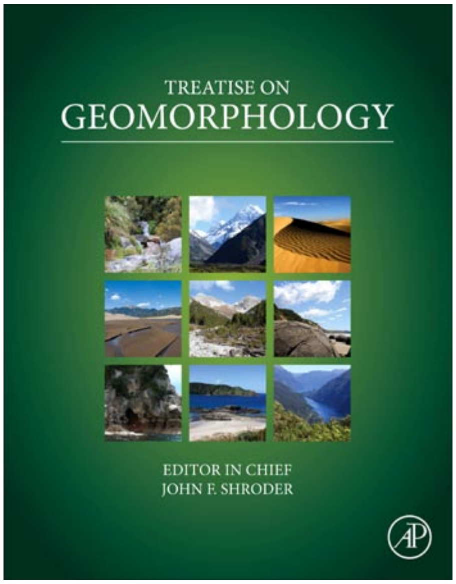

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4.9 Catenas and Soils

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Glossary

Catena A sequence of soils along a slope, having different characteristics due to variation in relief, elevation, and drainage (depth to water table), as well as the influence of slope processes on sediment removal and delivery.

Cumulization The slow, upward growth of the soil surface due to additions of sediment on top of the soil. The additions, for example, alluvium, loess, and slopewash, must occur slowly enough so that pedogenesis can incorporate the sediment into the profile's horizons.

Debris flux The movement of sediment (organic and inorganic) across a slope, usually on the surface but also including subsurface transfers.

Drainage class (soil-drainage class) Under natural conditions, not artificially drained, this term refers to a group of soils defined as having a specific range in relative wetness due to a water table (apparent or perched), in conditions similar to those under which the soil developed.

Edge effect The condition whereby soils located near sharp breaks in slope profile – at slope 'edges' – are markedly different from those upslope and downslope. Two types of edge effects exist, at 'wet edges' and 'dry edges'.

Endosaturation The condition of saturation of a zone or soil horizon by groundwater (not perched water).

Episaturation The condition in which the soil is saturated with water in one or more layers but in which it also has one or more unsaturated layers below. Episaturation is usually synonymous with the condition of having a perched water table.

Hydrosequence A sequence of related soils, usually along a slope, that differ, one from the other primarily with regard to wetness.

Moisture flux The redistribution of water and solutes on and within soils on a slope.

Pedogenesis The natural processes involved in the formation of soils.

Pedon A theoretical term that represents the smallest volume that can be called "a soil". Pedons are three-dimensional bodies of soil with lateral dimensions large enough to permit the study of horizon shapes and relations. The area of a pedon typically ranges from 1 to 10 m^2.

Redoximorphic (redox) processes Chemical processes associated with wetting (saturation) and drying (aeration) of soils. The term is an abbreviation of the chemical terms 'reduction' and 'oxidation'.

Slope element A segment of a hillslope, as viewed in cross section. Traditionally, slopes have five elements. From the top of the slope, downward, these are: summit, shoulder, backslope, footslope, and toeslope.

Solum (plural: sola) The upper and most weathered part of the soil profile; the A and B horizons.

Time zero The moment at which soil formation begins. The sudden draining of a lake, with subsequent exposure of the bottom sediments to impact of climate and organisms, illustrates how time zero may be introduced into an area. Theoretically, each soil has had a time zero.

Toposequence A sequence of related soils on a slope that differ, one from the other, primarily because of topography as a soil-formation factor.

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Abstract

Soil development is intimately tied to the slopes on which soils form. Soils across slopes are connected, process-wise, like links in a chain. This analogy has led to the concept of a catena – a term for a series of soils on a slope. This chapter explores the reasons for soil variation on catenas, focusing on (1) debris and moisture flux along the slope and (2) depth to the water table. Fluxes of sediment, commonly facilitated by water, vary predictably as a function of position on the slope, leading to soils that may be thinner or thicker than expected on steep slope segments where runoff is accentuated. Conversely, soils on lower, flatter slope segments may be overthickened from many years of slow but episodic sediment accumulations from upslope; when sediment accumulations are particularly fast or large, soils here can become buried. Soil texture and infiltration capacities dramatically impact these processes; on slopes composed of coarser, more permeable materials, catenary position is less important because there is less runoff, and thus, even on the steepest slope segments, much of the water infiltrates vertically. Water tables, commonly deepest on the steepest slope segments, vary predictably as a function of position on the slope. High water tables can dramatically affect internal soil processes, as well as weathering and related phenomena.

4.9.1 Introduction

Soils form on surfaces, and, thus, they are affected by aboveground and below-ground slope processes and by their position on that slope. That soils vary as a function of slope position has been known for decades, and a great amount of research has been conducted on these interrelationships. The field of soil geomorphology has at its core these fundamental soil–slope linkages. Most of this sort of research has focused on documenting, and then explaining, the changes manifested in soils as one traverses the various slope positions. This type of research operates within the paradigm that soils on slopes change regularly, but ultimately, in a predictable manner across them and that each soil individual is genetically connected to the one next to it.

The examination of soils along a catena is one of the best ways to discern the interrelationships between soils and topography. A catena is a transect of soils from the top to the base of a slope, generally interpreted as a transect perpendicular (or nearly so) to the slope contour. Its name comes from the Latin *catenaria*, or chain. Soils in a catena can be visualized as interconnected chain links; solid materials, fluids, and gases move through and between the soils (links) that are connected on the slope, making each soil (pedon) like a link in a chain. Visualizing this type of chain catenation is what first resulted in the formation of the catena concept.

Variation along and within a soil catena is a manifestation of Jenny's (1941) 'relief' soil-forming factor. Although relief itself is passive, it functions by providing potential and kinetic energy to the soil system, through its impact on the flows of matter and energy within the soil-landscape system.

4.9.2 The Catena Concept

Some of the earliest field (and theoretical) work on catenas was done in the 1930s by Geoffrey Milne (Brown et al., 2004). Milne and his colleagues were trying to explain some complex soil–landscape associations in Uganda. He noted that, over large areas with regular (or rhythmic) topographic variability, the soils also had repeatable patterns and that these patterns "would have to be interpreted as indicating the occurrence of not a single soil but of a sequence of soils…" (Milne, 1932: 5). This sequence of soils was Milne's catena – a concept focused on soils that have repeated patterns on the landscape, due mainly to the effects of topography and slope (Milne, 1935a, 1935b). The term has stood the test of time and remains in widespread use today. Later, Milne would note that soils along catenas also vary because of: (1) differences in drainage conditions; and (2) the effects of erosion and sedimentation on the slope. Holliday (2006) noted that Milne's unique contribution was actually in his linking of soil–catenary patterns to specific slope-related processes: wetness, solute transport, and erosion/deposition.

Milne's catena concept was found to be useful for soil mapping in the United States and elsewhere, and hence it was incorporated into one of the US Department of Agriculture (USDA)'s earliest soil-classification systems (Baldwin et al., 1938). Mapping soils along catenary sequences of otherwise similar parent materials helped to develop the notion of soil-drainage classes (see below), as the overall wetness and depth to the water table of these soils tended to also vary predictably along slopes. Soils along catenas that differed only in drainage class, as manifested in their profile characteristics, came to form one of the smallest and tightly defined taxonomic classes of soil – the soil series (Soil Survey Staff, 1951). Holliday (2006) noted that the early US soil-survey efforts utilized a catena concept that focused on soils that vary along slopes mainly due to the effects of topography and drainage. Together, these incremental advances in our knowledge of soils within their various catenary settings led to fundamental progress in the fields of soil genesis, soil geomorphology, and soil classification.

The notion of parent-material uniformity along a catena, although utilized by many in the US, including the Soil Survey, was not a part of Milne's original concept. However, it soon would be. In a classic paper, Bushnell (1942) expanded on the catena concept and offered additional theoretical suggestions and refinements. Bushnell formally suggested that the term 'catena' be limited to slopes where the soils have all formed in one parent material, that is, all soil-forming factors except topography ('drainage' was the word he used) are held constant. Taken together, these developments devalued slope-influenced transport/depositional processes, previously so important to the explanation of soil development along slopes.

Today, the catena concept is used primarily for soils along a slope, but particularly where they are generally all formed in a similar parent material. Thus, it is assumed that their genetic and morphologic differences have accrued due mainly to the influence of topography. Knowing that such 'pure' catenas are more often the exception than the rule, two other terms eventually came into use for the 'less than perfect' catenas. If the topographic influence is mainly manifested by (or from) differences in soils wetness (or depth to the water table), the term 'hydrosequence' is sometimes used, as in Cremeens and Mokma (1986), Mokma and Sprecher (1994), and Smeck et al. (2002). The term 'toposequence' is now commonly used for any sequence of soils along a slope, regardless of the uniformity – or lack thereof – of the other soil-forming factors, as in Alvarado and Buol (1975), Evans and Franzmeier (1986), and Bravard and Righi (1991). Hydrosequences and toposequences commonly focus on morphologic changes due to differing wetness conditions (Hall, 1983), whereas soils along a true catena may differ because of drainage condition changes *and* fluxes of sediment. For ease of reading, in this chapter the term 'catena' will be used for any sequence of soils along a slope, essentially mirroring the term 'toposequence'.

By definition, the term 'catena' implies a two-dimensional (2D) transect along a hillslope. However, by nature, of course, flows of matter and energy within the geomorphic system are inherently 3D. Flowlines down slopes can converge or diverge, rendering the base of the slope drier or wetter, respectively, than would be expected if the flowlines were simpler – straight down the slope (**Figure 1**). Soils on nose-slope catenas, for example, are drier and generally thinner than might be expected because nose slopes are water- and sediment-diffusing slopes. These areas are called divergent slopes. On head slopes, where concave contour/plan curvature exists, flowlines will converge onto the lower parts of the slope; these areas are called convergent slopes. Soils on convergent slopes tend to be wetter and runoff here is initiated onto (and from) these sites more rapidly, other things being equal. On the lower ends of convergent slopes, sediment will preferentially accumulate, and soils tend to be thicker (King et al., 1983). Contrast that to areas at the base of nose slopes; these areas tend not to accumulate as much sediment and run-on as do other types of slopes, and soils are thinner here.

Obviously, slope curvature and complexity can dramatically affect soil development, and it occurs in more than just the simple, catena-based, 2D manner. For this reason, recent research has commonly focused on soils within a 3-D system, whether it be via terrain/geographic information systems (GIS) modeling or empirical research (Huggett, 1975; Moore et al., 1991, 1993; Western et al., 1999; Yang et al., 2007; Pei et al., 2010; Zhao et al., 2010). The focus in this chapter, however, is on the 2D, that is, the traditional, soil catena.

Lastly, it is important to note that catenas fall into two main categories: closed and open. Closed catenas are formed in internally draining depressions, that is, little or no sediment can leave the system (Richardson et al., 1994). In closed catenas, soil burial is much more likely in lower slope positions because sediment continually accumulates there via slopewash and other processes but cannot leave the system (Walker and Ruhe, 1968; Weitkamp et al., 1996). Most catenas on geomorphologically mature landscapes form as part of an open system, where the lower slope segments connect to some sort of integrated stream or drainage system, which can

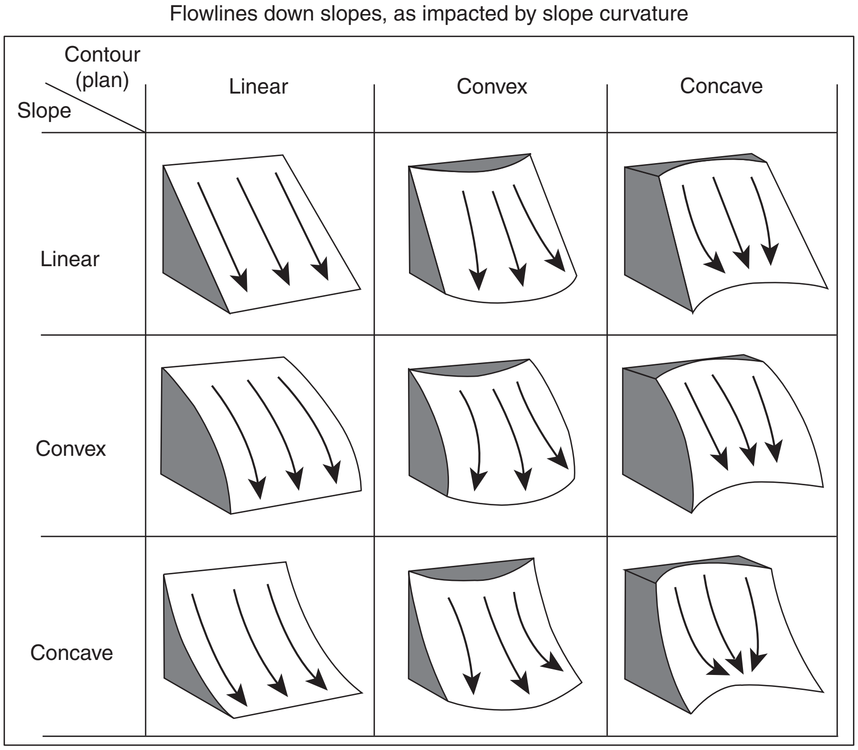

Figure 1 Flowlines down slopes of various curvatures. Reproduced from Ruhe, R.V., 1975. Geomorphology. Houghton Mifflin Co., Boston, 246 pp and Huggett, R.J., 1975. Soil landscape systems: a model of soil genesis. Geoderma 13, 1–22.

remove sediment from the system (Ruhe and Walker, 1968). Thus, soil burial in lower slope segments is less common but can be accomplished via flooding of streams.

4.9.3 Elements and Characteristics of Catenas

Slopes, like catenas, can be simple or complex, convex, concave or straight, short or long, and steep or gentle. There are no rules. Perhaps the easiest way to comprehend this complexity is to partition the slope into smaller and, hence, more easily handled units, or elements (**Figure 2(b)**).

Most simply, all slopes can be viewed as having an erosional component nearer the top, a transportational component in the mid-slope position, and a depositional component nearer the base (De Alba et al., 2004). This three-part slope categorization fits well with most slopes/catenas, especially the steeper ones. Soils respond to these general slope-development processes, in that some may thicken or even get buried at the bases of the slope, others may erode on the upper slope components, while others may maintain a balance between pedogenic and slope development. Thus, along a given slope or catena, the evolutionary stories of soils change; some soils may be undergoing long-term, gradual erosion, whereas others are becoming progressively buried. In short, catena slopes can generally be considered time transgressive – the ages of the surfaces change progressively along the slope, in this case, induced by erosion and burial processes. The introduction of differing soil ages along the slope complicates the catena concept, but is important – and commonplace – nonetheless. These points illustrate that soils and slopes 'codevelop'.

A related way to examine slopes is to consider that they have three main components: a rounded upper edge or waxing slope, a constant slope (of varying length), and a waning slope where sediment and debris accumulation is most pronounced (Wood, 1942; Ahnert, 1970). Waxing slopes are generally concave downward; waning slopes are concave upward. Most slopes also have a flat, horizontal (or nearly so) component in the middle and at their base, even if these segments are short. On simple slopes, the pattern (from the top) is convex, straight, and concave. Many slopes are more complex or compound, but each segment still retains the convex–straight–concave pattern, in a downslope direction, over at least some part of the slope.

Taking slope description one step further, Ruhe (1960) defined five elements of slope, and hence, of soil catenas. From the top to the base, they are: summit, shoulder, backslope, footslope, and toeslope. Most slopes and catenas contain all of these elements, and soil properties vary consistently and predictably as a function of these landscape positions (**Figure 2(b)**).

4.9.3.1 Summits

Summits are generally stable surfaces, especially if flat, with minimal amounts of erosion or accretion. Thus, summits are commonly dominated more by chemical weathering than by

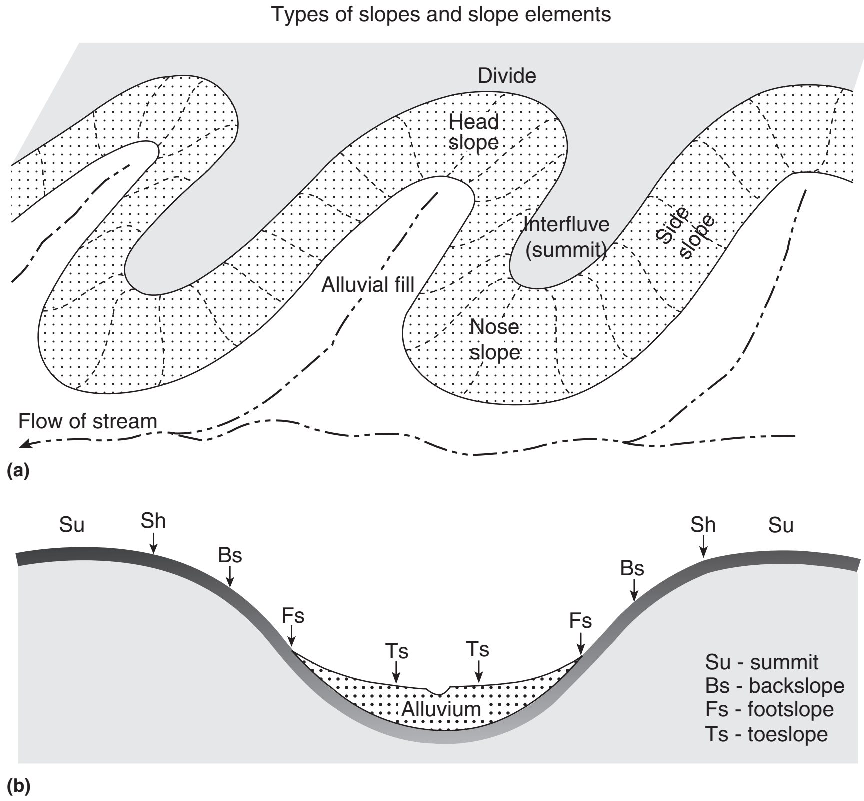

Figure 2 Three-dimensional slope types (a) and the various slope elements commonly used in soil geomorphology (b). Reproduced from Ruhe, R.V., 1975. Geomorphology. Houghton Mifflin Co., Boston, 246 pp.

physical weathering and erosion (King, 1957). Exceptions occur either where the summit is narrow or where runoff is common because of wet climates and slowly permeable soils. Wide summits may be the oldest and most stable of the five slope elements, because water is unlikely to run off. Most of the water that falls on summits infiltrates, leading to better-leached and developed soils than on slope elements that are immediately downslope. For example, clay maxima may be deeper here than on steeper slope elements because more water infiltrates. However, on slowly permeable sediment or soils, or on bedrock, the summit may be an area where water perches either on the soil surface or within the profile, making these upland soils much wetter than would otherwise be expected. Indeed, on many low-relief landscapes formed on slowly permeable materials, the flat uplands are some of the very wettest sites. Because water and sediment fluxes across summits tend to be minimal and spatially uniform, soils are also minimally varying across them, with the exceptions being sharp-crested and/or undulating summits.

4.9.3.2 Shoulders and Free Faces

On shoulder slopes, slope convexity is maximal. Runoff and erosion are dominant processes (Pennock, 2003). The steepest of shoulder slopes are called 'free faces'. On steep shoulder slopes, runoff dominates to the point that erosion can effectively outstrip soil formation (Walker and Ruhe, 1968). As a result of the continual erosion on shoulders, surfaces and soils there are usually the youngest and least stable of all the surfaces on a catena. Soils on shoulders are comparatively thin, lower in organic matter, coarser textured, and drier. Surface instability on shoulders can be initiated either by surface runoff or by lateral flow of water in the subsurface, which is especially common where bedrock is near the surface. Nonetheless, the shoulder is generally the driest slope position, and, during most years, it undergoes the greatest amount of water-table fluctuation (Khan and Fenton, 1994). Sites farther downslope are more uniformly wet with high water tables, whereas flat summit positions are wetter due to minimal amounts of runoff.

4.9.3.3 Backslopes

Backslopes are comparatively steep, transportational slopes. They are commonly straight, that is, neither convex nor concave, being positioned at the junction between upslope areas dominated by erosion and lower-slope areas of sedimentation. Where backslopes are short, soils can change markedly from those just upslope to those downslope (King et al., 1983). Materials move through and across backslopes, depending in part on slope gradient and length. Water may run off on the surface as well as in throughflow on top of less permeable layers in the subsurface (Huggett, 1976; Schlichting and Schweikle, 1980). On long backslopes, sediments may become increasingly sorted and finer-textured downslope. As is the case with slope processes on backslopes vis-à-vis other slope elements, soils here tend to be intermediate in character. It is difficult to generalize about soil attributes on backslopes, as much depends on the relationships between, and rates of, runoff (erosion) versus pedogenesis.

4.9.3.4 Footslopes

Footslopes are the most concave parts of a catena and, because they are also on the lower slope, footslopes are the most favored sediment- and water-receiving slope positions. Materials, carried in solution and suspension, whether above or below the surface, are commonly transported onto footslopes. The results, generally, are thicker A horizons and sola, and even buried soils, in footslope positions. These slope positions are commonly cooler than are upslope areas because of cold air drainage and more complete shading in the valleys. Wetter conditions also exist here, due to higher water tables. Thus, conditions at the base of the slope may promote more plant productivity and inhibit decomposition of the organic materials they produce, combining to make soils in the footslope (and toeslope) positions much richer in organic matter than on other slope elements (Kleiss, 1970).

Water and sediment impinge upon footslopes, especially where flowlines converge. As a result, spring sapping is common here, which may in turn lead to gullying. As these gullies erode upslope, into the backslope, more sediment impacts the footslope, and small depositional fans may form, burying still more soils.

4.9.3.5 Toeslopes

Toeslopes, a.k.a alluvial toeslopes, are at the outward limit of footslopes. Like footslopes, toeslopes are constructional sites (Vreeken, 1973). Sediment accumulates here from upslope areas and also from streams that flood and deposit overbank alluvial sediments. Sediment accumulating on footslopes and toeslopes tends to get progressively finer, farther away from the upslope-contributing areas because slopewash processes tend to transport finer material farther (Walker and Ruhe, 1968; Malo et al., 1974; Nizeyimana and Bicki, 1992). Accumulation of slope-derived sediment at the bases of slopes is especially important in basins of closed drainage, where few mechanisms exist to remove it (Walker and Ruhe, 1968).

Soil development on toeslopes reflects the inherent wetness of the site (relative to the other slope elements), the tendency for high plant productivity and organic-matter production on such sites and the intermittent accumulations of surficial sediment. Thus, A horizons tend to be thicker than anywhere else along the catena, and soil burial and overthickening are common (Gregorich and Anderson, 1985).

Overthickened soils develop because of sediment accumulations from upslope-contributing areas. If this sediment accumulates so gradually that it can be pedogenically incorporated into the upper profile, overthickened A horizons and sola thicken. This process is referred to as 'cumulization' or 'developmental upbuilding'; it is driven not only by slopewash sediment, but also aeolian and anthropogenic additions of mineral particles to the soil surface of a soil (Riecken and Poetsch, 1960; Johnson, 1985). More rapid rates of sediment accumulation in footslope and toeslope locations will, instead, lead to soil burial. Cumulization can be considered a type of progressive pedogenesis, if the new material is effectively assimilated into the profile (Johnson et al., 1990).

4.9.3.6 Catenary Variation as Affected by Sediments and Climate

Figure 3 summarizes many of the points made above, by showing the relative intensity of various surficial processes on a typical catena. Areas of more concentrated erosion and thus, thinner soil profiles, that is, shoulder slopes, contrast with more stable landscape positions. This general 'model' of soil–slope–process linkages would best fit a catena developed on moderately permeable soils in a humid climate. In areas of highly permeable soils and deep water tables, there may be minimal runoff, no water-table influence, and thus, much less soil morphologic variation along the catena (Figure 4). The same can be said for some catenas in dry climates, where, again, water tables may be very deep, and thus, lower slope soils may be as dry as soils on upper catenary positions. Runoff may be considerable, however, in some of these catenas because of heavy (albeit infrequent) rainfall events. Thus, Figure 3 presents the 'mode' of processes and soils for catenas, but variations on this theme are myriad, and one must always strive to understand the relative intensities of the various process drivers on the catena in question, for example, precipitation and snowmelt, as well as the inherent properties of the soil–sediment system, for example, infiltration capacity, slope steepness, and water-table depth, all of which affect runoff intensity and, hence, soil variation across the slope (Figure 5).

4.9.4 Soil Variation on Catenas – Why?

Soils on a catena generally vary only subtly at a pedon-to-pedon scale, but taken as a whole, soils across the full catena may be drastically different from the top of the slope to its base, for example, Wieder et al. (1985) and Weitkamp et al. (1996). Regardless, the soils on the catena are all linked to one another through lateral translocations of fluids, gases, and materials, as well as, potentially, by their similar inheritance of the various state factors – parent materials, climate, biota, surface age, and relief (Dan and Yaalon, 1964). That is, at time zero, all or most of the soils (or non-soil sediments) on the slope may have been essentially or nearly identical.

Over time, pedogenesis and slope processes act non-uniformly across the slope, causing soils there to become increasingly dissimilar over time, as each develops along its own, unique pedogenic pathway (Johnson and Watson-Stegner, 1987). Vertical and lateral translocations within the soils can vary in intensity at different locations on the slope (Figure 5(b)), and therefore, so do clay–mineral genesis and weathering. These, and a suite of other pedogenic processes, act in unison to place each pedon on its own unique pedogenic pathway. As time passes, the pedogenic divergence across the slope usually increases. Of course, all of this developmental divergence occurs because some (or all) of the state factors, which may have been similar across the slope at time zero, sort themselves out over time and become increasingly more variable, with time, across the slope. These state factor differences, for example, in vegetation or depth to water table, eventually

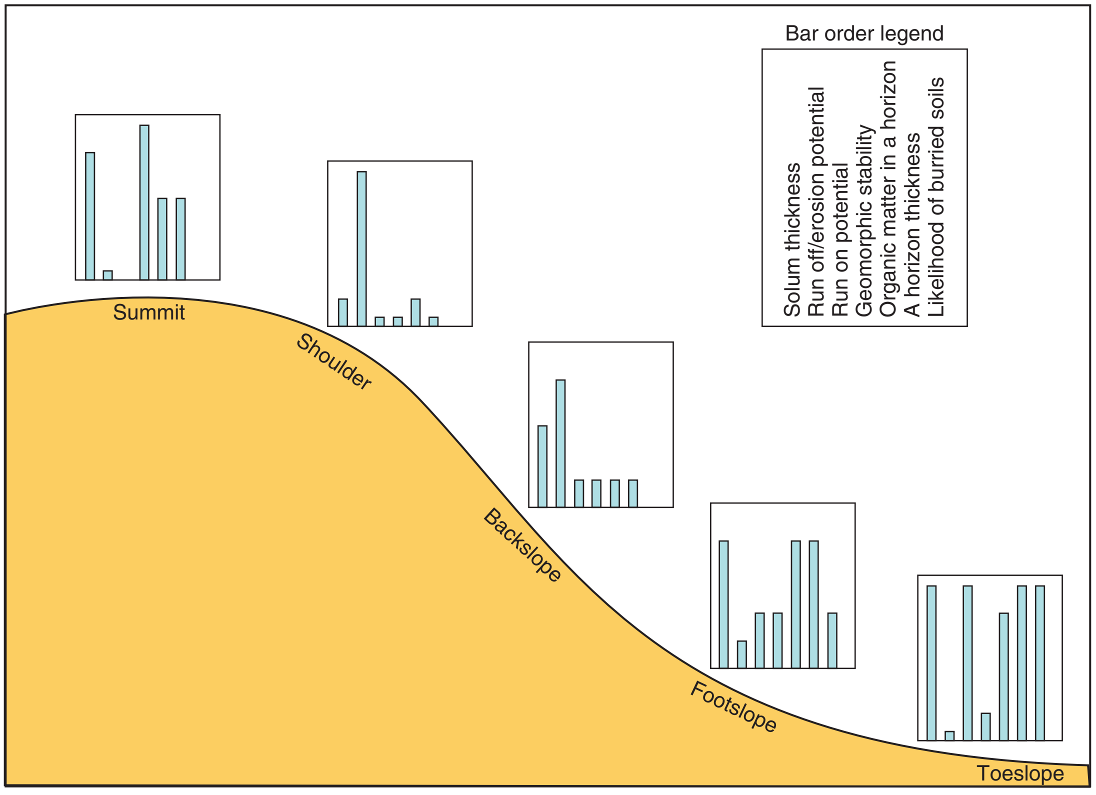

Figure 3 Estimates of relative variation in soil characteristics and slope-process intensity along a typical catena in a humid climate.

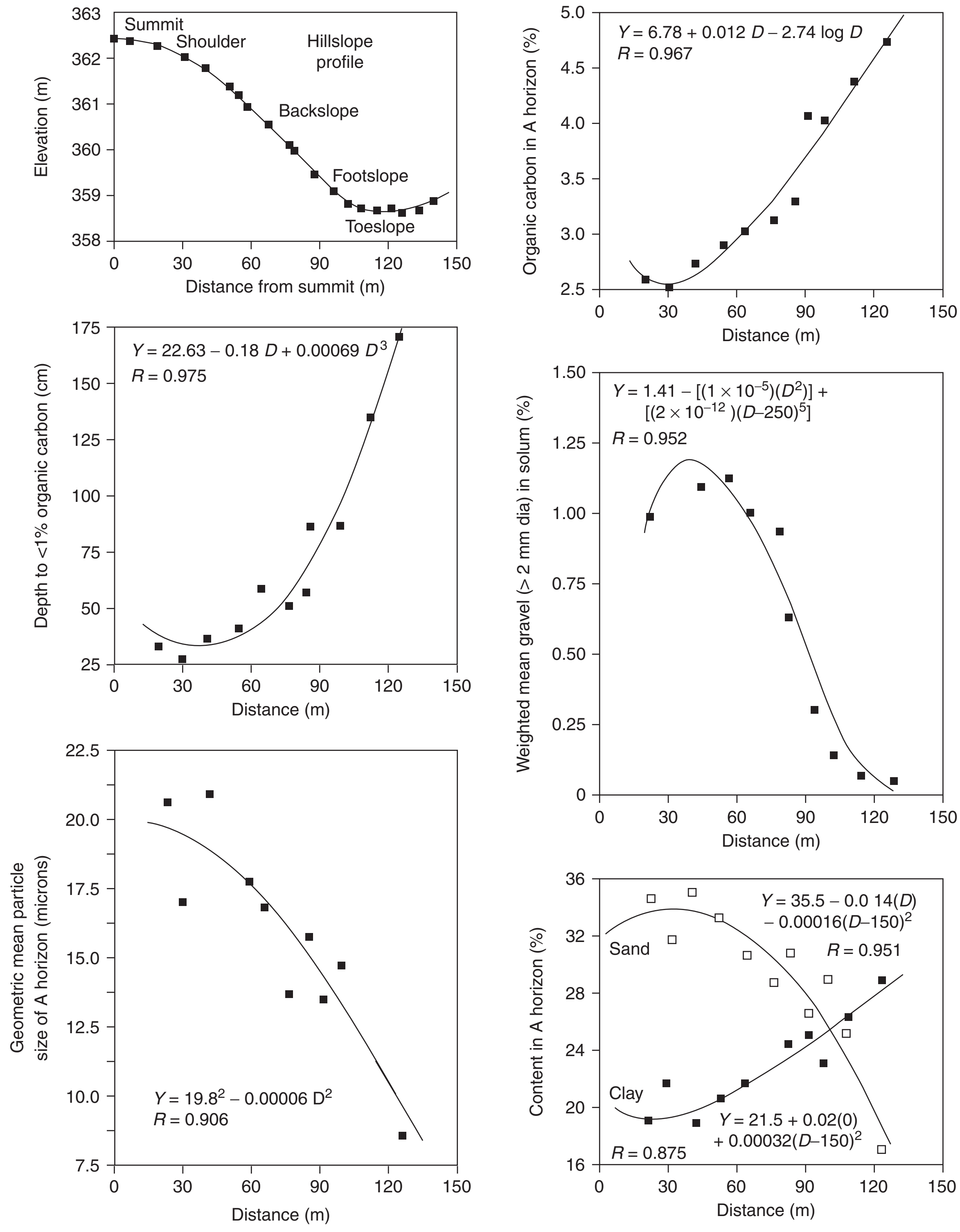

Figure 4 Quantitative relationships between slope (catenary) position and various soil properties. Reproduced from Malo, D.D., Worcester, B.K., Cassel, D.K., Matzdorf, K.D., 1974. Soil-landscape relationships in a closed drainage system. Soil Science Society of America Proceedings 38, 813–818.

force these pedogenic process changes to occur, and these processes drive the morphological and chemical changes in the soils across the catena. State factors may vary dramatically across the slope, but such variation is minimal between adjoining pedons; this fact explains why adjacent soils may be only subtly different, whereas soils on the summit are dramatically different from those in lower slope positions. Thus, soils vary across slopes according to how the state factors vary, and these pedogenic differences may become increasingly manifested over time.

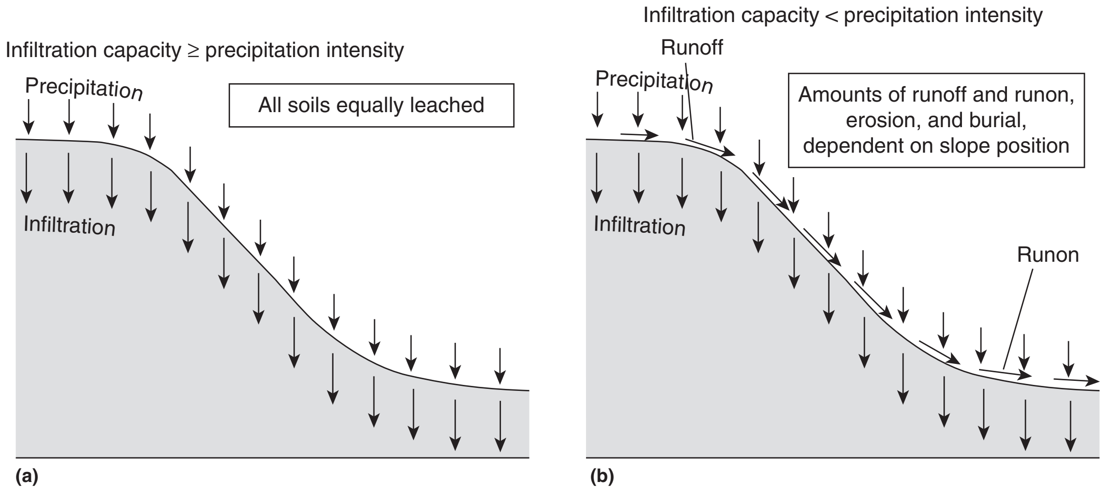

Figure 5 Two end-member scenarios illustrating the importance of, and interactions between, precipitation amount and intensity vs. infiltration capacity along a catena, and how these variables affect slope/soil processes. Reproduced from Schaetzl, R.J., Anderson, S.N., 2005. Soils: Genesis and Geomorphology. Cambridge University Press, Cambridge, 832 pp.

This section also explores some of the main 'process' reasons that soils vary across catenas. Materials, gases, and liquids are translocated on (above) and through (within) the slope materials, ultimately forming the differences in these soils on the various slope positions (Hall, 1983). Groups of processes – translocations, transformations, additions, and removals – that were championed by Simonson (1959) as useful for explaining intra-pedon, that is, horizon-related, differences, also help explain inter-pedon differences across catenas.

Schaetzl and Anderson (2005) explained that soils vary along catenas for two main reasons: (1) fluxes of water and matter, generally but not always in the downslope direction and (2) influence of the water table in the lower portions of the catena, or as perched water on flat summits (**Figure 6**). They pointed out that there are two main types of fluxes along slopes: debris flux and moisture flux (ignoring gas fluxes as very minor components of the story). Debris fluxes involve both sediment and organic material (Malo et al., 1974). Debris flux is so important that, on many slopes, soils more strongly reflect the hillslope-sedimentation system than the pedologic system (Kleiss, 1970). Sommer and Schlichting (1997) presented an idealized scheme to represent the main types of fluxes within catenas, emphasizing that fluxes can be downslope, horizontal, and even upward, and are usually driven by water (**Figure 7**).

Debris flux (again, usually driven by moisture fluxes) involves an erosional component and a depositional component, usually on the same catena. Where overland flow and rainsplash are the primary drivers of this flux, the term 'slopewash' is generally used. On summits, water may infiltrate or run off, depending on the slope curvature and the balance between precipitation and infiltration rates (**Figure 5**). Because they are the steepest slopes on the landscape, shoulders and upper backslopes have the most potential for runoff and hence exhibit the most eroded, thinnest soil profiles. Indeed, shoulders and upper backslopes are the most likely areas for rock outcrops (**Figure 3**). Because finer sediment is more easily eroded, coarser materials may remain on eroding slope positions, making soils there more sandy or gravelly and rendering the depositional areas (and soils) downslope finer textured. Debris-flux processes tend to sort materials during transit; thus, sediment texture tends to get finer as one progresses from the shoulder and backslope positions to lower positions along the catena. This trend is especially well expressed in closed basins because, in open basins, either the translocated sediment may be removed by streams, or other sediment may be added to the lower slope by fluvial processes. Backslopes are generally areas of transportation, with maximal debris and moisture flux. If interflow or throughflow is present along a catena, it will be most pronounced here, perhaps accentuated by slowly permeable layers in the subsoil (**Figure 7**). Farther downslope, debris fluxes slow, and deposition becomes an increasingly dominant process, such that cumulization can occur on toe- and footslopes. Moisture flux parallels debris flux; indeed, it is the driving force behind it. Slope steepness and curvature directly affect water flow, both within and above the soil (Huggett, 1975, 1976). The amount of water entering a soil on a slope depends on a number of factors, such as infiltration capacity, slope steepness

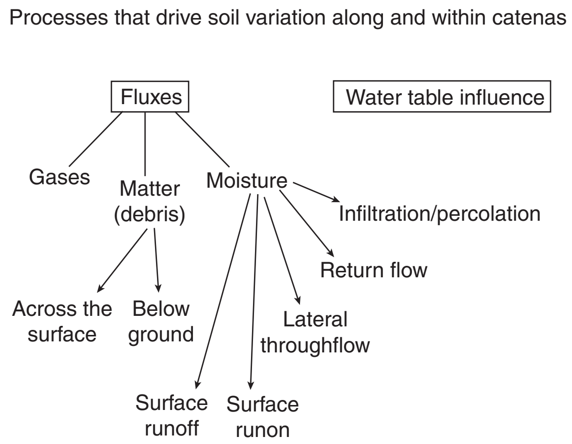

Figure 6 The main clusters of processes that drive soil variation along and within catenas.

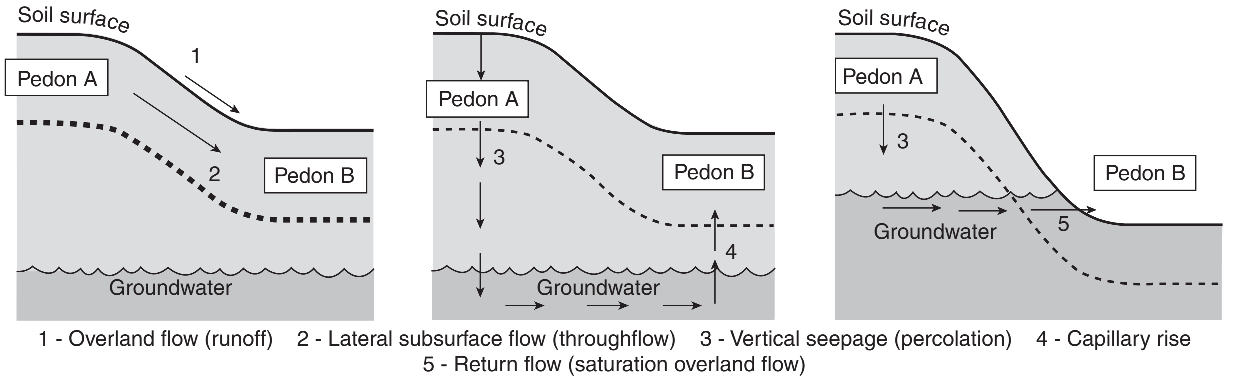

Figure 7 Idealized diagram of the various fluxes that can occur along a catena. Reproduced from Sommer, M., Schlichting, E., 1997. Archetypes of catenas in respect to matter – a concept for structuring and grouping catenas. Geoderma 76, 1–33.

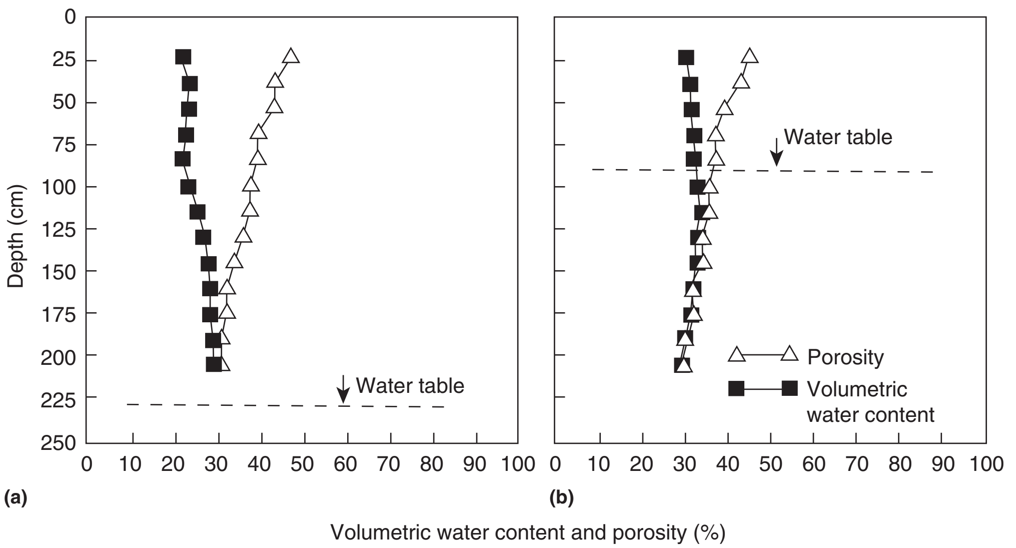

Figure 8 Relationship between volumetric soil-water content and porosity in two soils in Iowa: Clarion ((a) summit, well drained) and Canisteo ((b) toeslope, poorly drained). Reproduced from Khan, F.A., Fenton, T.E., 1994. Saturated zones and soil morphology in a Mollisol catena of central Iowa. Soil Science Society of America Journal 58, 1457–1464.

and plan curvature, intensity/frequency of rainfall events, and cover type. In theory, inputs of water from precipitation are evenly distributed along the catena. If soil-infiltration capacities exceed rates of precipitation input, most of the precipitation will immediately enter the soil and catenary differences due to moisture flux will be small (Figure 5). However, this situation may hold only in the coarsest textured catenas. Generally, inputs of precipitation are redistributed unevenly across the surface, affected by the varying slope gradients and infiltration capacities, such that the actual amount of water that infiltrates individual soils may be vastly different across the catena.

Soils in lower slope positions may be influenced by the water table, or not, depending on a number of local conditions, as well as the regional climate (Figure 8). If water table is high, soils there may classify as aquic or hydromorphic soils (Vepraskas and Guertal, 1992; Bell and Richardson, 1997; Vepraskas et al., 2004). In most humid areas, where the water table subtly mimics the surface topography, soils in the lower slope areas receive discharge from the groundwater and are continually wet, variously impacted by slowly moving or stagnant groundwater (Figure 9). In drier climates, the water table may be much deeper. Here, water that runs off the slope impacts the soils on the lower slope positions as run-in and, potentially, added amounts of infiltration. Soils in these recharge areas are more variably wet, ranging from dry to saturated, and, because of the downward percolation of water, are more leached (Figure 9).

High water tables inhibit certain pedogenic processes, especially those related to vertical translocation, for example, lessivage or podzolization. As vertically percolating soil water encounters the water table, it loses kinetic energy and diffuses into the groundwater. Any dissolved or suspended substances in the water tend to be deposited at or near the water table, and little or no additional vertical translocation, below the water table, occurs.

The presence of a water table in soils brings with it an entirely new suite of pedogenic processes, generally associated with redoximorphic processes, as well as vertical influx (including capillary rise) and lateral influx of soluble materials

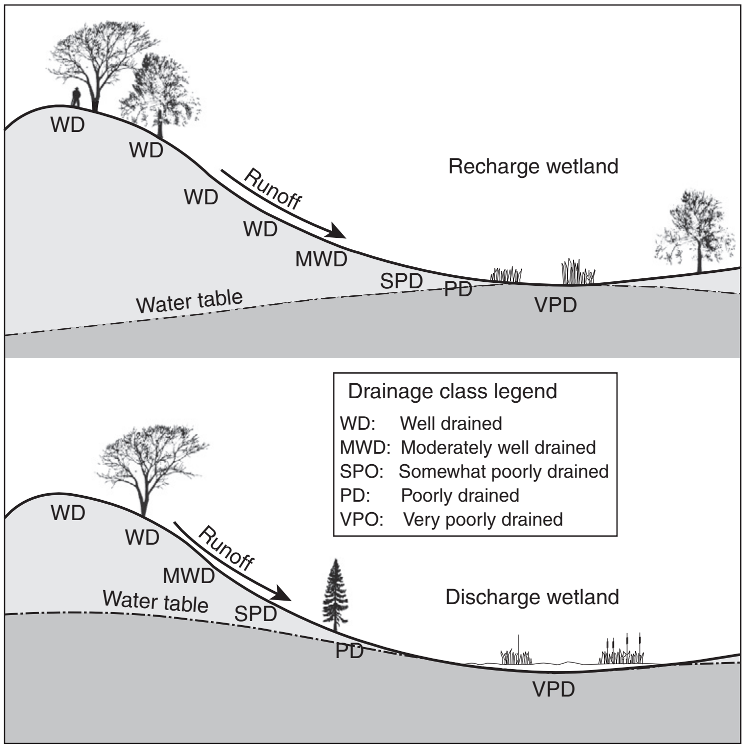

Figure 9 Two end-member scenarios for discharge vs. recharge wetlands and conditions on the lower slopes of catenas. Soil-drainage classes are also shown. Reproduced from Schaetzl, R.J., Anderson, S.N., 2005. Soils: Genesis and Geomorphology. Cambridge University Press, Cambridge, 832 pp.

(Vepraskas, 1999). Redox processes affect mainly Mn, Fe, and S compounds. However, saturated conditions also impact many solubility-based pedogenic processes, such as leaching, salinization, and sodicity (White, 1964; Peterson, 1980; Dan and Yaalon, 1982; Berger and Cooke, 1997). Organic-matter decomposition is commonly inhibited in the lower slope positions in humid climate soils because saturated conditions reduce the amount of oxygen needed for complete decomposition. For this reason, the lower portions of many catenas in humid climates, especially in recently glaciated landscapes where the lower slopes are replete with high water tables, have thick sequences of Histosols. Here, the wet, saturated conditions, coupled with the inherently cool nature of the climate, leads to only partial decomposition of any raw organic matter that may accumulate there.

Many soil-classification schemes now refer to soils impacted by a shallow water table as having a type of 'endogenic' water regime, or the condition of endosaturation; for example, the Natural Resources Conservation Service (NRCS) classifies a wet Spodosol with a shallow water table as an 'Endoaquod'. Alternatively, perched water tables – disconnected from the much deeper apparent water table by an unsaturated zone – are distinguished, taxonomically, by the term 'epi', for example, Epiaquod or the condition of episaturation (McDaniel and Falen, 1994). Water may perch on any slowly permeable layer, such as a clay-rich B horizon, a Ca-cemented horizon, or even slowly permeable, dense till in a C horizon. Perched water tables can occur at any catenary position but are most common on sites of lowest slope, where soil water has the most difficult time moving out of the profile laterally. Thus, in such situations, the water will have the greatest potential to perch on the slowly permeable layer.

4.9.5 Soil Drainage Classes along Catenas

Loosely tied to landscape position, and generally correlating with depth to the water table, is the concept of natural soil drainage classes (Soil Survey Division Staff, 1993; Schaetzl and Anderson, 2005; **Table 1**). With the exception of perched water tables, natural soil drainage classes vary systematically as a function of topography (Mackintosh and van der Hulst, 1978; **Figure 10**). Soils with deep water tables are on uplands and upper backslopes, whereas, at the lower slope positions, the highest water tables – and the wettest drainage classes – are likely to occur. Indeed, on many landscapes, the driest soils – those with the deepest water tables and the driest drainages class – are on shoulders and upper backslopes, not on the flat summits.

Schaetzl et al. (2009) integrated the concept of natural soil drainage classes with that of other soil characteristics that influence long-term wetness, for example, texture, depth to bedrock, and organic-matter content, to develop the Natural Soil Drainage Index (DI). The DI is an ordinal index, ranging from 0 for the driest soils to 99 (open water) and is derived from the soil's taxonomic classification, which it assumes is a reflection of its long-term wetness. Although the DI has some degree of subjectivity, it has nonetheless proven to be highly useful for various types of landscape scale, soil wetness analysis and visualization. Particularly enlightening is the use of

Table 1 Generalized features of the various natural soil drainage classes recognized by the NRCS[a]

Natural soil drainage class	*Typical depth to water table (cm)*	*Uppermost horizon(s) in which redox features and gleying are typically observed*	*Other characteristics*
Excessively drained	>150	None	Very coarse-textured soils
Somewhat excessively drained	>150	None	Coarse-textured soils
Well drained	100–150	Upper C or lower BC	Typical of upland soils with deep water tables
Moderately well drained	75–125	Lower B horizon	Slightly wetter and farther downslope than upland, well-drained soils
Somewhat poorly drained	30–75	Upper B (gleying in lower B)	Water table impacts some part of the profile in all seasons
Poorly drained	<30–50	Throughout the profile (gleying in all or most B horizons)	Water near or at the surface year-round; overthickened A and O horizons
Very poorly drained	0–15 (but usually above the mineral soil surface)	Throughout the profile (gleying throughout)	Organic materials accumulate above mineral soil surface, sometimes to great thicknesses

[a] From Soil Survey Division Staff., 1993. Soil Survey Manual. USDA Handbook No. 18. US Government Printing Office, Washington, DC, 437 pp. and Schaetzl, R.J., Anderson, S.N., 2005. Soils: Genesis and Geomorphology. Cambridge University Press, Cambridge, 832 pp.

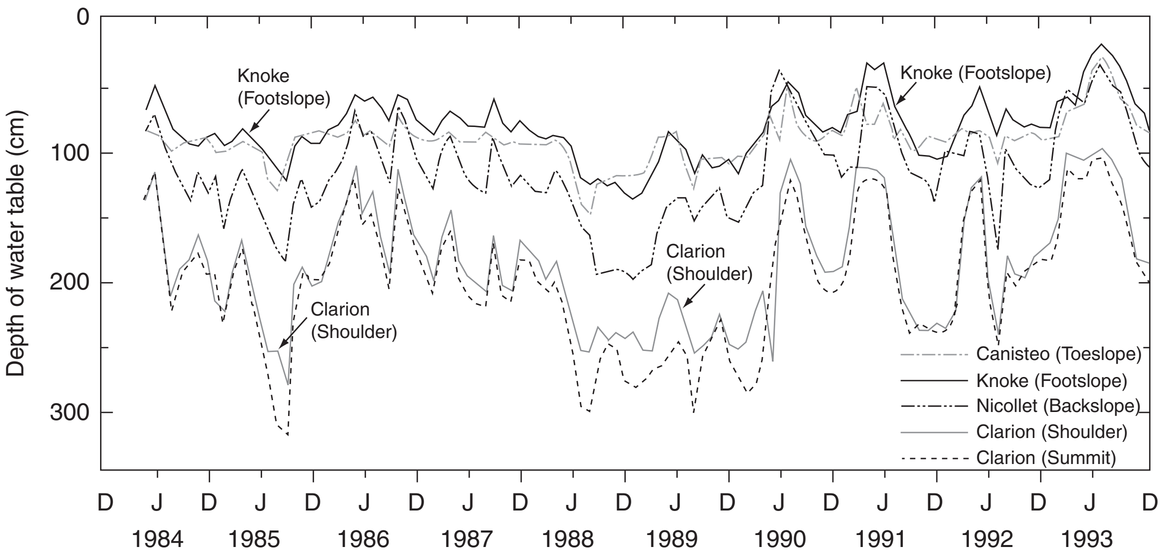

Figure 10 Relationship between water-table depth and various drainage classes and catenary positions, for some soils in Iowa. Reproduced from Khan, F.A., Fenton, T.E., 1994. Saturated zones and soil morphology in a Mollisol catena of central Iowa. Soil Science Society of America Journal 58, 1457–1464.

the DI in a geographic information system, where the DI values are shown in various colors, representing wetness, ranging from light orange (the driest soils) through yellow, green, blue, and finally purple (the wettest soils). **Figure 11** illustrates the wetness of a sample landscape, using the DI color scheme outlined above.

4.9.6 The Edge Effect

As noted earlier, shoulders tend to be some of the driest sites along a catena (Daniels et al., 1971a). Especially dry are shoulder slopes on stepped landscapes, where the shoulder represents a 'drop' down onto a steep escarpment. Such a site is referred to as a landscape 'edge' (Daniels and Gamble, 1967). The case above, in which the escarpment drops off to a drier (shoulder slope) landscape, is a 'dry edge'. Short escarpments that fall off into a wet depression are called 'wet edges'. The edge effect is an example of the close linkages between soil development, the water table, and geomorphology.

Daniels and Gamble (1967) studied dry edges and observed that soils change the most, pedon to pedon, along catenas, at these edges. Here, state factors are changing most rapidly across short horizontal distances. Particularly noteworthy is the great change in depth to the water table along such an edge (Daniels et al., 1971b). At a dry edge, water tables are generally deeper than at sites upslope or downslope, and changes in the depth to the water table are most extreme. Redder soil hues, especially in the B horizons, show that

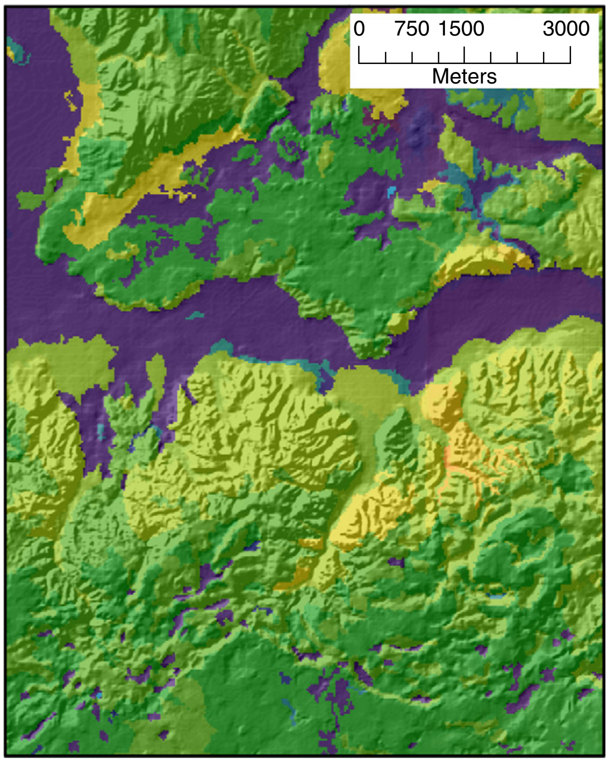

Figure 11 Soil-wetness map for a small area in northeastern Otsego County, Michigan, using the Natural Soil Drainage Index of Schaetzl et al. (2009). (See: http://www.drainageindex.msu.edu/). This is an area of predominantly sandy soils, with very poorly drained Histosols (purple) in the broad, swampy lowlands. Note the areas of Histosols in the small bogs on the otherwise flat upland. The well-drained soils (green) on the flat upland contrast with the incised backslopes, which have notably drier soils (light green) due to their steeper slopes. Areas with yellow hues are excessively drained sandy soils. In a few places, somewhat poorly drained soils (teal) on footslopes can be seen, intermediate in wetness between the Histosols of the valley floors and the well-drained soils of the backslopes.

conditions are drier and water tables are deeper, nearer the edge. For this reason, Daniels and Gamble (1967) also referred to this area as the 'red edge'. Increased translocation of clay in edge soils occurs, perhaps because this area experiences more wet–dry cycles per unit time that do other parts of the landscape.

At wet edges, soils also change predictably but in the opposite way. The wet soils directly downslope from a wet edge are gray, low in iron, and have lost much of their clay to weathering and translocation (Daniels and Gamble, 1967).

4.9.7 Summary

Soils are best examined and explained where they are viewed fully within the landscape that they have formed in. To simply examine a soil exposed in a pit face – literally with blinders on – is to ignore perhaps the most important factor in that soil's development – the landscape. In this chapter, the term 'landscape' includes all the components of slope: gradient, curvature, permeability, and depth to water table, among several others. These factors all combine to influence soil development differently along – up and down and across – a slope, through fluxes of water and sediment, as well as by water-table influences. The term 'catena' has traditionally been used to refer to these soil linkages and changes that occur along slopes. It is a valuable concept that anyone who studies soils within landscapes needs to have in their conceptual bag of tricks.

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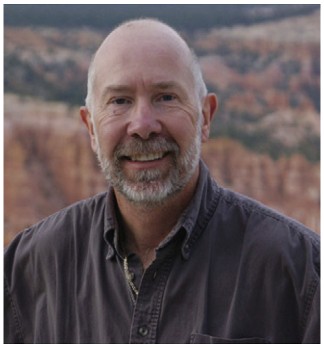
Biographical Sketch



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