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MODELING LANDFORMS AND SOILS IN YELLOWSTONE NATIONAL PARK

The advent of GIS software and digital elevation models (DEMs) has provided new opportunities for quantitative analysis in geomorphology. This paper describes how ARC/INFO was used in conjunction with the TAPES-Topographic Analysis Programs for the Environmental Sciences to create a landform/parent material polygon coverage for the 15-minute USGS Mammoth, Wyoming quadrangle. Landform and parent material map units were delineated on a 1:62,500-scale surficial geology map from aerial photography and fieldwork. Selected terrain attributes (slope gradient, aspect, specific catchment area, plan and profile curvature, wetness index, etc.) were estimated with TAPES and a 30 m DEM and imported into ARC/INFO as a series of grids. Overlays were performed in ARC/INFO to attach attributes to polygons and map units. Statistical summaries were generated for each delineation (polygon) and map unit (polygons representing the same landforms). These products are being used to: (a) distinguish map units; (b) support soil survey quality control and legend development; and (c) produce maps for editing and field use. A park-wide coverage will eventually provide a digital database for the development of soil survey map units, preparation of publication quality maps including 3-D displays, and the provision of terrain attributes for future scientific work requiring knowledge of park landscapes.

The advent of GIS software and digital elevation models (DEMs) has provided new opportunities for quantitative analysis in geomorphology. Dikau (1989), for example, recently described a system to quantify landforms through a hierarchical subdivision of the land surface into relief units. This system uses logical combinations of slope gradient, aspect, profile and plan curvature, distance to drainage divide, distance to drainage channel, elevation above the channel, gradient variability, etc. computed from a DEM to divide the landscapes into relief units. These units, in order of decreasing size and complexity are referred to as relief forms, form elements, and form facets. Field work indicated that the landforms simulated with their system matched natural landforms very well. The quantitative analysis of landforms and their elements in these ways has important implications for studies exploring the relationship between form and process in geomorphology as well as for geoecological and pedological applications at landscape and larger scales (Dikau 1989; Moore et al. 1993b).

The current study takes a slightly different approach in that landforms and soil parent materials were concurrently mapped in the field by one of the authors (Shovic). A preliminary (i.e. test) series of landform/ parent material polygon coverages was prepared from field maps and notes, and the TAPES-Topographic Analysis Programs for the Environmental Sciences (Moore et al. 1988) software was used in conjunction with ARC/INFO to prepare quantitative descriptions of these landform units. TAPES computes a series of primary and secondary topographic attributes from DEM data, including specific catchment area, which was omitted by Dikau (1989), but is important for modeling the distribution of soil water in landscapes (Moore et al. 1993b). These attributes were summarized by delineation (polygon) as well as landform map class and used to evaluate mapping concepts and procedures.

This paper describes how ARC/INFO and TAPES were combined to provide quantitative descriptions of the LFPM (landform/parent material) units delineated in the field. The bulk of the paper discusses methodology; however, some preliminary results for the 15-minute USGS Mammoth, Wyoming quadrangle are presented to illustrate the kinds of data summaries that will be produced.

MAPPING LANDFORMS AND SOIL PARENT MATERIALS

Yellowstone National Park has an ongoing soil survey program. Soils are being mapped using a GIS database, remotely sensed imagery, and a rule-based model because of limited ground access in the park. Since the spatial distribution of soils is closely tied to our knowledge of landforms (i.e. geomorphology) and parent materials (i.e. the material from which the soils are formed), a GIS layer was needed to provide that information.

The landform/parent material (LFPM) layer was produced using interpretation of 1:50,000-scale color infrared aerial photography, 1:62,500-scale surficial geology and topographic maps, and extensive field investigation. Landforms were mapped at a scale of 1:62,500 (Figure 1), with a minimum delineation size of 40 acres. The legend was left entirely open to gain the maximum amount of information with the minimum "lumping" of different landform/parent material combinations (Table 1). The first sub-legend represents the landform characteristics of the area. Each landform stands on its own; that is, it is defined separately from its relationship with other adjacent landforms. The second sub-legend represents the characteristics of the soil matrix. These characteristics are usually linked to the types of rocks occurring in the soil parent material

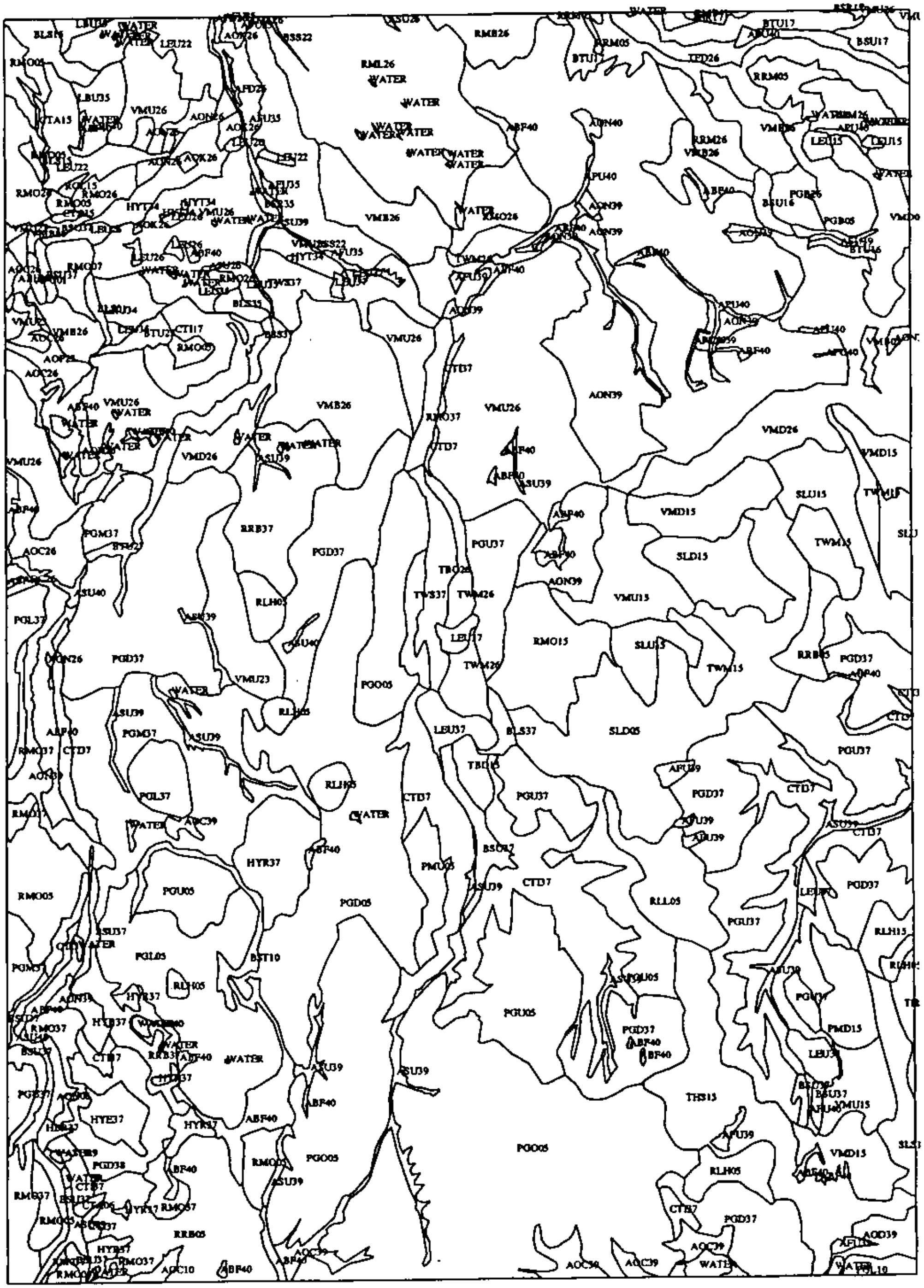

FIGURE 1. Landform/parent material coverage corresponding to 15-minute USGS Mammoth, Wyoming quadrangle.

TABLE 1. Landform and Parent Material Map Legends.

LANDFORM MAP LEGEND (Numbers in parentheses refer to numbers of landform map classes)

Glaciated Uplands and Valleys
- -- Rolling uplands & hills (9)
- -- Valley moraines (5)
- -- Ridgetops (3)
- -- Planar-plateaux (12)

Glaciated Mountains (5)

Glacial Erosional Landforms
- -- Cirques (4)
- -- Troughs (7)

Alluvial Landforms
- -- Stream areas (8)
- -- Terraces (5)
- -- Alluvial fans (4)
- -- Lacustrine plains (2)
- -- Lacustrine flats (2)
- -- Alluvial basins & fill depressions (1)

Glaciofluvial Landforms (7)

Fluvial Mountains (2)

Fluvial Uplands
- -- Plateaux (1)
- -- Rolling uplands (2)

Mass Wasting Landforms
- -- Coarse colluvium (4)
- -- Snow avalanche debris fans (4)
- -- Earth flows (4)
- -- Debris flows (4)
- -- Rockslides (2)
- -- Landslide scarps (1)

Breaklands
- -- Structural breaks (1)
- -- Stream breaks (5)

Hydrothermal Landforms (9)

PARENT MATERIAL KEY
(Partial list only)

Frost rubble
Glacial rubble/sandy matrix
Hydrothermally altered rhyolite
Glacial rubble in limestone or travertine
Kame material in rhyolite
Upper till
Rhyolite flows
Andesite (Wiggins Formation)
Andesite (Wapiti Formation)
Andesite (Langford Formation)
Andesite (Lamar River Formation)
Other andesite
Basalt
Granite
Diorite
Coarse-grained igneous rocks
Obsidian
Sandstone
Siltstone, shale or mudstone
Sandstone/shale mixture
Limestone
Metamorphic rocks
Rock mixtures (Northern Range)
Rhyolite/andesite mixtures
Siliceous sinter
Lacustrine silt with cobbles and gravels
Travertine
Andesite tuff, etc., etc.

and the mechanics of the glacial and fluvial transport systems which have operated within different parts of the park during the past several thousand years.

Any combination of the landform and parent material legends referred to in Table 1 is allowed. This approach has produced a larger number and variety of map classes than would have been practical with a traditional field-based, manual mapping project. The large data handling and presentation capabilities of GIS have allowed us to map approximately 300 combinations of the two sub-legends in the 30% of the park which has been mapped to date. The lack of "lumping" (i.e. aggregation of landform and parent material classes) will enhance both the future opportunities for information transfer and the accuracy of the final maps.

TOPOGRAPHIC ATTRIBUTES

The topographic attributes used in this study included both primary and secondary attributes. Primary attributes are calculated directly from digital elevation models (DEMs) and include elevation, slope gradient, aspect, profile and plan curvature, and specific catchment area. Secondary or compound attributes consist of combinations of primary attributes and are used to characterize the spatial variability of specific processes (soil water movement, radiation fluxes, etc.) occurring in landscapes (Moore et al. 1993b). Most topographic attributes are calculated from the directional derivatives of a topographic surface, either directly from a grid-based DEM or by fitting a bivariate interpolation function to those values and then estimating the derivatives of the function (Moore et al. 1993a). The topographic attributes were computed with Version 2 of the TAPES software (Moore et al. 1988) directly from the 30 m DEMs for the 7.5 minute USGS quadrangles that match the 15-minute USGS Mammoth, Wyoming quadrangle used for field mapping.

Slope Gradient

The maximum slope or gradient β (in degrees) is calculated from the directional derivatives by:

$$\beta = \arctan (f_X^2 + f_Y^2)^{1/2} \quad (1)$$

which Moore et al. (1993a) calls the finite-difference (FD) approach. Version 6.1 of ARC/INFO uses a simpler approximate approach (D8) in which the gradient is the steepest slope in one of eight cardinal directions in a moving 3x3 square-grid matrix.

Aspect

Aspect ψ (measured in degrees clockwise from north) can be estimated from the directional derivatives by:

$$\psi = 180 - \arctan(f_Y/f_X) + 90(f_X/|f_X|) \quad (2)$$

The aspects computed with Equation 2 are somewhat arbitrary when the gradient is less than some minimum value (β_{min}), and Moore et al. (1993a) recommend that terrain be classified as flat or as a singular point with undefined aspects in these instances.

Curvature

Curvature in the direction of maximum slope (profile curvature) and traverse to the slope (plan and tangential curvature) are important for hydrological and geomorphological applications. Profile curvature (κ_p) is the rate of change of the potential gradient and influences water flow and sediment transport processes (Moore and Wilson 1992). Plan curvature (κ_h) is the curvature of contour lines as measured in a horizontal plane. It is a measure of the topographic convergence and divergence and therefore the distribution of water in a landscape (Moore et al. 1993b). The two terms are calculated in TAPES as follows:

$$\kappa_p = (f_{XX}f_X^2 + 2f_{XY}f_Xf_Y + f_{YY}f_Y^2)/(pq^{3/2}) \qquad (3)$$

$$\kappa_h = (f_{XX}f_Y^2 - 2f_{XY}f_Xf_Y + f_{YY}f_X^2)/p^{3/2}$$

where $p = f_X^2 + f_Y^2$ and $q = p + 1$. Profile and a modified version of plan curvature could have been computed in ARC/INFO (Version 6.1) as well.

Drainage Area/Specific Catchment Area

The estimation of both drainage area and specific catchment area (drainage area per unit width orthogonal to a streamline) are dependent on the estimation of flow direction(s) from a given node to one or more of eight possible neighboring nodes in a moving 3x3 grid network. There are several choices, and we used the FRho8 algorithm so that flow dispersion or catchment spreading could be represented. This algorithm allows flow to be distributed to multiple nearest-neighbor nodes in upland areas above defined channels. The proportion of flow or upslope contributing area assigned to multiple downslope nearest neighbors is determined on a slope-weighted basis using methods similar to those proposed by Freeman (1991) and Quinn et al. (1991).

The Rho8 (random-eight node) algorithm developed by Fairfield and Leymarie (1991) is a stochastic version of O'Callaghan and Mark's (1984) deterministic-eight node (D8) algorithm. The D8 algorithm permits flow from a node to only one of eight nearest neighbors based on the direction of steepest descent. This algorithm is used by ARC/INFO and several other GIS systems for determining drainage areas even though it tends to produce flow in parallel lines along preferred directions (Moore et al. 1993a). The stochastic version is superior in that it simulates more realistic flow networks, and this algorithm was used here to direct water flow below points of channel initiation.

Maximum Flow Path Length

The maximum flow path length is the length of streamline upslope from a given point. The D8 and Rho8 algorithms can be rewritten to accumulate distances rather than areas, and the Rho8 algorithm was used here to accumulate flow distances across cells (λ when travelling directly across cells and $\sqrt{2}\lambda$ when travelling diagonally across cells).

Steady-State Wetness Index

This compound topographic index, $\ln(A_S/\tan\beta)$, has been used extensively to describe the effects of topography on the location and size of saturated source areas of runoff generation in topographically complex terrain (e.g. Beven and Kirkby 1979; O'Loughlin 1986; Moore et al. 1988, 1990; Wood et al. 1990). The index can be derived from simple subsurface flow theory so long as it is assumed that: (a) the gradient of the piezometric head, which dictates the direction of subsurface flow, is parallel to the gradient of the land surface, and (b) steady-state conditions apply. The form of the index shows how its value increases with increasing specific catchment area and/or decreasing slope gradient.

These topographic attributes were output to an ASCII file with one record per grid cell by the TAPES software. We prepared another Fortran program to allow the user to select one of the terrain attributes and write the estimates for this attribute to a new ASCII file with the header information and values required by the ASCIIGRID command in the GRID module of ARC/INFO. A series of ARC/INFO grids representing different topographic attributes was prepared for the land surface corresponding to the 15-minute USGS Mammoth, Wyoming quadrangle by running this program multiple times.

SPATIAL ANALYSIS

The next series of tasks were accomplished with a series of Arc Macro Language programs (AMLs) prepared by the authors. These AMLs were used to: (a) combine selected landform/parent material map units and topographic attributes; (b) classify the topographic attributes into two or more user-defined classes (e.g. 0-7%, 7-15%, 15-30%, etc. for slope gradient); and (c) provide an improved user interface for map production and analysis. The remainder of the discussion focuses on the first of these tasks.

The polygon attribute table (PAT) for the landform/parent material coverages contained the four default items (AREA, PERIMETER, COVER_, and COVER_ID) plus one called LABEL. The values for LABEL recorded the landform/parent material mapping unit and consisted of five characters (BSS22, LEU22, RML26, etc.; see Figures 1 and 2 for additional examples). The first pair of AMLs contained an INFO program, and added several new items and assigned values to them as follows: (a) a new item called POLYGON was added and assigned an 8-digit number based on the values of COVER_ID (first 4 digits) and a new item called CATEGORY (to be discussed next); (b) the CATEGORY item was assigned values from 1 to n where n is the number of unique values (i.e. 5-character landform/parent material map unit codes) from the

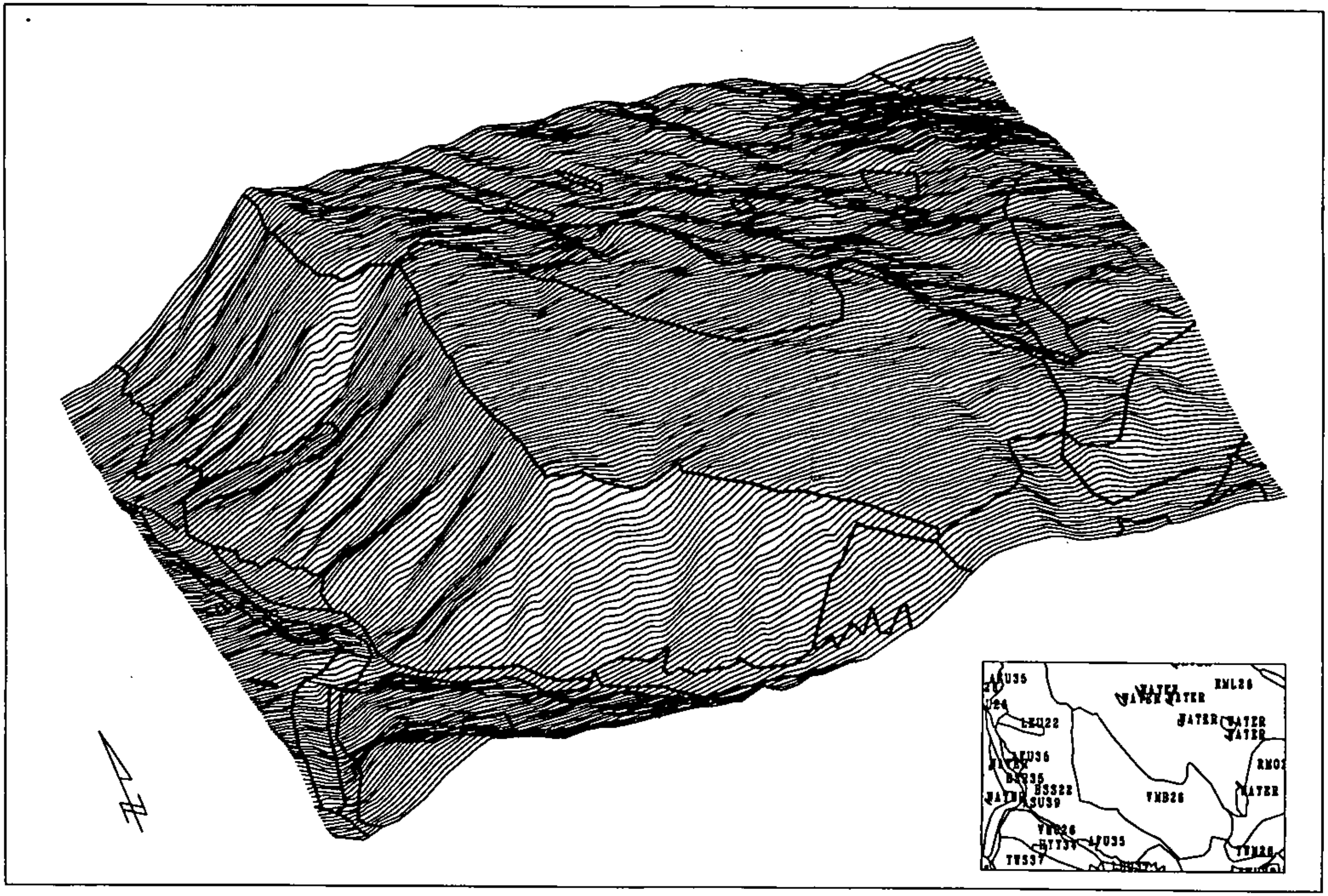

FIGURE 2. Three-dimensional view of Mount Everts area, directly east of Mammoth, WY, in Yellowstone National Park. The LFPM (landform/parent material) layer is draped on the 30 m DEM. The inset shows a 2-D view of the same layer with labels. Scale is approximately 1:30,000.

LABEL item; (c) a third item called LANDFORM was created and assigned the alphanumeric portion of LABEL (BSS, LEU, RML, etc.); (d) another new item called LANDFORMCAT was added and assigned values of 1 to n where n is the number of unique values (i.e. 3-letter landform codes) from the LANDFORM item; and (e) an item called MCCAT was added and assigned the numeric portion of LABEL (22, 24, 26, etc.).

The next AML created four new grids: three from the expanded landform/parent material coverage and the fourth from the ASCII file containing topographic attribute values. The POLYGRID command was used to create the first three grids, and the values from the POLYGON, CATEGORY, and LANDFORMCAT items were copied to the VALUE item in the appropriate grid value attribute tables (VATs) in each case. The POLYGON item meant that 1 record was created in the grid VAT for each landform/parent material polygon that was large enough to constitute at least one grid cell (i.e. 30 m by 30 m areas). The Mammoth quadrangle contained 358 such polygons (records). The transfer of values from CATEGORY to the VALUE item in the VAT for the second grid meant that 104 records were created with each one corresponding to a unique 5-character landform/parent material mapping unit code (BSS22, LEU22, RML26, etc.). Taking the VALUE item in the grid VAT from the LANDFORMCAT item in the PAT in the case of the third grid meant that 56 records were created, one for each of the unique 3-letter landform codes (BSS, LEU, RML, etc.). The fourth and final grid was generated by selecting one of the nine topographic attributes computed with TAPES, compiling these data to match the input format required for the ASCIIGRID command, and importing the appropriate data into ARC/INFO with this command.

The final AML in this series was used to generate three more grids by overlaying the topographic attribute grid on each of the landform grids. An item is added to each of the VATs and assigned the values from the VALUE item in the appropriate landform grid VAT. The names of these items (POLYGON, CATEGORY, and LANDFORMCAT respectively) indicate their origins. The COMBINE command in GRID was used to perform all three overlays, and the new item in each VAT serves as the relate item when joining the new grids to the LFPM (landform/parent material) PAT. These data can then be exported and/or downloaded to another system (PC ARC/INFO, SPlus, dBase, etc.) for additional analysis. This process was repeated for the remainder of the topographic attributes with the exception of the steady-state wetness index. These values were computed in ARC/INFO from the slope gradient and specific catchment area grids.

RESULTS

The methodology that we have just described allows the compilation of terrain data by individual map delineation (i.e. polygon), landform/parent material class (i.e. 5-character LFPM code), and landform class (i.e. 3 letter landform code). Table 2 summarizes a small fraction of the terrain information for the land surface covered by the 15-minute USGS Mammoth, WY quadrangle. This table shows the terrain data for four of the TAPES attributes and five of the landform classes represented in the portion of the Mammoth quadrangle reproduced in Figure 2. These five landform classes covered 13.3% (73.65 km^2) of the land surface. The terrain data can be used in a variety of ways, some internal to the LFPM mapping process (which is 30% complete)

TABLE 2. Selected topographic attributes by landform class for 15' Mammoth, WY quadrangle.

Topographic attributes	Selected landform codes (from Figures 1 & 2) BSS[1]	LEU[2]	RML[3]	RMO[4]	VMB[5]
Count (# of grid cells)	5935	12880	16136	28147	18730
Elevation (m)					
Maximum	2341	2695	2384	2704	2407
Minimum	1760	1710	1846	1894	1834
Mean	2009	2139	2224	2360	2221
Range	581	985	538	810	574
Slope gradient (%)					
Maximum	114.0	127.0	100.0	132.0	92.0
Minimum	2.0	0.0	0.0	0.0	0.0
Mean	59.3	26.0	19.7	21.1	14.0
Standard deviation	18.9	13.5	19.7	12.3	9.8
Plan curvature ($m\ m^{-1}$)					
Maximum	44.8	133.3	68.4	80.0	80.0
Minimum	-12.7	-66.7	-66.7	-66.7	-80.0
Mean	0.0	0.2	0.0	-0.1	0.0
Standard deviation	1.8	4.6	5.4	5.3	6.5
Specific catchment area ($m^2\ m^{-1}$)					
Maximum	20070	30360	16530	56670	19170
Minimum	30	30	30	30	30
Mean	573	588	234	273	228
Standard deviation	1407	1815	549	1032	609

1 Breaklands, stream break, dissected, sharp spurs (interfluves) (1 of 5 stream break mapping units referenced in Table 1).

2 Mass wasting, earthflows (1 of 4 earth flow mapping units).

3 Glaciated, rolling uplands, moraine with linear bedrock ridges (1 of 9 rolling uplands and hills map units).

4 Glaciated, rolling uplands, moraine (1 of 9 rolling uplands and hills map units).

5 Glaciated, valley moraine, some rounded bedrock exposures (1 of 5 valley moraine map units).

and others related to a variety of landscape-scale scientific applications in ecology, geomorphology, and pedology.

The quantitative results assist with the differentiation of map units, quality control and legend development, and in describing the individual map units and their variability. For example, a comparison of the topographic attributes for the individual delineations (i.e. polygons) that have been classified into a particular landform class (like those shown in Table 2) may reveal that one or two delineations have very different slope gradients, plan curvatures, specific catchment areas, etc. compared to the others. The polygons that display these topographic characteristics may be candidates for remapping as another kind of landform; or they may be representative of a highly variable, though valid map unit; or they may indicate a poorly defined landform and/or parent material class. These kinds of decisions, which are often required as part of the mapping process, are aided by the quantitative summaries shown in Table 2.

The topographic attributes may also help us to characterize and explain the spatial variability of specific processes occurring in landscapes. The elevation data summarized in Table 2, for example, shows five landform classes which occur at high elevations (> 1700 m) and are characterized by large variations in elevation (i.e. relief). In addition, the breaklands (BSS) landform class displays consistently steeper slopes than the other four landform classes as measured by the mean slope gradient and the coefficient of variation (i.e. the standard deviation divided by the mean). The existence of this pattern and the value of the topographic attributes is confirmed by the three-dimensional view of one of the BSS polygons reproduced in Figure 2. The contrast between the BSS polygon (i.e. the large west-facing slope) and the other polygons is especially obvious in this view. This diagram also shows the irregular land surfaces which characterize the RML landform polygons and therefore why this class has a relatively high slope gradient coefficient of variation in Table 2. The significance of plan curvature is largely dependent on spatial pattern and therefore difficult to interpret without the aid of a map, unlike the specific catchment areas results which point to several obvious similarities and differences among the five landform classes. Two examples will suffice: (a) the minimum values (30 m in all five cases) indicate that all five landform classes included cells which are adjacent to a drainage divide and from which drainage is initiated; and (b) the higher mean specific catchment areas shown for the BSS and LEU landform classes indicate landforms that are more effective in collecting and concentrating runoff and therefore landforms that are likely to display a greater variability in terms of soil water content compared to other landforms. Dikau (1989), Moore et al. (1993b), and others have shown that the spatial variability in these kinds of indices has important consequences for a variety of physical and biological characteristics, including overland and subsurface flow velocities and runoff rates, soil erosion and deposition rates, present and future soil characteristics, and the distribution and relative abundance of flora and fauna.

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