Chapter 1

Rainfall runoff management techniques for erosion control and soil moisture conservation

Water generally is a limiting factor for crop production where irrigation is not available. It can be limiting even in humid and sub-humid regions where there is a theoretical need to dispose of excess water. Dry periods with water deficit frequently occur in these regions and positive responses to moisture conservation techniques are commonly obtained. Over 80% of the agricultural land of the world is not irrigated. In Africa, where a little over 0.3% of the land is under irrigation (FAO 1987), rainfed agriculture prevails. In rainfed systems the constraint is not only the erratic rainfall distribution but the amount of rainfall that can be stored in the root zone and its effective utilization.

Rain falling at soil surface may (a) infiltrate and be stored in the root zone, or (b) pass downwards to groundwater, or (c) be stored in surface depressions to either infiltrate or evaporate or run off over the surface. These disposal routes are represented in a field water balance equation (Verplancke *et al*. 1988) as:

$$P = S + D + M + U + \mathit{S}\mathrm{Edt}$$

where P is rainfall or precipitation received, S is surface runoff, D is increase in surface detention, M is increase in soil water storage, U is increase in the groundwater storage and *S*Edt is the total evaporation over a period of time.

Runoff is perhaps the greatest water management problem on rainfed crop lands because not only is it the loss of a potential water resource but it may cause damaging soil erosion.

Runoff occurs when rainfall intensity exceeds the infiltration capacity of the soil which is a measure of the ability of the soil to absorb and transmit rain water. Runoff is limited on soils with a high infiltration capacity. This in turn depends on the water transmission characteristics and structural stability of the soil and its ability to maintain continuous pores. The transmission pores may exist in the soil as a result of coarse texture, good aggregation, or from the burrowing activities of the soil fauna, particularly certain species of earthworms (De Vleeschauwer and Lal 1981; Aina 1984). The rate and amount of runoff are also influenced by the intensity and

TABLE 1
Effects of methods of deforestation and post-clearing management on erosion and runoff (Lal 1984)

Treatment	Basin area (ha)	Runoff (mm)	Soil loss (tons ha^{-1})
Forest	15	Trace	Trace
Traditional farming	2.6	6.6	0.02
Manual clearing with no tillage	3.1	16.1	0.40
Manual clearing with conventional tillage	3.2	79.7	9.8
Shearblade with no tillage	2.7	104.8	4.8
Treepusher-root rake with no tillage	3.2	170.0	15.7
Treepusher-root rake with conventional tillage	4.0	330.6	24.3

amount of rainfall received, the previous soil moisture content, the degree of relief, slope steepness and aspect. These factors manifest themselves in a wide range of runoff management problems and conservation needs.

This paper collates information on the various different runoff management techniques and discusses their effectiveness in erosion control and soil moisture conservation. Examples from diverse agro-ecological and climatic regions are given to generate wider appreciation of the problem and provide planners and managers with information with which to make informed decisions.

EFFECTS OF RUNOFF ON EROSION AND SOIL AND WATER RESOURCES

There is a pronounced relationship between rate of runoff and incidence of erosion. Runoff water has the energy to detach soil particles by scour and to transport entrained soil materials either in suspension or by pushing or rolling larger particles. In this way overland flow causes erosion. Erosion by scouring accounts for less than 10% of the erosion process, the rest being caused by raindrop impact. Secondary forms of erosion resulting from the transporting effects of runoff are more damaging and are usually classified as rill, gully and stream channel erosion according to increasing concentration of runoff and the degree of damage caused to land. Runoff erosive capacity is a function of its volume and velocity; as the volume and velocity increase, so do the energy to scour away soil particles and the load-carrying capacity or transportability. Doubling the velocity of runoff increases its scouring capacity and transportability to the fifth and sixth powers, respectively (Shaxson *et al*. 1977).

The consequences of runoff and erosion are the impairment of the quality and productivity of the land, both that eroded and that receiving soil material from upslope. Erosion results in the decline of soil fertility as a result of loss of topsoil and nutrients, loss of organic matter and clay and the consequent loss of the soil's capacity to retain nutrients and water. It can also result in the compaction and sealing of soil surface giving lower infiltration rates and increased runoff. There are many areas in the world where erosion has led to serious impoverishment of the land and rendered it unusable for crop production. Erosion is a great cause of concern in the developing world as a whole. Runoff, wherever it occurs, results in washing away of crops and fertilizer inputs, loss of soil moisture and recharge capacity, so consequently there is frequent drought stress in crop production. Runoff, as it increasingly concentrates in drainage lines, can build up and cause severe physical damage down-slope including the washing away of roads, bridges, buildings and the development of dangerous gullies. The effects of extreme runoff are usually visually emphasised by the development of gully systems along which the erosion is concentrated. Deposition of particles carried by runoff causes channel sedimentation, silting up and pollution (by nutrients, pesticides and toxic chemicals) of dams and reservoirs and flooding and sedimentation of bottomlands.

Most arable systems, especially those involving complete tree clearances, mechanical tillage and continuous cultivation, disturb the surface soil and expose it to the weather, so making the land liable to serious runoff and erosion. Deforestation by mechanized systems followed by plough-based tillage, for example, causes severe runoff and erosion (Table 1). Runoff and erosion under such systems can be very substantial and seriously limit crop production. Appropriate runoff management techniques that enhance water conservation and reduce erosion to acceptable rates will minimize these effects.

RUNOFF MANAGEMENT TECHNIQUES

Improvements in soil conditions and soil-water regime to optimize crop production can be accomplished by runoff management techniques which vary with the situation, depending on existing conservation problems, on soil and on ecological region. The various types of run-off management may be classified as those which:

- increase water intake and storage and so reduce runoff,
- control water movement over the soil surface,
- dispose safely of the excess rainfall as runoff or concentrate inadequate rainfall runoff.

Soil and water conservation are interrelated; methods that control and conserve water on hillsides also conserve the soil and control erosion.

In the arid and semi-arid regions, the choice of management is clear; all rainfall must be retained by techniques that reduce storm-water runoff, improve infiltration and increase the water storage capacity of the soil. In the humid and sub-humid areas a balance has to be struck between conservation of soil and water by runoff control and the avoidance of surface waterlogging, so the options are not as straightforward. In general, runoff is best minimized by ensuring high infiltration of rainwater into the soil through biological conservation measures. Where this cannot be done to full effect, particularly in areas of high-intensity storms or where there are periods of poor crop cover, earth works (physical control measures) can provide surface protection by holding water to give it time to soak through the surface. Such physical conservation measures involve land shaping, the construction of contour bunds, terraces and ridges. These require considerable technical design, supervision, proper construction and maintenance. In contrast, the biological methods include some soil management and agronomic cultural practices that are normally the companion of profitable agriculture such as appropriate land use and preparation, fertility maintenance, crop residue management, the use of cover crops and appropriate crop husbandry. Much research on rainfall-runoff management and its influence on erosion and soil-water conservation has been accumulated over the years. Some of the successful practices are briefly described in the following section.

PRACTICES THAT REDUCE RUNOFF THROUGH IMPROVED INFILTRATION CAPACITY AND SOIL TRANSMISSION CHARACTERISTICS

Mulch Farming

Mulch farming is a system of maintaining a protective cover of vegetative residues such as straw, maize stalks, palm fronds and stubbles on the soil surface at all times. The system is particularly valuable where a satisfactory plant cover cannot be established at the time of year when erosion risk is greatest. The beneficial effects of mulching include protection of the soil surface against raindrop impact, decrease in flow velocity by imparting roughness, and improved infiltration capacity. It also enhances burrowing activity of some species of earthworms (e.g. *Hyperiodrilus* spp. and *Eudrilus* spp. (Lal 1976)) which improves transmission of water through the soil profile (Aina 1984) and reduces surface crusting and runoff and improves soil moisture storage in the root zone. These effects have been widely reported. That a mulch effectively reduces soil loss has been shown in both field (Borst and Woodburn 1942; Lal 1976) and laboratory (Lattanzi *et al*. 1974) studies. Lal (1976) reports an annual saving of 32% of rainfall in water runoff from mulching in humid Western Nigeria. Roose (1988) (Table 2) reports drastic reductions in runoff and erosion from a mulched pineapple field on a 20% slope. The quantity of mulch required for maintenance of favourable infiltration capacity and structural stability depends on the rate of residue decomposition, climate, soil properties, relief and rainfall characteristics. Studies relating soil loss to bare ground indicate that about 70% of the soil surface must be covered by mulch to be effective and for straw, the optimum rate of mulch appears to be 4 to 6 t/ha^{-1} in the tropics, though improvements in soil physical properties have been observed up to a mulch rate of 12 t/ha^{-1} (Lal 1976). Crop residue mulch has also been known to beneficial as well when ploughed in or when brought in after the soil has been ploughed.

Favourable effects of mulching on soil and water conservation have been reported similarly for the arid and semi-arid regions (Lawes 1966; Djokoto and Stephens 1961; Adeoye 1985). Adequate or durable mulching material is less readily available in these regions with their long dry season. There are however other techniques providing utilisable mulch by using cover crops, alley cropping and no tillage.

Soil Conditioners

The size and stability of the pore spaces and the infiltration rate have been found to be improved by application of soil conditioners. Soil conditioners are oil or rubber based emulsions of poly-functional polymers that are capable of developing chemical bonds with the clay minerals in the soil, resulting in the formation of aggregates. Effective temporary erosion control achieved when the whole soil surface is covered has been found to be comparable with the 70% coverage required for erosion control using mulches and plant covers. Numerous conditioners now commercially available are yet to be fully tested with regard to: appropriate application rates; period of effectiveness; their effects on plant emergence and costs of application. Tests on the use of soil conditioners for water runoff control show that some bitumen treatments are only effective for a few storms (Gabriels *et al*. 1977). While high infiltration rates may be achieved with Poly-acrylamide conditioners regardless of the size or distribution of aggregates, for most emulsions such as asphalt and latex emulsions, aggregates must be at least 2 mm in size and ideally greater than 5 mm (Pla 1977) to be effective.

TABLE 2
Residue mulch effect on runoff and soil erosion

	Runoff (% rainfall)		Erosion (t ha^{-1} yr^{-1})	
	Bare	Mulched	Bare	Mulched
Ghana[1]	49.8	1.4	313.0	0.42
	36.4	0.33	18.3	1.9
Côte d'Ivoire[2]	29.0	0.1	410.0	1.0
Nigeria[3]	42.1	2.4	232.6	0.2
Nigeria[4]	69.0	2.0		

[1] Mensah-Bonsu and Obeng (1979); [2] Roose (1988); [3] Lal (1976); [4] Lawes (1966)

Cover Crops

Planted cover crops such as *Mucuna pruriens utilis*, *Pueraria phaseoloides*, *Centrosema pubescens*, *Setaria* spp., *Stylosanthes* spp. and *Glycine* spp. provide another technique of achieving *in situ* mulch. Fallowing with suitable cover crops conserves soil water (Pereira *et al*. 1958) improves water use efficiency, weed control and soil organic matter. It is the most satisfactory method of building up the organic content of soil. Wilson (1979) reported that dry weight of residue from cover crops can be as much as 6.5 to 11 t/ha^{-1} yr^{-1}. The effectiveness of cover crops in soil and water conservation however depends on species characteristics including ease of establishment, vigour of growth, depth of rooting, rapidity of establishment of surface cover etc. As shown in Figure 1, fallowing for one or two years with *Mucuna pruriens utilis*, *Pueraria phaseoloides*, *Centrosema pubescens* has been reported to improve soil structure and infiltration capacity (Pereira *et al*. 1958; Kannegieter 1967; Okigbo and Lal 1977; Lal *et al*. 1978).

Alley Cropping

Alley cropping is an agro-forestry system integrating trees and shrubs with annual food crop production (Kang *et al*. 1981; Vegara 1982). In this system arable crops are grown in the spaces between rows of planted woody shrubs or trees, which are pruned during the cropping season to provide *in situ* green manure and to prevent shading of crops. The beneficial effects of the system in reducing erosion, surface runoff and soil moisture loss depend on the proper choice of the protective species. Promising results have been obtained in alley-cropping arable crops (such as maize) with *Gliricidia* and *Leucaena*. The ecological compatibility of this system is yet to be established for the different eco-regions.

No-tillage Farming

Sound soil management is essential to the success of soil conservation schemes because it ensures good plant cover. No-tillage involves a method of seeding through a crop residue mulch by opening a narrow slot in the soil for seed placement without mechanical or secondary tillage operations. Chemical weed control is used. The beneficial effects of no-tillage in soil and water conservation are widely recognised in humid and sub-humid climates where the system seems to have a broad application (Table 3). The benefits include soil moisture conservation due to reduction in storm runoff, improved infiltration capacity, enhanced earthworm activity, and

FIGURE 1
Influence of cover crops on infiltration rate (Lal, Wilson and Okigbo 1978)

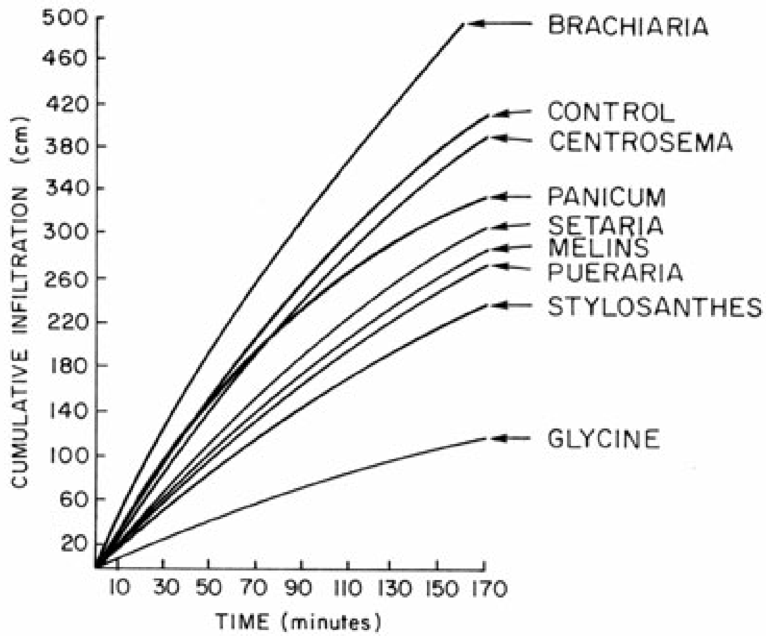

TABLE 3
Effects of tillage system on soil loss and runoff in Ghana (Mensah-Bonsu and Obeng 1979)

Treatment	Runoff (%)		Soil loss (tons ha^{-1} yr^{-1})	
	Kwadaso	Ejura	Kwadaso	Ejura
Bare fallow	49.8	36.4	313.0	18.3
No tillage	3.4	0.52	1.96	9.2
Mulching	1.4	0.33	0.42	1.9
Ridging (across slope)	1.9	1.30	2.72	4.5
Minimum tillage	1.7	1.10	4.90	3.8
Mixed cropping	13.2	5.10	33.6	2.5

reduced evaporation loss. It also reduces soil erosion and maintains organic matter content at high levels. As much as a 5-fold reduction in runoff has been reported under no-tillage compared to conventional tillage (Lal 1976). The effectiveness of no-tillage farming in soil and water conservation is improved when used in association with planted cover crops.

No-tillage systems have proven less effective on some soils especially hydromorphic soils with poor internal drainage and those with compacted surface and subsoils. Increasing costs of herbicides may also prohibit continuous use of no-tillage systems even where found suitable, thus making mechanical cultivation necessary. Soils on which no-tillage is less effective are commonly found in the arid and semi-arid regions and include

Ustropepts, Ustalfs, Alfic Eutrustox and other Aridisols, characterized by weak structure, low porosity and low infiltration rates. Note however that the beneficial effects of ploughing have also been demonstrated in the humid and sub-humid tropics (Lal 1984, 1986; Ogunremi *et al*. 1986).

Ploughing

Plough operations help to keep the upper soil layers porous at least for a short time especially in compact soils that restrict root development and infiltration. Ploughing can help to minimise runoff by assisting infiltration. To be effective over a longer term, the soil aggregates must be stable and resistant to breakdown under raindrop impact. A wide range of special tillage operations involving soil inversion, chiselling, subsoiling or deep tillage (for soils with an impeding layer within rooting depth) have been found to be beneficial in improving surface detention, storage, infiltration, root development and by minimising soil hardening (Ofori and Nandy 1969; Ofori 1973; Lal 1984; Ogunremi *et al*. 1986). The effectiveness of plough in soil and water conservation also depends on the conditions under which it is carried out and its frequency. Recent studies have emphasised the importance of cultivating only when soil conditions, particularly the soil moisture content are right to avoid structural breakdown and smearing (Davies 1974; Spoor 1975). The pulverizing effect of conventional tillage can be minimized by reducing the number of operations on the land. this can be achieved by cultivating only the small strips of land required for seedbeeds thus leaving wide untilled zones (strip zone tillage); by carrying out tillage with a mulch retained on the ground (mulch tillage) or completing as many activities as possible in one pass (minimum tillage) as with plough-plant operations.

PRACTICES THAT REDUCE RUNOFF BY CONTROLLING WATER MOVEMENT OVER THE SURFACE

The principle of these practices is to minimise the concentrations of runoff volume and to slow down the runoff velocity, allowing the water more time to soak into the soil, limiting its capacity to transport soil particles and diminishing its ability to cause scour erosion.

Strip Cropping

This is farming of sloping land in alternate contoured strips of intertilled row crops and close-growing crops (for example, a cover crop or grass) aligned at right angles to the direction of natural flow of runoff. The close-growing strip slows down runoff and filters out soil washed from the land in the intertilled crop. Usually, the close-growing and intertilled crops are planted in rotation. Strip cropping provides effective erosion control against runoff on well-drained erodible soils on 6 to 15% slopes. The width of the strips is varied with the erodibility of the soil, and slope steepness. Reference is usually made to tables of recommended widths (FAO 1965).

Contour Farming

Contour farming involves aligning plant rows and tillage lines at right angles to normal flow of runoff. It creates detention storage in the soil surface horizon and slows down the runoff thus giving the water time to infiltrate into the soil. The effectiveness of contour farming in water and soil conservation depends not only on the design of

TABLE 4
Soil loss and runoff from plots and watersheds under different management systems

Site	Management	Soil loss t/ha/yr	Runoff %
Samaru[1]	Broadlands	21.0	20.4
	Cropped ridges (downslope)	19.6	27.9
	Cropped alternate tied ridges	5.7	18.2
	Flat cultivation (bare)	3.8	25.2
	Flat cultivation (arables)	4.0	20.3
Burkina Faso[2]	Tied ridges	1.4	0.9
	Sloping ridges	6.1	6.3
	Ploughed ridges	13.2	12.2
Ibadan[3]	Bare (runoff plots)	232.6	42.1
	Mulched (runoff plots)	0.20	2.4
	Terraced (watershed)	0.66	18.1
	Unterraced (watershed)	2.25	18.8
Sierra Leone[4]	Bench terracing	7.5	
	Stone bunding	29.5	
	Stock bunding	27.3	
	Contour bunding	18.0	
	No conservation	46.7-54.5	

[1] Kowal (1970); [2] Fournier (1967); [3] Lal (1976; 1983); [4] Millington (1985)

the system but also on soil, climate, slope aspect and land use. the beneficial effect is least marked on compact or slowly permeable soils because these become saturated quickly compared to highly permeable soil. Contour bunds are another important physical measure. These are earth banks, 1.5 to 2 m wide, forming buffer strips at 10 to 20 m intervals across the slope. Although little reduction in runoff occurs, there is considerable reduction in soil loss as demonstrated by Roose (1967) in West Africa.

Ridge and Mound Tillage

The ridge-furrow system is a commonly used physical conservation practice. Ridge-and-furrow systems when aligned parallel to the contour lines have the dual purpose of erosion control and surface drainage. Their advantages are greater, the less steep the terrain and the more permeable the soil. Fournier (1967) reported a 7 to 13-fold decrease in erosion and runoff in parts of West Africa due to ridging (Table 4). Ridge-tying is also an effective soil and water conservation system especially in arid and semi-arid regions. Mounds and tied mounds are also effective in conserving water and soil. the effectiveness of tied-ridges depends on soil, slope, rainfall and design characteristics. Tied ridging on clay soils may induce waterlogging which may be followed by mass movement (Gray and Brenner 1970). In severe storms, poorly designed ridge-furrow systems may fail, the row catchments can over-top and the water flow unimpeded down the slope with the danger of it accumulating enough energy to scour and transport soil.

Generally, for small landholders with only hand implements or animal traction and low-value subsistence crops, the ridge-furrow system used along the contour is a satisfactory method of enhancing infiltration and reducing runoff. Tying ridges or mounds to permit more rainwater to infiltrate is an effective system in drier areas (< 1000 mm annual rainfall) on gentle slopes (< 7%) but not in wet years or more humid areas. Other useful practices for small farmers include contour planting and strip cropping. For large-scale mechanized farming, additional devices to cope with large and exceptional runoff are necessary. These include: terraces and contour bunds to break up long slopes; and diversion channels and watercourses to dispose safely of unavoidable runoff.

Terrace Farming

Terrace farming involves earthworks made at right angles to the steepest slope consisting of an excavated channel on the uphill side, the spoil from which forms a bank on the downhill side. It converts a steep slope into a series of steps with horizontal or nearly horizontal ledges and vertical walls of stone, brick or timber between ledges. Terraces are built by various techniques and called (according to method of construction) bench terraces; diversion terraces with mangum; Nichols terraces; broad-based and narrow-based types; channel terraces; retention terraces etc.

Although commonly found in many parts of the world, for example, Peru, Malawi and the Philippines, and effective in soil and water conservation as shown in Table 4, terraces are prohibitively expensive, relative to returns from subsistence farming, to construct and maintain. they are more often a legacy from the past than part of present day development schemes. A design procedure for terraces which reflects soil type, slope, hydrological and rainfall characteristics may be found in Schwab *et al*. (1966). Retention and bench terraces are generally usable on slopes up to 8% and slope of 12% to 40% respectively.

PRACTICES THAT PERMIT SAFE DISPOSAL OF RUNOFF

Where land use management alone is insufficient to prevent runoff, the excess water has to be removed without causing erosion.

Undesirable runoff can be intercepted or diverted from an area above cultivated land and led away safely by a combination of physical measures including interception terraces, diversion ditches or stormwater drains, waterways and terrace channels. The interception terraces and diversion ditches are placed upslope of areas where protection is required to intercept runoff on the hillside and channelled across slope at a non-erosive velocity along a nearly level, gently-graded, terrace channel, to a suitable outlet which may be a natural or artificial waterway. Diversion terraces are recommended on slopes up to 12%. Waterways are smooth channels usually lined with sods for the safe removal (without erosion) of runoff water. Grass sod is the most satisfactory and economical protection for waterways. Sod waterways are best suited where runoff is intermittent as permanent streams can kill the grass. Effectiveness of sod waterways depends on the design criteria and adaptability of the sod species to the climate and soil. Grass-lined waterways have become less popular in recent years because they take up land which could otherwise be used for crops and increase cost of maintenance. In the USA, they are now being replaced with tile drains.

In arid regions, another method of runoff management and utilization is to concentrate any surplus rainfall-runoff by water harvesting techniques thus concentrating it sufficiently to obtain useful plant growth. The earliest water harvesting systems date back to the times of the Nabateans and others in the Negev Desert of the Middle East before the time of Christ. Although the basic idea is ancient, recently the possibilities of improving efficiency of water harvesting by use of thin asphaltic pavements to increase runoff have been investigated.

CONCLUSIONS

Most developing countries undertake too little research on runoff management. The work done is inadequate to provide proven alternative practices for erosion control and soil moisture conservation. Although some basic concepts in this field are potentially of universal application, conservation practices developed in one country need testing and verification, especially in relation to rainfall, soil and local cropping practices, before they are adopted elsewhere. Runoff management is based on the principles of minimising the concentrations of runoff volume, slowing the runoff velocity so diminishing its capacity to cause scour erosion. It aims to enhance surface detention storage, thus allowing the water more time to soak into the soil, and to conduct away unavoidable runoff non-erosively. A wide range of runoff management techniques are in use. Because the choice of appropriate measures depend on soil, topography, climatic and socio-economic considerations, generalisation about their applicability is difficult. The techniques are broadly grouped into biological and physical protection measures.

Biological control measures combining good agronomic and soil management practices are directed at selecting land uses that provide good protection of the soil from raindrop impact, increase surface depression storage and infiltration capacity of the soil to reduce the volume of runoff, improve soil aggregate stability to increase its resistance to erosion and increase the roughness of the soil surface to reduce the velocity of runoff. Mulch farming appears to be an effective conservation measure in all ecological regions especially when used with planted cover crops. Mulch farming in combination with a no-tillage system has a wide application and is an effective conservation technique for grain crop production on a range of soils in the humid and sub-humid regions. It is not so effective in arid and semi-arid regions with naturally compact surface soils, where ploughing and subsoiling have been found to be effective. Ridging is widely practised and is effective in soil and water conservation, especially contour ridging in the more humid regions and tied riding in the semi-arid and arid regions. As shown by Temple (1972), biological measures are easily incorporated into existing farming systems. Physical conservation measures such as terraces and contour bunds are considered of secondary importance in runoff management for small-scale farmers but it may be necessary for large-scale mechanized farming to cope with larger exceptional runoff on steep cultivated lands. The use of terraces and contour bunds as physical protection measures is limited by the poor socio-economic conditions of farmers in developing nations. Because of prohibitive costs of construction of terraces, other methods such as contour hedges, straw barriers and buffer strips of grass or alley cropping are often suggested for use on steep cultivated lands. Where a risk of runoff remains, an artificial drainage or waterway (sodded) system is constructed to dispose of it non-erosively.

The most appropriate strategy for runoff management depends upon identifying the key factors influencing runoff and applying appropriate techniques based on acquired knowledge.