot{m}$ is the mass flow rate of air in kg/s and v is the speed of the wind in m/s. The mass flow rate is mathematically given by:

$$\dot{m} = \rho A v \qquad (20.2)$$

where ρ is the density of air in kg/m^{3}and A is the cross section area in m^2. The density of air, ρ, varies with the air pressure and temperature. It changes proportionally to the air pressure at constant temperature. For example at 100 kPa, -10 °C, the density of air is 1.324 kg/m^3 while at 100 kPa, 30 °C the density is 1.149 kg/m^3.

If the elevation, z and temperature, T of a site is known then the density of air can be calculated by

$$\rho = \frac{353.049}{T}\exp\left(-0.034\frac{z}{T}\right) \qquad (20.3)$$

From equation 20.3 it can be seen that the density of air decreases with increase in elevation and temperature of a site. For most practical applications, air density is taken as 1.225 kg/m^3.

Substituting for $\dot{m}$ into equ. 20.1, the total wind power is given by:

$$P_w = \frac{1}{2}\rho A v^3 \qquad (20.4)$$

From equ. 20.4, it is seen that for a given cross-sectional area, A, the wind power depends on air density and cubic power of the wind speed.

Wind turbine power

To effectively use wind power, a wind turbine should take as much power from the wind as possible. The ratio of the power used by the turbine P_T to the power content P_w of the wind is called the power coefficient.

The maximum power coefficient attainable is referred to as the Betz power coefficient ($C_{p,\ betz}$) and is about 0.593. Real wind turbines do not reach this theoretical optimum; however, good systems have power coefficients between 0.4 and 0.5. The ratio of the used power P_T of the turbine to the ideal usable power P_{ideal} defines the efficiency, η, for the power utilization of the wind:

$$\eta = \frac{P_T}{P_{ideal}} = \frac{P_T}{P_w c_{p,Betz}} = \frac{P_T}{\frac{1}{2}\rho A v^3 c_{p,Betz}} = \frac{c_p}{c_{p,Betz}} \qquad (20.5)$$

For sizing purposes, an overall efficiency, η_T, is used to calculate power generated by a particular wind turbine of a given cross-sectional area, A_T and wind velocity V.

$$P_T = \frac{1}{2}\eta_T \rho A_T v^3 \qquad (20.6)$$

Analysis of wind regime

Because the cubic relationship between air velocity and its power content, even a small variation in wind speed may result in significant change in the amount of power produced. For example, an increase of wind speed by 5 percent will enhance the productivity of the turbine by 15.7 percent. Therefore it is important that the site with appropriate wind regime be chosen.

This can only be achieved by thorough analysis of wind regime in an area.

Wind measurement

Wind direction is reported by the direction from which it originates. For example, a northerly wind blows from the north to the south. Weather vanes pivot to indicate the direction of the wind. Wind speed is measured by anemometers, most commonly using rotating cups or propellers. When a high measurement frequency is needed (such as in research applications), wind can be measured by the propagation speed of ultrasound signals or by the effect of ventilation on the resistance of a heated wire. Sustained wind speeds are reported globally at a 10 metres height and are averaged over a 10 minute time frame. Where measurements are not immediate, the *Beaufort scale* (Table 8.1) is often applied to give the wind force. This scale allows an approximate estimation of wind speed without complicated measurement systems.

Wind speed and height

Wind flow above the ground is slowed by frictional resistance offered by the earth surface. The resistance to flow is caused by the ground itself, the vegetation and buildings, and other structures. The rate at which the velocity increases with height depends on the roughness of the terrain. The roughness of terrain is usually represented by roughness class or roughness height.

For the estimation of the wind potential, wind speed measurements at other heights are necessary. However, if the type of ground cover is known, the wind speed at other heights can be calculated.

The wind speed v_{h2} at height h_2 can be calculated directly with the *roughness length*, z_0 of the ground cover and the wind speed v_{h1} at height h_1 with the help of the following equation:

$$v_{h_2} = v_{h_1} \frac{ln\left(\frac{h_2 - d}{z_o}\right)}{ln\left(\frac{h_1 - d}{z_o}\right)} \tag{20.7}$$

Obstacles can cause a displacement of the boundary layer from the ground. This displacement can be considered by the parameter *d*. For widely scattered obstacles, parameter *d* is zero. In other cases, *d* can be estimated as 70 percent of the obstacle height.

The *roughness length*, z_0 describes the height at which the wind is slowed to zero. In other words, surfaces with a large roughness length have a large effect on the wind. Roughness length ranges from 0.0002 at open sea to 2 at inner cities.

Mean wind speed

The mean wind speed is often used to give the site quality. However, mean wind speed only partly describes the potential of a site because of the stochastic nature of wind. In simplicity, the average wind speed at a site can be expressed as:

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{20.8}$$

However, for wind power calculations, because wind power is not linearly dependent on wind speed, equ. 20.8 can result into errors. This can be rectified by weighting the velocity of its power content when computing the average. Thus, the average wind should be expressed as:

$$v_m = \left(\frac{1}{n}\sum_{i=1}^{n} v_i^3\right)^{\frac{1}{3}} \tag{20.9}$$

Wind speed distribution

The wind is stochastic in nature. The speed of wind in an area will vary from time to time and even on a year-to-year basis. Hence, before a decision is made as to whether a wind energy technology should be adopted, it is important that the wind behaviour in a given location be thoroughly understood. This enables the designer to decide on viability of a project and in the selection of appropriate turbine characteristics.

The average wind speed in an area gives the designer a preliminary indication on the wind energy potential of the site. However, detailed planning requires that the distribution also be considered. A wind speed frequency distribution gives much better information about the wind conditions of a certain site than the mean wind speed. Statistical models have been used successfully to define distribution of wind regime over a period of time.

The most commonly used models are the Weibull and Rayleigh distribution. These models facilitate the determination of factors, such as the percentage of time the wind regime is within a useful velocity range; the most frequent wind velocity; velocity contributing maximum energy to the regime and duration of extreme wind speed.

The Weibull model closely mirrors the actual distribution of hourly wind speeds at many locations. The *Weibull distribution* of wind speed, v with shape parameter, *k* and scale parameter, *c* is given by:

$$f_{Weibull}(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{20.10}$$

The cumulative distribution of the velocity function (equ. 20.10) gives the fraction of time that the wind velocity is equal or lower than v. Thus the cumulative distribution $F(v)$ is the integral of equ. 20.10 and is given by:

$$f_{Weibull} = 1 - \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (20.11)$$

The shape and scale parameters depend on the site. Substituting $c = 2V_m / \sqrt{\pi}$ in the Weibull distribution and using $k = 2$ results in the *Rayleigh distribution*.

Wind turbine topologies

Wind turbines are broadly classified into two categories based on their axis of rotation: the horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT).

Horizontal axis wind turbines

Horizontal axis wind turbines (HAWT) have their axis of rotation horizontal to the ground. Today, almost all wind power plants use rotors with horizontal axes. Systems with vertical axes are only used for very special applications.

The advantages of horizontal axis turbine are:

1. The rotor solidity is lower than VAWT, thus cost is lower compared.
2. The average height of rotor swept area can be high above ground. This tends to increase productivity on a per kW basis.
3. Low cut-in wind speed and easy furling.
4. Relatively high power coefficient.

The disadvantages of horizontal axis turbines include:

1. The generator and gearbox of these turbines are to be placed over the tower, which makes its design more complex and expensive.
2. The need for the tail or yaw drive to orient the turbine towards wind.

Depending on the number of blades, horizontal axis wind turbines are further classified as single bladed, two bladed, three bladed and multibladed. Single-bladed turbines are cheaper because savings on blade materials. The drag losses are also less for these turbines.

Single-bladed designs are not very popular because problems in balancing and visual acceptability. Two-bladed rotors also have these drawbacks, but to a lesser extent. Most of the present commercial turbines used for electricity generation have three blades. Three-bladed rotors have an optically smoother operation and hence visually integrate better into the landscape. The mechanical strain is also lower for three-bladed rotors. The advantages of three-bladed rotors compensate for the disadvantage of the higher material demand so that today mainly three-bladed rotors are built.

Rotors with more number of blades (6, 8, 12, 18 or even more) are also available. The ratio between the actual blade areas to the swept area of a rotor is termed as the solidity. Hence, multibladed rotors are also called high-solidity rotors. These rotors can start easily as more rotor area interacts with the wind initially. Some low-solidity designs may require external starting.

Though frictional losses are high in multibladed turbines, some applications such as water pumping require a high starting torque. For such systems, the torque required for starting goes up to 3-4 times the running torque. Starting torque increases with the solidity. Hence to develop high starting torque, water pumping wind mills are made with multibladed rotors.

Vertical axis wind turbines

The axis of rotation of vertical axis wind turbines (VAWT) is vertical to the ground and almost perpendicular to the ground and to the wind direction. These systems are mostly used for special applications. The major designs in the market include the: Darrieus rotor, Savonius rotor and Musgrove rotor.

The advantages of VAWT include:

1. Their structure and their assembly are relatively simple.
2. The electric generator and the gear as well as all electronic components can be placed on the ground. This simplifies the maintenance compared to rotors with horizontal axes.
3. Rotors with vertical axes need not be oriented into the wind; therefore, they are perfectly suited for regions with very fast changes of wind direction, i.e. no need for yaw system.
4. The blades have a constant chord or twist. Thus, the blades can be manufactured easily.

The disadvantages of VAWT are:

1. The poorer efficiency.
2. Higher material demand of the systems.

Generation of electrical energy from wind turbines

Electricity generation is the most important application of wind energy today. The major components of a wind turbine generator shown in Figure 20.12 include the: tower, rotor, high speed and low speed shaft, gear box, generator, sensors and yaw drive, power regulation and controlling units, and safety systems.

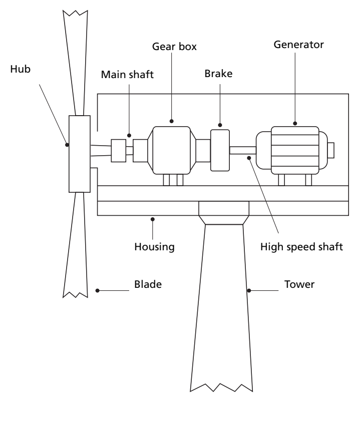

Figure 20.12 **Components of a wind turbine generator**

The tower supports the rotor and nacelle of a wind turbine at the desired height. The major types of towers used in modern turbines are lattice tower, tubular steel tower and guyed tower. The box has gear trains that are used to manipulate the speed of the rotor according to the requirement of the generator.

The rotor brake should stop the wind turbine below a predefined starting wind speed (*cut-in wind speed)* typically, 2.5–4.5 m/s. At the rated speed (nominal wind speed) typically 10–16 m/s, the wind turbine generates the rated power. The nominal wind speed is usually higher than the design wind speed typically 6–10 m/s.

Above the nominal wind speed, the power of the wind turbine must be limited. If the wind speed becomes too high, the wind power plant can be overloaded and damaged. Therefore, wind turbine must be stopped. The rotor brakes stop the wind turbine and the rotor is turned out of the wind if possible.

The generator is one of the most important components of a wind energy conversion system. The generator must be well suited to work under fluctuating conditions because the wind speed keeps on varying from time to time. Different types of generators are being used with wind machines. Small wind turbines are equipped with DC generators of a few watts to kilowatts in capacity. Bigger systems use single or three phase AC generators.

Wind turbine siting

A siting study needs to be undertaken to determine where to locate a wind turbine. The major objective of a siting study is to locate a wind turbine such that cost of energy is maximized while minimizing such things as noise and visual compacts. The scope of a siting study can have a very wide range, which could include everything from wind prospecting for suitable turbine sites over a wide geographical area to considering the placement of a single wind turbine on a site or of multiple wind turbines in a wind farm (this is generally called micrositing).

Several steps are involved in the successful planning and development of a wind turbine installation site. These include:

1. preliminary site identification;
2. detailed technical and economical analysis;
3. environment, social and legal appraisal;
4. micrositing and construction.

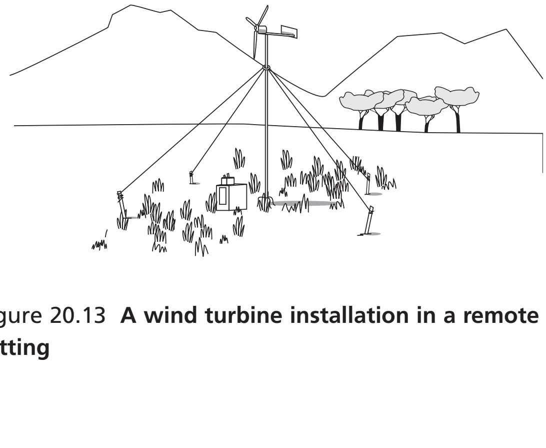

Figure 20.13 **A wind turbine installation in a remote setting**

Figure 20.13 shows a typical wind turbine installation in a remote setting. Before such an installation is made, the steps above must be followed.

In the first step, one identifies a suitable location having reasonably high-wind velocity. A candidate site must usually have a minimum annual average wind speed of 5 m/s. Wind data from local weather stations, airports or published documents such as wind maps may be used for this purpose.

In the second step, more rigorous analysis is required. The nature of the wind spectra available at the sites must be thoroughly understood for the detailed technical analysis. For this, wind speed has to be measured at the hub height of the proposed turbine. Anemometers installed on guyed masts are used for wind measurement.

In step three, environmental issues are analysed and documented. The major concerns are visual effects, avian interaction, noise emission and ecological factors. Local survey and consultation with the local planning authority would be helpful in determining the environmental acceptability of the project. It should also be ensured that the proposed project is acceptable to the local residents.

Once the proposal for the project is approved by the competent authority, then it is possible to proceed further with the micrositing. Micrositing involves laying out the turbine and its accessories at optimum locations at the selected site. In the case of a wind farm project, the turbines are placed in rows with the direction of incoming wind perpendicular to them.

HYBRID POWER SYSTEMS

A hybrid system is a combination of different but complementary energy supply systems based on conventional and renewable energies. Hybrid systems capture the best features of each energy resource. They can be integrated in minigrid, which is usually connected to diesel-based plants. If carefully designed, these systems can provide high-quality electrical power that can be used to meet power needs in rural settings or as a backup to grid supply. Where applicable, the excess power can be sold to the national grid.

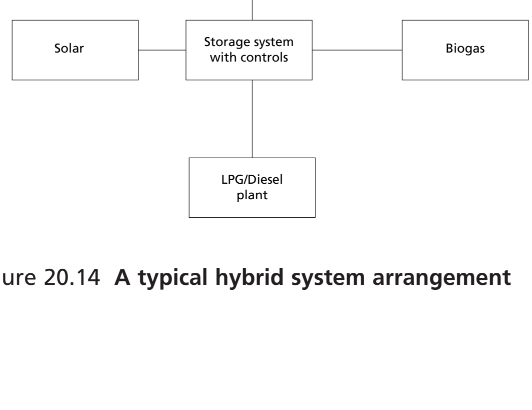

Figure 20.14 **A typical hybrid system arrangement**

Figure 20.14 shows a typical hybrid system arrangement. The system combines two or more energy sources from renewable energy technologies, such as biogas, small hydro, PV panels and wind, with conventional technologies, such as diesel/Liquefied petroleum gas (LPG) generators. The subsystems are electrically and electronically connected. The controls are done via electronics and electricity stored in batteries.

The supplementation of the diesel-based plants with renewable sources of energy is environmentally friendly. It significantly minimizes delivery and transport problems with regard to diesel and drastically reduces maintenance cost and emissions from such plants.

The choice of a right combination of renewable energy options to be used in a hybrid system is reached after doing a thorough feasibility study that takes into consideration the economic, technical and socio-cultural factors.

ENERGY EFFICIENT RURAL BUILDINGS

Planning buildings for energy efficiency reduces maintenance costs required to achieve optimal operational conditions during its productive use. Energy efficiency is achieved by proper selection and placement of materials, proper siting and sizing of a building so that it is responsive to local conditions.

Another way of ensuring that buildings are energy efficient is through landscaping, given that the surroundings of structures have been found to influence the internal climate. For example, buildings surrounded by trees/scrubs are always cooler, during hot seasons, compared to those in open spaces making them more comfortable if there is no air-conditioning service or if there is air-conditioning, energy use in such buildings will be lower. Landscaping strategies will depend on climatic conditions of a site. Some of the techniques that promote energy conservation include:

- Siting buildings to take advantage of natural landforms that can then act as windbreaks.
- Tree planting for the purpose of providing shade and thus reducing cooling costs.
- Planting or building windbreaks to slow winds near buildings thus preventing heat loss.
- Sheltering walls with plants, e.g. vines to create a windbreak directly against a wall.
- Building green roofs that cool buildings with extra thermal mass and evapotranspiration.
- Reducing the heat island effect with permeable paving and minimizing paved areas.

ENERGY AUDITS

This is the assessment of current energy use and developing a cost-effective plan to upgrade or add energy efficient equipment. Energy audits help review efficiency as regards use of electric energy and fossil fuels and may help in deciding whether renewable energy technologies are appropriate for a particular establishment.

For a small establishment, such as a residential house, one can perform a personal energy audit. This will require that one understands: energy transformation units, rate of energy transformation and power rating of appliances in use before conducting the audit. Auditing would then simply mean going around the house to list the appliances in use and their power consumption. One can then analyse the data to establish if the appliances are efficient enough in terms of energy usage.

Inefficient appliances may require repair or may be totally replaced with new more efficient technologies. The audit may also help one decide on what energy needs may be met by use of renewable sources of energy. For example, it may be appropriate to use a solar water heater instead of an electrical water heater.

However, sometimes an energy audit of an enterprise may be required by government or by a bank especially if a grant or loan is to be given. In such a scenario, an energy audit is usually done with the help of a hired energy auditor who is usually an engineer or technically oriented person. The steps involved in energy auditing include:

- An initial interview to gather information about the operation and explain the audit process.
- A site visit to collect information about energy use.
- Data analysis by the expert.
- Audit report analyzing current energy use and recommendations for improvement.
- Review of audit recommendations and discussion of opportunities for implementation.

The energy audit usually ends with a final report that gives detailed information about efficient energy needs of the establishment. It should give recommendations on energy savings at the enterprise level that can be achieved. This should be reported in units understood by the end user. The energy savings recommendations should be made for each major activity, including a comparison with the baseline condition for estimated cost of equipment replacement or upgrade, estimated savings in energy cost, including appropriate assumptions and documentation, and estimated payback period for implementing each recommendation. Various standards have been developed to assist in energy auditing. A good reference on this is the American Society of Agricultural and Biological Engineers, Standard 612 for Performing On-farm Energy Audits.

ENERGY ECONOMICS

In the process of deciding on which energy system to invest in, it is important to consider the economic efficiency of the system. In most cases, economic efficiency has been the primary decision factor. Therefore, the solution with the best economic benefits is usually chosen before consideration of technical and environmental aspects.

There are classical economic calculations that can be put into use. The aim of these calculations is to find the one system out of the various possible energy solutions that provides the desired type of energy at the lowest cost. The result of economic calculations is the cost for one unit of energy.

For example, for electricity-generating systems the costs are related to a kilowatt-hour of electricity. For estimating a specific final cost, all the costs, such as installation of the power plant, operations and maintenance costs as well as disposal costs, are divided by the total number of kilowatt-hours generated during the plant's lifetime. If the aim is to compare cost over the life span of the plant, then inflation must be taken into consideration.

REVIEW QUESTIONS

1. Explain the forms of energy.
2. Differentiate between renewable and non-renewable energy sources.
3. Outline the uses of solar energy in a rural setting.
4. What factors would you consider before deciding on an energy source?
5. Discuss the role of renewable energies in the future.
6. What is an energy audit?
7. How would you design a rural building to ensure that energy is efficiently used?
8. How can proper landscaping result into energy savings in a rural setting?
9. If a building uses ten bulbs drawing 240 V and 0.25 A for eight hours per day, how many kWh will have been used in 30 days?
10. Explain the working principle of a PV cell.
11. Explain how you would size up a biogas and wind energy system for a family of five.
12. What are hybrid energy systems and what are their advantages?

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