7

HILLSLOPES

Hillslopes are an almost universal landform, occupying some 90 per cent of the land surface. This chapter will explore:

- The form of hillslopes
- Hillslope transport processes and hillslope development
- Humans and hillslopes

Hazardous hillslopes

Any geomorphic process of sufficient magnitude that occurs suddenly and without warning is a danger to humans. Landslides, debris flows, rockfalls, and many other mass movements associated with hillslopes take their toll on human life. Most textbooks on geomorphology catalogue such disasters. A typical case is the Mount Huascarán debris avalanches. At 6,768 m, Mount Huascarán is Peru's highest mountain. Its peaks are snow- and ice-covered. In 1962, some 2,000,000 m^3 of ice avalanched from the mountain slopes and mixed with mud and water. The resulting debris avalanche, estimated to have had a volume of 10,000,000 m^3, rushed down the Rio Shacsha valley at 100 km/hr carrying boulders weighing up to 2,000 tonnes. It killed 4,000 people, mainly in the town of Ranrahirca. Eight years later, on 31 May 1970, an earthquake of about magnitude 7.7 on the Richter scale, whose epicentre lay 30 km off the Peruvian coast where the Nazca plate is being subducted, released another massive debris avalanche that started as a sliding mass about 1 km wide and 1.5 km long. The avalanche swept about 18 km to the village of Yungay at up to 320 km/hr, picking up glacial deposits *en route* where it crossed a glacial moraine. It bore boulders the size of houses. By the time it reached Yungay, it had picked up enough fine sediment and water to become a mudflow consisting of 50–100 million tonnes of water, mud, and rocks with a 1-km-wide front. Yungay and Ranrahirca were buried. Some 1,800 people died in Yungay and 17,000 in Ranrahirca.

HILLSLOPE ENVIRONMENTS

Hillslopes are ubiquitous, forming by far the greater part of the landscape. Currently, ice-free landscapes of the world are 90 per cent hillslopes and 10 per cent river channels and their floodplains. Hillslopes are an integral part of the drainage basin system, delivering water and sediment to streams. They range from flat to steep. Commonly, hillslopes form **catenas** – sequences of linked slope units running from drainage divide to valley floor. Given that climate, vegetation, lithology, and geological structure vary so much from place to place, it is not surprising that hillslope processes also vary in different settings and that hillslopes have a rich diversity of forms. Nonetheless, geomorphologists have found that many areas have a characteristic hillslope form that determines the general appearance of the terrain. Such characteristic hillslopes will have evolved to a more-or-less equilibrium state under particular constraints of rock type and climate.

Hillslopes may be bare rock surfaces, regolith and soil may cover them, or they may comprise a mix of bare rock and soil-covered areas. Hillslopes mantled with regolith or soil, perhaps with some exposures of bare rock, are probably the dominant type. They are usually designated **soil-mantled hillslopes**. However, hillslopes formed in bare rock – **rock slopes** – are common. They tend to form in three situations (Selby 1982, 152). First, rock slopes commonly form where either uplift or deep incision means that they sit at too high an elevation for debris to accumulate and bury them. Second, they often form where active processes at their bases remove debris, so preventing its accumulation. Third, they may form where the terrain is too steep or the climate is too cold or too dry for chemical weathering and vegetation to create and sustain a regolith. More generally, bare rock faces form in many environments where slope angles exceed about 45°, which is roughly the maximum angle maintained by rock debris. In the humid tropics, a regolith may form on slopes as steep as 80° on rocks such as mudstones and basalts because weathering and vegetation establishment are so speedy. Such steep regolith-covered slopes occur on Tahiti and in Papua New Guinea where, after a landslide, rock may remain bare for just a few years. Rock properties and slope processes determine the form of rock slopes. There are two extreme cases of rock properties. The first case is 'hard' rocks with a very high internal strength (the strength imparted by the internal cohesive and frictional properties of the rock). These usually fail along partings in the rock mass – joints and fractures. The second case is 'soft' rocks of lower intact strength or intense fracturing that behave more like soils. As a rule of thumb, bare rock slopes form on hard rocks. However, there are circumstances that favour the formation of bare rock slopes on soft rocks. For example, steep rock slopes may occur on mudstones and shales that lie at high elevations where the slopes are regularly undercut. Even so, such slopes denude far more rapidly than do slopes on hard rocks, and they are far more likely to develop a soil and vegetation cover (Selby 1982, 152). Some rock slopes speedily come into equilibrium with formative processes and rock properties, their form reflecting the strength of the rock units on which they have developed. Such rock slopes occur on massive and horizontally bedded rocks. On dipping and folded rocks, the form of bare rock slopes conforms to underlying geological structures.

HILLSLOPE FORMS

Slope units

The term slope has two meanings. First, it refers to the angle of inclination of the ground surface, expressed in degrees or as a percentage. Second, it refers to the inclined surface itself. To avoid misunderstanding, the term **hillslope** usually applies to the inclined surface and the term **slope angle**, **slope gradient**, or simply **slope** to its inclination. All landforms consist of one or more slopes of variable inclination, orientation, length, and shape (Butzer 1976, 79). Most hillslope profiles consist of three slope units – an upper convex unit where gradient increases with length, a straight middle unit of constant gradient, and a concave lower unit where gradient decreases with length (Figure 7.1) (White 1966). The transition between these slope units may be smooth or abrupt (Figure 7.2). The middle unit is sometimes absent, giving a **concavo-convex slope profile**, as commonly found in English Chalklands (Plate 7.1; see also p. 290). The terms used to describe slope units vary.

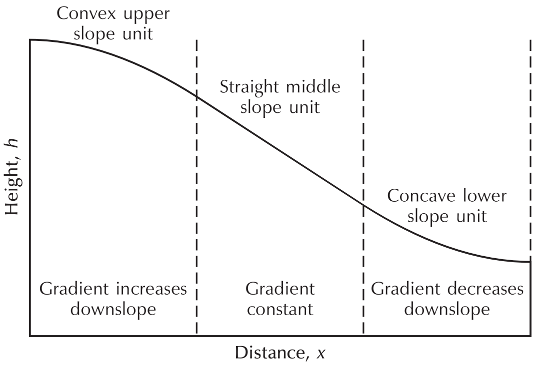

Figure 7.1 Three form elements of slopes.

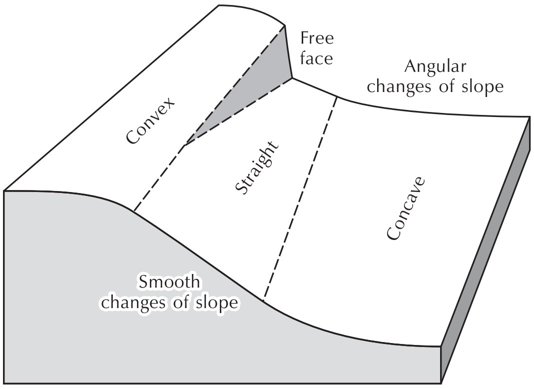

Figure 7.2 Abrupt and smooth transitions between slope elements.

Anthony Young (1971) defined them as follows: a **slope unit** is either a segment or an element, whereas a **segment** is a portion of a slope profile on which the angle remains roughly the same, and an **element** is a portion of a slope profile on which the curvature remains roughly the same.

Convex, straight, and concave hillslope units form a **geomorphic catena**, which is a sequence of linked slope units (cf. Speight 1974; Scheidegger 1986). Several schemes devised to describe hillslope profiles recognize these three basic units, although subunits are also distinguished (Figure 7.3). One scheme recognizes four slope units: the waxing slope, also called the convex slope or upper wash slope; the free face, also called the gravity or derivation slope; the constant slope, also called the talus or debris slope where scree is present; and the waning slope, also called the pediment, valley-floor basement,

Plate 7.1 Concavo-convex slope on the chalk ridge, Isle of Purbeck, Dorset, England. The ruins of Corfe Castle lie in the middle ground.
(*Photograph by Tony Waltham Geophotos*)

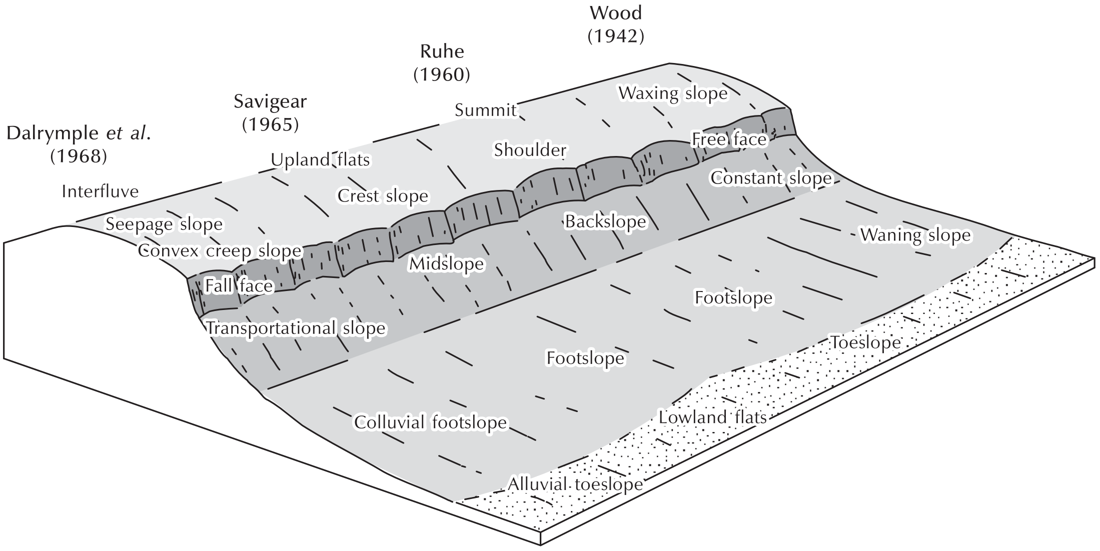

Figure 7.3 Systems for naming hillslope elements.

and lower wash slope (Wood 1942). A widely used system has five slope units – summit, shoulder, backslope, footslope, and toeslope (Figure 7.4) (Ruhe 1960). A similar system uses different names – upland flats (gradient less than 2°), crest slope, midslope, footslope, and lowland flats (gradient less than 2°) (Savigear 1965). The nine-unit land-surface model embraces and embellishes all these schemes and distinguishes the following units – interfluve, seepage slope, convex creep slope, fall face, transportational slope, colluvial footslope, and alluvial toeslope (Dalrymple *et al.* 1968).

Different slope processes tend to dominate the various slope elements along a catena. On convex slope segments, commonly found on the upper parts of hillslope profiles, soil creep and rainsplash erosion dominate, at least when slopes are below the threshold for rapid mass wasting; subsurface movement of soil water is also important. Where convex segments are steeper than about 45°, fall, slide, and physical weathering are the chief processes. Straight (mid-slope) elements usually receive a large amount of material from upslope by mass wasting processes (including flow, slump, and slide), surface wash, and subsurface water movement. Concave slope elements are commonly sites of transport and deposition. They usually develop near the base of hillslope profiles in situations where waste material moving down the hillside through mass wasting and surface and subsurface water action comes to rest and rivers at the hillslope base do not remove it.

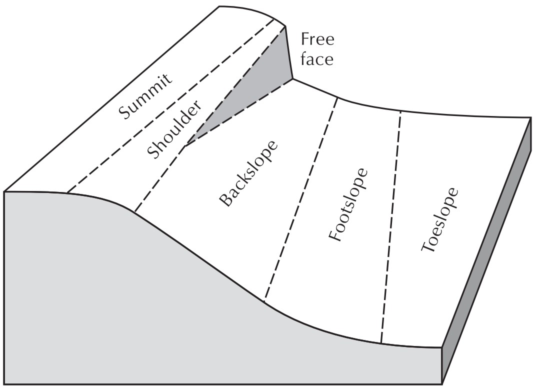

Figure 7.4 Ruhe's (1960) slope units.

Landform elements

From a geomorphological viewpoint, the ground surface is composed of landform elements. **Landform elements** are recognized as simply-curved geometric surfaces lacking inflections (complicated kinks) and are considered in relation to upslope, downslope, and lateral elements. Slope is essential in defining them. Landscape elements go by a plethora of names – facets, sites, land elements, terrain components, and facies. The 'site' (Linton 1951) was an elaboration of the 'facet' (Wooldridge 1932), and involved altitude, extent, slope, curvature, ruggedness, and relation to the water table. The other terms appeared in the 1960s (see Speight 1974). Landform element is perhaps the best term, as it seems suitably neutral.

Landform elements are described by local land-surface geometry. Several parameters are derivatives of altitude – slope angle, slope profile curvature, and contour curvature. Further parameters go beyond local geometry, placing the element in a wider landscape setting – distance from the element to the crest, catchment area per unit of contour length, dispersal area (the land area down-slope from a short increment of contour). Digital elevation models (DEMs) have largely superseded the classic work on landform elements and their descriptors. Topographic elements of a landscape can be computed directly from a DEM and these are often classified into primary (or first-order) and secondary (or second-order) attributes (Moore *et al.* 1993). **Primary attributes** are calculated directly from the digital elevation data and the most commonly derived include slope and aspect (Table 7.1). **Secondary attributes** combine primary attributes and are 'indices that describe or characterise the spatial variability of specific processes occurring in the landscape' (Moore *et al.* 1993, 15); examples are irradiance and a wetness index (Table 7.1). Such methods allow

Table 7.1 Primary and secondary attributes that can be computed from DEMs

Attribute	*Definition*	*Applications*
Primary attributes		
Altitude	Height above mean sea level or local reference point	Climate variables (e.g. pressure, temperature), vegetation and soil patterns, material volumes, cut-and-fill and visibility calculations, potential energy determination
Slope	Rate of change of elevation – gradient	Steepness of topography, overland and subsurface flow, resistance to uphill transport, geomorphology, soil water content
Aspect	Compass direction of steepest downhill slope – azimuth of slope	Solar insolation and irradiance, evapotranspiration
Profile curvature	Rate of change of slope	Flow acceleration, erosion and deposition patterns and rate, soil and land evaluation indices, terrain unit classification
Plan curvature	Rate of change of aspect	Converging and diverging flow, soil water characteristics, terrain unit classification
Secondary attributes		
Wetness Index	$\ln = \frac{A_s}{\tan b}$ where A_s is specific catchment and b is slope	Index of moisture retention
Irradiance	Amount of solar energy received per unit area	Soil and vegetation studies, evapotranspiration

Source: Adapted from Huggett and Cheesman (2002, 20) modellers to represent the spatial variability of the processes, whereas in the past they could model them only as point processes. An enormous literature describes the use of DEMs to produce both primary and secondary attributes; an equally large literature also considers how best to incorporate primary and secondary attributes into spatial models that simulate physical processes influenced and controlled by the nature of topography (e.g. Wilson and Gallant 2000).

Slope and aspect are two of the most important topographic attributes. **Slope** is a plane tangent to the terrain surface represented by the DEM at any given point. It has two components: (1) **gradient**, which is the maximum rate of change of altitude and expressed in degrees or per cent; and (2) **aspect**, the compass direction of the maximum rate of change (the orientation of the line of steepest descent expressed in degrees and converted to a compass bearing). Because slope allows gravity to induce the flow of water and other materials, it lies at the core of many geomorphological process models. For instance, slope and flowpath (i.e. slope steepness and length) are parameters in the dimensionless Universal Soil Loss Equation (USLE), which is designed to quantify sheet and rill erosion by water (p. 178).

Landform classification

The toposphere contains a stupendous array of landforms. Unfortunately, landforms are notoriously difficult to classify quantitatively. Geomorphologists make a fundamental distinction between erosional landforms (sculptured by the action of wind, water, and ice) and depositional landforms (built by sediment accumulation). They also recognize basic differences between landforms in terrestrial, shallow marine, and deep marine environments, each of which fosters a distinct suite of geomorphic processes. However, many landform classifications use topographic form, and ignore geomorphic process. For example, one scheme for large-scale landform classification uses three chief topographic characteristics (Hammond 1954). The first characteristic is the relative amount of gently sloping land (land with less than an 8 per cent slope). The second characteristic is the local relief (the difference between highest and lowest elevation in an area). The third characteristic is the 'generalized profile'. This defines the location of the gently sloping land – in valley bottoms or in uplands. In combination, these characteristics define the following landforms:

- Plains with a predominance of gently sloping land combined with low relief.
- Plains with some features of considerable relief. This group may be subdivided by the position of the gently sloping land into three types – plains with hills, mountains, and tablelands.
- Hills with gently sloping land and low-to-moderate relief.
- Mountains with little gently sloping land and high local relief.

There are many such schemes, all with their good and bad points. Modern research in this field combines terrain attributes to create some form of regional topographic classification (e.g. Giles 1998; Giles and Franklin 1996).

HILLSLOPE PROCESSES

Gravity, flowing water, and temperature changes are the main forces behind hillslope processes, with the action of animals and plants being important in some situations. Weathering on hillslopes, as elsewhere, includes the *in situ* conversion of bedrock into regolith and the subsequent chemical and mechanical transformation of regolith. Several hillslope processes serve to transport regolith and other weathering products. They range from slow and continual processes to rapid and intermittent processes. Slow and continual processes fall into three categories: leaching, soil creep, and rainsplash and sheet wash.

Transport processes

Leaching

Leaching involves the removal of weathered products in solution through the rock and the soil. Solution is an efficacious process in hillslope denudation. It does not always lead to surface lowering, at least at first, because the volume of rock and soil may stay the same. Solution takes place in the body of the regolith and along subsurface lines of concentrated water flow, including throughflow in percolines and pipes.

Rainsplash

Rainsplash and **sheet wash** are common in arid environments and associated with the generation of Hortonian overland flow (p. 66). There is a continuum from rainsplash, through rainflow, to sheet wash. Falling raindrops dislodge sediment to form 'splash', which moves in all directions through the air resulting in a net downslope transport of material. Experimental studies using a sand trough and simulated rainfall showed that on a 5° slope about 60 per cent of the sediment moved by raindrop impact moves downslope and 40 per cent upslope; on a 25° slope 95 per cent of the sediment moved downslope (Mosley 1973). Smaller particles are more susceptible to rainsplash than larger ones. The amount of splash depends upon many factors, including rainfall properties (e.g. drop size and velocity, drop circumference, drop momentum, kinetic energy, and rainfall intensity) and such landscape characteristics as slope angle and vegetation cover (see Salles *et al.* 2000). **Rain power** is a mathematical expression that unites rainfall, hillslope, and vegetation characteristics, and that allows for the modulation by flow depth (Gabet and Dunne 2003). It is a good predictor of the detachment rate of fine-grained particles.

Rainflow

Rainflow is transport caused by the traction of overland flow combined with detachment by raindrop impact, which carries them further than rainsplash alone. **Sheet wash** carries sediment in a thin layer of water running over the soil surface (p. 66). This is not normally a uniformly thick layer of water moving downslope; rather, the sheet subdivides and follows many flow paths dictated by the microtopography of the surface. Sheet wash results from overland flow. On smooth rock and soil surfaces, a continuous sheet of water carries sediment downslope. On slightly rougher terrain, a set of small rivulets link water-filled depressions and bear sediment. On grassed slopes, sediment-bearing threads of water pass around stems; and, in forests with a thick litter layer, overland flow occurs under decaying leaves and twig. The efficacy of sheet wash in transporting material is evident in the accumulation of fine sediment upslope of hedges at the bottom of cultivated fields.

Through-wash (suffossion)

In well-vegetated regions, the bulk of falling rain passes into the soil and moves to the water table or moves underneath the hillslope surface as throughflow. Throughflow carries sediment in solution and in suspension. This process is variously called **through-wash**, **internal erosion**, and **suffossion**, which means a digging under or undermining (Chapuis 1992). Suspended particles and colloids transported this way will be about ten times smaller than the grains they pass through, and through-wash is important only in washing silt and clay out of clean sands, and in washing clays through cracks and roots holes. For instance, in the Northaw Great Wood, Hertfordshire, England, field evidence suggests that silt and clay have moved downslope through Pebble Gravel, owing to through-wash (Huggett 1976). Where throughflow returns to the surface at seeps, positive pore pressures may develop that grow large enough to cause material to become detached and removed. Throughflow may occur along percolines. It may also form pipes in the soil, which form gullies if they should collapse, perhaps during a heavy rainstorm.

Creep and dry ravel

Soil creep (p. 66) is common under humid and temperate climates. It occurs mainly in environments with seasonal changes in moisture and soil temperature. It mainly depends upon heaving and settling movements in the soils occasioned by biogenic mechanisms (burrowing animals, tree throw, and so on), solution, freeze–thaw cycles, warming–cooling cycles, wetting–drying cycles, and, in some hillslopes, the shrinking and swelling of clays and the filling of desiccation cracks from upslope. **Dry ravel** is the rolling, bouncing, and sliding of individual particles down a slope (Gabet 2003). It is a dominant hillslope sediment-transport process in steep arid and semiarid landscapes, and includes the mobilization of particles during fires when sediment wedges that have accumulated behind vegetation collapse, as well as mobilization by bioturbation and by small landslides.

Mass wasting

Rapid and intermittent hillslope transport processes involve **mass wasting** – creep, flow, slide, heave, fall, subsidence (p. 63–6).

Bioturbation

Geomorphologists have until recently tended to dismiss the effects of animals and plants on hillslope processes, this despite the early attribution of soil creep to the action of soil animals and plant roots (Davis 1898). However, animals and plants make use of the soil for food and for shelter and, in doing so, affect it in multifarious ways. For instance, the uprooting of trees may break up bedrock and transport soil downslope. Since the mid-1980s, the importance of **bioturbation** – the churning and stirring of soil by organisms – to sediment transport and soil production on hillslopes has come to the fore. Andre Lehre (1987) found that biogenic creep is more important than inorganic creep. Another study concluded that bioturbated areas on Alpine slopes in the Rocky Mountains of Colorado, USA, have sediment movement rates increased by one or two orders of magnitude compared with areas not subject to significant bioturbation (Caine 1986). A review in 2003 concluded that bioturbation is undeniably a key geomorphic factor in many landscapes (Gabet *et al.* 2003), a fact strongly supported by William E. Dietrich and J. Taylor Perron (2006).

Climate and hillslope processes

Extensive field measurements since about 1960 show that hillslope processes appear to vary considerably with climate (Young 1974; Saunders and Young 1983; Young and Saunders 1986). Soil creep in temperate maritime climates shifts about 0.5–2.0 mm/year of material in the upper 20–25 cm of regolith; in temperate continental climates rates run in places a little higher at 2–15 mm/year, probably owing to more severe freezing of the ground in winter. Generalizations about the rates of soil creep in other climatic zones are unforthcoming owing to the paucity of data. In mediterranean, semi-arid, and savannah climates, creep is probably far less important than surface wash as a denuder of the landscape and probably contributes significantly to slope retreat only where soils are wet, as in substantially curved concavities or in seepage zones. Such studies as have been made in tropical sites indicate a rate of around 4–5 mm/year. Solifluction, which includes frost creep caused by heaving and gelifluction, occurs 10–100 times more rapidly than soil creep and affects material down to about 50 cm, typical rates falling within the range 10–100 mm/year. Wet conditions and silty soils favour solifluction: clays are too cohesive, and sands drain too readily. Solifluction is highly seasonal, most of it occurring during the summer months. The rate of surface wash, which comprises rainsplash and surface flow, is determined very much by the degree of vegetation cover, and its relation to climate is not clear. The range is 0.002–0.2 mm/year. It is an especially important denudational agent in semi-arid and (probably) arid environments, and makes a significant contribution to denudation in tropical rainforests. Solution (leaching) probably removes as much material from drainage basins as all other processes combined. Rates are not so well documented as for other geomorphic processes, but typical values, expressed as surface-lowering rates, are as follows: in temperate climates on siliceous rocks, 2–100 mm/millennium, and on limestones 2–500 mm/millennium. In other climates, data are fragmentary, but often fall in the range 2–20 mm/millennium and show little clear relationship with temperature or rainfall. On slopes where landslides are active, the removal rates are very high irrespective of climate, running at between 500 and 5,000 mm/millennium.

Transport-limited and supply-limited processes

It is common to draw a distinction between hillslope processes limited by the transporting capacity of sediment and hillslope processes limited by the supply of transportable material (Kirkby 1971).

In **transport-limited processes**, the rate of soil and rock transport limits the delivery of sediment to streams. In other words, the supply of sediment exceeds the capacity to remove it, and transport processes and their spatial variation dictate hillslope form. Soil creep, gelifluction, through-wash, rainflow, rainsplash, and rillwash are all hillslope processes limited by transporting capacity. On **supply-limited** (or **weathering-limited**) **hillslopes**, the rate of sediment production by weathering and erosional detachment (through overland flow and mass movement) limits the delivery of sediment to streams. In other words, weathering and erosional processes dictate hillslope form. Leaching of solutes, landsliding, debris avalanches, debris flows, and rockfall are all hillslope processes limited by sediment supply.

The distinction between transport-limited and supply-limited process is often blurred. Nonetheless, it is an important distinction because it affects the long-term evolution of hillslopes. Hillslopes and landscapes dominated by transport-limited removal typically carry a thick soil layer supporting vegetation, and slope gradients tend to reduce with time. Hillslopes and landscapes dominated by supply-limited removal often bear thin soils with little vegetation cover, and characteristically steep slopes tend to retreat maintaining a sharp gradient. Mathematical models of hillslope evolution support these findings, suggesting that the wearing back or wearing down of the mid-slope depends upon the processes in operation. As a generalization, surface wash processes lead to a back-wearing of slopes, whereas creep processes lead to a down-wearing of slopes (e.g. Nash 1981). Nonetheless, the pattern of slope retreat and slope decline is crucially dependent on conditions at the slope base, and especially on the transport capacity of streams.

A study of young fault scarps formed in alluvium in north-central Nevada, USA, showed that hillslope processes change as the scarps age (Wallace 1977) (Figure 7.5). The original fault scarps stand at 50° to 70°. At this stage, mass wasting is the dominant process, a free face develops at the scarp top, which retreats through debris fall, and material accumulates lower down. Later, the scarp slope adopts the angle of repose of the debris, which is about 35°. At this gentler gradient, wash erosion dominates hillslope development and further slope decline occurs.

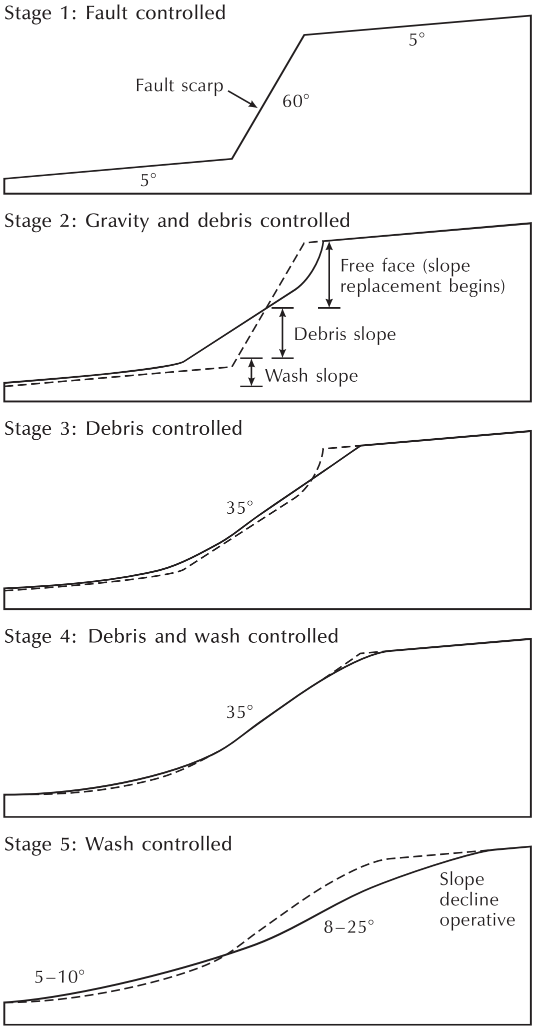

Figure 7.5 Proposed sequence of change on a fault scarp developed in alluvium, Nevada, USA. The changes are incremental, the dashed line shown at each stage representing the hillslope profile at the previous stage. *Source:* Adapted from Wallace (1977)

Hillslope development

Slope processes fashion hillsides over hundreds of thousands to millions of years. It is therefore impossible to study hillslope evolution directly. Location–time substitution allows the reconstruction of long-term changes in hillslopes under special circumstances (p. 25). Mathematical models offer another means of probing long-term changes in hillslope form.

Michael J. Kirkby is a leading figure in the field of hillslope modelling. He used the **continuity equation** of debris moving on hillslopes and in rivers as a basis for hillslope models (Kirkby 1971). In one dimension, the equation of debris on a hillside is:

$$\frac{\delta h}{\delta t} = -\frac{dS}{dx}$$

where h is the height of the land surface and S is the sediment transport rate, which needs defining by a transport (process) equation for the process or processes being modelled. A general **sediment transport equation** is:

$$S = f(x)^m \left(\frac{dh}{dx}\right)^n$$

where $f(x)^m$ is a function representing hillslope processes in which sediment transport is proportional to distance from the watershed (roughly the distance of overland flow) and $(dh/dx)^n$ represents processes in which sediment transport is proportional to slope gradient. Empirical work suggests that $f(x)^m = x^m$, where m varies according to the sediment-moving processes in operation, representative values being 0 for soil creep and rainsplash and 1.3–1.7 for soil wash. The exponent n is typically 1.0 for soil creep, 1.0–2.0 for rainsplash, and 1.3–2.0 for soil wash (Kirkby 1971). For a hillslope catena, the solution of the equation takes the general form:

$$h = f(x, t)$$

This equation describes the development of a hillslope profile for specified slope processes, an assumed initial state (the original hillslope profile), and boundary conditions (what happens to material at the slope base, for example). Some of Kirkby's later models demonstrate the process, and some of the drawbacks, of long-term hillslope modelling (Box 7.1).

Hillslope models have become highly sophisticated. They still use the continuity equation for mass

Box 7.1

HILLSLOPE MODELS

Michael J. Kirkby's (1985) attempts to model the effect of rock type on hillslope development, with rock type acting through the regolith and soil, nicely demonstrates the process of hillslope modelling. Figure 7.6 shows the components and linkages in the model, which are more precisely defined than in traditional models of hillslope development. Rock type influences rates of denudation by solution, the geotechnical properties of soil, and the rates of percolation through the rock mass and its network of voids to groundwater. Climate acts through its control of slope hydrology, which in turn determines the partitioning of overland and subsurface flow. With suitable process equations fitted, the model simulates the development of hillslopes and soils for a fixed base level. Figure 7.7 is the outcome of a simulation that started with a gently sloping plateau ending in a steep bluff and a band of hard rock dipping at 10° into the slope. The hard rock is less soluble, and has a lower rate of landslide retreat, than the soft band but has the same threshold gradient for landsliding. Threshold gradients, or angles close to them, develop rapidly on the soft strata. The hard rock is undercut, forming a free face within a few hundred years. After some 20,000 years, a summit convexity begins to replace the threshold slope above the hard band, the process of replacement being complete by 200,000 years when the hard band has little or no topographic expression. The lower slope after 200,000 years stands at an almost constant gradient of 12.4°, just below the landslide threshold. Soil development

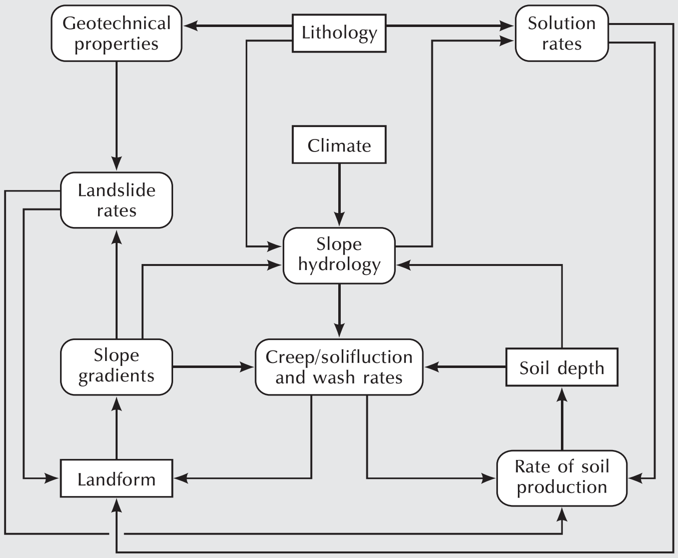

Figure 7.6 Components and linkages in Kirkby's model of hillslope evolution.
Source: Adapted from Kirkby (1985)

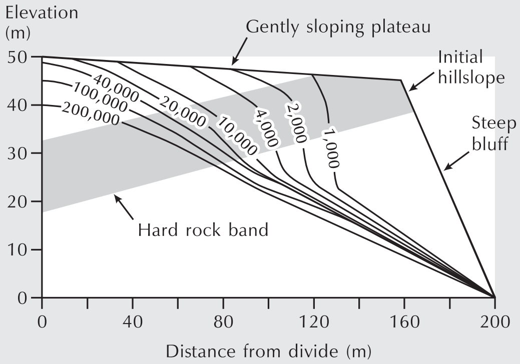

Figure 7.7 Simulation of hillslope change for an initial gently sloping plateau ending in a steep bluff with a band of hard rock dipping at 10° into the hillside. Time is in years.
Source: Adapted from Kirkby (1985)

(not shown on the diagram) involves initial thickening on the plateau and thinning by landslides on the scarp. Soil distribution is uneven owing to the localized nature of landslides. Once the slope stabilizes, thick soils form everywhere except over the hard band. From this simulation and another in which solution is the sole process, Kirkby makes a number of deductions that appear to correspond to features in actual landscapes. First, geotechnical properties of rock, in particular the rate of decline towards the threshold gradient of landslides, are more important than solution in determining slope form. Only on slopes of low gradient and after long times (200,000 years and more) do solutional properties play a dominant role in influencing slope form. Second, gradient steepening and soil thinning over 'resistant' strata are strictly associated with the current location of an outcrop, though resistant beds, by maintaining locally steep gradients, tend to hold the less resistant beds close to the landslide threshold and so increase gradients everywhere. Third, gradients close to landslide threshold gradients commonly outlive landslide activity by many thousands of years and, because of this, may play a dominant role in determining regional relief in a tectonically stable area. Fourth, soils are generally thin under active landsliding and wash; thick soils tend to indicate the predominance of solution and creep or solifluction processes.

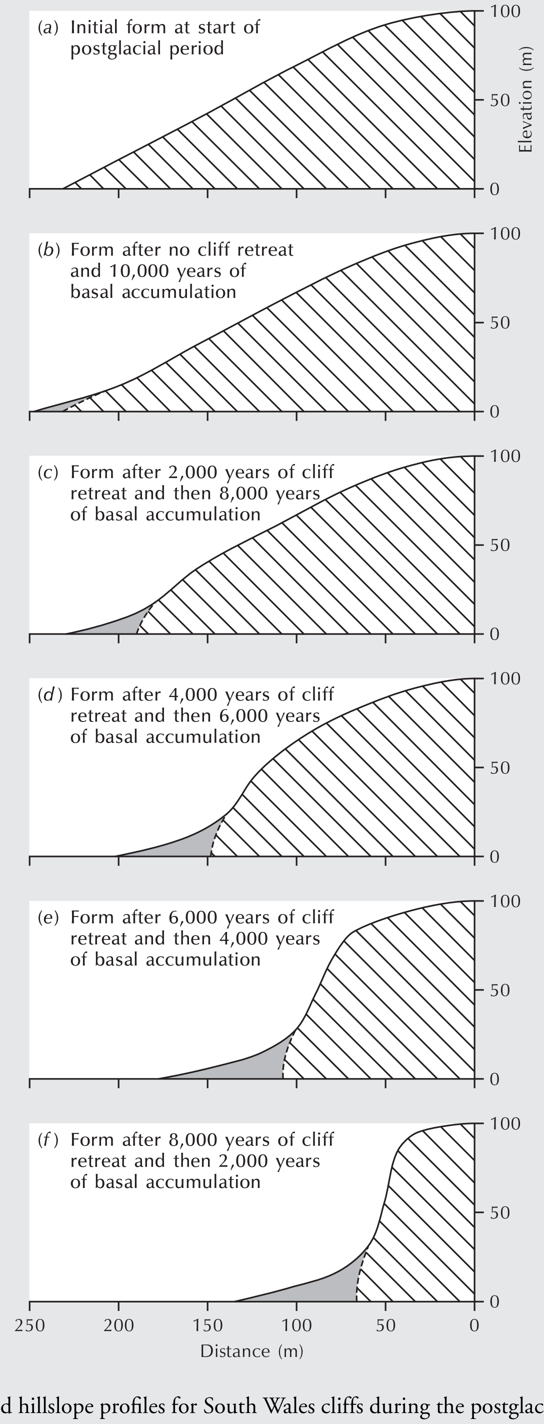

Figure 7.8 Kirkby's modelled hillslope profiles for South Wales cliffs during the postglacial period. The model assumed basal retreat of 20 mm/yr for the first 8,000 years and basal accumulation for the last 2,000 years.
Source: Adapted from Kirkby (1984)

Catenas in humid climates can be expected to develop thicker soils in downslope positions but in semi-arid areas, where wash keeps soils thin except on the lowest gradients, catenas can be expected to have deeper soils upslope and thinner soils downslope.

A drawback with modelling long-term changes is the assumption that climate has remained constant. However, it is possible to allow for climatic change in models. Kirkby (1984), for instance, included changes of climate in his model of cliff retreat in South Wales, as originally studied by Savigear (1952) and often quoted as an exemplar of location–time substitution (p. 25). Kirkby ran the model for three phases. First, for a period, starting 500,000 years ago and ending 50,000 years ago, corresponding roughly to inland valley development with a fixed base level under mainly periglacial conditions; second, for a period of cliff retreat from 50,000 to 10,000 years ago; and, third, for a period of basal removal covering the last 10,000 years (Figure 7.8). The observed upper convexities of the slope profiles as surveyed by Savigear can, according to the model, only be formed during the periglacial phase and require at least 100,000 years to form. They are today relict features.

conservation, but now apply reasonably well established **geomorphic transport laws** (e.g. Dietrich and Perron 2006). Figure 7.9 shows how a three-dimensional hillslope model explains the development of ridge-and-valley topography in soil-mantled terrain.

HUMANS AND HILLSLOPES

Hillslopes are the location of much human activity, and their study has practical applications. Knowledge of runoff and erosion on slopes is important for planning agricultural, recreational, and other activities. Land management often calls for slopes designed for long-term stability. Mine tailing piles, especially those containing toxic materials, and the reclamation of strip-mined areas also call for a stable slope design. This final section will consider the effects of humans upon hillslope soil erosion.

Soil erosion modelling

Soil erosion has become a global issue because of its environmental consequences, including pollution and sedimentation. Major pollution problems may occur from relatively moderate and frequent erosion events in both temperate and tropical climates. In almost every country of the world under almost all land-cover types the control and prevention of erosion are needed. Prevention of soil erosion means reducing the rate of soil loss to approximately the rate that would exist under natural conditions. It is crucially important and depends upon the implementation of suitable soil conservation strategies (Morgan 1995). **Soil conservation strategies** demand a thorough understanding of the processes of erosion and the ability to provide predictions of soil loss, which is where geomorphologists have a key role to play. Factors affecting the rate of soil erosion include rainfall, runoff, wind, soil, slope, land cover, and the presence or absence of conservation strategies.

Soil erosion is an area where process geomorphological modelling has had a degree of success. One of the first and most widely used empirical models was the **Universal Soil Loss Equation (USLE)** (Box 7.2). The USLE has been widely used, especially in the USA, for predicting sheet and rill erosion in national assessments of soil erosion. However, empirical models predict soil erosion on a single slope according to statistical relationships between important factors and are rather approximate. Models based on the physics of soil erosion were developed during the 1980s to provide better results. Two types of physically based model have evolved – lumped models and distributed models (see Huggett and Cheesman 2002, 156–9). **Lumped models** are non-spatial, predicting the overall or average response of a watershed. **Distributed models** are spatial, which means that they predict the spatial distribution of runoff and sediment movement over the land surface during individual storm

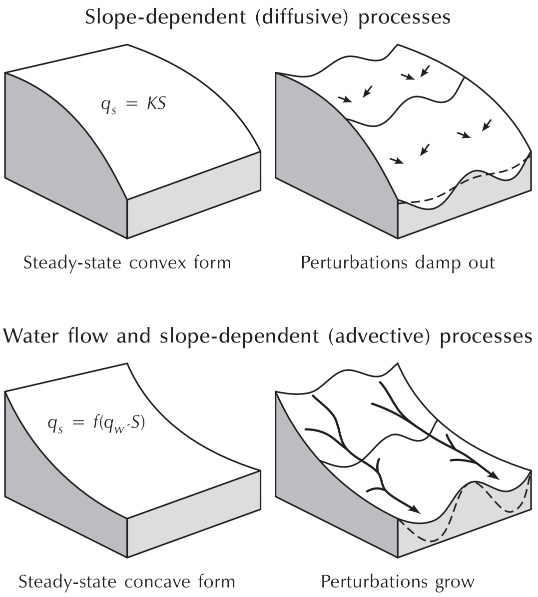

Figure 7.9 An explanation for the development of ridge-and-valley topography in soil-mantled terrain. Slope-dependent (diffusive) transport leads to convex hillslopes, and when the topography is laterally perturbed the transport direction (black lines) causes the topographic highs to lower and topographic lows to fill in, resulting in smooth topography, as suggested by the dashed line. In contrast, advective transport, which depends on water flow and slope gradient, carries sediment downslope and produces concave hillslopes. Flow concentrations (black flowpaths) resulting from lateral topographic perturbation lead to incision, as suggested by the dashed lines. The competition of these two processes leads to diffusion-dominated ridges and advection-dominated valleys.
Source: Adapted from Dietrich and Perron (2006)

events, as well as predicting total runoff and soil loss (Table 7.2). Many physically based soil-erosion models have benefited from **GIS technology**.

Hillslope erosion along trails

The trampling of humans (walking or riding) and other animals along trails may lead to **soil erosion**. Anyone who has walked along footpaths, especially those in hilly terrain, is bound to have firsthand experience of the problem. The problem has become acute over the last twenty or thirty years as the number of people using mountain trails, either on foot or in some form of off-road transport, has risen sharply. A study in Costa Rican forest confirmed that trails generate runoff more quickly, and erode sooner, than is the case in off-trail settings (Wallin and Harden 1996). This finding, which is typical of trail erosion studies in all environments, underscores the need for careful management of ecotourism in trail-dependent activities. Strategies for combating trail erosion can work. Smedley Park lies in the Crum Creek watershed, Delaware County, near Media, Pennsylvania, USA. The trails in the park pass through several areas with fragile environments (Lewandowski and McLaughlin 1995). A strategy was devised using network analysis, which altered the efficiency of the trail system by more fully connecting sites with robust environments and reducing the potential for visitors to use environmentally fragile sites. Some of the severest erosion is associated with logging trails. In the Paragominas region of eastern Amazonia, tree damage in unplanned and planned logging operations was associated with each of five logging phases: tree felling, machine manoeuvring to attach felled boles to chokers, skidding boles to log landings,

Box 7.2

THE UNIVERSAL SOIL LOSS EQUATION (USLE)

The USLE (Wischmeier and Smith 1978) predicts soil loss from information about (1) the potential erosivity of rainfall and (2) the erodibility of the soil surface. The equation is usually written as:

$$E = R \times K \times L \times S \times C \times P$$

where E is the mean annual rainfall loss, R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the crop management factor, and P is the erosion control practice factor. The **rainfall erosivity factor** is often expressed as a rainfall erosion index, EI_{30}, where E is rainstorm energy and I is rainfall intensity during a specified period, usually 30 minutes. **Soil erodibility**, K, is defined as the erosion rate (per unit of erosion index, EI_{30}) on a specific soil in a cultivated continuous fallow on a 9 per cent slope on a plot 22.6-m-long. **Slope length**, L, and **slope steepness**, S, are commonly combined to produce a single index, LS, that represents the ratio of soil loss under a given slope steepness and slope length to the soil loss from a standard 9 per cent, 22.6-m-long slope. **Crop management**, C, is given as the ratio of soil loss from a field with a specific cropping-management strategy compared with the standard continuous cultivated fallow. **Erosion control**, P, is the ratio of soil loss with contouring strip cultivation or terracing to that of straight-row, up-and-down slope farming systems. The measurements of the standard plot – a slope length of 22.6 m (72½ feet), 9 per cent gradient, with a bare fallow land-use ploughed up and down the slope – seem very arbitrary and indeed are historical accidents. They are derived from the condition common at experimental field stations where measured soil losses provided the basic data for calibrating the equation. It was convenient to use a plot area of 1/100 acre and a plot width of 6 feet, which meant that the plot length must be 72½ feet.

To use the USLE, a range of erosion measurements must be made, which are usually taken on small bounded plots. The problem here is that the plot itself affects the erosion rate. On small plots, all material that starts to move is collected and measured. Moreover, the evacuation of water and sediment at the slope base may itself trigger erosion, with rills eating back through the plot, picking up and transporting new sources of sediment in the process. Another difficulty lies in the assumption that actual slopes are uniform and behave like small plots. Natural slopes usually have a complex topography that creates local erosion and deposition of sediment. For these reasons, erosion plots established to provide the empirical data needed to apply the USLE almost always overestimate the soil-loss rate from hillslopes by a factor twice to ten times the natural rate.

Table 7.2 Examples of physically based soil erosion models

Model	*Use*	*References*
Lumped or non-spatial models		
CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems)	Field-scale model for assessing non-point-source pollution and the effects of different agricultural practices	Knisel (1980)
WEPP (Water Erosion Prediction Project)	Designed to replace USLE in routine assessments of soil erosion	Nearing *et al.* (1989)
EUROSEM (European Soil Erosion Model)	Predicts transport, erosion, and deposition of sediment throughout a storm event	Morgan (1994)
Distributed or spatial models		
ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation)	Model surface runoff and soil erosion within a catchment	Beasley *et al.* (1980)
LISEM (Limburg Soil Erosion Model)	Hydrological and soil erosion model, incorporating raster GIS, that may be used for planning and conservation purposes	De Roo *et al.* (1996)

constructing log landings, and constructing logging roads (Johns *et al.* 1996).

The nature of **trail use** affects the degree of soil erosion. The comparative impact of hikers, horses, motorcycles, and off-road bicycles on water runoff and sediment yield was investigated on two trails – the Emerald Lake Trail and the New World Gulch Trail – in, and just outside, respectively, the Gallatin National Forest, Montana, USA (Wilson and Seney 1994). The results revealed the complex interactions that occur between topographic, soil, and geomorphic variables, and the difficulty of interpreting their impact on existing trails. In brief, horses and hikers (hooves and feet) made more sediment available than wheels (motorcycles and off-road bicycles), with horses producing the most sediment, and sediment production was greater on pre-wetted trails. In the northern Rocky Mountains, Montana, USA, trails across meadow vegetation bear signs of damage – bare soil and eroded areas – through human use (Weaver and Dale 1978). The meadows were principally Idaho fescue–Kentucky bluegrass (*Festuca idahoensis–Poa pratensis*) communities. Experiments were run on meadows underlain by deep sandy-loam soils at 2,070 m near Battle Ridge US Forest Ranger Service Station, in the Bridge Range. They involved getting hikers, horse riders, and a motorcyclist to pass up and down slopes of 15°. The hikers weighed 82–91 kg and wore hiking boots with cleated soles; the horses weighed 500–79 kg and had uncleated shoes; the motorcycle was a Honda 90 running in second gear at speeds below 20 km/hr. The experiments showed that horses and motorcycles do more damage (as measured by per-cent-bare area, trail width, and trail depth) on these trails than do hikers (Figure 7.10). Hikers, horses, and motorcycles all do more damage on sloping ground than on level ground. Hikers cause their greatest damage going downhill. Horses do more damage going uphill than downhill, but the difference is not that big. Motorcycles do much damage going downhill and uphill, but cut deep trails when going uphill.

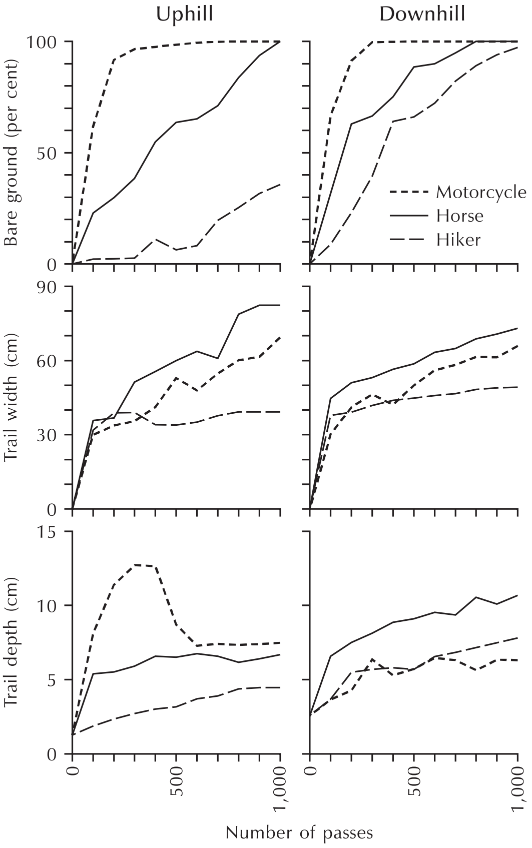

Figure 7.10 Experimental damage done by hikers, bikers, and horses moving uphill and downhill on trails in Bridge Range, Montana, on a sloping 15° meadow site.
Source: Adapted from Weaver and Dale (1978)

SUMMARY

Hillslopes are the commonest landform. There are bare and soil-mantled varieties. A hillslope profile consists of slope units, which may be slope segments (with a roughly constant gradient) or slope elements (with a roughly constant curvature). A common sequence of slope elements, starting at the hilltop, is convex–straight–concave. These elements form a geomorphic catena. Different geomorphic processes dominate different slope elements along a catena. Landform elements are basic units of the two-dimensional land surface. Properties such as slope angle, slope curvature, and aspect define them. Land-surface form is also the basis of landform classification schemes. Geomorphic processes that transport material over and through hillslopes include leaching, rainflow, throughwash (suffossion), creep, dry ravel, mass wasting, and mixing by organisms (bioturbation). Transport-limited processes, such as creep and rainsplash, are distinct from supply-limited processes, such as solute leaching and debris avalanching. Hillslopes with transport limitations tend to carry a thick soil mantle, and their slopes tend to decline with time. Hillslopes limited by the supply of material through weathering tend to be bare or have thin soils, and their slopes tend to retreat at a constant angle. Mathematical models based on the continuity equation for mass conservation and geomorphic transport laws provide a means of probing long-term hillslope development. Human activities alter hillslope processes. This is evident in the erosion of soil-mantled hillslopes caused by agricultural practices, logging, road building, and so forth. The movement of people, animals, and vehicles along trails may also cause soil to erode.

ESSAY QUESTIONS

1. **Compare and contrast the role of surface and subsurface process in hillslope development.**
2. **How useful are mathematical models in understanding long-term evolution of hillslopes?**
3. **How important is slope gradient in predicting soil erosion on hillslopes?**

FURTHER READING

Anderson, M. G. and Brooks, S. M. (eds) (1996) *Advances in Hillslope Processes*, 2 vols. Chichester: John Wiley & Sons.
A very good state-of-the-art (in the mid-1990s) and advanced text.

Morgan, R. P. C. (2005) *Soil Erosion and Conservation*, 3rd edn. Oxford: Blackwell.
Probably the best introductory text on the topic.

Selby, M. J. (1993) *Hillslope Materials and Processes*, 2nd edn. With a contribution by A. P. W. Hodder. Oxford: Oxford University Press.
An excellent account of the geomorphology of hillslopes.

Thornes, J. B. (ed.) (1990) *Vegetation and Erosion: Processes and Environments*. Chichester: John Wiley & Sons.
A collection of essays that, as the title suggests, considers the effects of vegetation on soil erosion in different environments.