Chapter 9

SOIL EROSION AND SOIL CONSERVATION FOR VERTISOLS

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9.1. INTRODUCTION

Soil erosion is frequently cited as a major limitation to long term production on Vertisols (Hudson, 1984; Lowole, 1985). This is a consequence of their low infiltration rates when wet, and relatively high erodibility. Because Vertisols are difficult soils to manage, being strong when dry and sticky when wet, and have the capacity to store large amounts of soil water, cropping systems have evolved that have long periods without crops, commonly leaving soils susceptible to high intensity rain when infiltration capacity is low and little crop or residue cover is available. Construction of earthen banks to reduce slope length has been the mainstay of erosion control measures. The cost and inconvenience of these structures make such measures unpopular in many cropping systems around the world.

While many management practices for erosion control are not specific to Vertisols, there are some features of Vertisols which require them to be considered separately. Soils high in clay have not been extensively researched in terms of water relations and erosion processes, and are not well dealt with in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), with only one site used to determine a K (erodibility) factor.

This chapter reviews the literature dealing with erosion on Vertisols, and also presents as a case study the linkages in a research program based in the northern cereal production area of Australia. Findings from this region have some generality due to the wide range of crops grown and landscape features. Prediction of soil erosion on Vertisols will be discussed and some applications demonstrated, including the extension of experimental data and consideration of some interactions between management, erosion and production.

9.2. SPECIAL FEATURES OF VERTISOLS

One of the difficulties faced in research and management of Vertisols has been a failure to realise that these soils differ from rigid soils in a number of important respects. Attempts to apply techniques appropriate to rigid soils have produced both misleading and unsatisfactory results. This section examines important differences between Vertisols and more rigid soils, as well as evidence of variability between Vertisols.

Textures of Vertisols range from light to heavy clay, with clay contents varying from about 30 to more than 80 percent. If the soil is considered as a binary mixture of coarse and fine particles (sand and clay respectively), then a coarse matrix could be expected for clay contents <35 percent clay (Bodman and Constantin, 1965), where sand grains are in contact and clay particles pack into the pore spaces between them. At higher clay contents, a fine matrix occurs, with sand grains embedded in a matrix of clay particles. The transition from coarse to fine matrix is not as clearly defined in field soils as it is in remoulded mixtures with fixed sand and clay properties (Smith, 1984). This can be attributed both to variations in clay mineralogy, with soils higher in clay tending to have higher proportions of more strongly swelling clays (Smith, 1984), and to dilation of the coarse particle matrix (Smith et al., 1978) due to orientation of clay particles around sand grains.

From void ratios, Smith (1984) identified two groupings of Vertisols, based on clay content:

(i) a matrix co-existence region (approx. 35–50 percent clay), and

(ii) a fine matrix region (greater than about 50 percent clay).

Cracking clays fall predominantly in the fine matrix group, but it should be noted that the properties of all Vertisols will be strongly influenced by clay properties because the soil framework is primarily clay.

The dominance of clay in aggregation of Vertisols means that these soils tend to be strongly aggregated, and hence erode largely as aggregated material. Therefore, erosion and erodibility of Vertisols are strongly affected by aggregate (sediment) properties—size (as affected by stability to wetting), wet density and water uptake on wetting. It also means that sediment eroded from Vertisols is often relatively coarse and deposits readily.

Also, Vertisols in the "fine matrix" group are largely self-mulching, and therefore not subject to consolidation under successive rainfalls. Self-mulching soils behave as if they have been recently-tilled most of the time, greatly increasing the supply of loose material.

9.2.1. High erodibility

Vertisols tend to be highly erodible. For example, Freebairn and Wockner (1986) reported a 7-year average annual soil loss from a black, cracking clay under wheat/bare fallow cropping of 61 t ha^{-1} with land slope of 5–7 percent. For a grey clay in the same region, with slopes of 4–5 percent and shorter slope lengths (35–40 m cf. 56–61 m), they reported a 7-year average annual soil loss of 32 t ha^{-1}. For the Vertisols that dominate the eastern uplands of the Darling Downs, erosion from a single extreme rainfall/runoff event (approximate amount: 92 mm, I_{30}: 104 mm h^{-1}, and EI_{30}: 264 metric units) ranged from 10–25 t ha^{-1} for areas under grazed crop to 400–450 t ha^{-1} for areas of finely tilled soil (Marshall et al., 1980).

Similarly, erodibility indices are high. Erodibility (K factors in metric units) reported for the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) for three clay soils by Loch and Rosewell (1992) were 0.40, 0.30 and 0.44, with the lowest value being considered an underestimate. In comparison, of K values reported in the USLE Handbook for 23 US soils on erosion research stations, only one soil had a metric K value >0.40, only three had values greater than 0.30, and 14 had K values lower than 0.25 (metric).

9.2.2. *Why are Vertisols highly erodible?*

The higher erodibility of Vertisols appears to be due partly to higher rates of sediment transport resulting from their distinctive sediment characteristics, and, for some Vertisols, to the effects of self-mulching on soil strength and hence, on erosion processes.

(1) Low sediment density

For many soils, eroded sediment contains a high proportion of aggregates (Young, 1984). This is particularly true for Vertisols. For example, for a black, cracking clay on the eastern Darling Downs, Queensland, Loch and Donnollan (1983b) reported that although the soil contained 72 percent clay (<2 μm), generally only 6–10 percent of the sediment was <2 μm. With much of the sediment being aggregated, densities of sediment particles from swelling soils can be relatively low. Loch and Donnollan (1983b) used aggregate water contents to estimate a wet density of 1.42 Mg g^{-1} for sediment from a swelling clay, compared to 1.76 Mg g^{-1} for sediment from an Oxisol. Although sediment sizes for the two soils were similar, approximately 80 percent higher rates of bedload transport were associated with the lower sediment density of the Vertisol.

Loch and Rosewell (1992) reported that erodibilities predicted by the USLE nomograph (Wischmeier et al., 1971) were consistently low for soils that were high in clay and had low wet densities of sediment. They suggested that the soils on which the nomograph was based generally had low clay contents and wet aggregate densities in the order of 2.2 Mg g^{-1}. Estimates of wet sediment densities for a range of soils (based on comparisons of equivalent sand sizes derived from settling velocities with size distributions from wet sieving) showed that wet density was strongly related to the proportion of sand >0.020 mm. Therefore, densities of wet sediment can be predicted from readily-available data. Reasonable estimates of USLE K factors could be obtained if the Wischmeier et al. (1971) nomograph was based on a measurement of aggregate breakdown to <125 μm under high energy rain, provided the estimate of K was then modified to take account of density of wet sediment. This calculation effectively makes wet sediment density the major determinant of K. They noted that wet sediment density would be related to K factors not only via effects on rates of sediment transport, but via self-mulching, and hence, soil strength and resistance to entrainment.

(2) Sediment size distribution

Sediment size distributions of Vertisols do not appear to be greatly different from those measured for other soils (Loch et al., 1989a). Also, data on aggregate

TABLE 9.1.

Effects of erosion process on the proportion of particles <0.020 mm in sediment eroded from rainulator plots.

Soil	Percent of sediment <0.020 mm in sediment from plots eroded by:	
	Rilling and rain-flow	Rain-flow only
Irving clay	17.9	35.8
Moola clay	16.7	44.0

breakdown at the soil surface under rain indicate no major differences between Vertisols and other soils (Loch and Foley, 1994). However, there are concerns for all soils in establishing valid concepts of "sediment size" and in making realistic measurements thereof.

"Sediment size distribution" is not a constant property of a soil. Sediment sizes leaving some defined area will vary depending on the processes of both detachment and deposition that are operating. For rainulator plots on a cracking clay, Loch and Donnollan (1983b) found that the proportion of sediment <2 μm was greater for non-rilled plots, and a similar effect of erosion on sediment size was reported for a grey clay in the same region by Loch and Thomas (1987) (Table 9.1).

(3) Prediction of sediment sizes

Process-based erosion models such as CREAMS (Knisel, 1980) require information on the sizes of particles available for entrainment and deposition. Prediction of sediment sizes has a number of inherent difficulties that become even more critical when dealing with Vertisols, and at this stage, there is no method for sediment size estimation that appears relevant to all soil types. Therefore, this section outlines some of the perceived difficulties, and suggests alternative approaches.

The first requirement in the prediction of sediment sizes is some definition of what the estimated size distribution represents. Logically, the only estimate relevant to an erosion model is the size distribution at the point of *initial entrainment*. This rules out the use of measurements of sediment removed from a plot where sorting and deposition may have occurred. Also, the degree of deposition and selective transport can vary with plot size, runoff rates, and erosion processes. It is possible to attempt to create conditions where deposition is absent or minimal (Rhoton et al., 1982), but it is doubtful whether that approach is successful, especially for soils that include a proportion of coarse particles, e.g., >1 mm, that may not be moved at all by some processes of erosion. Moss (1991) noted that particles >1 mm were relatively immobile on rain-impacted surfaces.

Also, the processes of erosion that are of interest need to be taken into account. For example, sediment available for initial entrainment by rill erosion would refer to particles (aggregates and primary particles) present in a much deeper layer of soil (and having coarser sizes) than the shallow surface layer of soil exposed to interrill (raindrop dominated) erosion. Therefore, the wetting process used to generate a sample of "sediment available for erosion" must also take account of the erosion processes for which a measure of sediment size is required. Any laboratory method of estimating sediment size must also consider wetting rates and kinetic energy of rainfall.

Vertisols have been reported to be sensitive to wetting rates (Coughlan, 1979, 1984), and use of immersion wetting for Vertisols appears particularly ill-advised. Loch and Foley (1994) showed that steady infiltration rates of high energy simulated rain were strongly correlated with the percentage of particles <125 μm at the soil surface under high energy rain; much less strongly correlated with breakdown to <125 μm after immersion wetting; but the correlation was greatly improved if swelling soils were excluded from the immersion-wet data set.

In many respects, it is easier to incorporate rainfall in a laboratory method, as the kinetic energies and soil conditions associated with raindrop impacts are easier to produce via simulated rain than they are to simulate via some treatment of the sample such as shaking or ultrasonic dispersion. Therefore, it is advisable for any laboratory method for estimating sediment sizes to be based on rainfall wetting.

(4) Splash detachability

Because of their self mulching nature, light sediment and tendency not to hard set, Vertisols appear to be highly detachable. Table 9.2 shows that splashed soil greatly exceeded the weight of soil eroded from the plots under simulated rainfall at all except the highest rainfall intensities. At the highest intensities (and resulting higher runoff rates), not only was sediment transport in flow more efficient, but the greater flow depths reduced the proportion of the plot projecting above ponded water and contributing splashed sediment.

While raindrop action is no doubt an important mechanism for detachment of soil for subsequent transport, Loch and Foley (1994) have shown that aggregate

TABLE 9.2

Comparison of sediment loss from 12 m^2 rainulator plots on an Irving clay with splash trapped in containers set into the soil surface.

Plot No.	Rainfall intensity (mm/h)	Kinetic energy of Rain ($J\ m^2\ mm^{-1}$)	Total sediment loss from plot ($t\ ha^{-1}$)	Total splash ($t\ ha^{-1}$)
1	70	25	1.8	11.5
2	100	25	6.0	14.6
3	180	25	6.2	7.6
4	200	25	15.1	15.5
5	60	17	0.6	8.3
6	130	17	5.1	8.1

breakdown under rain is little affected by raindrop energy for a wide range of soils. However, there is evidence that the processes of detachment and transport cause aggregate breakdown, and it seems that higher proportions of finer sediment sizes in rain-flow eroded sediment are at least partly due to increased aggregate breakdown rather than sorting alone. Loch and Donnollan (1988) showed that the proportion of sediment $<20\,\mu m$ in runoff from $12\,m^2$ rainulator plots on a black cracking clay was related to the proportion of plot surfaces exposed to raindrop impact, leading to the conclusion that drop kinetic energy is an important factor in dispersing clay from aggregates in these soils. Similarly, Govers and Loch (1993) found that rates of rill erosion on two Vertisols appeared to be related to wet strength of aggregates, as a soil with high incipient failure was more susceptible to entrainment than a soil showing little evidence of incipient failure. This finding suggests that detachment by rill flow largely entailed aggregate breakdown for those soils.

(5) Wet aggregate strength

Wet aggregate strength can be inferred to be a major factor affecting rates of rill detachment for a range of soils. Govers et al. (1990) showed a good relationship between water uptake on wetting and rates of rill erosion of a loamy soil. Govers and Loch (1993) found a similar relationship for two Vertisols. As the amount of water uptake on wetting is an indication of the stresses imposed on aggregates during wetting (and may also be related to the rate of water uptake), it is also likely to be a reasonable indicator of wet aggregate strength. There appears to be potential to use water uptake on wetting to assess both erodibility and its short-term variations due to antecedent soil water contents across a wide range of soils.

9.2.3. Response to slope length

Measured responses of erosion to slope length are highly variable (Foster et al., 1982a). The USLE describes responses to slope length (the L factor) as being

$$L = (x/72.6)^m$$

where x is the slope length being considered (in ft); 72.6 refers to the reference 72.6 ft slope length, and m is an exponent. Measured values of m varied from 0 to 0.90, indicating that responses range from no increase in erosion with extra slope length, to, at greatest, a near linear increase (i.e. double the length would double the erosion rate). Variation in slope length responses may be associated not only with soil differences, but also with variations in surface soil strength associated with variations in tillage frequency.

The vertical profile of shear strength resulting from tillage has important effects on rill erosion, and hence on responses to slope length. Firstly, there is little resistance to rill initiation on self-mulching soils. Loch and Donnollan (1983a) noted that for a tilled Vertisol and Oxisol, critical discharges for rill initiation were similar to those reported by Moss et al. (1982) for a cohesionless 200 μm sand, and suggested that the loosely tilled soils behaved as beds of cohesionless particles. bservations of rilling on field areas of self-mulching soils show a very high density of rills, consistent with low resistance to rill formation. Little comparative data are available on Vertisols' susceptibility to gullying except that of Crouch and Novruzi (1989).

Consolidation and increased resistance to erosion in the absence of tillage has been reported (Alberts et al., 1980; Foster et al., 1982a), although self-mulching soils show little consolidation under successive rainfalls, nor any associated increase in resistance to erosion (Loch and Donnollan, 1989). Shear strengths and bulk densities measured by Loch and Donnollan (1989) immediately after wetting of a self-mulching clay in tilled and untilled condition showed little difference in either property between tilled and untilled soil in the 0–500 mm layer. Whether tilled or not, the surface layer had very low wet shear strength (2–4 kPa), with much higher shear strengths (34.7–38.7 kPa) in the undisturbed layer below plough depth. The main difference between tillage histories was that in tilled soil the layer of low strength was deeper.

Responses of rill erosion to increasing slope length or discharge are influenced by this abrupt transition from loose soil of low strength to an undisturbed and relatively less erodible layer. As discharge increases, the extra flow is initially accommodated by a slight increase in flow depth, followed by widening of rills (Loch and Donnollan, 1989). Consequently, rill depth remains relatively constant while transport capacity per unit width of rill does not vary greatly, and rill sediment concentrations remain relatively constant across a range of discharges (Loch and Donnollan, 1983a).

If increasing discharge is equated with increasing slope length rather than increasing runoff rates on a unit area basis, this result can be interpreted as suggesting that slope length will have little effect on erosion—for the situation where a surface layer of very low strength overlies soil of considerably greater strength. Many tilled soils other than Vertisols would fit this description, though they would fit it less consistently (due to occasional consolidation in the absence of tillage). Data for cracking clay soils in Texas, U.S.A. (Smith et al., 1954; Smith and Henderson, 1961) confirm the lack of effect of slope length on erosion rates.

The temporal pattern of rill erosion on self-mulching soils can provide some traps for experimentation. If, under experimental conditions, a fixed discharge is applied for some time, sediment available for transport is rapidly depleted as the rills incise to a non-erodible layer (Loch and Donnollan, 1989; Maroulis et al., in prep; and Govers and Loch, 1993) This depletion of sediment can cause the relative importance of rilling to be underestimated (Maroulis et al. in preparation). Data from rainulator plots on Vertisols in Queensland suggest that for relatively short runoff events, rilling may contribute approximately 65 percent of eroded sediment (Loch and Donnollan 1983a; Maroulis et al., in preparation), which is a similar estimate to those from a range of studies on other soils (Govers and Poesen, 1988; Crouch and Novruzi, 1989).

9.2.4. Contrasting infiltration capacity

An understanding of infiltration behaviour of soils is necessary where erosion control relies partly on modifying the hydrology of a cropping system. A distinguishing feature of Vertisols is their very high infiltration capacity when dry and cracked in contrast to low infiltration rates (4–0.25 mm h^{-1}) when wet (Swartz, 1966; Freebairn et al., 1984).

Low infiltration rates are generally a result of (i) a crusted surface (<1 cm thick layer) (Freebairn et al., 1984), (ii) a wet surface layer (>10 cm) or, (iii) a wet profile (Swartz, 1966). In the first two cases a shallow layer restricts infiltration even though a moisture deficit exists and cracks may be present, although not hydraulically connected to the surface. When the profile is fully wet, infiltration is determined by the hydraulic conductivity of the soil matrix. The role of residual cracks as pathways for infiltration is not well described but suspected as an important pathway for internal drainage of Vertisols.

When Vertisols are dry, wetting has been observed to occur from the bottom up. This occurs when flood irrigation or local runoff moves directly to the bottom of the water extraction profile via cracks (Fig. 9.1). In flood irrigation conditions, advancing water infiltrates quickly by filling crack voids (Collis-George and Freebairn, 1979). Redistribution within the soil blocks between cracks probably takes many days or weeks before equilibrium is achieved.

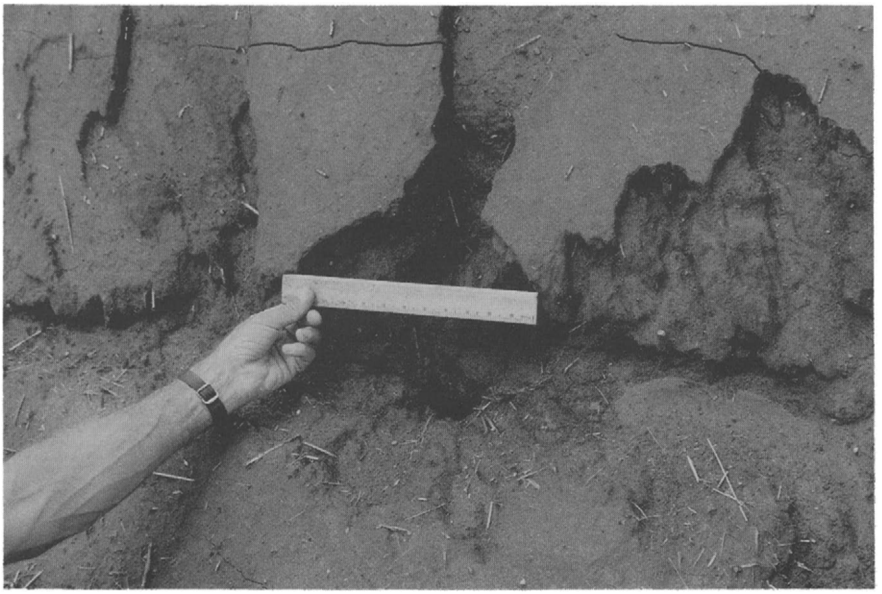


Fig. 9.1. Rills cutting back from cracks due to local runoff.

9.3. MANAGEMENT OPTIONS FOR EROSION REDUCTION

Since Vertisols occur in a wide range of locations with diverse cropping systems, we will deal with the principles of erosion control rather than specific practices. Even though many factors influence both hydrology and sediment detachment and transport, it is useful to separate these processes. Factors which reduce runoff volume and runoff velocity will be considered.

9.3.1. Reducing runoff volume

(1) Soil moisture deficit

Soil moisture content is the most important factor in determining the proportion of rainfall which will infiltrate (Fig. 9.2.). A statistical analysis of runoff data (550 runoff days) from two catchment studies in southern Queensland showed that apart from event rainfall, antecedent 10 day rainfall (an index of soil water status) was the most significant factor determining runoff amount. Rainfall intensity and energy, cover and roughness were less important.

Although seasonal conditions have a strong (and unavoidable) influence on soil moisture, sequence and number of crops grown have a major effect on the timing of soil water deficits during the year and hence on runoff (Adams et al., 1959; Smith and Henderson, 1961). As an example, runoff and soil erosion from a winter and summer crop rotation in a summer rainfall environment are presented in Table 9.3. Less runoff results from a summer crop system because crop water use coincides with the summer-rainfall maximum. Fallowing during the rainy season on Vertisols in India results in high runoff and poor water use efficiency. One element of a system to improve water use efficiency includes planting of crops

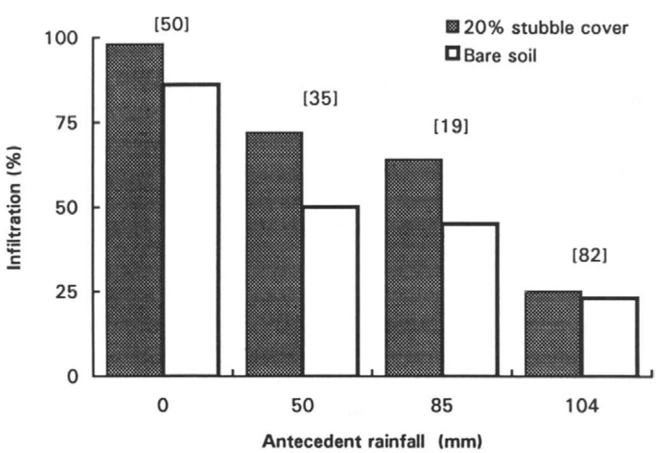


Fig. 9.2. Influence of antecedent moisture (rainfall) on infiltration for a series of storms on a grey clay soil on the eastern Darling Downs, Queensland. Storm rain in brackets [ ].

TABLE 9.3

Runoff and soil movement for two crop sequences from a Black Earth on the Darling Downs (Greenmount, 1978–84)

		Crop sequence	
		Winter crop (wheat) summer fallow	Summer crop (sorghum) winter fallow
Runoff	mm	96	53
Soil movement	t ha^{-1}	71	26

before the onset of the wet season, to make better use of incident rainfall and reduce runoff (Krantz, 1980).

Increasing cropping intensity can also reduce runoff by increasing the time period when the soil has a large soil water deficit—such a practice can also result in greater total productivity although yields per crop may be reduced (Berndt and White, 1976; Freebairn et al., 1991). The concept of "opportunity" cropping has been practised to a limited extent in the semi-arid tropics of north eastern Australia. Opportunity cropping involves matching cropping intensity with rainfall expectancy and current moisture conditions (which are a function of recent crop and rainfall history). Crop rotations are planned more on current conditions rather than a fixed pattern, thus exploiting above-average rainfall conditions when they occur (Fig. 9.3). Soil water status needs to be monitored for such a management technique to succeed. This can be achieved through simple hand driven soil probes which detect soft or moist soil, through to direct sampling and gravimetric moisture

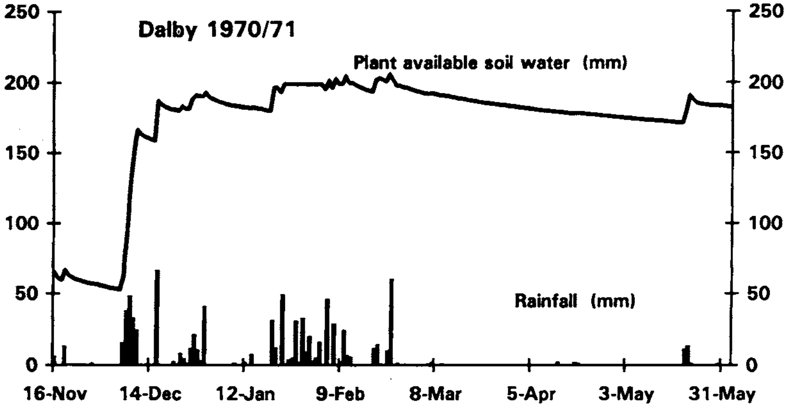


Fig. 9.3. Soil water accumulation during a fallow after wheat harvest in November. Above average rain in December recharged the soil water store. Extending the fallow beyond mid December would be wasteful and result in high runoff and erosion potential.

determination. Most farmers do not see the value in what appears to be a laborious process to determine soil water, but after a limited number of detailed estimates, they become adept at good estimates based on feel of the soil and examination of rainfall records.

(2) Cover

The soil surface may be protected from raindrop impact by the canopy of a growing crop and crop residue. Soil cover reduces the volume of runoff by reducing raindrop energy dissipated on the soil, thus reducing aggregate breakdown, compaction of the surface by rain drops, loss of transmission pores (Loch, 1989) and resultant surface sealing (McIntyre, 1958; Glanville and Smith, 1988). Maintaining higher infiltration rates and increasing the time before surface ponding occurs, leads to increased infiltration, especially during high intensity rainfall.

The effectiveness of surface cover is influenced by soil water status. Surface cover reduces raindrop impact and maintains crack continuity, especially when a moisture deficit exists (Fig. 9.4). When the soil profile is near field capacity or has maximum moisture content in the surface layers, very little scope exists to modify infiltration behaviour using management options as the soil profile, rather than surface characteristics, control water entry.

The amount of crop residue available to provide surface cover is determined by crop type, yield and tillage method (Sallaway et al., 1988; Unger and Jones, 1989). Tillage that breaks down or buries crop residue results in higher runoff compared with tillage that leaves more residue on the surface (compare bare fallow, stubble incorporated and stubble mulch, Table 9.4). Reduced tillage or zero-till fallow practices have been developed which result in less stubble

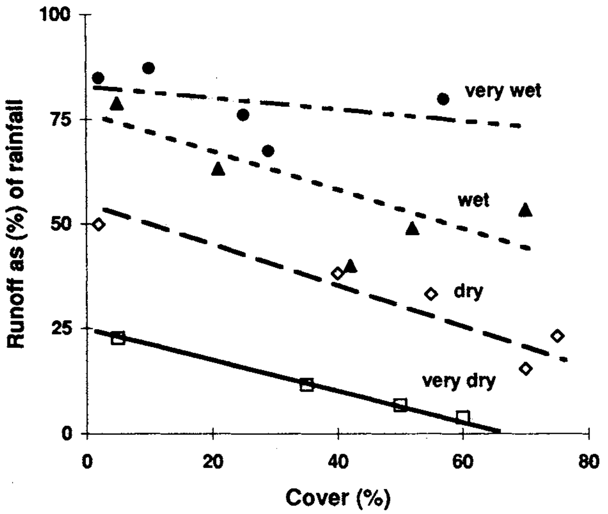


Fig. 9.4. Runoff as influenced by cover and soil moisture content for a black earth.

TABLE 9.4

Mean runoff, fallow efficiency, and yield for four management options at Greenmount. Mean of eight years, 1978–79 to 83–84, 1986–87 to 87–88 (after Wockner and Freebairn, 1991)

		Fallow management			
		Bare fallow, stubble burnt	Stubble incorp.	Stubble mulch	Zero tillage
Cover[a]	%	<10	50–10	>40	>70
Runoff	mm	98	75	71	81
Fallow efficiency[b]	%	16	17	20	21
Soil erosion	$t\ ha^{-1}$	64	20	8	4
Wheat yield	$t\ ha^{-1}$	2.78	2.78	2.95	2.77

[a]Cover during the summer fallow period (November–May).
[b]Fallow efficiency is the percentage of fallow rainfall stored in the soil at planting.

breakdown (Unger and Stewart, 1988; Freebairn et al., 1986a) and minimise the deleterious features of tillage while maximising water storage. This has been achieved through the use of sweep or tine implements and herbicides.

(3) Tillage, roughness

Tillage is an operation over which farmers have considerable control, and is therefore a target for attention when developing improved management practices for soil and water conservation. Tillage modifies aggregate and pore size distribution, roughness, residue cover and strength of the surface soil.

Tillage can increase infiltration by breaking surface crusts, increasing surface porosity and surface storage capacity (El-Swaify et al., 1985; Pathak et al., 1987). An example of the modifications of the soil surface due to tillage is the use of primary tillage to create a rough and porous surface. Subsequent tillage and rainfall reduce roughness and generally result in reduced porosity of the tilled layer. Further tillage may be needed to prepare a seedbed if the surface is cloddy.

Smooth soil surfaces associated with no-till systems can result in higher runoff compared to tilled soil (Table 9.4). For example, during a summer fallow (1988–89) runoff from a hard setting Vertisol with chisel tillage (rough) and no-tillage (smooth) was 16 and 34 mm respectively. Tillage operations on the chisel tilled catchments created surface roughness and broke the crust formed by rainfall.

Depression storage can be purposefully constructed using specialised tillage equipment. Its function is to store excess rainfall, allowing more time for infiltration. Such storage is variously referred to as furrow dikes, tied ridges or pits. Using simulated rainfall on 1 m^2 plots on a Vertisol in Queensland, S. Glanville (personal communication) found that both surface pitting and cover improved infiltration. Similar pitting applied to 3 ha catchments showed no effect on runoff over 3 years, highlighting the sometimes contradictory results from experiments at different scales. Observation after a intense rainfall event of adjacent field areas tilled with tine furrows and with pits either present or absent indicated that overland flow was less organised where pits had been created, with less rilling. It is uncertain whether total soil movement was reduced.

A particular example of surface configuration used to improve productivity and reduce risk is the broad bed and furrow system developed for Vertisols at ICRISAT (El-Swaify et al., 1985; Virmani et al., 1989). Crops are sown into a bed approximately 1 m wide separated by furrows 15 cm deep with a bed slope of 0.4–0.8 percent. This system reduces the risk of waterlogging, and by controlling runoff, reduces soil erosion (Kampen et al., 1981). Such a system is an alternative to graded banks or terraces and has particular advantages where farm sizes are small.

Deep tillage (20–40 cm depth) has been practised to reduce runoff, improve water storage and root growth but results have been variable. Radford et al. (1992) found no benefit to wheat and sorghum from "paraploughing" in southern Queensland while Mead and Chan (1988) found that any beneficial effect of deep tillage was short-lived. In contrast Postiglione et al. (1988) found that tillage reduced runoff and erosion on a steep (14 percent) vertic soil in southern Italy. The variability in results between studies indicates that there should be caution exercised in generalities.

(4) Crack management

The cracking nature of Vertisols offers potential to capture intense falls of rain which might otherwise runoff. Nevertheless, it is a common practice to cultivate the soil after harvest, regardless of weed growth or soil water status, especially where mechanical tillage is available to deal with high strength soils when dry.

Water movement to depth via cracks, sometimes referred to as "wetting from the bottom up", can occur during high intensity rainfall, and provides a means for improving the efficiency of water storage (Fig. 9.5). Cabidoche and Ney (1987) found that water entry was reduced in Vertisols when cultivated. Infiltration was largely dependent on the presence of crack voids with continuity to the surface. In their irrigated situation, high soil water content was maintained, thus reducing the opportunity for cracks to reform. They found that yield from tomatoes was increased when cultivation which obliterated soil cracks was avoided.

9.3.2. Reducing runoff erosivity

The drag or shear stress which occurs when water flows across a soil surface is an important force in detaching (Rose, 1985) and re-entraining soil (Hairsine et al., 1992). Flow velocity is the product of several factors and is the final determinant of stresses applied to the soil from overland flow. The modified USLE's introduced the concept of runoff erosivity, by replacing the rainfall erosivity term of the USLE with indices of rainfall and runoff energy (Onstad and Foster, 1975; Williams, 1975). Rose (1985) developed Bagnold's (1966) concept of stream power to describe the erosive power of overland flow. Erosive forces can be modified by changing the effective slope and velocity of runoff water.

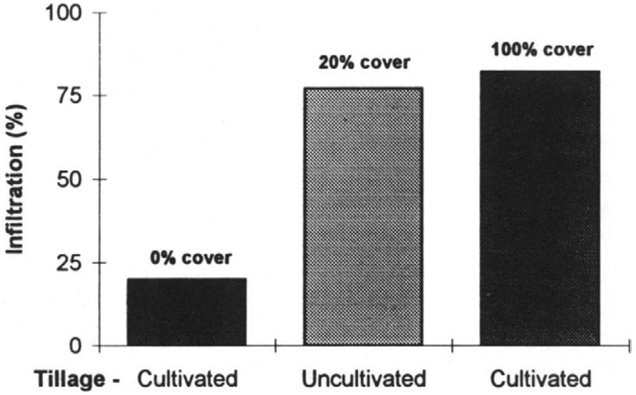
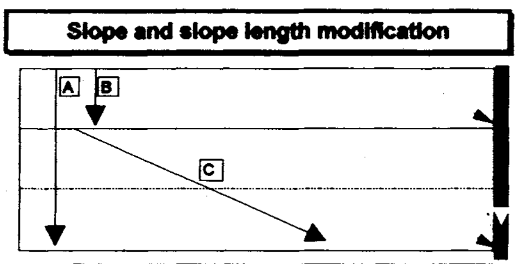


Fig. 9.5. Percentage infiltration of a 40 minute simulated rainfall (at 100 mm h^{-1}) on three soil treatments near Wallumbilla, November 1990. The soil was dry and cracked. Rain was applied to the soil as found, uncultivated—20 percent cover; cultivated—0 percent cover, and cultivated with stubble added, cultivated—100 percent cover.

(1) Slope

Land slope can be managed in some cropping systems where there is control of the direction of runoff. Row crops are one such case where each row carries all the water from its own "catchment". Within the limits of practicality, slope can be modified by a scheme similar to that shown in Fig. 9.6. By running furrows obliquely to the slope, slope is reduced while slope length may be increased. The main consideration is that each furrow is capable of carrying its own water without



Slope length configuration	*Length (m)*	*Slope (%)*	*Slope length factor*
A	150	5	1.19
B	50	5	0.69
C	150	2	0.33

Fig. 9.6. Slope and slope length can be modified by soil conservation structures and tillage/planting direction in a row crop situation. Case A is before any water control structures have been constructed, Case B is when the paddock is divided into three units by banks, and Case C is where slope has been reduced by oblique cultivation furrows. Note that slope length increased in C, but slope was reduced, reducing the erosivity of the layout, according to the USLE LS relationships (Wischmeier and Smith, 1978).

overtopping, whence the two systems will perform in a similar manner. One advantage of the oblique furrows is that when erosion does occur, sediment is deposited evenly along the interception channel (contour bank or bund) thus reducing the chance of self-destructing silt fans which reduce channel capacity and cause the structure to fail. A simple empirical model such as the USLE can be used to determine whether the risks of erosion are reduced sufficiently to justify the change in tillage layout. Of course, if sufficient land is available, lower slopes can be chosen for cultivation, but few land users have such flexibility.

(2) Cover and hydraulic roughness

Field studies have shown that cover has a greater influence on erosion of Vertisols than any other management factor (Smith and Henderson, 1961; Foster et al., 1982a,b; Lang, 1984; Freebairn and Wockner, 1986; Loch and Donnollan, 1988; Sallaway et al., 1990). "Contact" cover reduces erosion primarily by reducing overland flow velocity, stream power and thus ability for water to detach and transport sediment (Rose and Freebairn, 1983). Contact cover is the element of cover which is in close contact with the soil surface, thus acting as a roughness element for flowing water, increasing flow tortuosity, reducing effective slope and resultant overland flow velocity. Changes in overland flow velocities are observed as attenuation of hydrographs associated with surface residue. Even when runoff volumes are not affected by soil conditions, reduction in peak flow rates and increased time of concentration of hydrographs confirm these reduced overland flow velocities.

To further demonstrate the role of contact cover in modifying watershed hydrology and erosion processes, runoff depth, peak runoff rate, sediment concentration at the watershed outlet and soil movement are presented for four watersheds managed with different tillage regimes (Fig. 9.7). Long term erosion rates from small (1 ha) watersheds clearly show the maintenance of surface cover dramatically reducing soil erosion (Fig. 9.8). Where surface cover was removed by burning stubble, soil loss rates were 30–50 t ha^{-1} yr^{-1} compared to less than 4 t ha^{-1} yr^{-1} where stubble was retained on 5–7 percent slope Vertisols under annual winter cropping on the Darling Downs, Queensland (Freebairn and Wockner, 1986; Wockner and Freebairn, 1990). Baird (1964) showed that sediment yields from Blackland watersheds in Texas were 7–9 t ha^{-1} yr^{-1} when cultivated compared to 0.1 t ha^{-1} yr^{-1} under permanent grass, while differences in runoff were small. Vertisols appear to react similarly to other soils in the observed erosion reductions associated with soil cover, although they may be somewhat more responsive in terms of erosion reduction than the majority of soils for which the USLE was developed (Fig. 9.9). The ability for mechanical structures to survive events greater than the design recurrence interval is also strongly influenced by soil cover (Fig. 9.10).

Reduction in raindrop impact from surface cover also reduces soil detachment, but changes in overland flow conditions appear more important. Evidence for this deduction comes from high erosion rates when canopy cover is high and contact cover is low, such as occurs under a sunflower crop.

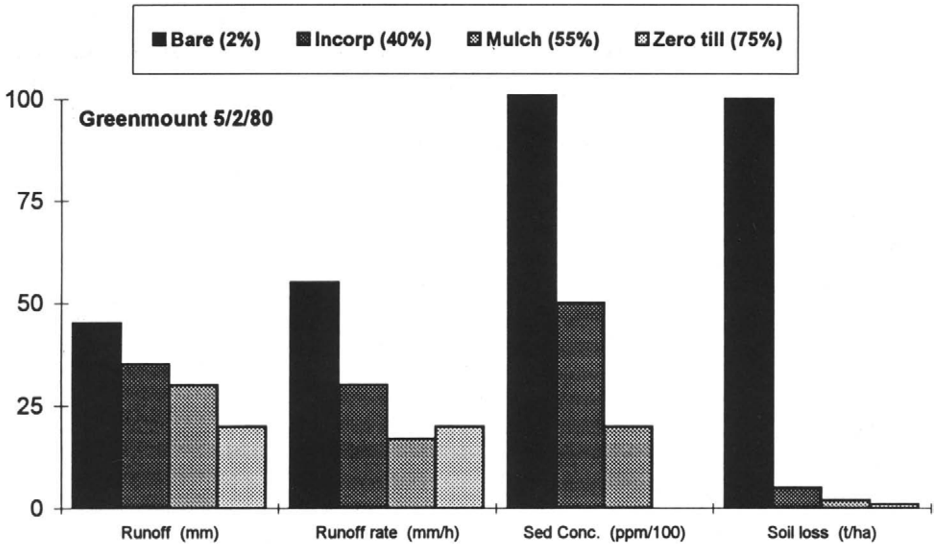


Fig. 9.7. Influence of soil surface conditions on hydrology and soil erosion from a 6 percent slope Vertisol on the eastern Darling Downs, Queensland. Tillage treatments referred to are Bare-stubble removed at harvest by burning, incorporated stubble partly buried by disc tillage, mulch stubble retained on the surface using 1 m sweeps, and zero till, weed control by chemicals, no tillage. Average soil cover is shown in brackets.

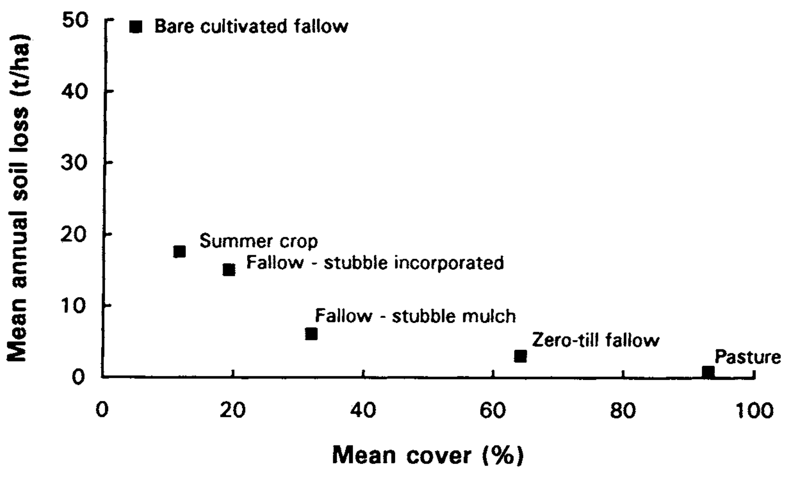


Fig. 9.8. Average annual soil loss vs cover for contour catchments on the eastern Darling Downs (7% slope, 60 m slope length, 1978–92).

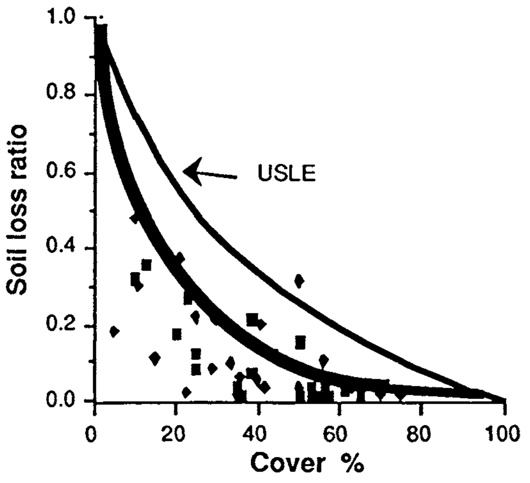


Fig. 9.9. Soil loss ratio vs cover for two vertisols. The lighter curve represents the cover-soil loss ratio derived for the USLE (Wischmeier and Smith, 1978). The heavier curve has been used to describe the erosion response of Vertisols in Queensland, Australia to cover.

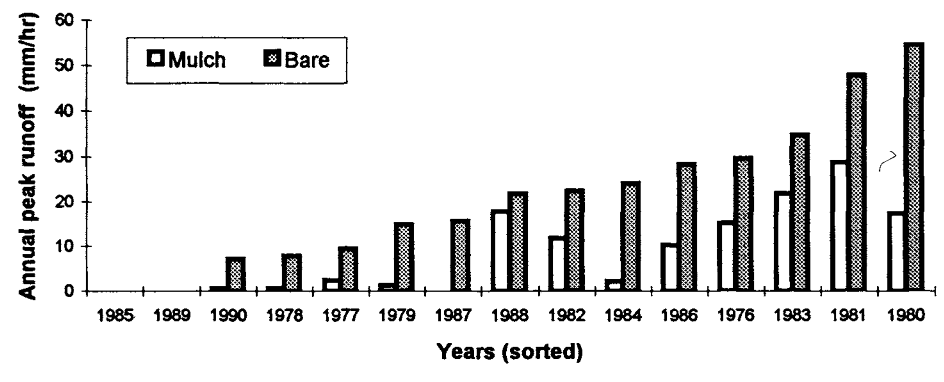


Fig. 9.10. Series of annual peak runoff values from 1.2 ha catchments with two tillage treatment; winter wheat and stubble burnt after harvest in November, bare fallow; and winter wheat with stubble retained on the surface with sweep tillage, stubble mulch, for the period 1976–1990. The maximum peak runoff from the conservation tillage catchment is 50 percent of that from the bare fallow—when combined with a 10 fold reduction in soil movement, enables soil conservation structures to withstand greater than 1:10 year deign storms.

From a practical point of view, cover levels >30 percent appear to be critical for erosion control (Fig. 9.10). Although the 30 percent level is somewhat arbitrary, it appears to be universal that the steepest part of the cover-soil loss relationship is at cover levels around 30 percent. The quadratic relationship is a consequence of soil loss being the product of runoff and sediment concentration,

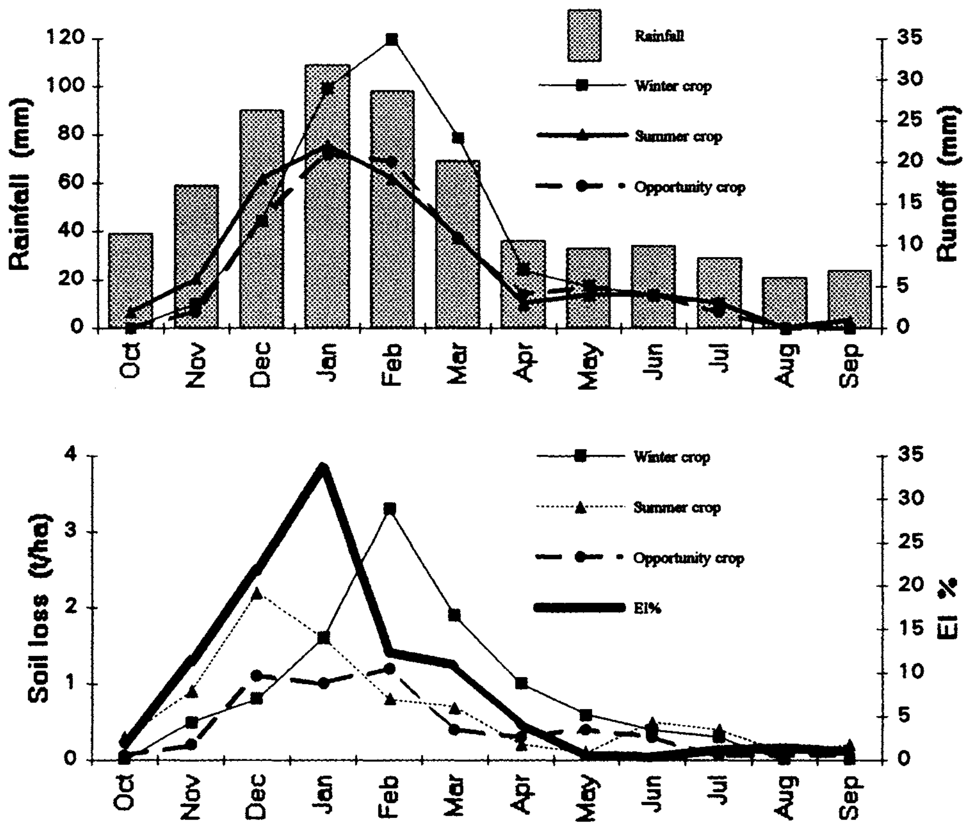


Fig. 9.11. Runoff and soil loss patterns do not strictly reflect rainfall patterns. Monthly distribution of rainfall, runoff and soil erosion for three cropping systems in Central Queensland. Runoff patterns reflect different water use patterns while soil loss is a result of runoff and soil cover when the runoff occurs. High runoff and soil loss occurs in Feb/Mar in a winter crop rotation because cover is low, soil water is increasing and runoff is high.

both related, often linearly to cover (Wischmeier and Smith, 1978; Elwell and Stocking, 1982).

An important aspect of erosion control is to have protection present when the greatest threat (runoff) is most likely to occur. Wischmeier and Smith (1978) considered the timing aspect of cover by weighting their C factor by the proportion of total rainfall erosivity in each month. Figure 9.11 shows that the distribution of runoff and soil loss during the year depends on the cropping system, which determines water use patterns (soil water deficit) and cover. Rainfall and EI_{30} are only general guides to the distribution of erosion. Coupled daily water balance and erosion models allow this to be done on a daily basis where the dynamic nature of soil water, tillage and cover can be considered explicitly (Williams et al., 1984; Knisel, 1980; Littleboy et al., 1992a,b).

TABLE 9.5

Effects of tillage treatments on Mannings n values for a Vertisol on the eastern Darling Downs, from (Maroulis et al. 1988)

Tillage treatment	Mannings n values for discharges of:		
	0.3 ($l\,s^{-1}$)	0.3–0.6 ($l\,s^{-1}$)	0.6–1.2 ($l\,s^{-1}$)
Rough tillage	ND	0.087	0.063
Fine tillage	0.081	0.045	0.028
Zero tillage	0.191	0.115	0.045

Values of Manning's n measured during rill studies on a Vertisol on the eastern Darling Downs, Queensland, show that roughness values for Vertisols are affected by tillage, stubble retention, and discharge (Table 9.5) (Maroulis et al., 1988). At larger flows, the Mannings n values measured were similar to those reported previously for other soils.

(3) Slope length

Mechanical structures. Contour banks, graded banks or bunds designed to reduce slope lengths are regarded as the panacea for many erosion problems and have been the mainstay of soil conservation strategies. Reduction in slope length remains a major method of erosion control in developing countries where crop residues are too valuable to be left on the field. Graded channel and earthen bank structures (typically with a grade of 0.3–0.5 per cent) have functioned well in curtailing gully formation and reducing loss of soil from hillsides (Mullins and Stephens, 1985).

However, graded or contour terraces have been found wanting in some environments. For example, contour channels on Vertisols in India result in excessive ponding and water logging (Central Soil and Water Conservation Research and Training Institute, 1980). Chittaranjan and Patnaik (1980) found that "conservation ditches" which stored runoff water for a short period for supplemental irrigation provided a good compromise between erosion control and water harvesting. For Vertisols in Ethiopia, Escobedo (1988) stated that "much attention has been given to physical conservation measures, but the results are not very significant . . ." indicating that the so called "traditional" approach to soil erosion control was somewhat lacking.

In most situations, spacing between structures has been determined mainly from experience, rather than designed to achieve soil loss rates below a critical level, as is the case in the U.S.A. Although not widely used operationally in soil conservation design, models are available that provide a more rational basis for hydraulic design of soil conservation structures. Models such as KINCON (Connolly et al., 1988), based on kinematic wave theory for open channel hydraulics, can be used to determine flow depth and velocity at any point along channels and waterways. Catchment size, channel length and channel condition can be designed to meet criteria such as maximum flow velocity and depth using knowledge of catchment hydrology and topography. Variables such as channel roughness, slope, cross-section and length can be readily modified to examine effects of various design options (Connolly et al., 1991a). This procedure is a departure from some of the "rule of thumb" approaches adopted in the past and allows the designer to experiment with and optimise layouts for more efficient farming. Reports from the Texas Blacklands suggest channel length is not important in determining erosion rates and that long channels may be useful in maintaining channel integrity (Smith et al., 1953).

Judging by the high degree of implementation of contour terraces and associated waterways in many regions, there appears to be little question of the effectiveness of soil conservation structures in reducing erosion as perceived by farmers. Yet these structures have measurable costs such as construction, maintenance, less efficient tillage, and in some cases, loss of productive area. These disadvantages need to be reduced to encourage the continued adoption of this suite of erosion control measures. Parallel banks have been implemented in some regions but are limited to relatively simple landscape shapes. The extra effort in design and construction and problems with removing water from low spots have limited the adoption of such structures.

A modification of conservation terraces or banks is the conservation bench terrace or Zingg terrace developed on the Vertisols in Texas, USA (Hauser and Xo, 1962). This involves reforming the land slope to create a level or ponded area on the bottom 20–30 percent of a terrace catchment. The ponded area is designed to collect and store runoff from the remainder of the terrace area, thus concentrating runoff water for improved crop production. The ponded area acts as a settling basin with a resultant reduction in water and sediment loss from the field. Conservation bench terraces apparently are profitable (including high capital costs), but there has been little adoption (V. Hauser, personal communication).

Vegetative barriers. The use of vegetative barriers to reduce erosion on Vertisols has taken several forms ranging from strip cropping, through to grass strips and narrow strips of specialist species such as vetiver grass (*Vetiveria zizanoides*). Strip cropping is described as the growing of crops in a systematic arrangement to act as barriers for flow of water (Jones, 1949). A typical arrangement for flood plains and areas of long and low (<1%) slopes is to have alternating summer and winter crops in rotation such that a standing crop or standing residue is present on approximately 30 percent of the area. Macnish (1980) in a review of strip cropping on the Darling Downs of Queensland found that strips on low slopes and flood plains provided "reasonable" control of erosion. The modal width of strips was 80–120 m, but it was considered that widths should be reduced to slow overland flow in major flood events. Marshall et al. (1980) recorded losses of the top 30 cm of soil in flood lines where no strip cropping was practised while soil appeared stable in well implemented strip crop layouts.

Grass strips were used to reduce erosion in extensive cropping areas of Queensland where the cost of structures was considered prohibitive (Shaw, 1967). Strips of grass on the contour were left uncultivated in cultivated paddocks in an attempt to slow runoff and trap eroding soil. Grass strips were not effective as a control measure as sediment built up in the strips, concentrating flow and causing further rilling and gully formation.

(4) Slope length considerations

The evidence in the literature is ambivalent regarding the role of slope length in controlling erosion on Vertisols (Smith et al., 1953), yet the use of structures to reduce slope length and hence, runoff erosivity, is common practice in soil erosion control. Two conceptual approaches can be considered.

First, erosion could be regarded as showing a *gradual* increase with increasing slope length as a result of increasing detachment by flow. It follows that some slope length at which *average* erosion rate is acceptable could be selected. This approach would be most applicable to soils that showed some resistance to rill initiation (as a result of either soil properties or residue retention), and for which rill incision was not limited by a relatively non-erodible layer.

Secondly, the response of erosion to slope length could be regarded as being characterised by a relatively sharp increase in erosion rate once rills develop (Loch and Donnollan, 1983a), with little further increase in sediment concentrations or erosion rates per unit area until gully development begins. This second approach leads to a definition of the major purpose of reducing slope length as being the *prevention of rill initiation* and would be more applicable to tilled soils and to self-mulching soils, where rills form easily and once formed, show little increase in erosion rates despite large increases in either slope length (Smith et al., 1954) or discharge (Loch and Donnollan, 1983a).

For self-mulching clays such as that studied by Loch and Donnollan (1983a), it can be questioned whether there is any practical value in using structures to reduce slope length and prevent rill initiation. With a discharge of $0.6\,\mathrm{L\,s^{-1}}$ required to form rills in bare soil on 4 percent slope, a runoff rate of $30\,\mathrm{mm\,h^{-1}}$ and a rill catchment width of 30 m (typical for those soils) would result in rill formation at a slope length of 3.6 m. For those Vertisols that are relatively resistant to rill erosion, such as the grey clay reported by Loch and Thomas (1987), rills developed on bare soil over the discharge range of 0.6–$3.0\,\mathrm{L\,s^{-1}}$. Similar runoff rates and rill catchment widths would generate rills at a slope length of 18 m. The use of graded banks to control erosion on *bare* Vertisols would result in bank spacings so close as to render mechanised farming impractical on slopes of 4 percent or greater.

Fortunately, retention of crop residues, can greatly delay the initiation of erosion by overland flow (Foster et al., 1982a,b; Loch and Donnollan, 1988). As slope length and discharge increase, mulches will eventually "fail", and overland flow can then remove both mulch and the underlying soil (Foster et al., 1982a,b). Clearly, an ideal soil conservation system for sloping agricultural land would use a combination of residue retention to allow for longer slopes (an incentive for land managers) together with structures to keep slope lengths sufficiently short to prevent "mulch failure".

Unfortunately, data on critical discharges for "mulch failure;' are extremely scarce and insufficient to provide a basis for planning spacings of banks in areas where crop residues are retained. Experience suggests that critical slope lengths for rill initiation are increased many times by the presence of crop residues. For example, Freebairn and Wockner (1986) reported annual soil erosion of 61 t ha^{-1} on a self-mulching cracking clay on 6–7 percent slope with a bank spacing of approximately 60 m. Retention of crop residues reduced average annual erosion to values between 18 and 2 t ha^{-1}, depending on the tillage method used and the quantities of residue retained. It can be concluded that data on critical slope lengths for mulch failure remain one of the greatest needs for field planning of soil conservation systems, and one of the more neglected areas of soil conservation research.

9.3.3. Modification of erodibility

One way to reduce erosion from agricultural land is to reduce the erodibility of the particular soils. This is not a widely-considered option, and erodibility has generally been treated as an intrinsic soil property. An example of this assumed invariance is the K factor of the universal soil loss equation, although modifications to the USLE do consider changes in erodibility factor, K, due to season (Renard et al., 1991).

Age of cultivation and type of tillage have been implicated in the decline of soil structure on Vertisols (Donaldson and Marston, 1984; Harte, 1985; Dalal and Mayer, 1986). In contrast, Loch and Coughlan (1984) and Harte (1985, 1988) found only subtle changes in soil physical properties of Vertisols after 8 years of reduced tillage. Recently, Connolly (1995) has shown that there is considerable variation between soils in changes associated with age of cultivation, and these changes have variable effects on productivity depending on starting conditions and climate. For example, a well structured black earth that has been cultivated for 30 years exhibits large reductions in steady state infiltration rates under simulated rainfall, but still has relatively high infiltration capacity (25 mm h^{-1}) compared to a solodic soil with an initial infiltration capacity of 20 mm h^{-1} that declines to 12 mm h^{-1}. Although declining aggregate stability may reduce infiltration capacity and increase runoff, there is little information available on erodibility.

Hydrology of soil profiles may change subtly when the soil surface is not cultivated for extended periods such as under a zero-till regime (Khatibu et al., 1984). Surface porosity is commonly lower under zero-till, although the amount and connectivity of macropores may be greater than in cultivated soils (Foley et al., 1991) with resultant improved drainage characteristics (Ehlers, 1975). These changes may be associated with more active macro-fauna (e.g. earthworms) and absence of disruption of voids and soil structure due to tillage. Higher macropore numbers may lead to better aeration, quicker drainage of water during wet periods resulting in reduced losses of water by evaporation and improved water storage

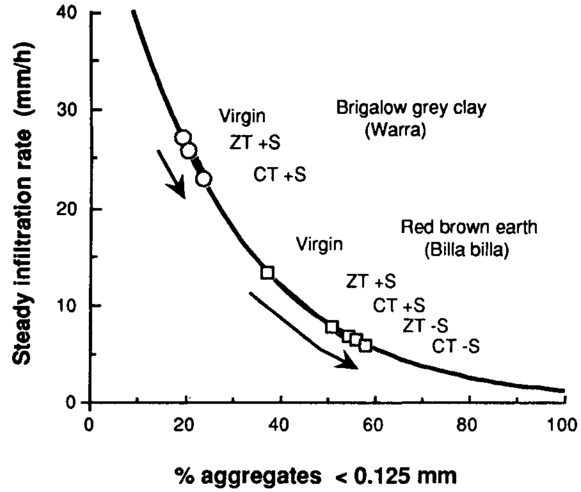


Fig. 9.12. Effect of tillage on steady infiltration rate and an index of infiltration (percent aggregates <125 μm, after Loch, 1989) for two soils, a Vertisol (grey clay) and a duplex soil (Red Brown Earth). ZT and CT refer to zero tillage and conventional disc/scarifier tillage and +S and −S refer to stubble retained and removed respectively.

(Marley and Littler, 1989). Adams and Baird (1966) found that oats, clover and grass grown in rotation with sorghum improved soil physical conditions. They indicated that these crops had a beneficial effect for the season after, reducing runoff and soil erosion.

There have been reports of variations in erodibility associated with some crops, particularly soybeans (Bradford et al., 1988). It is possible that erosion models have, to some extent, incorporated variations in erodibility into the "crop" (cover) and "practice" factors. There has been a need to distinguish between direct effects on erosion of some crop or management treatment (via quantities or location of crop residues) and actual changes in the erodibility of a given soil. Studies of changes in erodibility have therefore tended to concentrate on changes in soil aggregation correlated with erodibility.

The evidence available suggests that changes in cropping practices have little effect on erodibility, particularly for Vertisols, although they do have considerable effect on erosion (Freebairn and Wockner 1986; Wockner and Freebairn, 1990). Freebairn and Wockner (1986) found that reductions in erosion under direct drilling of a Vertisol could be related directly to the amount of surface cover by crop residues, with there being no apparent extra benefit associated with no-till. Consistent with this deduction, Loch (1994) found that effects of changes in tillage methods on aggregate stability under rainfall wetting were both inconsistent and small for a range of Queensland soils, including several Vertisols (Fig. 9.12).

Loch (1994) noted that tests of aggregate stability based on immersion and tension wetting commonly gave results different to those obtained from rainfall wetting (especially for soils observed to show some cracking under field conditions), and hence were inappropriate for characterising dryland soils. Also, it appeared that for some soils, immersion wetting showed particularly large responses to tillage treatment, and use of that technique may have encouraged undue expectations of the potential for changes in tillage management to significantly improve aggregate water stability and reduce erodibility.

The relatively small effects of tillage management on aggregate water stability found by Loch (1994) may be associated with a lack of response to changes in soil organic matter, as Coughlan and Loch (1984) found no effect of organic matter content on the water stability of a range of Vertisols. The lack of response can be attributed to the dominance of clay as a bonding agent within those soils. Also, variations in soil organic matter content with tillage practice are not large within dryland cropping regions of Queensland (Loch, 1994).

However, Loch (1994) did show greater variations in organic matter content and in stability to rainfall wetting between virgin and cropped soils, leading to the suggestion that appreciable changes in aggregation may be possible under ley pastures, and that pasture leys may also achieve reductions in erodibility. This is supported by data of Loch and Rosewell (1992), for measurements of erodibility (based on the K_a method described in that paper) on a strongly swelling heavy clay after 6 years of cropping and subsequently after 2 years of volunteer pasture. The K_a values (in SI units) declined from 0.046 after cropping to 0.035 after 2 years of pasture. These results have prompted greater interest in the use of ley pastures to achieve significant improvements in aggregate stability.

It appears that the potential for a change in crop/tillage management to significantly reduce erodibility will be limited to regions of higher rainfall and/or to the use of ley pastures, both being situations where there is greater potential for significant increases in organic matter to be achieved. Inappropriate methods for measuring aggregate water stability for many dryland soils have resulted in undue expectations of improvements in aggregate stability under "improved" tillage methods.

9.3.4. Some considerations in implementing control measures

The response of crop yields to tillage practices appears to depend on soil type, farming system and climate, with experiments often giving contradictory results. For example in west Africa, Charreau and Nicou (1971) and Chopart (1989) report benefits from tillage whereas Lal (1975) and Maurya and Lal (1981) report best results from zero-tillage. Tillage experiments on Vertisols in Queensland further demonstrate yield variability, both in magnitude and direction of response depending on seasonal conditions, disease history and crop species (Thomas et al., 1990; Radford et al., 1991). Such variable responses make extension of apparently more sustainable practices difficult , but this superficial unpredictability is often a result of climatic variation, and interactions between environmental conditions and the soil/plant system.

The lack of tillage and planting equipment well suited to operation in stubble can be a major limitation to the adoption of stubble retention practices, even though some farmers and soil conservationists are aware of the potential for stubble retention to conserve water and soil. A problem with retention of crop residues on the surface is the difficulty in planting the following crop with mechanised systems (Chopart, 1989). However these problems are typically dealt with by the adaptation of planting equipment to handle crop residue and create micro-seedbeds.

The aim of farming should be to use tillage only when necessary, both from an economic and soil sustainability viewpoint. For example, Chopart (1989) advocates a double-cropping corn–cotton system in which the soil is tilled before corn, but not before cotton. Such a recommendation reflects a knowledge of what tillage is doing to soil hydrologic properties and root-bed conditions. Weed control poses a major challenge in reduced tillage systems, but the knowledge base for herbicide strategies continues to grow as chemical companies, researchers, extension personnel and farmers experiment with different application technologies and chemical formulations. Disease and nutrient aspects of conservation tillage systems should not be neglected since pathogens and nutrition can negate the potential benefits of reduced tillage and stubble retention systems (Rees, 1987; Rovira, 1987).

9.4. AN INTEGRATED APPROACH TO EROSION RESEARCH

In this section we describe elements of a research program carried out by the Queensland Department of Primary Industries in the period 1975–1993. Vertisols are the dominant soil type used for cultivation in the dryland cropping area of north eastern Australia. Of Queensland's 50 m ha, 1.2 m ha are used for grain production, with the high water holding capacity of these soils allowing cropping to be carried out in an extremely unreliable rainfall regime. Much of this area is sloping and subject to severe erosion as a result of high intensity rainfall.

We describe a number of studies at different scales. The purpose of the increments in scale is to provide a description of hydrology and sediment properties along the hydrologic pathway (Fig. 9.13). Such knowledge allows for extrapolation of site and time specific data to more general conditions using models developed from this experimental database. It would be misleading to believe that the research components we had at the end were all planned in the beginning, but we present our experience as a case study of a well integrated approach. Regardless of the conceptual framework used, a comprehensive study of hydrologic and erosion processes is necessary to best understand how to modify these processes to achieve landscape stability.

9.4.1. Integration of management and process research

Soil erosion is like any other physical process. The complexity is determined by how many pieces or mechanisms are considered. We know, for example, that water erosion starts with a raindrop hitting the soil surface. Do we start at this

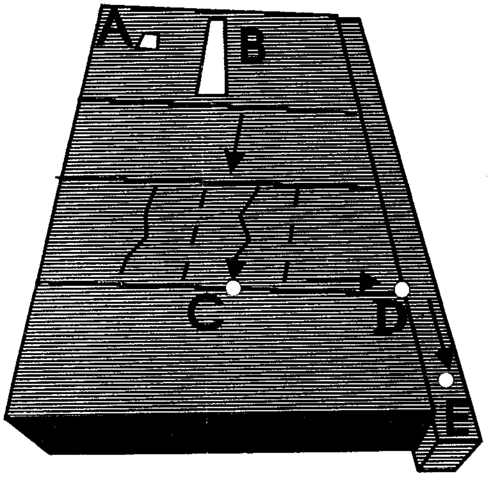


Fig. 9.13. Diagrammatic representation of the different scales of study from (A) 1 m^2 rainfall simulator plot; (B) 22 m × 4 m Rainulator plot; (C) 0.1 ha rill catchment; (D) contour bay catchment; (E) a collection of contour bay catchments, paddocks or farms.

<1 cm scale, or is a purely empirical approach adopted where responses to natural conditions are only measured on fields or catchments (>1 ha)? Obviously we consider that a blend of approaches is appropriate.

We have arbitrarily divided erosion research into two categories; process and management research; being respectively an investigation into *why* something happens from basic physical principles, or alternatively describing *what* happens in the real world, with inferred cause and effect. These categories are not exclusive as process work is also done in the field. A simpler description might be that management research predominantly studies erosion under natural conditions while process research relies more on controlled conditions.

Management and process research obtain quite different data and the combination of these two approaches can be particularly effective if it is realised that they are complementary rather than competing. For any research effort, management (field) research is the obvious starting point. It gives not only some definition of the environment, but also a broad indication of management systems likely to control erosion. Data from field research can arouse public interest and support.

Process research provides a clearer understanding of the results of management research, and, through the development of predictive models, allows data and recommendations to be extrapolated to a wider range of environments. However, it is important to note that field data are essential for validation/calibration of predictive models.

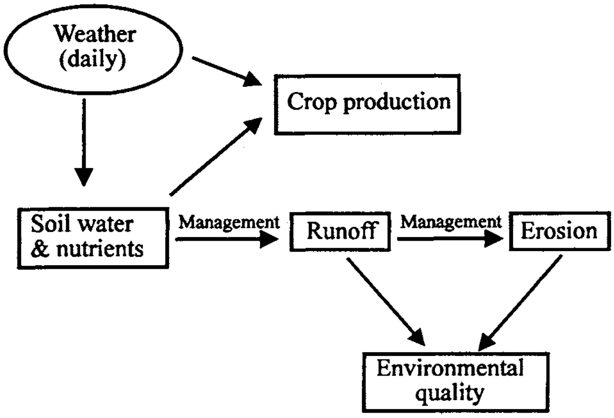


Fig. 9.14. Schematic of the inter-relationship between weather, management, hydrology, erosion and crop production and environmental quality.

9.4.2. The need for integration

Most environmental-oriented research activities including studies of soil erosion, commonly address two broad areas: establishing the current status of the problem and developing an understanding of the processes involved so as to better target control measures. Also, erosion *per se* may not be an issue, but the impact of erosion on production and environmental quality are community concerns (Fig. 9.14). This connection must be made, or erosion research will be seen as a purely academic pursuit.

Resources are generally limited for any research effort. The amount of data available is likely to be limited, thus purely empirical relationships cannot be generated for a wide range of conditions. Process based research is more likely to provide results that can be extrapolated to other soils and conditions, and when linked to field measurements, will have generality and credibility.

(1) Establishing the status of soil erosion

In erosion studies, this typically refers to studies being carried out under natural rain on a range of catchment sizes. Common treatments studied include a range of management strategies, either in current practice, or experimental systems. Advantages of such studies are that:

(a) Results are "real", usually being derived from field scale areas under natural rain.

(b) A wide range of measurements can be made, e.g. runoff, soil loss, soil water storage, crop yield, that allow impacts of a particular management strategy to be assessed in terms of economic and agronomic considerations rather than soil loss alone.

(c) Research areas can be used as demonstration areas, so that both the trial area and the data obtained have immediate relevance to extension efforts.

Disadvantages of field/management studies are that:

(a) results are site specific;

(b) the range of treatments studied is often small, due to logistic constraints; and

(c) climate variability may be such that experiments need to be run for long periods if they are to provide an adequate measure of long-term results.

(2) Developing an understanding of processes

Research into soil erosion processes generally has three main purposes; (a) increasing understanding of the processes of runoff and erosion, thus aiding the development of runoff and soil loss models needed to extrapolate data from a limited range of sites to a wider range of environments or from a short period of record to a longer term, (b) gathering resource data (e.g. infiltration and erodibility parameters), and (c) examining potential management techniques in greater detail, to identify refinements or alternative approaches that could be considered.

Process research typically deals with some component of the overall runoff/erosion system. Conditions are generally more precisely defined or controlled, and the measurements made can be relatively detailed. It should be noted that process research does not produce "real world" data, though it is possible to use data from process research as inputs to appropriate models to obtain good predictions of either erosion (Freebairn et al., 1986, 1989; Loch et al., 1989a) or runoff (Connolly et al., 1991b; Silburn and Freebairn, 1992) under field conditions. If there is reasonable agreement between process and management research scales , extrapolation beyond the conditions used in all experiments can be achieved with greater confidence. Computer models that allow several processes to simulated, and consider interactions between processes and the environment provide the framework for linking different scales, locations and approaches (Table 9.6 and Fig. 9.14).

9.4.3. Process studies

(1) Small plot rainfall simulation

Rainfall can be simulated on small plots (approx. 0.1–4 m^2) using a variety of mechanisms, the most commonly used being either a rotating disc design of Morin et al. (1967) or a reciprocating nozzle (Meyer and McCune, 1958). Infiltration can be studied for a range of rainfall intensities, surface cover and antecedent moisture conditions. Plot sizes typically start from 0.3×0.4 m trays (>0.1 m deep) in the laboratory where detailed measures of infiltration rates, soil moisture potential under soil crusts and particle size distribution of detached material can be monitored in detail (Silburn and Foley, 1994). Larger tray sizes can be used to

TABLE 9.6

Feature of different scales of study used in research of erosion on Vertisols is Queensland

Method	Scale	Main process	Treatments
Rotating disc Reciprocating nozzle	1–4 m^2	Infiltration	Soil type, cover
Rainulator	6–90 m^2	Infiltration, hydrology, soil erosion	Soil type, cover, roughness and tilth
Rill catchment	0.1 ha	Hydrology, soil erosion	Tillage, cover delivery ratio
Contour bay catchment	1–10 ha	Infiltration, hydrology, descriptive erosion	Soil type, soil moisture, tillage, cover, roughness, crop type and history
Agricultural catchment	250–5000 ha	Hydrology, sediment delivery	Soil moisture, scale, management

avoid preferential loss of some size fractions by splash biasing the results obtained (Loch and Foley, 1992).

The control provided by a laboratory installation allows for large number of soils to be processed, and is used primarily for determining infiltration (Silburn et al., 1990b; Silburn and Foley, 1994) and erodibility parameters (Loch and Rosewell, 1992) and can also be used to estimate splash or detachability indices (Rose, 1960).

Small field plot areas range from 1 m^2 (Glanville et al., 1984; Silburn et al., 1990a) to 4 m^2 (Fig. 9.15). This scale is ideally suited to studies of infiltration behaviour. Runoff results have been used to generate USDA Curve Numbers (Hawkins, 1979) and parameters for the modified Green and Ampt equation as used in infiltration models of the CREAMS model (Knisel, 1980). Green and Ampt parameters have been reported by Connolly et al. (1991a,b) and Foley et al. (1991). Most simulator runs have been carried out on wet profiles without soil cracks as estimates of curve numbers are likely to be more meaningful on moist soils (Hawkins, 1979). The Green and Ampt parameter, saturated hydraulic conductivity, had similar values from field catchments and simulated rainfall studies (Freebairn et al., 1984), an encouraging result for the independent measurement of soil hydraulic properties of cultivated soils.

(2) Rainulator

The rainulator (Meyer and McCune, 1958; McKay and Loch, 1978) applies simulated rain to a 22.5 × 4 m plot, or subsets of this area (Fig. 9.16). The standard intensity used in studies in Queensland has been 95 mm h^{-1} with rainfall energy about 80 percent that of high intensity storm rain. Plot installation and measurement procedures are described by Loch and Donnollan (1983a).

The rainulator plot size is well suited to the study of infiltration phenomena that operate at a scale larger than 1 m^2, such as soil cracking and large roughness elements. From an erosion viewpoint, plot size can be modified to allow either

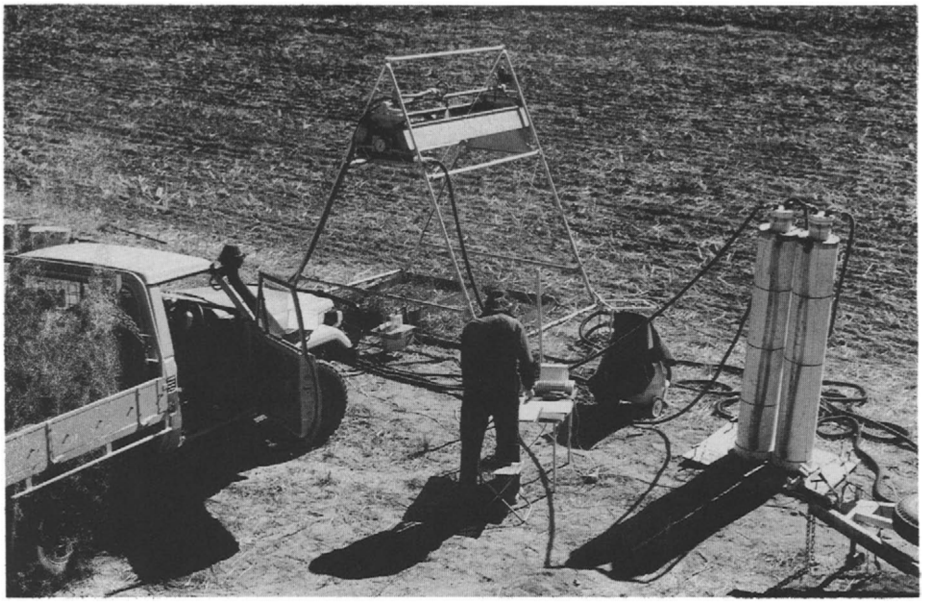


Fig. 9.15. Photograph of a small plot rainfall simulator used primarily to study hydrology of different soils and management options. Typically the 'rain' area is split into two 0.9×1.8 m plots. This allows for twice the number of plots and treatments to be studied and has been an extremely effective extension tool (Cawley et al., 1992).

Fig. 9.16. Photograph of the "Rainulator" used to study erosion processes. The plot area is 22×4 m and rainfall can be applied at up to 100 mm hr^{-1} (McKay and Loch, 1978).

rain-flow or rill transport processes to dominate. The large plot size has slope lengths and discharges not very different to those found under natural conditions, and allows a more complete suite of erosion processes to be studied in detail. The rainulator has allowed separate evaluation of factors involved in soil erodibility. The integration of infiltration capacity and sediment transportability into a single erodibility factor, together with modification of that factor for rainfall pattern, makes derivation of soil erodibility as per the USLE difficult from rainfall simulator studies. For example, Loch (1984) showed that the interaction of plot length and rill development could cause up to three-fold variation in estimated erodibility factors.

Part of the problem comes from attempting to use what are, effectively, single-event data to derive parameters for a long-term erosion model. It is much more appropriate to use rainfall simulator data to estimate parameters for single-event models.

The alternative approach used in several single-event soil loss models such as CREAMS and MUSLE (Williams, 1975) of separating soil erodibility into infiltration capacity and sediment transportability is more realistic, and the necessary data are simpler to obtain and interpret. For example, erosion predicted by the CREAMS model is quite sensitive to sediment density and size (Silburn and Loch, 1989), and these sediment properties can be measured easily and directly during rainfall simulator studies, with the only parameters needing to be derived by optimising model output to available data being a surface roughness parameter and a detachability parameter (Loch et al., 1989b). Provided these latter two parameters were derived from studies where the erosion processes operating were consistent with that at a field scale, parameters from rainfall simulator data were found to enable the CREAMS model to give good predictions of measured erosion from field catchments (Loch et al., 1989b). The larger size of the rainulator plots provided essential background data on the variation of the surface roughness parameter, and ensured that the erosion processes operating were generally consistent with the field situation.

Where questions of land or resource use require quick answers, rainfall simulation studies and subsequent modelling of erosion and sediment movement can provide information within a relatively short time. For example, the CREAMS model with data from laboratory studies of sediment properties and infiltration rates and some parameters from previous rainulator studies, were combined to consider potential sediment movement from waste rock dumps at a proposed mining operation (Silburn et al., 1990b). This approach produced the requested information in a matter of months, rather than years which might be required if erosion under natural conditions was studied.

9.4.4. Watershed studies

A watershed can be regarded as any natural or man made land unit that is hydrologically separate from other units. Fig. 9.17 shows typical patterns of water flow and erosion on basalt derived Vertisols in eastern Queensland, Australia.

Fig. 9.17. Typical patterns of water flow and erosion on basalt derived vertisols in north eastern Australia. Once rilling occurs, subsequent rills develop in the same area reinforcing a fixed pattern of erosion.

Emphasis on research will change for different regions, depending on the problems and issues of concern. These issues also change with time as social perceptions change. For example, in the last two decades, research emphasis in Australia has shown a gradual swing from on-farm soil and water conservation toward broader catchment and environmental issues such as water quality and river health.

(1) Scale of study

The definition of soil erosion can be contentious, and is dependent on the scale of consideration. For example, one extreme definition is that for soil to be lost it must reach the ocean. It can be argued also that soil moved from a slope with shallow soil to a deep alluvial plain is indeed lost, as the relocation causes a decline in the quality of one area with no apparent benefit to another (or possibly a loss of production due to deposition). In studying erosion we normally consider areas ranging in size from a 1 m^2 plot to a 1000 ha catchment, or many thousands of square km for a river basin. Whatever the viewpoint, scale has a major influence on results obtained and therefore needs to be well defined and described. An example of trends in erosion process and sediment concentration with increasing area for the grain cropping area of the eastern Darling Downs, Queensland is:

rain-flow $<$ rill $\gg$ contour bank channel $>$ or $=$ waterway $<$ or $>$ ephemeral stream

An understanding of sediment movement through a landscape at different scales offers potential for improving management of the drainage network by targeting critical regions in terms of flow conditions, sediment entrainment and transport capacity. The dominance of different processes will change as water volume increases and slope decreases. For example raindrop detachment and shallow overland flow will dominate at the head of a watershed, while stream bank erosion, gullying and deeper flow will characterise flow on flood plains. Sediment concentration, while an indication of instability within a catchment, can be a source of instability in itself at a longer time scale. Deposition in drainage lines and flood plains, such as occurs on the eastern Darling Downs results in unpredictable flow paths in the future. A description of several types of studies used in Queensland follows.

(2) Confined plot studies

Measurement of erosion rates on Vertisols probably began in the 1930's and was carried out by United States Department of Agriculture and Texas Agricultural Experiment Stations based near Temple Texas (Hill, 1935). Much of the data base from which the USLE relationships were derived came from small rectangular bounded-catchments or plots. These plots had the advantage of being easily managed, and a large number of treatments could be monitored at any one time. The standard USLE plot size for erosion measurements was 22 m long and 4 m wide although there appears to be considerable variation. This configuration has not been used in Queensland but several sites were monitored for up to 30 years in New South Wales (Wiltshire, 1948). Runoff and erosion was measured from 100 m^2 plots at Gunnedah on a Vertisol for the period 1949–1974. Soil loss rates of 7 $t\,ha^{-1}\,yr^{-1}$were measured for a wheat–long fallow rotation with an average runoff of 28 $mm\,yr^{-1}$. Soil loss from adjacent pasture was negligible. While it is useful in retrospect to have a long record of hydrology and erosion data, the efficiency of such studies would receive critical review today. The main limitations of such studies are that the original treatments tend to become redundant (although they need not) and that treatments do not have enough in common with field scale processes—results may be heavily biased by the experimental approach.

(3) Row crop furrows

One of the most elegant catchment scales to monitor is the area confined by ridges in row crops such as sugar cane, maize or cotton. Ridges are created in normal cultivation operations or deliberately constructed as part of a system of furrow irrigation. The furrows not only control water for irrigation efficiency (Smedema, 1984) but also provide an ideal catchment boundary for erosion studies. Carroll et al. (1990) used such catchments to examine the relative erosion occurring during irrigation and rain runoff in cotton fields with slopes $\approx$1 percent.

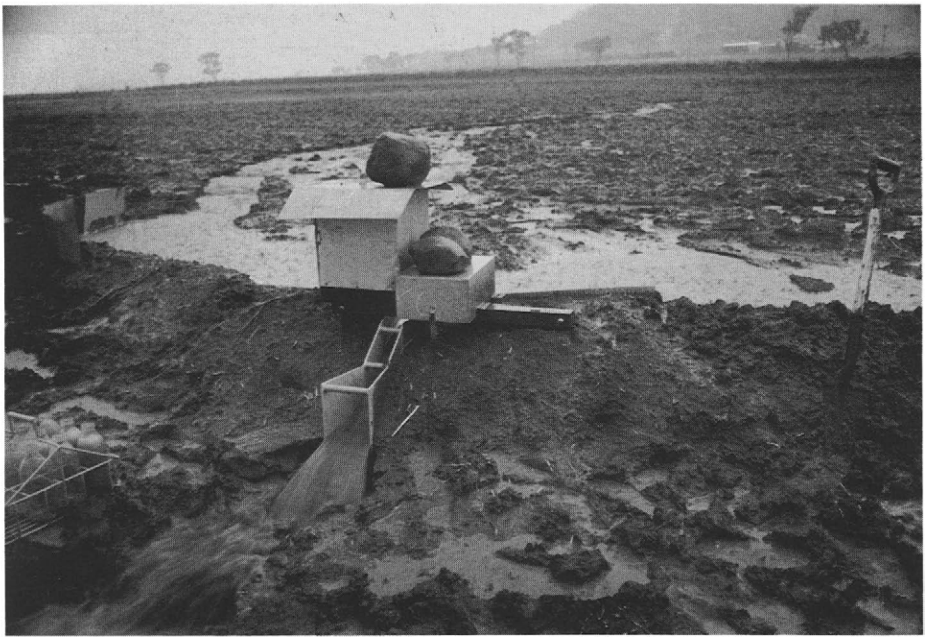


Fig. 9.18. "Rill" catchment instrumented to measure runoff and sample water.

Runoff was measured by directing water from several rows through a parshall flume fitted with a stage recorder (Fig. 9.18). Water was sequentially sampled for sediment load by manually collecting samples of the whole flow through the flumes using wide mouthed bottles. Where a significant proportion of total sediment is bed load, it is difficult to ensure that point samples taken by a pump sampler are representative of the whole flow at any point in time. Automatic sampling can be achieved if sufficient mixing is created by turbulence in a drop pool. Alternatively, a bedload trap can be placed before the flume. The most important aspect to consider is that the trap be large enough to collect the expected load, otherwise the estimate of total load will be biased after the trap fills. In cotton fields, Carroll et al. (1990) found that soil losses were greatest during storm runoff, especially if irrigation shortly preceded rain. Sediment concentrations declined during the growth of the cotton crop, reflecting increasing cover and soil consolidation.

Another simple but effective approach for monitoring soil movement in row crops is the measurement of changes in cross-section of each furrow-hill. Datum points are established changes recorded with time using "profilemeters" (manual or electronic) where heights from the datum are recorded at intervals across the section. Consideration must be given to whether changes are due to consolidation or to soil loss. Generally consolidation occurs soon after tillage, and obviously soil movement can only be associated with runoff. While some subjectivity will always remain, this approach is inexpensive and effective, and particularly suited to situations where soil loss rates are high (>20 t ha^{-1}), thus reducing relative errors due to consolidation and sampling density. Similar methodology has been used to examine hydrology and erosion from sugarcane and pineapples (Sallaway, 1979; M. Capelin, personal communication) although not on Vertisols. Recording channel cross sections using a photograph of a marked "sight" board is a rapid and effective method for describing channel characteristics and estimating soil movement.

Installations such as shown in Fig. 9.18 can be temporary to allow for cultivation with field scale machinery. The low hydraulic conductivity of wet Vertisols makes installation of such structures relatively simple as the surrounding soil can be used as structural material. In some cases a "fondue" or sloppy mix of lime and cement is used to create a seal between the flume or weir and the channel. This mix is easy to remove, but is strong enough to support structures and provide a seal.

(4) Rill watershed

A pattern of rills generally develops on cultivated Vertisols with slope (Fig. 9.17). The rills persist after installation of graded or contour banks, so a contour bay commonly contain several rill catchments, each draining to a channel. These rill catchments of 0.01–0.1 ha represent the smallest units in the fluvial system suitable for direct study in the field. Flow and sediment can be monitored using flumes or weirs in conjunction with stage recorders and sediment samplers similar to that described by Ciesiolka and Freebairn (1982) and shown in Fig. 9.18.

In a study on a black earth on 6 percent slope, peak runoff rate from a rill was almost three times greater than from the contour bay in which it was located, although total runoff for both scales showed reasonable agreement. Sediment concentrations in rills were up to 65 kg m^{-3}, with rill concentrations much higher than those in the contour bank channel. This is consistent with the much lower slope of the contour bank channel (0.3 percent compared with 6 percent slope for the rill), and therefore, much lower sediment transport capacity (Ciesiolka and Freebairn, 1982). Such high concentrations were difficult to sample using automated samplers, thus could only be practically sampled using hand collected samples. The value of these small catchments is that many erosion models (Rose, 1985; Foster and Lane, 1987) represent the processes of soil detachment and transport at this scale, yet hydrology and sediment data are generally collected at larger scales especially under natural rainfall conditions.

(5) Contour or bunded watersheds

Graded earthen banks commonly called terraces, contour banks or bunds, are used to reduce slope length and control runoff from sloping land. These structures result in the dissection of larger watersheds into a series of small (1–10 ha) watersheds. As such, these watersheds represent the smallest hydrologic management unit within the watershed (i.e. the same practice is implemented over the catchment). They are well suited to the study of management effects on erosion at a scale which is experimentally and logistically manageable, and results are directly relevant to land managers.

Fig. 9.19. Oblique aerial photograph of a field study showing five instrumented catchments. Different management options can be implemented in each catchment which represents the smallest management hydrologic unit in many agricultural areas. Distance across photograph is approximately 350 m.

A typical installation consists of a flume or weir at the outlet of each contour bay catchment (Fig. 9.19). Runoff is estimated by gauging flow height through a calibrated structure and water samples can be collected at the gauging point (Fig. 9.20). Soil loss is estimated by sampling runoff water for suspended sediment and measuring the volume of rills and sediment deposits (Freebairn and Wockner, 1986). A modification to the normal outlet can create ponding conditions to trap bedload (difficult to measure in flowing water) and also minimise flow attenuation due to the control structure (Fig. 9.21). Such studies have been implemented at a range of sites on Vertisols in the U.S.A. (Smith et al., 1954) and in Australia

Fig. 9.20. Cipoletti weir installed at the end of a contour bank or terrace, used to measure runoff from small agricultural catchments. H flumes and V notch wiers are similarly installed.

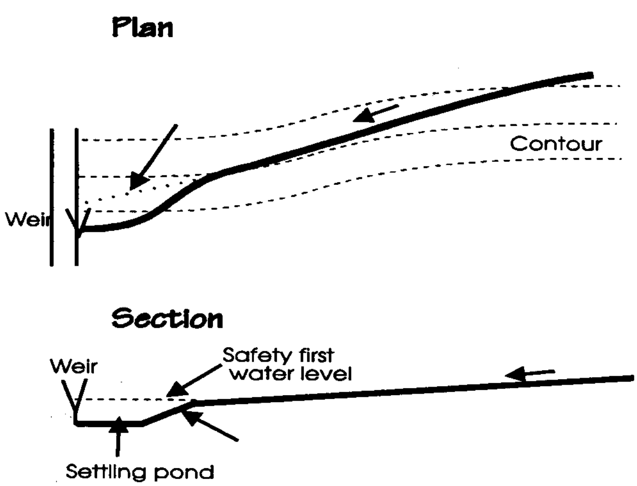


Fig. 9.21. Modification of a small watershed outlet to allow for bedload settling and minimising flow attenuation due to the control structure.

(Marston, 1978; Freebairn and Wockner, 1986; Freebairn et al., 1990; Sallaway et al., 1990).

(6) Small agricultural watershed

Small agricultural catchments generally consist of a number of contour bay catchments or a unit of management similar to a farm scale. The catchment may include soil conservation structures or have a natural drainage system. They are generally chosen to study the influence of mechanical structures on runoff and erosion and have been used to determine design criteria for mechanical structures (Titmarsh et al., 1991). The design of mechanical structures to control runoff and erosion has often been based on observation and experience with minimal empirical evidence while most studies of management strategies have been based on small catchments, bounded plots and simulated rainfall studies.

The performance of mechanical structures and agronomic measures in reducing runoff and erosion on a catchment scale has been studied on Vertisols in Texas (Baird and Potter, 1950; Baird and Richardson, 1970). This study reports on runoff from six catchments ranging in size from 1.3 to 140 ha. Terraces or graded banks reduced peak runoff rates but the effect on total runoff was variable. Terraces reduced runoff for small runoff events but increased runoff for some larger events and it was concluded that overall, terraces did not reduce runoff (Baird and Richardson, 1970). Titmarsh et al. (1985) reported on the hydrology of a 260 ha catchment on the eastern Darling Downs, Queensland. They found that at this scale, antecedent moisture was the dominant determinant of runoff while cover or vegetation effects were not apparent.

In a landmark study in central Queensland, three 12–17 ha catchments with natural Brigalow vegetation (*Acacia harpophylla*) have been monitored since 1965. After an 18 year calibration period, two catchments were cleared; one planted to pasture and the other cropped since 1982 (Lawrence, 1990). Runoff, soil erosion, nutrient status of soil and runoff, and crop production have been monitored. Under cropping, average runoff doubled from 41 to 86 mm yr^{-1} while runoff increased to 67 mm yr^{-1} with pasture over an 8 year period. Clearing also increased peak runoff rates. Studies such as these long term experiments provide valuable baseline data to gauge how agricultural development in newly developed areas is proceeding (Lawrence and Thorburn, 1989).

It appears universal that studies of hydrology and erosion at scales of less than 100 ha are rarely linked with river studies—soil conservationists and riverine hydrologists have not made a connection. With the current interest in water quality and sustainable development, there remains a large gap in our understanding of the movement of water, sediment and associated chemicals through the hydrologic pathway.

9.5. SIMULATION OF EROSION

Conceptual models have been developed to better deal with the complexity of hydrologic and sedimentation processes in action. These models summarise and represent mathematically the many processes involved in soil erosion, and are needed to extrapolate from the relatively few sites where erosion has been measured.

Some important capabilities required of soil erosion modelling are to predict the long term soil loss from a soil profile and the relative efficacy of alternative management practices. In practice no single model provides all the required capabilities. Several models are available for erosion prediction and the choice of model depends on the aims, scope, temporal and spatial scale of the particular problem. Some typical applications and type of model needed are:

—Decision support systems to assist land use planning: widely applicable and simple to use such as USLE.

—Interpretation of experimental data in terms of physically meaningful parameters so that generalised conclusions can be made across locations and scales: process models such as used in CREAMS (Knisel, 1980) and described by Rose (1985) and Hairsine et al. (1992).

—Effects of land use on off-site sediment load: multi-scale erosion deposition models such as ANSWERS (Beasley et al., 1980) and CREAMS.

—Estimation of interactions between erosion, management and productivity: systems models such as EPIC (Williams et al., 1984), PERFECT (Littleboy et al., 1989).

The process models have been tested with erosion data from Vertisols with some success (Loch et al., 1989b; Rose and Freebairn, 1983). The modified USLE's and the USLE have also been examined and found to be useful (Freebairn et al., 1990).

9.5.1. Modelling hydrology

Sediment yield is the product of sediment concentration and volume of runoff. Thus modelling hydrology is an important prerequisite to modelling soil erosion and deposition. Rose (1985) points out difficulties in hydrologic modelling posed by spatial variability in soil properties and by temporal changes in soil surface infiltration characteristics (Freebairn et al., 1990). To avoid these difficulties, Rose et al. (1984) presented a method for inferring the mean infiltration characteristic of a catchment from measured rainfall and runoff rates. Another approach is to explicitly model spatial variability and transient behaviour of the soil surface using independently measured infiltration and soil parameters (Connolly et al., 1991b). Prediction of the hydrology of Vertisols under a range of management practices and environments has been demonstrated by Littleboy et al. (1992a) and Silburn and Freebairn (1992). Due to the cracking nature of Vertisols, it was initially thought that these soils would be difficult to model. Our experience has been the opposite—the high infiltration capacity of dry Vertisols results in no runoff occurring in this condition. Antecedent moisture is the most important determinant of runoff, while cover and roughness are secondary modifiers.

9.5.2. *Predicting erosion*

To date, erosion models have not been used extensively in planning or extension of soil conservation. The exception is the United States where predicted values of soil loss using the USLE are criteria for participation in various government production control and soil conservation programs. The need for improved predictions of erosion for a broader range of conditions than was initially covered by the USLE has resulted in a major effort to develop an improved erosion model. Development of this model is being carried out under the Water Erosion Prediction Program (WEPP) (Foster and Lane, 1987). Nevertheless, there is still a strong demand for simple models based on the USLE. An interim product, RUSLE—revised universal soil loss equation (Renard et al., 1991a) has been released to bridge the period between the USLE and when WEPP is fully operational. RUSLE includes updated algorithms based on new research and covers a broader range of conditions for which erosion can be predicted. The database from which relationships have been developed is not particularly rich for Vertisols, with no long term fallow plots available (Renard and Foster, 1993). It appears that most information for erodibility of Vertisols is based on simulated rainfall studies. A computerised version of the USLE, "SOILOSS" (Rosewell and Edwards, 1988) has been developed for use in eastern Australia by incorporating local knowledge derived from plot and watershed studies in that region. Vertisols are represented in their database, with 30 years of standard plot available from a site near Gunnedah, NSW.

The accuracy of model predictions is determined by (a) how realistically all processes are represented and (b) inputs and parameter values. As the structure of a model is made more physically realistic, the model becomes more complex and requires more inputs and parameters. Simple models may appear easier to use with fewer parameters, but derivation of parameters values becomes more difficult unless a large experimental data base exists for the situation to be modelled. Soil loss models are generally capable of reasonable prediction of long term soil loss (Freebairn et al., 1989), and in some cases, of event soil loss (Loch et al., 1989a; Silburn and Loch, 1992).

(1) The universal soil loss equation (USLE)

The USLE is based on a statistical summary of annual average soil loss data from plot studies in the United States. It was intended for predicting long-term average soil loss for a specified management and field configuration, but "is not recommended for prediction of specific soil loss events" (Wischmeier and Smith, 1978). The USLE has been evaluated using data from 1 ha watersheds in Queensland, and found to provide good estimates of average erosion rates (Freebairn et al., 1989) (Table 9.7). A major limitation of the USLE is the uncertainty with which predictions can be made for conditions which vary significantly in terms of hydrology and for soils where no experimental data exist. Nevertheless, with all its limitations, the USLE is still a useful predictive model for land use planning, particularly when used as a comparative tool.

TABLE 9.7

Measured average annual erosion on two Vertisols with five crop/management strategies compared with predictions based on the USLE (from Freebairn et al., 1989).

Treatment	Annual soil loss ($t\,ha^{-1}$)			
	Black earth		Grey clay	
	Measured	Predicted	Measured	Predicted
Winter crop, summer fallow				
Stubble burnt	61	56	32	23
Disc tillage	18	27	8	11
Sweep tillage	5	17	4	9
Zero tillage	2	11	2	5
Summer crop, winter fallow				
Disc/chisel tillage	22	46	20	20

(2) Event erosion models

The following event models have been evaluated using watershed data from the Darling Downs, Queensland (Freebairn and Wockner, 1986) and rainfall simulator experiments carried out on freshly tilled bare soil (Loch and Donnollan, 1983b; Loch and Thomas, 1987; Silburn and Loch, 1992).

1. GUESS 1, the simplified model of Rose (Carroll et al., 1986) where Soil loss = runoff volume × sediment concentration (C), where $C = 2700\,SC_r\lambda$; S = sine of slope angle; Cr = fraction of soil exposed; λ = efficiency of entrainment.

2. GUESS 2, the model of Rose using average stream power (Carroll et al., 1986). This version of the simplified model of Rose includes a streampower term: $\lambda = h\,(1\text{-}\Omega o/\Omega)$, where h = efficiency of entrainment, Ω_o = threshold streampower and Ω = streampower. A value of $\Omega_o = 0.005$ was used (Carroll et al., 1986). Mean runoff rate was used to calculate Ω, therefore the Ω values can only be considered an index of streampower for the event.

3. MUSLE, the modified USLE of Williams (1975) uses an event runoff erosivity factor ($11.8(Q\,.\,q_p)^{0.56}$) in place of the rainfall erosivity factor of the USLE, where Q is the runoff volume and q_p the peak runoff rate. MUSLE was developed using data from catchments where deposition occurred between the point of entrainment and the catchment outlet, removing the need for a delivery ratio. Thus the equation inherently assumes some deposition.

4. The modified USLE of Onstad and Foster (1975) combines an event rainfall and runoff erosivity factor ($0.646\,EI_{30} + 0.45Q\,.\,q_p^{1/3}$), derived from fundamental erosion principles with the USLE slope length (LS), K, C and P factors to predict total soil loss for an event.

5. The overland flow erosion component of the CREAMS model (Foster et al., 1980) uses a process-based approach to erosion, representing sediment supply

TABLE 9.8

Evaluation of event soil loss equations using the 36 observed events of Freebairn et al. (1989) for Greenmount, 1976 to 1986

Model	Parameters				Regression[d]		
	Value source	RMSE[a] ($t\,h^{-1}$)	AAE[b] ($t\,h^{-1}$)	P/O[c] (–)	Slope	b	r^2
Guess 1	$l = 0.63$ P/O = 1.0	17.6	9.9	1.00	0.55	7.2	0.42
Guess 2	$h = 0.86$ P/O = 1.0	16.2	9.3	1.01	0.72	4.5	0.55
Onstad and	$K = 0.38$ Handbook[e]	10.1	7.7	1.07	0.75	5.2	0.82
Foster	$K = 0.37$ Min.RMSE[f]	10.1	7.7	1.04	0.76	5.2	0.82
MUSLE	$K = 0.38$ Handbook[e]	13.1	7.6	0.70	0.46	3.9	0.81
	$K = 0.53$ Min. RMSA[f]	10.0	6.6	0.98	0.73	4.0	0.81

[a]RMSE = root mean square error.
[b]AAE = average absolute error.
[c]P/O = Predicted total divided by observed total soil loss.
[d]Regression: Predicted soil loss = b + slope (observed soil loss).
[e]K values from USLE Handbook (1) (metric units).
[f]Fit and parameters for minimum root mean square error (RMSE) derived by optimisation.

from interrill and rill components, transport by flow and deposition explicitly. Sediment properties are represented in detail.

A summary of performance of all models is shown in Tables 9.8–9.10.

GUESS 1 was applied to data from Greenmount and Greenwood by Freebairn and Rose (1982) for a wide range of cover conditions. It was found that the data could be usefully understood in terms of the simplified form of the model and there was a strong relationship between λ and cover, which was common to the two soil types.

Inclusion of the streampower term in GUESS 2 gives a slight improvement in soil loss predictions (Table 9.8). Under-prediction of large events and over-prediction of small events still occurs, but is reduced.

The modified USLE (MUSLE) has also been evaluated by Freebairn et al. (1989). They found the equation underestimated soil loss by about 30 percent when the USLE Handbook K value was used. With the best fit K value, MUSLE gave predictions as good as the more complex Onstad and Foster equation. The best fit K value was greater than the Handbook K value as expected to compensate for deposition assumed by the model. The events are the same as those used by Freebairn et al. (1989), however, predictions are slightly improved because actual LS values of the contour bays on which the events occurred are used (Silburn and Loch, 1992), while an average LS for all bays was originally applied.

The Onstad and Foster model was evaluated for prediction of soil loss on a black earth and a grey clay by Freebairn et al. (1989). The model explained greater than 80 percent of the variance in measured soil loss and the USLE Handbook K value

TABLE 9.9

"Best values" of CREAMS parameters n_{bov} and K (English units) (source: Loch et al., 1989)

Soil	Dominant erosion process	No. plots	n_{bov} (t/ha)	K	RMSE[a]	P/O[b]
Black earth	Rilling	7	0.020	0.45	2.70	0.98
	Rain-flow	6	0.010	0.50	1.22	0.97
Grey clay	Rilling	3	0.020	0.30	3.23	1.05
	Rain-flow	3	0.008	0.23	0.51	0.93

[a]Root mean square error for optimum parameter values.
[b]Predicted total soil loss divided by observed total soil loss.

was within ± 0.05 K units of the best fit values. Statistics of prediction for events at Greenmount (black earth) for bare conditions are given in Table 9.8 for USLE Handbook and best fit (minimum RMSE) values of K.

The main soil parameters of the CREAMS model are K and n_{bov}, along with sediment size and density; K and n_{bov} cannot be measured directly and therefore must be derived from erosion data with all other inputs and parameters measured.

The optimised values (i.e. giving minimum RMSE and P/O $= 1.0 \pm 0.05$) of n_{bov} and K derived by Loch et al. (1989b) for two erosion processes on two soils are shown in Table 9.9. Similar n_{bov} values were obtained within erosion process groupings for the two soils. For rainflow (non-rilling), n_{bov} values are consistent with the value of 0.01 suggested for overland flow (Knisel, 1980). Where rilling is the dominant erosion process, 0.02 could be adopted as a "default value" of n_{bov} for clay soils. A value of K greater than 0.25 and 0.42 respectively for rainflow and rilling conditions, supplies sufficient sediment to satisfy the (limiting) transport capacity. For the grey clay, which exhibits resistance to rilling (Loch and Thomas, 1987), discharges on the "rilled" plots were not high enough for rilling to fully develop. The lower optimum K value (0.30) reflects this limit to detachment. For modelling soil loss in transport-limiting situations, it may be sufficient simply to use a reasonably high value of K, say 0.45.

(3) Prediction of field soil losses using rainulator-derived parameters for CREAMS

The n_{bov} and K values and sediment properties derived from rainulator data for rilling, were used to predict soil losses from field catchments on the black earth (Greenmount) and grey clay (Greenwood) soils (Loch et al., 1989b). The events used were taken from the data described above for black earth and a grey clay respectively, for events when surface cover was <10 percent and prior soil loss since tillage was minimal. Because rilling was a clearly visible component of the field soil losses, values of $n_{bov} = 0.02$ and $K = 0.45$ were used. Measured site

TABLE 9.10

Comparison for the CREAMS model of predicted and measured soil losses for field catchments using rainulator-derived parameter values. $n_{bov} = 0.02$, $K = 0.45$ (English units). Source: Loch et al. (1989). Peak runoff rates were adjusted to remove attenuation caused by measuring weirs.

Site	Regression[c]				
	RMSE[a] (t/ha)	P:O[b]	Slope	b	r^2
Greenmount	9.1	1.00	0.85	2.3	0.87
Greenwood	8.6	0.80	0.80	0.2	0.87

[a]Root mean square error.
[b]Predicted total soil loss/observed total soil loss.
[c]Regression: Predicted soil loss = b + slope (Observed soil loss).

conditions (slope, slope length) and hydrologic inputs were used except peak runoff rates which were adjusted to remove the effect of flow attenuation caused by the weirs or flumes.

For the 28 events at Greenmount, very good predictions were obtained (Table 9.10). For the 21 erosion events at Greenwood, soil losses were under-predicted by 20 percent. When the model was run using $K = 0.30$ (derived from rainulator plots on which rilling was not fully developed) soil loss was under-predicted significantly, reducing P:O to 0.61. This illustrates the point that parameters derived for one set of erosion processes will not be valid in a situation where the processes (or their importance) are different.

The performance of the model is particularly encouraging as the field data include storms with complex hydrology, some having several peaks in runoff, that were represented in the model only by total runoff volume and a single peak runoff rate.

One of the main objectives of research on process models has been to validate the use of parameter values that are independently estimated, generally being measured at small scales, to model hydrology and erosion at the field or watershed scale. Rainfall simulators are convenient for studying processes in hydrology and erosion and have an important role in estimating values for parameters used in models.

9.5.3. General

Models for soil loss prediction are based on a wide range of approaches, from statistical summaries of data through to detailed erosion–deposition process models. All have valid uses depending on the level of reliability and detail required. All also have one common limitation: How does the user obtain the parameter values that will give the best predictive accuracy? Recent research has shown that good predictions can be obtained using parameters measured at small scales provided the model is a realistic representation of the processes operating at the scale of interest.

9.6. APPLICATION OF EROSION MODELS IN SYSTEMS MODELS

Erosion models alone have had limited application except as a policy tool such as applied in the US Farm program, or as a simple planning tool. A reason for the relatively infrequent use of erosion models may be that erosion is often separated from production, yet farmers generally have to meet short term goals dealing with production and profit before substantive effort can be applied to conservation strategies.

A cropping system simulation model, PERFECT (Productivity, Erosion and Runoff Functions to Evaluate Conservation Techniques) (Littleboy et al., 1989) has been developed to simulate the dynamics of a plant–soil–water interactions in agricultural systems on the Vertisols of north-eastern Australia. PERFECT has much in common with EPIC (Williams et al., 1984) and CREAMS but has more detailed crop models applicable to the semi-arid tropics of north-eastern Australia and includes effects of cover on runoff and evaporation. The major effects of management (e.g. planting decisions, crop rotation, fallow management) and environment are simulated to predict soil water, runoff, erosion, drainage, crop growth and yield using daily climate data as a basic input. PERFECT has been used to assess the erosion and production risks associated with different management options (Littleboy et al., 1992b). Validation data for PERFECT are presented in Table 9.11 using experimental data from Vertisols in Queensland. Further explanation and validation of the soil and crop components of the model have been presented by Littleboy et al. (1989, 1992 a,b) and Freebairn et al. (1991). The following applications are presented to demonstrate the role of simulation

TABLE 9.11

Mean predicted runoff (pred.), soil loss and wheat yield for four stubble management practices for the period 1912–1985 using the PERFECT model and measured mean values (Obs.) for 8 years (1978/79–83/84, 1986/87–87/88) Greenmount, eastern Darling Downs (from Freebairn et al., 1991)

Stubble management	Runoff (mm)		Soil loss (t ha^{-1})		Wheat yield (t ha^{-1})	
	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
Bare fallow (burnt)	74	75	49	56	2.8	2.2
Disc tillage	56	59	16	13	2.8	2.6
Sweep tillage (mulch)	53	55	6	4	2.9	2.7
Zero-tillage	61	58	3	2	2.8	2.8

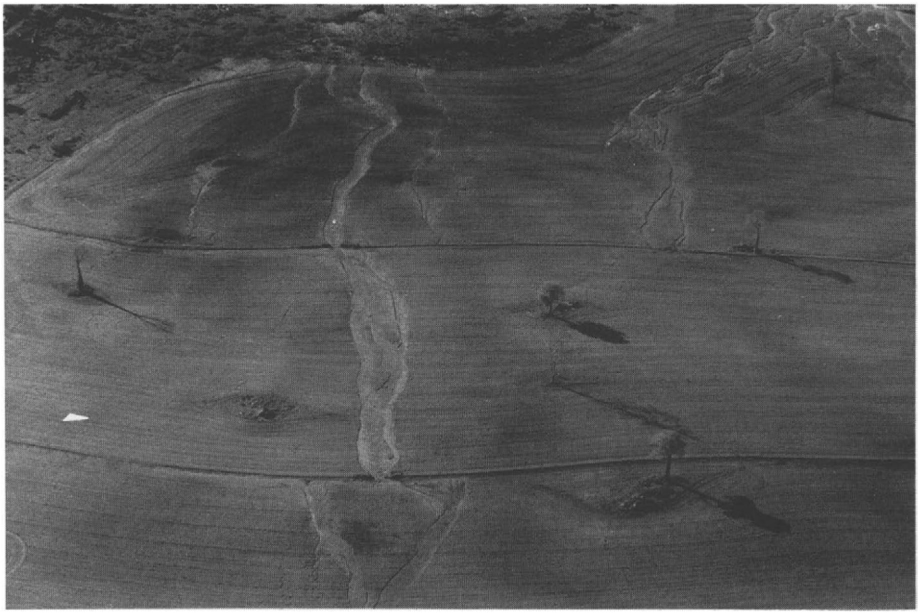


Fig. 9.22. Failure of contour or graded banks results in further damage as water concentrates, in this case after a "large" runoff event. Evidence of repair between storms in a 7 day period indicate that these banks have failed twice, probably due to established flow lines, a saturated catchment and high sediment loads reducing channel capacity with sediment deposition. Structures such as these are designed for a 10 percent chance of failure each year (1:10).

methodology as a aid in interpreting erosion experiments and adding value to existing data.

9.6.1. Assessing the value of contour banks in reducing erosion

Hydraulic structures such as contour or graded banks are designed to contain the flow from a specified design storm or runoff event. A common design criterion for contour banks is that they are able to control the 1:10 year event. Therefore, structures must fail and in the case of contour banks may cause a cascade of failures further down slope, the "domino" effect (Fig. 9.22). Such a failure will result in much of the soil conserving effectiveness of the structures being lost, with concentrated flow often causing increased damage in the form of wide rills and gully initiation. The question we would like to answer is—how much soil loss occurs in these large events?

Using the PERFECT crop production/erosion model we created a long term record of runoff and erosion from a relatively short experimental data base (12 years). Analysis of the time series of erosion showed that approximately 40–50 percent of total soil loss occurs in the greater than 1 in 10 year events (Fig. 9.23). For the conditions used in this analysis, soil conservation structures will reduce

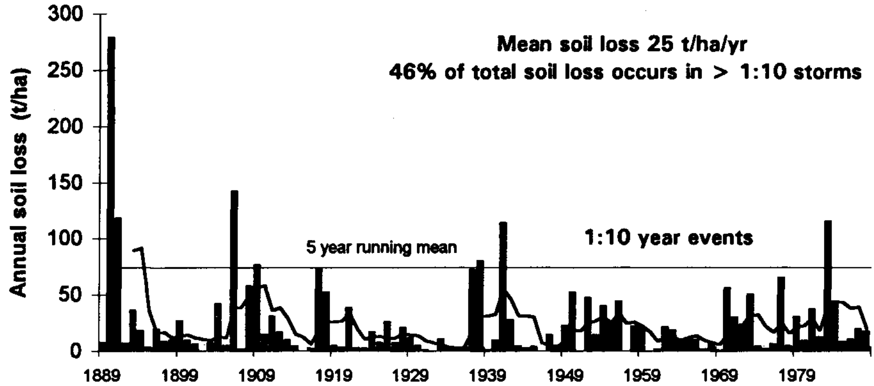


Fig. 9.23. Time series of estimated annual soil loss at Roma, showing 5 year running mean. Events greater than 1:10 year return period are above the horizontal line. For events larger than 1:10, contour banks are designed to fail.

soil losses by about 50 percent. It is noteworthy that stubble retention has reduced soil loss rates by 90 percent in similar situations in Queensland.

9.6.2. Analysis of cropping systems

A case study of comparing a traditional tillage/crop system with a range of modified technologies is presented by Singh and Raje (1984). Their experiment lasted 7 years and was able to show large improvements in crop production and noticeably less soil degradation. While such studies are essential for both integrating the practical elements of a new system, they are expensive, often site specific and require to be run for several seasons. Simulation methods need to be run in conjunction with such studies. Stinson et al. (1981) used a model to compare yield, runoff and erosion for two methods of growing sorghum in the Central Texas Blacklands; ratoon cropping and plant cropping. Ratoon cropping involves allowing the sorghum plant to re-grow after harvest. A potential benefit was to increase yields while reducing evaporation and soil exposure to rainfall. Their analysis showed that runoff and erosion could be reduced by 17 percent but that increases in total crop yield were too unreliable to justify the practice. They also pointed out the danger of relying on short duration experimental data in a variable climate. In a similar analysis, three cropping strategies (continuous wheat, continuous sunflower, and opportunity wheat/sunflower) and two fallow management strategies (bare fallow and zero-till) are compared using runoff, erosion, drainage and crop yield as indicators of performance. Opportunity cropping refers to the planting of crops when sufficient water is available rather than planting on a fixed rotation. A Vertisol on the eastern Darling Downs, Queensland is used to demonstrate the multiple changes that can occur when crop management is changed.

TABLE 9.12

Influence of cropping rotation and stubble management on predicted mean annual crop yield (of years planted), runoff, drainage and soil erosion for the eastern Darling Downs (from Freebairn et al., 1991)

Attribute	Fallow management	Crop rotation		
		Wheat	Sunflower	Wheat/sunflower
Years planted	(%)	83	88	50/73
Yield	($t\ ha^{-1}$)			
	Bare fallow	1.92	1.47	1.46/1.40
	Zero till	2.19	1.60	1.54/1.54
Runoff	(mm)			
	Bare fallow	77	89	66
	Zero till	60	79	56
Soil erosion	($t\ ha^{-1}$)			
	Bare fallow	46	57	37
	Zero till	2	26	15
Drainage	(mm)			
	Bare fallow	10.1	1.7	0.7
	Zero till	38.1	7.4	3.1

Planting rules-wheat 12.5 mm rain, soil water 75 mm, date 26/5–31/7; sunflower 20 mm rain, soil water 100 mm, date 1/1–29/2).

Predicted mean annual runoff, drainage, erosion and yield (for years planted) are presented in Table 9.12. Mean yield for both wheat and sunflower decreased as cropping intensity increased. Yield decreases for wheat are larger than for sunflower due to the summer dominant rainfall patterns. Fallow periods before wheat are shorter with higher cropping intensity. Total cropping intensity increased from 83 percent to 123 percent when opportunity cropping was practised. Both runoff and drainage were lower with opportunity cropping because transpiration used a higher proportion of rainfall.

The cropping system with the least erosion, zero-till wheat, has the highest drainage, demonstrating potential conflict in objectives for a sustainable cropping system.

9.6.3. Extrapolating a "short" duration record of erosion

Soil erosion is an episodic process, characterised by a few extreme events. For example, runoff and soil erosion have been monitored for up to 14 years on contour bay catchments in southern Queensland. At one site, approximately 70 percent of the 556 $t\ ha^{-1}$ of soil erosion over 14 years occurred in six storms in an annual wheat cropping system with bare summer fallow (Wockner and Freebairn, 1990). Average annual soil movement for two consecutive four year periods 1980/83 and

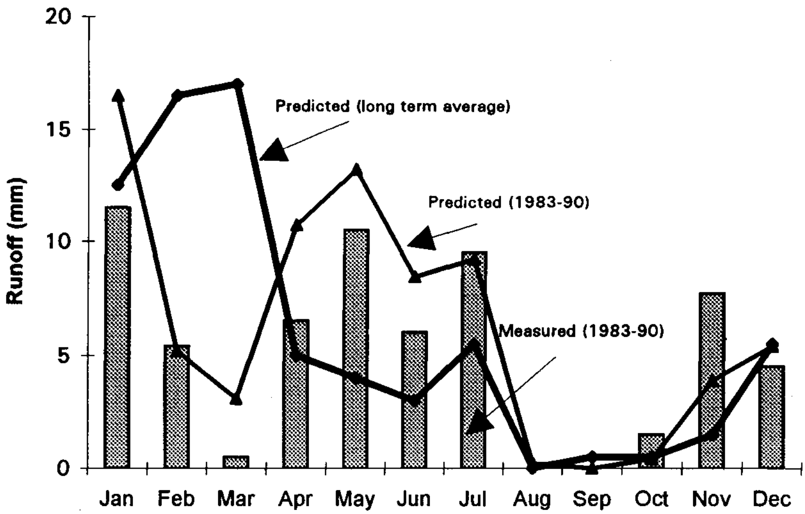


Fig. 9.24. Monthly distribution of runoff measured from the Wallumbilla catchment study (1983–90) and short (1983–90) and long term (1899–1975) runoff predicted using the PERFECT model. A short term record gives a false sense of security if stubble is removed in March.

1984/87 was 78 and 14 t $ha^{-1} yr^{-1}$ respectively, demonstrating that short duration of records could be misleading.

In response to changing stubble management practices, the question arose as to when was the most appropriate time to burn stubble—there was a perceived yield penalty due to disease associated with stubble retention even though it was generally accepted that retention of stubble was advantageous for erosion control. Data over 7 years from a catchment study in the region indicated that runoff was unlikely in March. Predicted and observed runoff were in close agreement, but comparison of the distribution of monthly runoff revealed that the 7 year record was grossly misrepresentative of longer term expectations of monthly runoff (Fig. 9.24). The period of measurement had 50 percent of the average rainfall for March, which, according to this analysis, is the month with the greatest risk of runoff and erosion. Our advice to farmers was to delay burning until after March if at all possible, contrary to the measured data!

9.6.4. Whole farm catchment-analysis

Physical evaluation of complex farming systems is often impractical but comparison of systems is well suited to simulation analysis. As an example of what might be considered a "model" of sustainable farming, a comparison of a farm system involving contour banks, stubble mulching and storage of runoff water for supplementary irrigation was compared to a system of bare fallow and no soil conservation structures. The simulation allowed us to combine what was known about stubble management, soil conservation structures and crop response to

TABLE 9.13

Influence of stubble management, contour banks and a farm dam designed supplementary irrigation on mean annual runoff, soil loss and yield for an eastern Darling Downs catchment. Data are based on experimental results and simulation using long term climate records.

		Wheat, bare fallow	Wheat, stubble mulch contour banks Dam + supple. irrigation
Runoff	(mm)	54	21
Sediment loss	(t ha^{21})	37	0.5
Wheat yield	(t ha^{21})	2.8	3.15

supplementary irrigation. Mean yields were increased by 12.5 percent (due to better water storage in the fallow resulting from stubble retention and supplementary irrigation) and sediment loss from the catchment was reduced to 0.5 t ha^{-1} yr^{-1} (Table 9.13).

9.6.5. *Effect of erosion on productivity*

It is generally accepted that soil erosion results in a loss of productivity, but information is sparse on the degree to which erosion reduces yields and is often ambiguous (Hamilton, 1970; Aveyard, 1983). This information has been difficult to obtain experimentally because erosion is slow and sporadic, and its effects are often masked by climatic variability and advances in technology.

PERFECT was used in two modes to estimate erosion effects on yield: (a) through loss of soil depth and plant available water capacity (PAWC) and (b) through loss of both PAWC and nitrogen. Data in Fig. 9.25 show that for a shallow soil (PAWC 125 mm) on the eastern Darling Downs, erosion causes yield declines and this decline in yield increases rapidly after 25–35 years due to loss of both

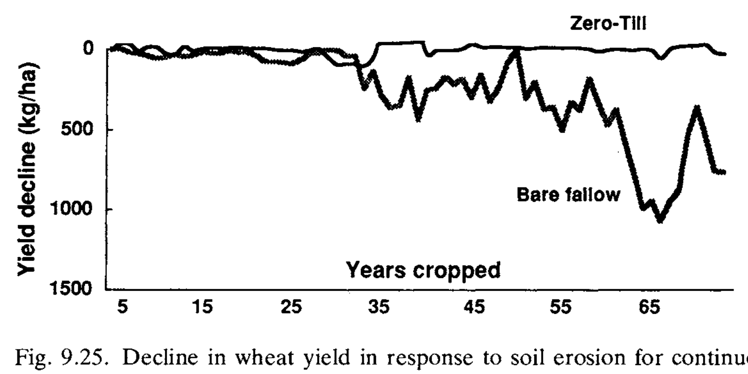


Fig. 9.25. Decline in wheat yield in response to soil erosion for continuous wheat, bare fallow and Zero till on the eastern Darling Downs. Yield declines due to loss of plant available water content land available nitrogen .

PAWC and nitrogen. It is interesting to note that much of the eastern Darling Downs has been farmed for this length of time or longer; how far along the time series in Fig. 9.25 are we now? Some areas have been retired from cultivation although no survey has been undertaken of either soil depth (remaining) or of land retired from cultivation. Deeper soils (PAWC 250 mm) do not show yield declines greater than 10 percent (due to loss of PAWC alone) for up to 100 years. Yield reduction is variable from year to year, depending on seasonal conditions. In favourable seasons, yield reduction is related to lower PAWC and less nitrogen in eroded soil, while yield reductions in drier years are smaller because yield is determined by growing season water supply rather than soil properties.

To examine the spatial distribution of erosion and its effect on production, Littleboy et al. (1992c) mapped the spatially distributed outputs from many cropping system model simulations. They combined information on soil type, slope and rainfall to produce a map of erosion rates, highlighting the areas most susceptible to erosion in a region. Such an analysis has powerful policy applications for targeting land management programmes.

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