FIGURE 9.10 A meteorological station installed within a rice paddy.

Lysimeters may be square (Fig. 9.19) or circular (Figs. 9.20–9.22), and made of steel, galvanized material, fiberglass, or plastic. Hydrologic inputs comprise precipitation and supplemental addition of water depending upon the management systems imposed. Hydrologic output comprises deep drainage or percolation water.

FIGURE 9.11 Recording and non-recording rain gauges.

FIGURE 9.12 A snow gauge.

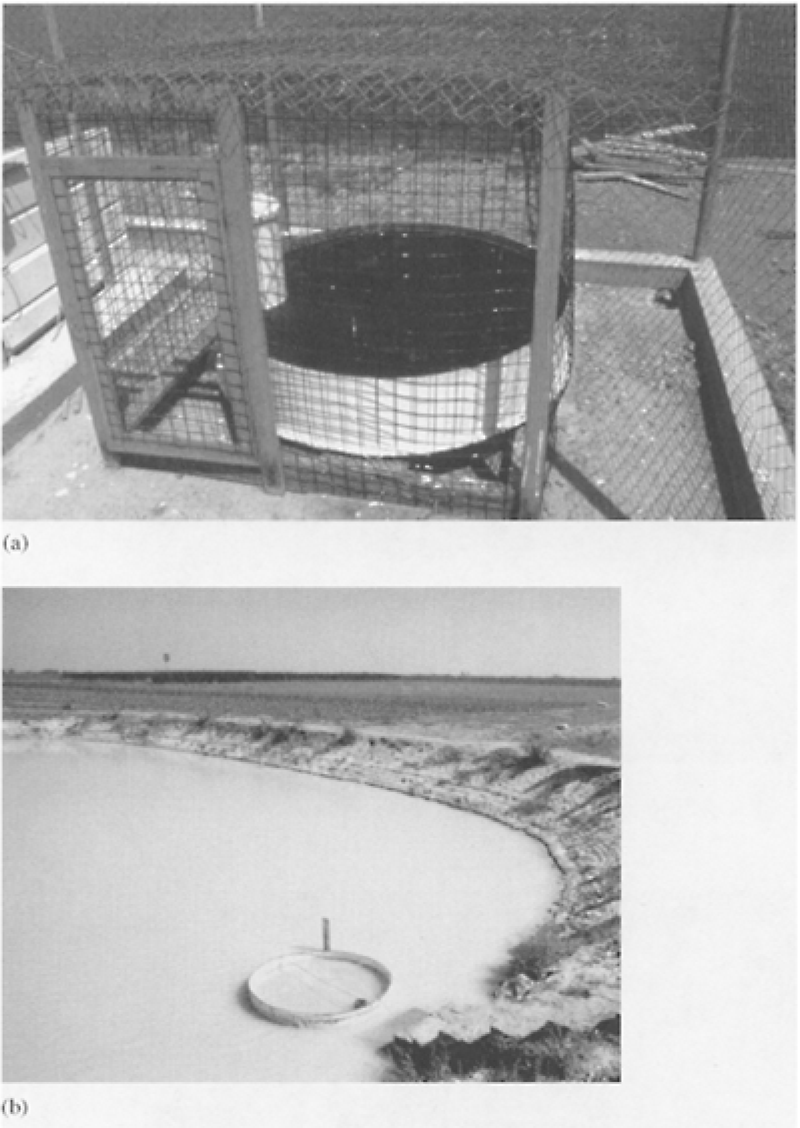

FIGURE 9.13 (a) Class A pan evaporemeter; (b) a device to measure evaporation in a lake.

Changes in soil-water storage can be measured by using neutron moisture meter or gypsum blocks.

There are several types of lysimeter depending on the method of construction, and evaluating hydrologic balance. Common types of lysimeters are outlined in Table 9.5.

The drainage is facilitated by using about a 5 cm thick layer of gravel, sand, or diatomaceous clay at the base

FIGURE 9.14 (a) Spider gauge to measure through-fall and (b) stem flow.

TABLE 9.4 Method of Measuring Surface Runoff

Technique/plot	Size	Equipment
Microplots	1–10m^2	A drum with a capacity of about 200 liter, or a small flume with water stage recorder
Field runoff plots	0.0025–100 ha	Multidivisor tanks, flume, water stage recorder
Small watersheds	1–10 ha	Flume, water stage recorder, proportional samplers
Large watersheds	>10ha	Weirs, waterstage recorders

Source: Adapted from Lal, 1990.

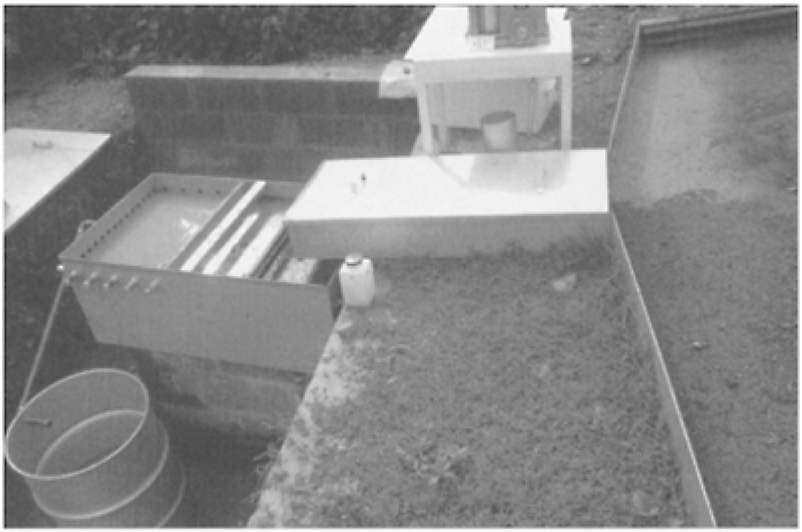

FIGURE 9.15 A multidivider tank and a flume with water stage recorder to measure runoff from a plot.

(Fig. 9.23). Lysimeters may be cited or different landscape positions in the field, or constructed at one cite to facilitate specific measurement (Figs. 9.24 and 9.25).

Lysimetric data are used to compute consumptive water use by plants or crops grown. An example of the method to use these data is shown below. Consider the data in Table 9.6 for 30-day period from a lysimetric experiment:

Consumptive use or ET per day=16 cm/30 days=0.53 cm/day

FIGURE 9.16 An H-flume and a water stage recorder to measure runoff from a steep agricultural watershed.

FIGURE 9.17 A wier with a slot-pipe to collect runoff sample.

There are numerous uses of lysimetric experiments, with the primary use of measuring the components of hydrologic cycle, especially deep drainage, soil-water storage, and evapotranspiration. In addition, chemical analyses of the deep drainage or percolation water can be extremely useful to study transport of chemicals applied to the soil, e.g., fertilizers and pesticides. Temporal changes in concentration of NO_3–N, PO_4–P, organic P, dissolved organic carbon can provide useful information on the risks of contamination of groundwater. Fate and pathways of pesticides can also be studied by lysimetric analyses.

Lysimetric studies are also useful to evaluate transport of clay from surface to the subsoil by the process of illuviation (Roose, 1977). The

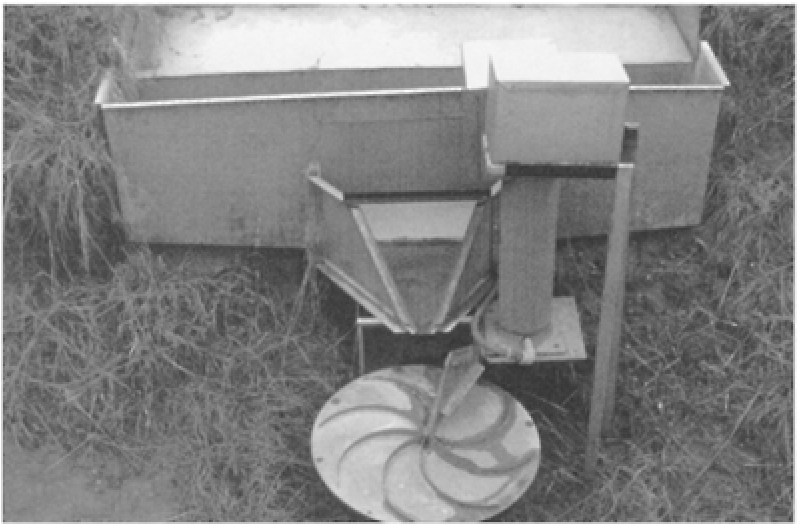

FIGURE 9.18 A Coshocton wheel sampler to obtain runoff sample.

(a)

FIGURE 9.19 A square filled in lysimeter (a) method and (b) with removable cover.

(b)

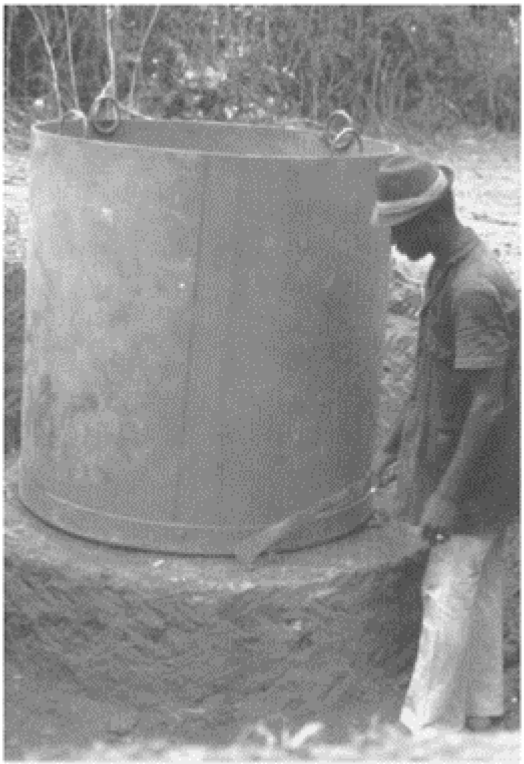

FIGURE 9.20 Installation of a circular monoleith lysimeter.

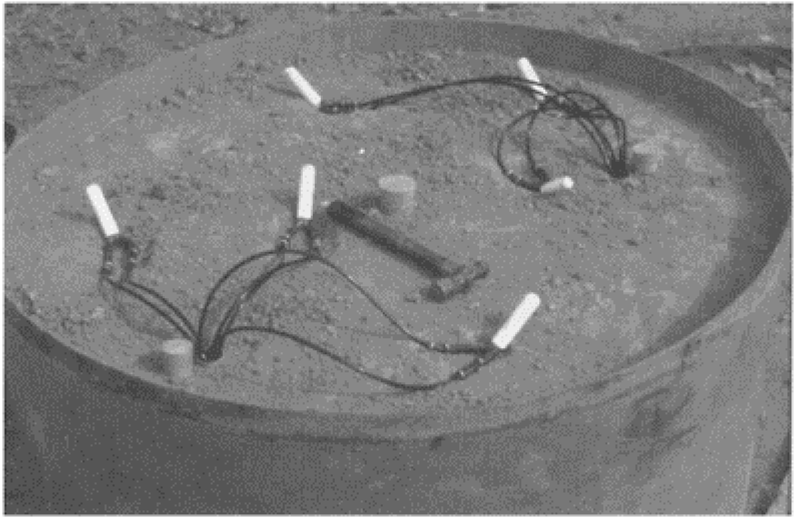

FIGURE 9.21 A suction cup and neutron probe access tube are installed at the base.

FIGURE 9.22 Suction cups are embedded in the diatomaceous clay.

information on solution weathering or rate of new soil formation can also be obtained by chemical analyses (Al^{+3}, Si^{+4}, cations) of the percolating water. For these measurements, lysimeters must be deep enough and include bedrock as a part of the monolith or soil solum being studied.

TABLE 9.5 Types of Lysimeters Used for Evaluating Components of the Hydrologic Cycle

Basis		Lysimeter types
Soil disturbance	(i)	Filled in, where disturbed soil is packed layer by layer at ρb similar to the field situation
	(ii)	Monolith, where a block of undisturbed soil is encased under natural conditions
Weighing		Nonweighing or drainage lysimeter in which water balance is obtained by carefully measuring the volume of water drained
		Weighing lysimeters monitor changes in total weight on a continuous basis or at regular time intervals. Weighing lysimeters may use a mechanical balance or a hydrologic weighing technique
Drainage	(i)	Gravity drainage

	(ii)	Suction drainage
Location	(i)	In situ, constructed with soil in place
	(ii)	Constructed with soil transported from different regions

Example 9.3

A runoff plot has a dimension of 25 m×4 m. The runoff collection system involves a Coshocton Wheel Sampler, which collects 1 % of the runoff. Total runoff collected after 2.5 cm of rainfall is 10 liters. The sediment load in runoff is 5 g/liter. Calculate runoff and erosion.

Solution

Total runoff volume=10 liters×100=1000 liters

$$\text{Runoff depth} = \frac{\text{volume}}{\text{area}} = 10^3\,\text{L} \times \frac{10^3\,\text{cm}^3}{\text{L}} \times \frac{1}{100\,\text{m}^2} \times \frac{10^4\,\text{cm}^2\,\text{m}^2}{10^4\,\text{cm}^2} = 1\,\text{cm}$$

$$\text{Runoff C\% of rainfall} = \frac{1\,\text{cm}}{2.5\,\text{cm}} \times 100 = 40\%$$

$$\text{Total sediments} = 1000\,\text{L} \times \frac{5\,\text{g}}{\text{L}} \times \frac{\text{kg}}{10^3\,\text{g}} = 5\,\text{kg}$$

$$\text{Soil erosion} = \frac{5\,\text{kg}}{100\,\text{m}^2} \times \frac{10^4\,\text{m}^2}{\text{ha}} = 500\,\text{kg/ha} = 0.5\,\text{Mg/ha}$$

PROBLEMS

1. A lake has a capacity of 1200 Km^3. The steady state evaporation flux is 200 $\text{Km}^3\,\text{y}^{-1}$. What is the mean residence time of water in the lake?

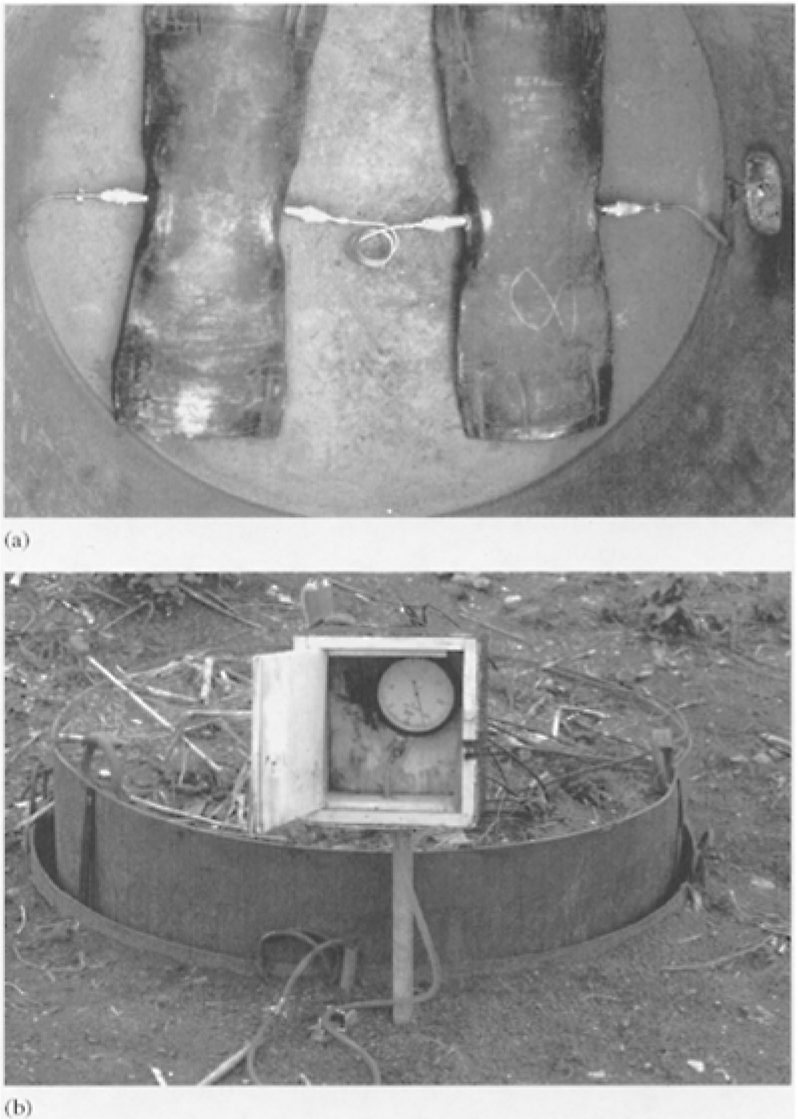

FIGURE 9.23 (a) A hydraulic weighting device may involve water-filled pillows placed beneath the lysimeter, and (b) connected to a pressure gauge.

2. A one hectare field contains 0.2 gg^{-1} of water to 10 m depth. Assuming a uniform soil bulk density of 1.5 Mg m^{-3}, calculate the total water content of soil in liters and equivalent depth.

3. Draw a landscape, and list principle components of the hydrologic cycles.

4. Tabulate methods of monitoring components of a hydrologic cycle along a hill slope.

(a)

(b)

FIGURE 9.24 A battery of drainage lysimeter (a) with a trench to collect seepage; (b) an underground weighing and seepage collection facility.

5. Draw up a table or a nomograph comparing different units of measuring water capacity and flux, and compute conversion factor to change from one unit to another.

6. Calculate the height of capillary rise in a soil pore of 50 μm inner diameter in winter (0°C), spring (10°C), early summer (20°C), and tropics (40°C).

7. Compute the pressure difference at the air-water interface in Question 1 above.

FIGURE 9.25 A series of lysimeters under a plastic shelter.

TABLE 9.6 Lysimetric Measurements

Period (days)	Precipitation	Irrigation	AS	Runoff	Deep drainage
0–10	0	5	−1	0	0
10–15	12	0	+4	3	2
15–30	5	0	−2	0	0

Calculate ET:
Solution:
ET=$P+I-(R+D+AS)$
ET For Period 1=0+5− (0+0−1)=6 cm
ET For Period 2=12+0−(3+2+4)=3 cm
ET For Period 3=5+0−(0+0–2)=7 cm
Total ET=16 cm

8. Consider the following equation of the height of capillary rise:

$$r = \frac{2}{h\rho g}$$

where γ and ρ refer to the surface tension and density of the fluid, respectively. What is the difference in the height of capillary rise in 20 µm diameter pore for water and alcohol at 20° C?

9. Write a brief essay on “surface tension.” As a diagram, explain interactive forces, and define units.

10. The 0–50 cm layer of a lakebed soil in northwestern Ohio has a field capacity of 30% by weight, soil-water content of 15% by weight, and bulk density of 1.2 Mg m^{3}. A rainfall of 4 cm was received of which 75% was lost as runoff. Calculate the following:

1. What is the volume of runoff from a test plot of 25 m×40 m?
2. What is soil erosion (*t*/ha) if the runoff contained sediments of 25 g/liter?
3. What is the total NO_3 loss if concentration in runoff is 5 g/liter?

11. Why are some soils more wettable than others? Why does burning crop residue or any biomass make a soil hydrophobic?

APPENDIX 9.1 SOME PHYSICAL PROPERTIES OF WATER AT ATMOSPHERIC PRESSURE

Temperature (°C)	Density ρ (Mg/m^3)	Specific weight γ ($N/m^3 \times 10^3$)	Dynamic viscosity μ ($N \times s/m^2 \times 10^{-3}$)	Kinematic viscosity (ηκ) ($m^2/s \times 10^{-6}$)
0	1.0	9.810	1.79	1.79
5	1.0	9.810	1.51	1.51
10	1.0	9.810	1.31	1.31
15	0.999	9.800	1.14	1.14
20	0.998	9.790	1.00	1.00
25	0.997	9.781	0.891	0.894
30	0.996	9.771	0.797	0.800
35	0.994	9.751	0.720	0.725
40	0.992	9.732	0.653	0.658
50	0.988	9.693	0.547	0.553
60	0.983	9.643	0.466	0.474
70	0.978	9.594	0.404	0.413
80	0.972	9.535	0.354	0.364
90	0.965	9.467	0.315	0.326
100	0.958	9.398	0.282	0.294

0.001 $N \times s/m^2$=0.001 Pa×s=−0.01P=1 cP=1 centipose

Source: Adapted from Weast, 1987; Julien, 1998.

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10
Soil's Moisture Content

Soil's moisture content is defined as the water that may be evaporated from soil by heating at 105°C to a constant weight. The choice of the temperature limit is arbitrary, and clayey soils retain a considerable quantity of water at this temperature.

Water in the soil is held by the forces of cohesion and adhesion in which surface tension, capillarity, and osmotic pressure play a significant role. There are two types of forces acting on soil moisture. Positive forces are those that enhance soil's affinity for water (e.g., forces of cohesion and adhesion). In contrast, some negative forces that take water away from soil include gravity, actively growing plant roots, and evaporative demand of the atmosphere. At any given point in time, soil's moisture content is the net result of these positive and negative forces. Considerable advances in our understanding of soil moisture regime were made in the first half of the twentieth century. Historical developments in the science of soil moisture are given in Taylor and Ashcroft (1972), Rode (1969), Rose (1966), Childs (1969), and others.

10.1 SOIL-WATER REGIME

There are three forms of soil moisture. The liquid water is held in the transmission and retention pores. The absorbed water is held by the forces of cohesion and adhesion on the soil particles, mostly colloidal particles such as clay and organic matter. The third form of water is the one held within the lattice structure of clay minerals. Two edaphologically important aspects of the liquid water held within the pores are field moisture capacity and permanent wilting point.

10.1.1 Field Moisture Capacity (FC)

When a fully saturated soil (s=Θ=1.0) is allowed to drain freely under the force of gravity and there is no loss due to evaporation, after some time the soil's moisture content will approach an equilibrium level (Fig. 10.1). This equilibrium in soil's moisture content is called *field moisture capacity*. It is the moisture content that a given soil reaches and maintains after it has been thoroughly wetted and allowed to drain freely. It is the upper limit of moisture content that a soil can hold. It is the moisture content when all macropores or transmission pores have been drained and water in the macropores has been replaced by air.

Being a highly heterogenous mixture, most natural soils do not have a well-defined field moisture capacity. Clayey soils (curve B in Fig. 10.1) rarely attain a field moisture capacity because they continue to drain for a long period of time. Soils with impeded drainage (curve C in Fig. 10.1) never attain a field moisture capacity.

Free drainage under the force of gravity removes excess water from the upper layer and transmits it to the lower layers (Fig. 10.2). If the water drained from the upper layer is more than that needed for attaining the field moisture capacity of the lower layer, the excess water will be drained and transmitted to the third layer, and so on.

Example 10.1

A soil with a bulk density of 1.2 g/cm^3 has an initial gravimetric moisture content of 0.083. If its field moisture capacity is 0.25 (g/g), how deep will 2 cm of rain penetrate into the soil? Assume density of water (ρ_w) is 10 g/cm^3.

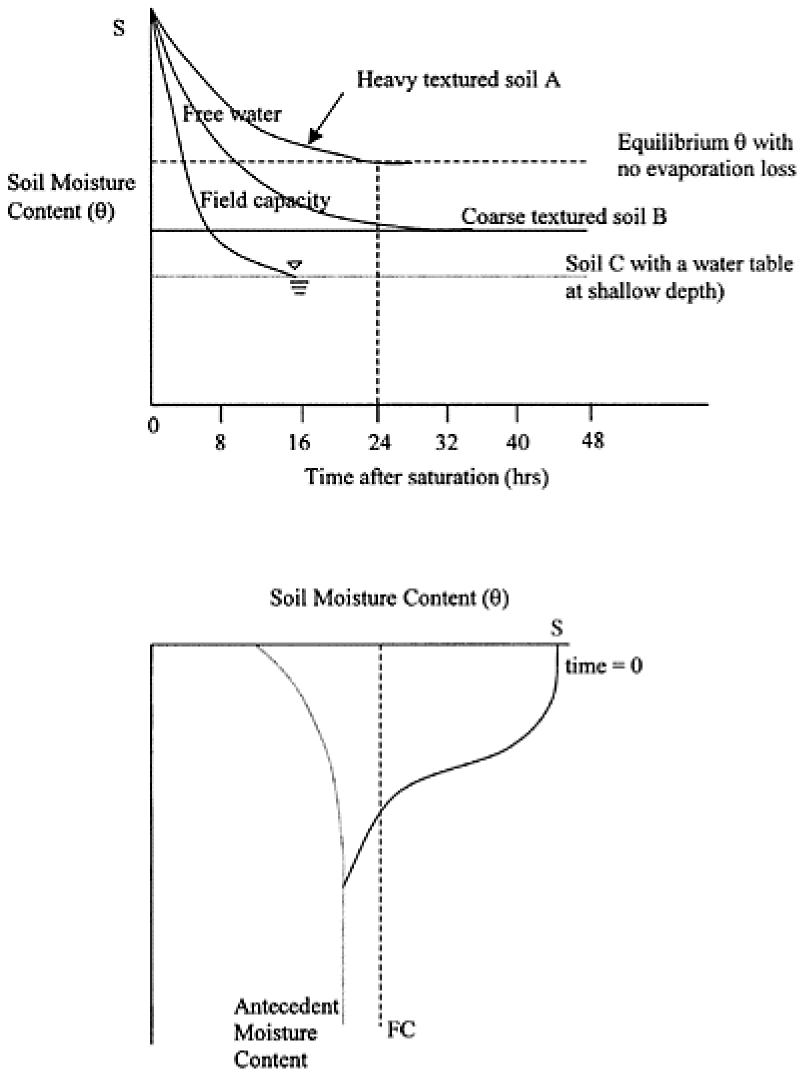

FIGURE 10.1 Field moisture capacity is the moisture held in the soil when free water in macropores is allowed to drain under the force of gravity.

Solution

$$\text{Initial volumetric moisture content } (\Theta_i) = \frac{0.083\text{ g}}{\text{g}} \times \frac{1.2\text{ g}}{\text{cm}^3} \times \frac{\text{cm}^3}{1\text{ g}} = 0.10$$

$$\text{Volumetric field moisture capacity } (\Theta_{fc}) = \frac{0.25\text{ g}}{\text{g}} \times \frac{1.2\text{ g}}{\text{cm}^3} \times \frac{\text{cm}^3}{1\text{ g}} = 0.30$$

$$\therefore \text{Soil moisture deficit} = \Theta_{fc} - \Theta_i = 0.30 - 0.10 = 0.20$$

$$\text{Depth of rain penetration} = \frac{\text{Rain fall amount}}{\text{Soil moisture deficit}} = \frac{2\text{ cm}}{0.20} = 10\text{ cm}$$

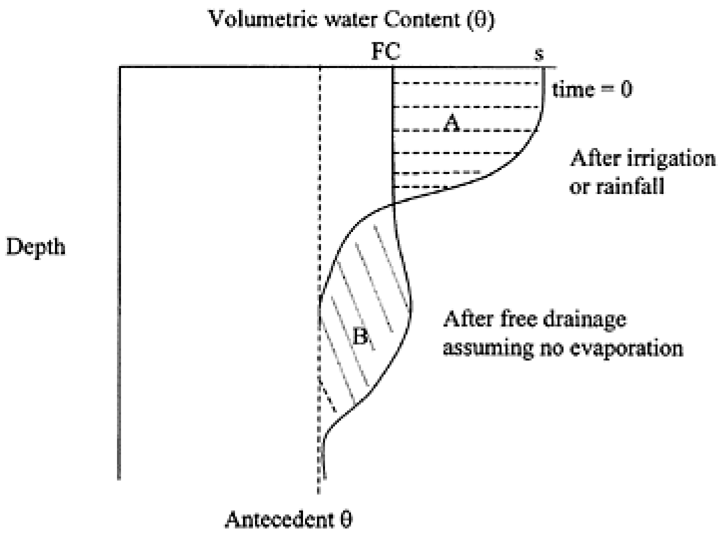

FIGURE 10.2 Free drainage following rainfall or irrigation transmits water in excess of field capacity to the layer beneath.

Example 10.2

Consider that soil in the above example is to be irrigated to field moisture capacity to 50 cm depth. How much of irrigation water is needed for 10 ha?

Solution

Soil moisture deficit $= \Theta_{fc} - \Theta_i = 0.30 - 0.10 = 0.20$

$\therefore$ Water needed to attain field moisture capacity to 50 cm depth =
depth $\times$ deficit $= 0.20 \times 50\,\text{cm} = 10\,\text{cm}$

Total water needed to irrigate 10 ha $= 10\,\text{ha} \times 10\,\text{cm}$

$$= 100\,\text{ha cm} \times 10^4 \frac{\text{m}^2}{\text{ha}} \times 10^{-2} \times \frac{\text{m}}{\text{cm}} = 10^4\,\text{m}^3$$

There are numerous soil factors that affect its FC. Important among these are texture and especially the clay content, clay minerals, porosity and pore size distribution, and soil organic matter content. The FC is more for soils with high than low clay content. For the same clay content, soils with 2:1 swelling type clay minerals have more FC than those with 1:1 clay minerals, and those with high % WSA and structural porosity have more FC than those with low % WSA and contain predominantly textural porosity. Soil's organic matter content has a positive effect on FC. All other factors remaining the same, soils with high organic matter content have a higher FC than those with low organic matter content. Effects of these factors on field capacity are shown in Figs. 10.3 and 10.4 (Lal, 1979a).

10.1.2 Permanent Wilting Point (PWP)

This is the lower limit of the moisture content of soil at which forces of cohesion and adhesion holding moisture in soil far exceed the pull that plant roots can exert to extract moisture from the soil. It is a unique moisture content that a soil attains beyond which soil moisture is no longer available to plants. This is the moisture content at which plant leaves wilt permanently and do not regain turgidity even when placed in an atmosphere with a relative humidity of 100%. The PWP is the moisture content at which even the retention pores have been depleted of their moisture content. The residue moisture content in soil at the PWP is of little use to plants.

Similar to field moisture capacity, moisture content at PWP also differs widely among soils. The PWP is higher in soils with higher clay content. It is higher with 2:1 type than 1:1 type clay minerals, and with expanding-lattice and more surface area than those with fixed-lattice and low surface area (Lal, 1979c). In contrast to FC, the PWP is not significantly influenced by aggregation, structural porosity, and soil organic matter content. Therefore, the PWP is primarily influenced by the amount and nature of clay content (Fig. 10.5).

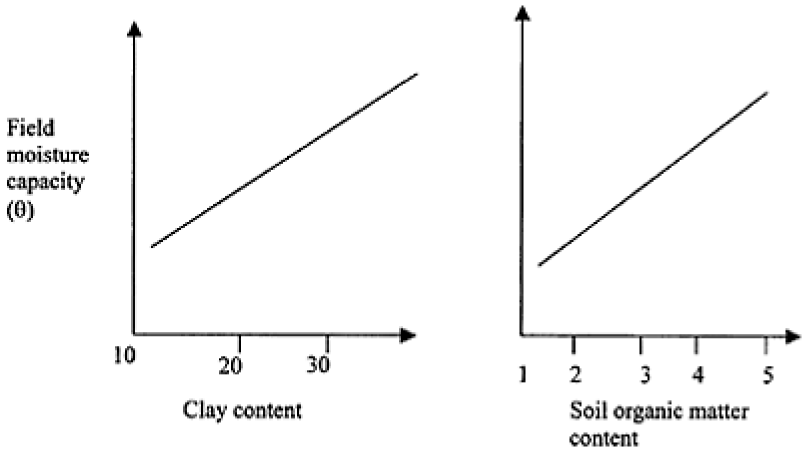

FIGURE 10.3 A schematic showing the effects of clay and soil's organic matter content on field moisture capacity.

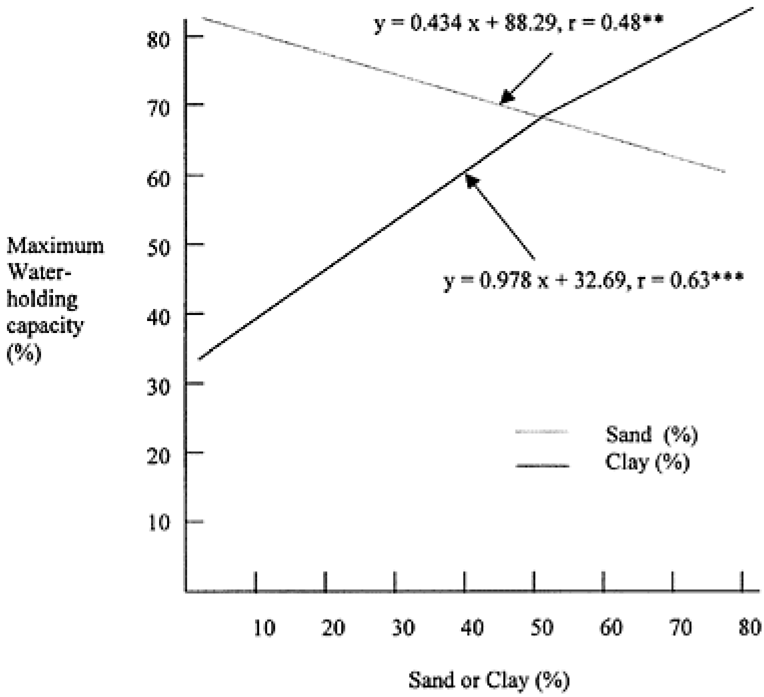

FIGURE 10.4 The effect of sand and clay content on the maximum water holding capacity of some Nigerian soils. (Redrawn from Lal, 1979.)

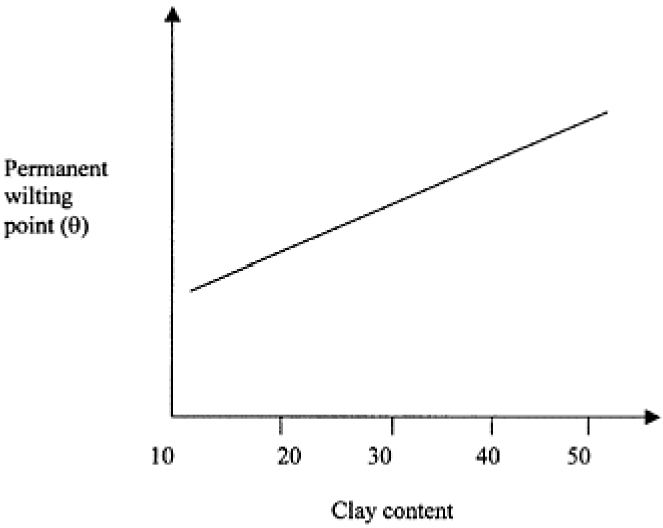

FIGURE 10.5 A schematic showing relation between clay content and the volumetric moisture content at the permanent wilting point.

10.1.3 Plant Available Water Capacity (AWC)

The available water capacity (AWC) is the difference in moisture content between FC and PWP [Eq. (10.1)].

$$AWC=FC-PWP \tag{10.1}$$

The AWC is an important characteristic that determines a soil's physical qualities. Soils with high AWC have higher potential to produce plant biomass than those with low AWC. In contrast to the effect on FC, it is difficult to generalize the effect of clay content on soil's AWC because increase in clay content increases both the FC and the PWP (Salter et al., 1966; Salter and Hawroth, 1961; Tran-vinh-An, 1971; Pidgeon, 1972; Hallis et al., 1977; Lal, 1979a; c; Jenny, 1980; Hudson, 1994; Emerson, 1995). On the other hand, the effect of soil's organic matter on the AWC is welldefined. Increase in soil's organic matter increases the FC but not the PWP, and therefore, increases the AWC (Fig. 10.6).

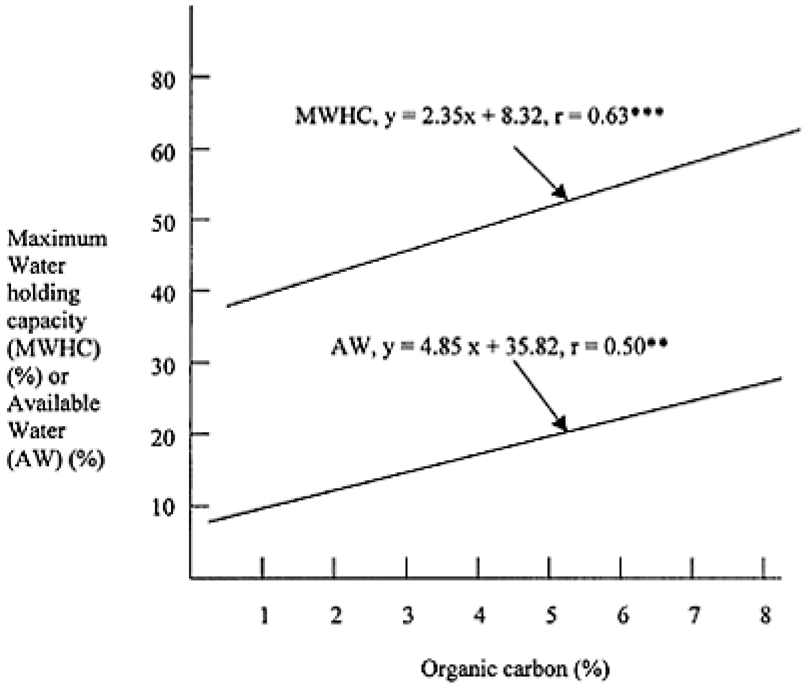

FIGURE 10.6 The relationship between organic matter content and soil water retention of some Nigerian soils. (Redrawn from Lal, 1979.)

10.1.4 Least Limiting Water Range

In addition to the moisture content of soil, AWC also depends on soil strength when moisture content is in the vicinity of the PWP and by poor aeration when close to field capacity. Letey (1985) proposed the "nonlimiting water range" (LLR) at which water uptake is neither limited by soilresistance when too dry nor poor aeration when too wet. Keeping in view that plant growth varies in a continuous fashion with change in soil strength (see Chapter 7), matric potential (see Chapter 11), and aeration (see Chapter 18) (Dexter, 1987; Allmares and Logsdon, 1990), Da Silva et al. (1994) proposed the term "least limiting water range" (LLWR). It refers to a range of soil's moisture content at which plant growth is least limited by either soil strength or poor aeration. The LLWR is also influenced by several soil properties including particle size distribution and soil's organic matter content (Da Silva et al., 1994), bulk density, and porosity. Relative bulk density ($\rho_{b-rel}=\rho_b/\rho_{b-\text{proctor max}}$) may also affect LLWR (Hakansson, 1988; Carter, 1990).

Example 10.3

From the data presented in Table 10.1, calculate the available water capacity of the profile to 1-m depth.

Solution

Follow the steps shown below:

1. Convert gravimetric moisture content *(w)* into the volumetric moisture content (Θ) by multiplying with soil bulk density *(ρ_b)* and dividing by the density of water.
2. Compute actual AWC as per Eq. (10.2).

$$AWC_{actual}=(\Theta_a-PWP_{\Theta})d \text{ cm} \tag{10.2}$$

where Θ_a is the antecedent or actual field moisture content, PWP_{Θ} is the volumetric moisture content at the PWP, and *d* is depth of the corresponding horizon. Obtain the sum total of AWC_{actua}l for all horizons.

3. Compute potential AWC as per Eq. (10.3).

$$AWP_{potential}=(FC_{\Theta}-PWP_{\Theta})d \text{ cm} \tag{10.3}$$

where FC_{Θ} and PWP_{Θ} represent volumetric field capacity and permanent wilting point, and *d* is depth of the horizon. Obtain sum total of $AWC_{potential}$ for all horizons.

TABLE 10.1 Computations of Plant Available Water Capacity

Depth (cm)	ρ_b (g/cm^3)	Field moisture content (*w*, g/g)	FC (*w*, g/g)	PWP (*w*, g/g)		Volumetric moisture	content	AWC (cm)
					Θ_a	FC_{Θ}	PWP_{Θ}	Actual potential
0–10	1.2	0.10	0.167	0.083	0.12	0.20	0.100.20	1.0
10–20	1.3	0.15	0.153	0.092	0.195	0.20	0.120.75	0.8
20–50	1.4	0.20	0.25	0.107	0.280	0.35	0.153.90	6.0
50–100	1.5	0.25	0.30	0.133	0.375	0.45	0.208.75	12.5
						Total	13.6	20.3

Example 10.4

How deep will 5 cm of rain penetrate in the soil profile for the data shown in Table 10.1?

Solution

Compute water deficit for each horizon.

1. Water deficit for horizon 1=(0.20–0.12)×10 cm=0.8 cm
2. Water deficit for horizon 2=(0.20−0.195)×10 cm=0.05 cm
3. Water deficit for horizon 3=(0.35–0.280)×20=1.4 cm
4. Water deficit for horizon 4=(0.45–0.375)×50=3.75 cm

∴ Amount of rain needed to saturate the first 3 horizons=2.25 cm

The balance of rain water=5 cm − 2.25 cm=2.75 cm

The remainder of the rain is sufficient to penetrate into the fourth horizon to=(2.75 cm)/(0.45–0.375)=36.7 cm

∴Total depth of penetration=10 cm+10 cm+30 cm+36.7 cm=86.7 cm

Example 10.5

Calculate potential and actual available water capacity from the data shown in Table 10.2.

Potential AWC=($\Theta_{fc} - \Theta_{pwp}$)×depth of soil layer

Actual AWC=($\Theta_a - \Theta p_{wp}$)×depth of soil layer

1. How deep will 7 cm of rain penetrate?	Balance of rain (cm)
Total deficit of the first layer=0.08×5 cm=0.40 cm	7–0.4=6.60
Total deficit of the second layer=0.07×25 cm=1.75 cm	6.60−1.75=4.85
Total deficit of the third layer=0.09×50 cm=4.50 cm	4.85–4.50=0.35
Fractional deficit of the fourth layer=0.07	
Depth of rain penetration in the fourth	
layer=0.35 cm/0.07=5 cm	
Total depth of rain penetration=80+5 cm=85 cm	

2. How much irrigation is needed to bring the soil profile of 100 ha farm to Θ_{fc}?

$$= (\text{Potential AWC} - \text{Actual AWC}) \times \text{area}$$
$$= (19.85 - 11.80)\,\text{cm} \times 100\,\text{ha}$$
$$= 805\ \text{ha} - \text{cm}$$
$$= 805\,\text{ha} \times 10^4 \frac{\text{m}^2}{\text{ha}} \times 10^{-2}\,\text{m} = 805 \times 10^2\,\text{m}^3 = 80.5 \times 10^3\,\text{m}^3$$

TABLE 10.2 Computation of Plant Available Water Capacity

Soil depth (cm)	Θ_{fc}	Θ_{pwp}	Θ_a	AWC Potential	AWC Actual
0–5	0.30	0.08	0.22	1.10	0.70
5–30	0.35	0.14	0.28	5.75	4.00
30–80	0.40	0.22	0.31	9.00	4.50
80–100	0.45	0.25	0.38	4.00	2.60

10.2 METHODS OF MEASUREMENT OF SOIL'S MOISTURE CONTENT

A quantitative measure of soil's moisture content is important to understanding soil behavior, plant growth, and soil's numerous other physical processes. Information on soil's moisture content is useful for assessing plant water requirements and scheduling irrigation, plant water uptake and consumptive use, depth of water infiltration into soil, water storage capacity of soil, rate and quantity of water movement, deep drainage and leaching of chemicals, soil-strength, soil's plastic properties, soil-compactability, soil cloddiness and consistency, and numerous other properties and processes.

Despite its numerous uses, an accurate assessment of soil's moisture content in the field has been a challenge to soil physicists and hydrologists for a long time. There are several difficulties encountered in an accurate assessment including the following:

1. Soils are highly variable even over short distances, especially in their water retention capacity as determined by differences in other soil properties, e.g., texture, soil organic matter content, and infiltration rate.
2. Actively growing roots and soil evaporation (or evapotranspiration demand) continuously alter the soil moisture status, which is a highly dynamic entity, and a constantly changing function.
3. Plant water uptake is highly variable because of differences in their growth caused by variable amounts of nutrients and water availability in the soil, and possible effects of pests and pathogens.

There is a wide range of methods used for measurement of soil moisture (Fig. 10.7). For details on these methods, readers are referred to reviews by Gardner (1986), Catriona et al. (1991), Topp (1993), Romano and Santini (2002) and Top and Ferré (2002). Most methods can be grouped under two categories: direct and indirect.

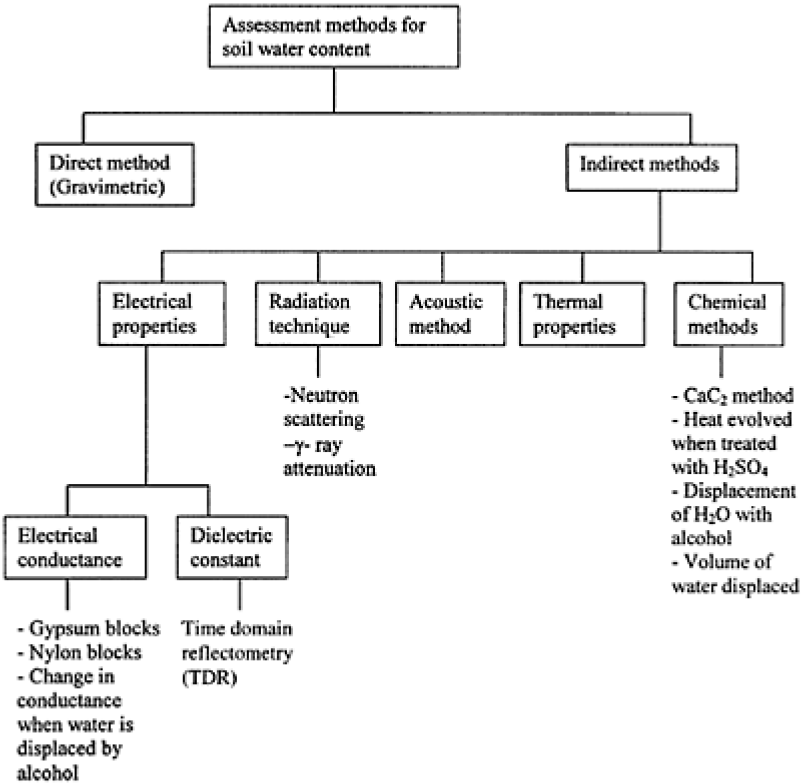

FIGURE 10.7 Principles underlying different methods of assessment of soil's moisture content.

10.2.1 Direct Methods

Direct methods are based on a physical or chemical technique of removing water from soil followed by its measurement. Gardner (1986) reviewed pros and cons of each direct method. Direct methods are based on three techniques: (i) removal of water by distillation or absorption by a desiccant, (ii) displacement of the water by another liquid and measuring water-induced changes in properties of the liquid, and (iii) measurement of the chemical reaction or reaction products when reactive chemicals are added to the soil. Some of these methods are also discussed under the section dealing with chemical properties related to soil moisture content.

Evaporation Method

The physical technique of removing water from soil involves its evaporation at 105°C. The chemical process of removing water involves leaching by alcohol, or other volatile compounds that can then be easily evaporated. The thermogravimetric method is simple, routine, reliable, inexpensive, and easy to use. The major limitation of this method is that it is destructive, laborious, and time consuming. Because it measures the gravimetric moisture content, it is important to know soil bulk density. Furthermore, evaporating water at 105°C does not remove all water, especially the bond water which may form a substantial amount in heavy-textured soils containing 2:1 clay minerals. There may be changes in the organic fraction of the soil due to oxidation at high temperature and in the water of hydration of the cations in soils containing high concentration of soluble salts.

Water may be present in the soil in all three states (solid, liquid, and gaseous) under cold environments, and in two states (liquid and gaseous) under normal conditions suitable for plant growth. In addition, the liquid water exists in two separate forms: (i) free water and (ii) adsorbed water. The adsorbed water, bonded by the electrostatic forces forming 1 to several molecular layers on the colloidal surfaces, is different than the free water. Most bonded water is released at a temperature of 110 to 160°C. In the conventional definition of soil moisture, therefore, water in the "bonded" state and vapor state is not considered in the definition used in this chapter and in the standard thermogravimetric evaluation. Because of the soil heterogeneity and spatial variability, large number of samples are required to obtain a representative value of soil moisture content. Soil's moisture content is expressed as a fraction and as a percentage on a gravimetric *(w)* or volumetric basis *(θ)*. The gravimetric soil moisture content is determined using Eq. (10.4) and can be expressed

$$w = \frac{\text{mass of wet soil} - \text{mass of dry soil}}{\text{mass of dry soil}} \tag{10.4}$$

either as a fraction or as a percentage. In addition to soil heterogeneity, another source of error is the temperature control in the oven. Temperature in the oven may not be uniform for different shelves, and/or the temperature control may not be accurate.

Leaching Method

The soil sample is saturated with an alcohol, and then burnt (Bouyoucos, 1931; 1937). Burning evaporates the soil moisture. Repeated leaching and burning can remove the entire soil moisture to a constant weight of soil in a short period of 15 to 20 minutes. In comparison with the thermogravimetric method, this method is rapid but less accurate.

10.2.2 Indirect Methods

The following methods are based on water-induced changes in soil properties that can be measured.

Electrical Conductivity and Capacitance

Soil's moisture content influences electrical conductivity and capacitance, and these properties can be measured routinely and accurately and correlated with soil-moisture content. Attempts have been made to measure soil's electrical resistance in relation to soil moisture content (Kirkham and Taylor, 1950). However, soil heterogeneity and presence of soluble salts pose major problems. Some of these interactive problems can be overcome by using porous blocks containing suitable electrodes, and equilibrated in soil at a given depth. Electrical conductivity is measured when these blocks reach equilibrium. Commonly used material to construct porous blocks is the gypsum or plaster of Paris (Bouyoucos, 1953). Gypsum blocks, however, are progressively dissolved in soils of low pH and have to be frequently calibrated. Therefore, a wide range of porous materials has been tested ranging from nylon cloth (Bouyoucos, 1949) to fiberglass (Cummings and Chandler, 1940; Coleman and Hendrix, 1949). The method is simple, inexpensive, and nondestructive. However, each block has to be calibrated separately. While gypsum blocks are progressively dissolved in acidic soils, the method has serious limitations in soils with high salt or electrolyte concentration. The calibration curve is also affected by soil-moisture hysteresis. Further, porous blocks equilibrate with soil-moisture suction rather than with soil-moisture content. Porous blocks must be calibrated for each soil, and the calibration must be periodically checked because it changes over time. Some units are insensitive to slight changes in soil moisture, and sensitivity also depends on soil temperature.

Porous blocks can also be calibrated to relate soil’s moisture content to electrical capacitance (Anderson and Edlefsen, 1942). However, electrical capacitance is more difficult to measure than electrical conductivity. The capacitance method will be discussed in relation to the electromagnetic properties and the dielectric constant.

Radiation Technique

There are two methods that use radiation techniques: one involves neutrons and the other γ-rays.

Neutron Thermalization. A neutron is an uncharged particle and almost has the same mass as that of a proton or of a hydrogen nucleus. When neutrons collide with larger nuclei, the collision is highly elastic and the loss of energy per collision is minimal. When neutrons collide with smaller nuclei, the collision is less elastic and the loss of energy is greater. Slowing down of a fast moving neutron to its thermal velocity may require 18 collisions with H, 114 with C, and 150 with O. Hydrogen in soil, in water and in organic substances (e.g., humus), has the capacity to thermalize neutrons because of elastic collisions. This characteristic is exploited in the neutron moderation technique. High-energy neutrons (5.05 MeV) emitted from a radioactive substance are slowed and changed in direction by elastic collision with the hydrogen. The process by which neutrons lose their kinetic energy through elastic collision is called *thermalization*. The loss of kinetic energy is the maximum when a neutron collides with a particle of a mass nearly equal to its own (e.g., H). The neutrons are reduced in energy to about the thermal energy of atoms in a substance at room temperature. Thermalized neutrons are counted and related to soil’s moisture content. Principles and limitations of these techniques are discussed in reviews by IAEA (1970), Bell (1976), Greacen (1981), and others.

Neutron moisture meters comprise two parts: (i) probe and (ii) scalar or rate meter (Fig. 10.8). The probe contains two components: a source of fast neutrons and a detector of slow or thermalized neutrons. The scalar or rate meter is usually powered by a rechargeable battery, and is designed to monitor the flux of slow neutrons.