successive velocity profiles is calculated and can be expressed as a volume of displacement per unit width of slope through time (for example, $cm^3\ cm^{-1}\ yr^{-1}$).

4.2.6 Techniques for the measurement of surface-water erosion processes on slopes

Surface-water erosion on slopes, often called slopewash, results from several mechanisms, already mentioned in the general discussion of hillslope processes. While it is convenient to think of the main mechanisms, rainsplash, unconcentrated flow and rill erosion, as distinct processes for the purpose of explanation, they really operate together and the effects of each are difficult to define. Measurement of slopewash rates is beset with difficulties. Total rates over large areas of slope are difficult to obtain due to the wide variation from point to point. Obviously, erosion along a rill during a storm may be orders of magnitude greater than adjacent unconcentrated areas. Also, many of the techniques have severe operational difficulties, which are discussed below. If rates due to rainsplash are to be separated from those due to surface flow erosion, even greater problems exist. Factors influencing the processes are manifold and include soil, rainfall characteristics, vegetation and slope factors. Often, it is difficult to isolate the factors under natural conditions and more precisely controllable experiments are possible in the laboratory to study process mechanics. The techniques discussed here are those to measure rates of erosion and are considered under the headings of rainsplash, surface flow erosion and total erosion. Brief reference is made to a few simulation studies.

4.2.6.1 Rainsplash

Measurement of rainsplash rates was pioneered by the work of Ellison (1944a, b, 1945). Ellison used a splashboard to measure rainsplash erosion. It consists of a board mounted across the slope, with two narrow troughs sunk flush with the soil surface at its base. The troughs are positioned to catch material splashed onto the upslope and downslope sides of the board respectively in order to estimate net transport (Fig. 4.30). Suitable dimensions for the splashboard are shown in Figure 4.30. After rainfall, material is cleaned from both sides of the boards and the troughs emptied, and the total upslope and downslope catch weighed. Net transport is then expressed in grams per centimetre of slope. Disadvantages of this apparatus include its susceptibility to overland flow entering the troughs and its obvious, though unknown, influence on wind turbulence near to the board.

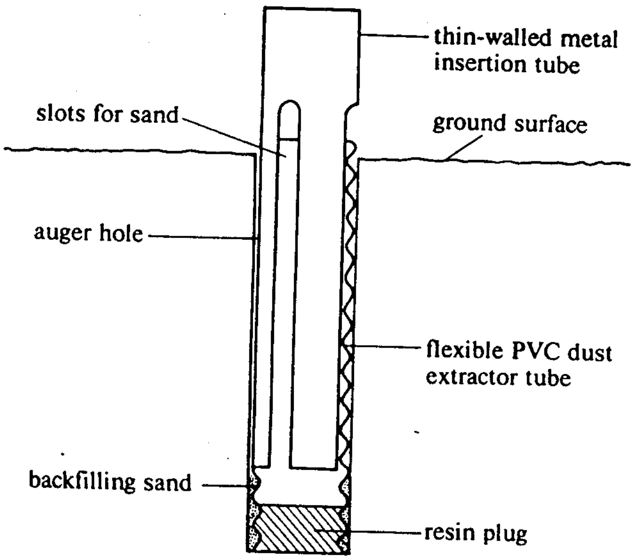

Figure 4.29 Installation of flexible soil creep tubes.

Goudie, A. et al. 1990.
Geomorphological Techniques, 2nd edition
Unwin Hyman Ltd., London, UK.
p. 251-256.

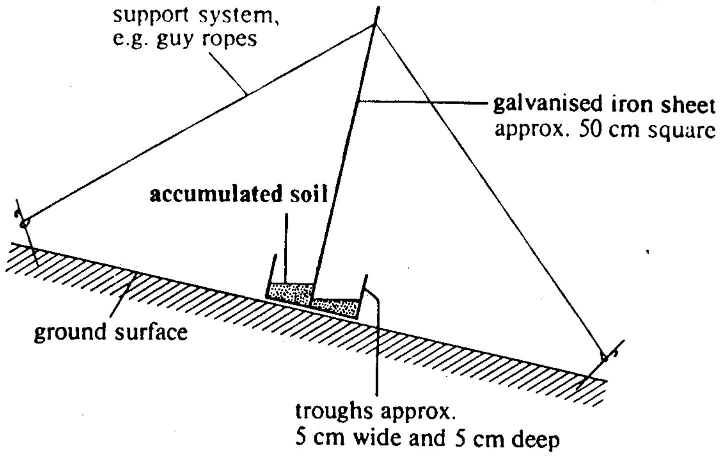

Figure 4.30 The splash trough.

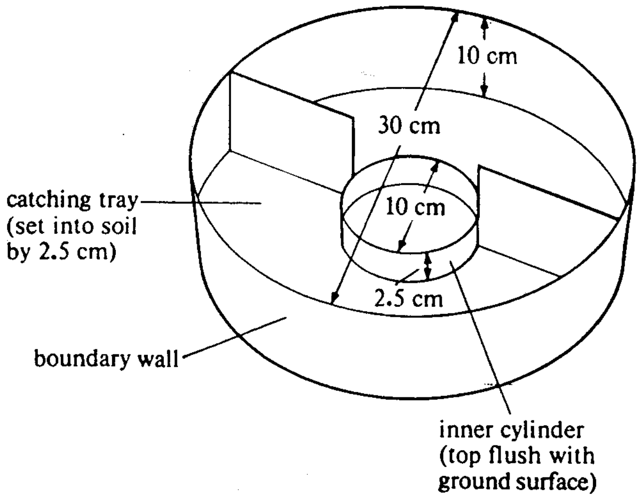

Figure 4.31 Morgan's splash cup.

Morgan (1978) has designed a splash cup to study rainsplash erosion (Fig. 4.31). It consists of an inner tube of 100 mm diameter, which is inserted into the ground until it is flush with the soil surface. An outer circular tray is sunk to a depth 25 mm around the inner tube. This tray catches material splashed from the inner tube and has a central divide so that upslope and downslope transport may be separated. Hence, net transport from the site may be measured and reported in g/m^2 in unit time. Morgan installed two cups at each site and used the average value. The apparatus is protected from overland flow by the outer rim of the collecting tray and it is much less likely to interfere with the wind flow near to the ground than the splashboard. Disadvantages are that only a very small area of soil is sampled by the splash cup in comparison with the splashboard, and that considerable disturbance of the soil occurs on installation.

Bolline (1978) used 52 mm diameter funnels, buried flush with the ground surface, to catch splashed soil. A rot-proof filter is placed into the funnel to catch the sediment. The funnel is weighed before placing in the ground and is removed after each rainfall event for reweighing. The funnel is cleaned on the outside and dried before reweighing to obtain the weight of splashed soil. This apparatus does not separate material splashed downslope from that splashed upslope; nor does it allow soil that has entered the trap from being splashed out again. Therefore, only cumulative splash is measured and estimation of absolute rates of downslope transport cannot be made. Comparative measurements may be made between sites to study the effects of various process controls on rainsplash. Similar to the splashboard, the funnels can suffer from ingress of overland flow, and therefore may not necessarily give a true measure of splash.

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A number of other techniques have been tried to investigate rainsplash. Coutts *et al.* (1968) labelled soil particles with a radioactive tracer, ^{59}Fe. The tracer was applied to the soil as a stock solution of $^{59}FeCl_3$. The method was tested in simulated soils and true field conditions, and it was possible to demonstrate the influence of slope and wind direction on soil movement. Unfortunately, the results were not of sufficient quality to allow estimates of rate erosion to be made. Kirkby and Kirkby (1974a) monitored painted stone lines on slopes during rainfall and were able to make interesting observations on the mechanics of the splash process. Generally, marked stone lines can only be used to measure total erosion by slopewash processes, since it is not possible to distinguish splash-displaced particles from overland flow movements without constant observation.

Field studies of controls and mechanics of rainsplash have often been inconclusive, probably due to the great number of factors that exert an influence on the process. Controlled simulations in the laboratory are a way in which this problem can be overcome. Specific controls may be isolated for investigation in the laboratory, which is not possible in the field. An example of this approach is Moseley's (1973) laboratory study of the influence of slope angle on rainsplash. Simulated rainfall is necessary for laboratory studies and it is important that the natural characteristics of rainfall are reproduced as closely as possible. Basically there are two main types of rainfall simulator (Hudson 1972): those that use non-pressurised droppers, and those that use spraying nozzles with pressure. The former suffer from the disadvantage that they need to be very high for the water particles to reach their terminal velocity. The latter suffer from the fact that if the spray is to include drops of the largest size that occur in natural rain, then the nozzle opening has to be large (about 3 mm diameter). Even with low water pressures, the intensity produced from nozzles of this size is much higher than from natural rain, though there are various techniques that have been developed to alleviate this problem. Moreover, as Hall (1970b) has pointed out, if a network of nozzles is used to generate artificial rainfall, an increase in working pressure increases the average intensity but decreases the range of drop sizes within the spray. In natural rainfall, on the other hand, the range of drop sizes increases with increasing rainfall intensity. Mutchler and Hermsmeier (1965), Bryan (1974), Riezebos and Seyhan (1977), Luk Shiu-Hung (1977) and Farres (1980) discuss some of these problems and give details of hardware, while Schumm (1977a) describes the use of a very large rainfall-erosion facility (REF), which can generate whole drainage networks.

4.2.6.2 Surface-water flow erosion

Sediment traps have been extensively used to measure erosion by flowing water on slopes for many years. A box dug into the slope surface with its top flush with the ground surface will catch any overland flow occurring on the slope above it, and most of the sediment being transported will be trapped. The Gerlach trough (Gerlach 1967) has been specially designed for this purpose.

A lid must be incorporated into the design to prevent splashed material from entering if one requires to separate the two processes, and drainage holes should be provided to prevent the trap filling with water and overflowing (Fig. 4.32). If the trap does overtop, a considerable amount of sediment of finer grain sizes would fail to be trapped. Inevitably, some disturbance of the soil must occur on installation of such a trap, which may lead to accelerated erosion near to the upslope lip of the box. However, if care is taken to ensure that the upslope lip is exactly flush with the ground surface, the effect of disturbance will be minimised. It should be mentioned that sediment traps measure net erosion loss for a section of slope above them by catching all sediment in transport at a point. There is often great difficulty in defining the contributing area to the troughs. They do not measure erosion at a point, unlike many of the techniques for total slopewash erosion.

Very few other ways of measuring surface flow erosion *only* have been devised, though many systems exist to measure *total* slopewash erosion, discussed below.

4.2.6.3 Total slopewash erosion

Since the early 1950s, erosion pins, stakes driven into the ground against which erosion can be gauged, have been used to measure slopewash. The technique was pioneered by Schumm (1956) and others, who used wooden stakes. More recently, metal stakes have been used in preference because they can be thinner for the same strength and are generally more resistant to decay. A comprehensive survey of the slopewash literature and summary of the use of erosion pins may be found in Haigh (1977). Many designs of erosion pin have been used since the method was first proposed, but after thorough examination of the literature, Haigh (1977) advocates the use of a design similar to that in Figure 4.33. The pins should be thin (5 mm diameter) metal rods up to 600 mm long, made out of non-corrosive metal if possible. They should be inserted a considerable distance into the ground to minimise risk of disturbance and frost heave, but should not be placed flush with the ground surface. Preferably about 20 mm of peg should protrude to facilitate relocation. Because slopewash rates are so variable between points on a slope, it is advisable to place a number of pegs at each measuring site, arranged in clusters or lines parallel with the contours. Readings are taken of the length of peg exposure using a simple depth gauge (Fig. 4.33) and should be made at least every six months, with the minimum of trampling of the site. If a loose-fitting washer is put round the peg on installation, it should be possible to record maximum and net erosion by the washer position and the depth of sediment accumulated over it respectively. In practice, washers inhibit erosion beneath them and are too smooth to be good sites for sediment deposition. Therefore, pins equipped with washers may give a rather poor indication of erosion and deposition at the site. Some workers have suggested that the washer only be placed over the peg at time of measurement to form a standard reference level on the soil surface, and should be removed after measuring is complete. The difficulties and drawbacks of erosion pins are discussed at length in Haigh (1977). Undoubtedly, there are serious soil disturbance problems on insertion and it is advisable to leave them to settle for some time before commencing observations. The pins also influence flow in their vicinity, though the importance of this problem is not really known.

A variation on the micro-erosion meter (Sec. 4.1.6) devised to measure directly the solution of limestone has been applied to slopewash (Campbell 1970, Lam 1977). Since rates of erosion due to slopewash are much higher than limestone solution, the apparatus need not be so accurate. The so-called 'erosion frame' consists of a rectangular grid of aluminium bars, which can be positioned over four permanently installed steel stakes driven into the ground at the measuring site (Fig 4.34). A depth-gauging rod may be

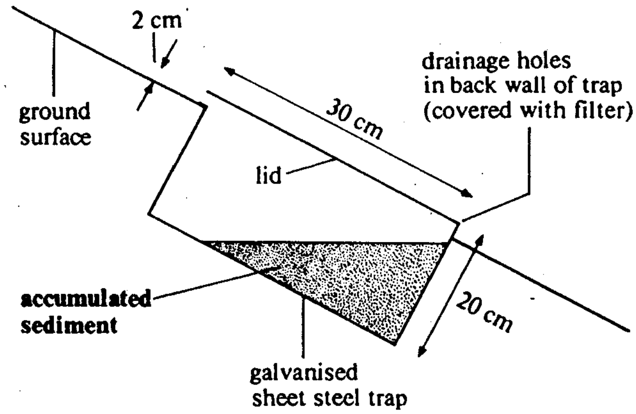


Figure 4.32 A sediment trap to measure surface-water flow erosion.

passed through holes drilled into the bars of the frame to measure changes in elevation of the soil surface, with respect to the frame, at a number of points. Several measurement sites may be established along a slope profile to examine changes in erosion downslope. The erosion frame has several advantages over erosion pins. The most significant are that no disturbance of the soil where measurements are made occurs when the site is established, that there is no modification of water flow, and that a number of measurements may be made at the same site.

Painted stones or sediment lines on slopes have already been mentioned in the context of rainsplash observation. When they are not observed continuously during rainfall, they only give information on total slopewash erosion. They have been used by many workers and obviously require little explanation. A paint line is sprayed neatly across the slope surface, or rows of painted stones are placed on the slope. The site is visited after rainfall and displacement of sediment and stones is measured. Particles that have been displaced should also be weighed to make estimates of total transport. Kirkby and Kirkby (1974a) found that the reliability of recovery declined with distance of transport downslope, and that the method was of no practical use at all for parts of the paint line that happened to cross concentrated flowlines, because particles were always lost. This highlights one of the major problem of measuring slopewash; namely rates of erosion fluctuate very widely between areas of concentrated and unconcentrated flow. Kirkby and Kirkby (1974b) have calculated slopewash rates from the degree of degradation of datable archaeological house mounds in Mexico. The calculation was based on the assumption that the transport rate is proportional to slope, on which basis the mound profile approximates to a normal curve whose variance increases linearly with time.

A final point about slopewash that should be made concerns the units in which erosion is measured. Rainsplash instruments and sediment traps catch material, which is weighed, and results are usually quoted in terms of a weight of material displaced from an area of slope, or in terms of a transport rate past a unit width of slope in unit time (for example, $g\ cm^{-1}\ yr^{-1}$). On the other hand, pegs and similar methods of measuring slopewash directly measure ground surface lowering. On this point, it is necessary to be careful to distinguish between vertical ground lowering and ground retreat parallel to the slope. It will be appreciated that these two measures of ground retreat differ by an amount that is a function of slope angle. Comparison of weight measures of transport

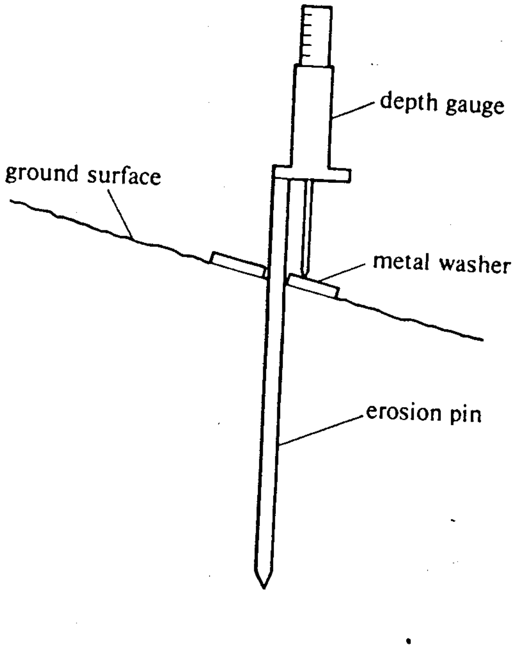


Figure 4.33 A typical erosion pin design.

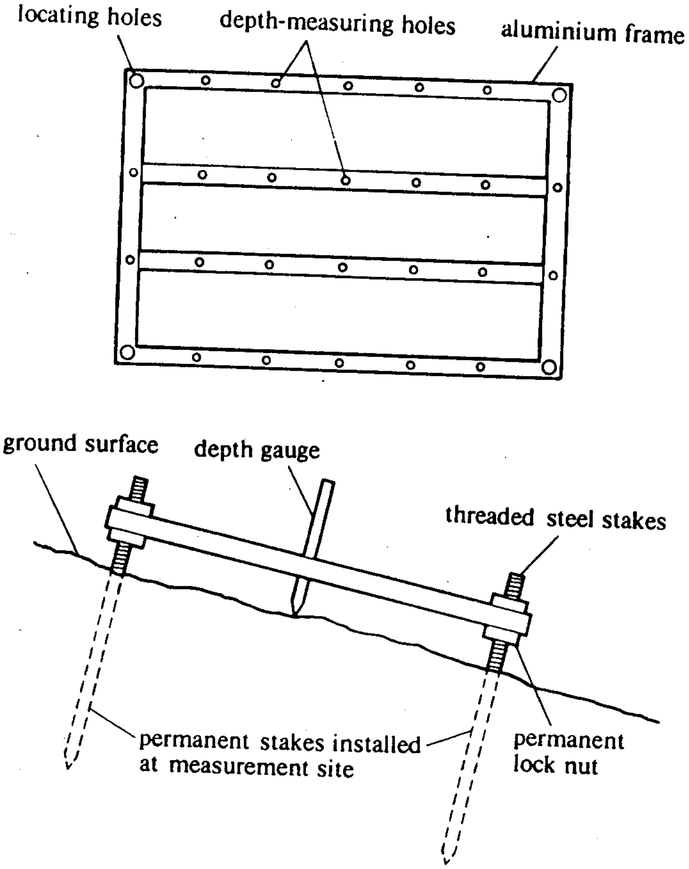


Figure 4.34 An erosion frame to measure slopewash erosion.

with direct surface lowering requires a conversion of the weights of soil into volumes. This in turn requires the unit weight of the undisturbed sediment surface to be assessed.

~~4.2.7 Frost heave and other ice-related soil movements~~

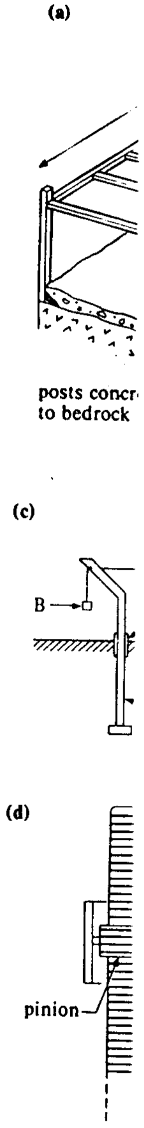
~~The formation of ice within the soil causes a displacement of the soil surface. This process, which is an important cause of sediment movement on slopes, is termed frost heave, and it may be of the order of 30 cm each season in a severe environment, though values of 1–5 cm are probably more typical. The methods available for frost-heave monitoring are summarised in this section. Two main types are recognised: the non-continuous and the automatic.~~

~~*4.2.7.1 Non-continuous methods*~~

~~**Frame-and-rod instruments** These use the principle of recording the movement of rods supported vertically on the soil surface by a metal frame (see Fig. 4.35a). Metal is preferable to wood because of the problems posed by warping. Such instruments can measure heave to an accuracy of 1 mm and are particularly effective where the magnitude of frost heave amounts to several centimetres. Thus, heaving beneath snow can be measured with a cheap, simple and efficient method.~~

~~**Levelling** Levelling can be used to record changes of level with reference to a stable benchmark.~~

~~**Direct measurement of frost-heave gauges** Various types are available (See Fig. 4.35) but James (1971, p. 16) states that buried frost-heave gauges have certain~~



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