USE OF GENERAL GEOMORPHOMETRY IN THE CHARACTERIZATION OF MOUNTAIN TOPOGRAPHY

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ABSTRACT

We characterized mountainous topography by a variety of landform measurements (geomorphometrics) taken across 10 digital elevation models (DEMs) that cover 10 7.5-minute topographic map quadrangles in Idaho and Montana. The eight metrics examined included elevation, slope, aspect, hypsometric integral, bumpiness, roughness, ruggedness, and skyward angle. Principal components analysis (PCA) indicated that roughness, skyward angle, and aspect collectively accounted for an average of 67 percent of the observed morphometric variance within each of the 10 study area quadrangles and, thus, conveyed the bulk of topographic information. Composite images made from the three principal metrics displayed map patterns closely resembling shaded relief (chiarascuro) renditions of the same terrain. The ability to numerically describe and map topographic geometry should help geographers and ecologists establish spatial correlations and other statistical relations between relief and various biophysical patterns and processes.

Key Words: geomorphometrics, digital elevation models (DEMs), geographical information systems (GIS), principal components analysis (PCA), roughness, skyward angle, aspect, biophysical environments, ecological mapping

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INTRODUCTION

Biophysical environment maps are used to describe terrestrial or aquatic ecosystems that behave in a similar manner given their potential ecosystem composition, structure, and function. Such maps also are commonly used to delineate environmental constraints for ecological pattern analysis and land use planning. Biophysical environment maps display areas with similar management response potentials and resource production capabilities and are based on landscape components that do not display high temporal variability at a given mapping scale, e.g, land form, regional climate, and surficial geology. Ecological units (Bailey et al. 1994, Cleland et al. 1997), land units (Zonneveld 1989), ecoregions (Omernick 1987), biogeoclimatic ecosystems (Meidinger and Pojar 1991), and land systems (Christian and Stewart 1968) are examples of biophysical environment mapping systems that delineate ecologically homogeneous environments at different spatial scales based primarily on geomorphologic, climatologic, and biotic criteria.

A problem common to all of these mapping systems is a failure to apply geomorphometrics that describe entire terrains. This failure stems from the fact that to date most geomorphometric descriptions have relied primarily on mapping specific land forms (Evans 1972, 1980, Jarvis and Clifford 1990). In this approach, mappers use aerial photos, topographic maps, orthophotoquads, and other information in the manual delineation of discrete features such as flood plains, cirques, and mountain slopes. This approach is not only costly and laborious but also quite subjective. Different mappers, who apply the same landform mapping criteria in a study area, often achieve different results. Reproducibility and precision of mapped regions are commonly low.

General geomorphometry offers an

alternative to mapping specific landforms (Evans 1987). In this approach, no prior designation of traditional geomorphic features is required. Instead, various metrics reflecting landform geometry and configuration are calculated for pixels, i.e., grid cells covering a study area. Based on mapping objectives, pixels are grouped by metric values into contiguous landform areas. These empirically-derived spatial units are referred to in the literature as raster regions, polygons, or patches and are normally constructed from one or several metrics in combination (Evans 1980). The primary advantages of this approach are that reproducibility is very high, i.e., different mappers using the same criteria and source materials obtain identical results, and landform raster region attributes are quantitatively described. Such numerical descriptions may be used in subsequent analysis of landform and biotic-pattern relations, e.g., fish distributions and vegetation types.

Until recently, numerical descriptions of relief, the foundation of general geomorphometry (Tricart 1947, Goldberg 1962), have been limited due to the tedium involved in making repetitive manual measurements on topographic maps and aerial photographs. However, recent advances in GIS software, satellite imagery, and digital elevation models (DEMs–matrices or rasters of land surface elevations arrayed as pixels) have enabled researchers to make rapid advances in applying geomorphometric techniques to the characterization of mass wasting and soil erosion processes (Gao 1993, Vertessy et al. 1990), stream and watershed delineation (Band 1986, Moore et al.1991), and surface and subsurface runoff (Tarboton 1997, Montgomery and Foufoula-Georgiou 1993). Despite development of such applications, little research has been directed toward discovering geomorphometrics that are most suitable in describing different kinds of land surface form at different hierarchical levels, and consequently, how a general geomorphometrical approach to landform description can be used to improve biophysical mapping.

The primary objective of this study was to determine geomorphometrics that are most useful in describing the overall topographic complexity of mountainous terrain representative of the Rocky Mountains in Idaho and Montana. A secondary objective was to determine whether raster-maps of these metrics provide visual representations of landscapes that are similar to standard United States Geological Survey (USGS) shaded relief maps commonly used by many land management agencies for biophysical mapping.

BACKGROUND INFORMATION

The interest and research concerning metrics appropriate to general geomorphometric characterization of land surface forms has a long and distinguished history. In a milestone paper, Hammond (1954) suggested that characteristic metrics should include area (surface arrangement), altitude, relief, volume (vertical dimension), profile (vertical arrangement of the surface), texture (horizontal dimension) and slope (deviation of the surface from the horizontal). Through laborious manual measurements Hammond (1964) eventually produced a map of land surface form for the entire United States incorporating three of these metrics. Using new technologies, e.g., computers, GIS, DEMs, Dikau et al. (1991) automated and tested Hammond's land surface form classification for New Mexico with good results. They showed that many of the metrics Hammond identified could be automated. Brabyn (1997) showed that Hammond's classification could identify macro-landforms across the mountain-plain transition zone of eastern South Island, New Zealand.

Following Hammond's pioneering lead, Van Lopick and Kolb (1959) and Wood and Snell (1960) suggested methods appropriate to land form classification using air-photo interpretation methods, which were subsequently reviewed by Parry and Beswick (1973). Primary metrics considered in these analyses included grain (horizontal distances between major ridges and valleys), relief (elevation difference between major ridges and adjacent valleys) average elevation, elevation-relief ratio, and the number of slope-direction changes. Following this work, Evans (1972, 1980, 1990) suggested four land form metrics calculated from altitude and its mathematical derivatives were most appropriate for land surface relief description. These metrics included point slope gradient, point slope aspect, point vertical convexity, and point plan curvature or rate of slope aspect change. Also, the parameters of average, standard deviation, skewness, and kurtosis were considered to be useful in summarizing metric statistical distributions. In a thorough review of existing manually-derived metrics for land-form description, Mark (1975) suggested that grain (relief wavelength or spacing between major ridges and valleys), texture (smallest desired relief wavelength), local relief (elevation difference between major ridges and valleys), mean slope inclination, roughness factor (a set of unspecified metrics), and hypsometric integral (Strahler 1952) were the "best in the class."

Beginning in the mid-1970's, many manual calculations of general geomorphometrics were considered for digital processing. Collins (1975) was among the first to advocate the use of DEMs in their calculation, suggesting that 14 important metrics could be measured through this technology. Similarly, Nogami (1995) classified many manual measurements into one of three categories (point, window, and basin) for computer application.

Elghazali and Hassan (1986) and Zevenbergen and Thorne (1987) provided formulas for the computation of many common metrics based on finite differences between elevations, and Gallant and Wilson (1996) provided computer programs that calculate 12 important metrics such as plan and profile curvature, flow direction, and flow path length. Additionally, morphometric algebraic and calculus equations are included within GIS software packages such as Arc/Info, Idrisi, and Surfer (Anon. 1999a, b).

METHODS

Study Area

In this study we selected 7.5-minute DEMs representing 10 quadrangles from a variety of mountainous terrains in the Rocky Mountains of the northern United States (Fig 1). These Level 1 DEMs included Elk Butte, Elk River, Grice Ridge, and Widow Mountain in Idaho and Gable Peak, Glenn Creek, Landowner Mountain, Lozeau, MacDonald Pass, and Mt. Haggin in Montana. The DEMs had 30-m resolutions (arrayed point elevations separated by 30 m on the ground) and spanned elevations ranging from a low of 670 m on Grice Ridge to a high of 3230 m on Mount Haggin. Local reliefs, i.e., elevation differences between the tops and bottoms of valley side slopes, for the quadrangles generally ranged between 300 and 1000 m. Both Lozeau and MacDonald Pass had significant areas containing <300 m of local relief. Low relief occurred primarily along the Clark Fork River in the Lozeau quadrangle and along the comparatively broad and gentle main summit of the MacDonald Pass quadrangle. Alpine glacial landscapes characterized the Gable Peaks, Mt. Haggin, and Widow Mountain quadrangles that were noticeably coarser and had higher reliefs than the other quadrangles that were dominated primarily by fluvial and mass-wasting processes.

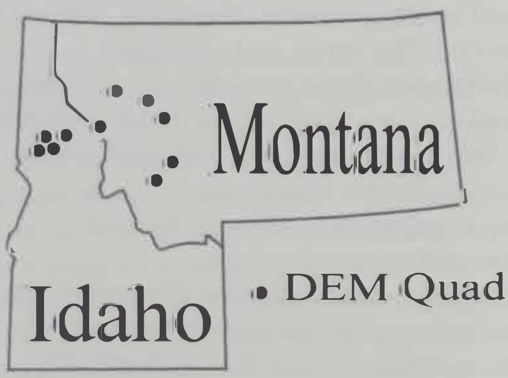

Figure 1. Locations of 10 USGS DEMS Used in Study.

Geomorphometrics Considered in This Study

In this study we focused on eight geomorphometrics that we thought could be most descriptive of overall landscape relief and patterns of mountainous topography. Four of the geomorphometrics were introduced or re-defined substantially for computer use (bumpiness, roughness, ruggedness, and skyward angle). These metrics as well as hypsometric integral were programmed in C++ language (Ellis and Stroustrup 1990) and run under DOS commands. Two metrics, aspect and slope, were calculated with the Idrisi Surface module and another, mean elevation, was calculated by the Idrisi Extract module, average option. All metrics were calculated from DEM pixel elevations. In this analysis we moved a 3x3-pane window, i.e., one pixel equals one pane, across each DEM image by placing its central pane over a DEM row's second pixel, calculating a metric based on elevations showing through the nine panes, assigning the result to the DEM pixel underlying the central pane, and moving the window to the next pixel in the row to continue the process (See Lillesand and Kiefer [2000] for more information concerning GIS window-based operations). The moving window was centered over every DEM pixel except for boundary columns and rows. The values of the newly calculated metric images (sometimes called digital terrain models or DTMs in the literature) were standardized across the range of 0 to 255. This normalization of all metric raw values to a common scale greatly reduces adverse statistical effects associated with magnitude differences between the absolute values of the metrics studied. A listing and brief description of the study metrics follows.

Aspect.—Aspect is the facing direction of the steepest slope directed through a moving window's central pane. It is the clockwise angle measured from a Universal Transverse Mercator (UTM) grid easting (directed north through the central pixel) and the down-slope direction of the slope gradient or fall line. Many ecologists view aspect as a fundamental geomorphometric because of its effects on solar radiation loadings on the ground. Our calculation of aspect used the following equation:

$$Asp = \arctan\{-[(V_{\text{[illegible]}} - V_{\text{[illegible]}})/(2\Delta x)] - [(V_{\text{[illegible]}} - V_{\text{[illegible]}})/(2\Delta y)]\}$$

where *r*, *c* are the row and column coordinates of a window's central cell; *V* is a pixel value, and resolution =Δx or Δy. For square pixels, Δx =Δy.

Bumpiness.—Bumpiness indicates the number of pixels at elevations lower than the central pixel elevation in a moving window. Bumpiness values range from 0 to 8 in a 3 x 3 moving window. For example, a value of 8 indicates that a central pixel is a peak or summit, a value of 7 implies a divide, and a value of 0 implies an enclosed depression. Bumpiness was incorporated into the study to serve as a surrogate for the number of changes in the facing directions of slopes in a moving window. Our calculation of bumpiness was based on:

$$Bmp = count(V_{r\pm2,c\pm2} - V_{r,c}) < 0$$

Mean Elevation.—This is the average height above sea level calculated for a moving window. Elevation represents the most fundamental geometrical attribute of the land surface. Elevation changes in mountainous terrain typically lead to the creation of various zones of different bioclimates and geomorphological activities.

Hypsometric Integral.—This value reflects the percentage of total area lying under an area / elevation summation curve of pixel elevations. In this study we calculated the hypsometric integral by summing the differences between every pixel elevation and the lowest elevation and dividing the sum by the number of pixels times the maximum elevation difference (window relief) between any two pixels. We included the hypsometric integral to hopefully pick out such slope discontinuities as cliffs and ledges. This metric was introduced by Strahler (1952) and shown by Pike and Wilson (1971) to be the same as the elevation-relief ratio (Wood and Snell, 1960). Our calculation of hypsometric integral used the following equation:

$$\boldsymbol{Hypso} = \{[\sum_{c=1}^{n}\sum_{r=1}^{n}(\boldsymbol{V}_{rc} - \boldsymbol{V}_{l})]/\boldsymbol{n}\}/(\boldsymbol{V}_{h} - \boldsymbol{V}_{l})$$

Roughness.—Zakrzewska (1963) defined roughness as the total number of contours intersecting the perimeter of a circle drawn on a topographic map. In essence, this parameter reflects a summation of relief ups-and-downs traced around the circle. We retained this notion of summed elevations by the re-definition of roughness. We define roughness here as the summation of absolute elevation differences between adjacent pixels aligned across rows and down columns in a moving window. Our calculation of roughness used the following equation:

$$\boldsymbol{Ro} = \sum_{c=1}^{n-1}\sum_{r=1}^{n-1}\left|\boldsymbol{V}_{rc} - \boldsymbol{V}_{r+1,c}\right| + \sum_{r=1}^{n-1}\sum_{r=1}^{n-1}\left|\boldsymbol{V}_{rc} - \boldsymbol{V}_{r,c+1}\right|$$

Ruggedness.—Beasom et al. (1983) defined ruggedness in terms of the total length of contours in a unit area. Such a line density depends on the slope and relief of a study area. This dependence is retained in this study, where ruggedness expresses the vertical dimension as a combination of two elements: window relief and window average slope. Strahler's (1958) ruggedness number (HDd) applies only to drainage basin morphometry and cannot be computed within moving windows. We calculated ruggedness as window relief, i.e., the maximum difference in elevation between two pixels in a moving window, and multiplying this difference by the tangent function of average slope in the same window. Window average slope is based on the mean of all pixel slopes encompassed within a moving window. Our calculation of ruggedness used the following equation:

$$Ru = (|V_{\max} - V_{\min}|)(\tan S_{avg})$$

where $V_{\max}$ = maximum value, $V_{\min}$ = minimum value, and S_{avg} is the average of all slope values within the moving window.

Skyward Angle.—Skyward angle is defined as the upward angle formed at the center of a moving window by the intersection of two profile slope segments, one directed from the highest elevation to the central pixel and the other from the central pixel to the lowest elevation. Skyward angle values of 180° indicate the junction of two slope segments at the window center; junctions <180° indicate upward concavity, whereas those >180° indicate upward convexity. Skyward angle reflects ground surface curvature, another fundamental surface attribute. Our calculation of skyward angle used the following equation:

$$SA=360-\{(180-\beta)+\alpha\}$$

where α = upper profile segment angle = arctan $\{(V_{\max} - V_{cr})$ / resolution $\}$ and β = lower profile segment angle = arctan $\{(V_{\min} - V_{cr})$ / resolution $\}$, $V_{\max}$ = maximum window pixel value, $V_{\min}$ = minimum window pixel value, and V_{cr} = window central pixel value.

Slope.—This metric reveals the degree of surface inclination through the central pixel. The method used for measurement of slope in this study was the Idrisi's Surface module (Degree-Gradient option). We based computation of slope values of the four closest (side) neighbors of a central pixel. Slope is another fundamental attribute of surface geometry. Indeed, it is generally regarded as the pre-eminent metric (Nogami 1995), principally because of its role in most geomorphological processes that draw materials downhill. Our calculation of slope reflects the following equation:

$$s = \arctan\left\{\sqrt{[(\boldsymbol{V}_{c-1} - \boldsymbol{V}_{c+1})/2\Delta_x]^2 + [(\boldsymbol{V}_{r-1} - \boldsymbol{V}_{r+1})/2\Delta_y]^2}\right\}$$

Programs for calculating the previous eight geomorphometrics were developed for routine use with ARC/INFO GIS software by Jim Barber of the USDA Forest Service, Northern Regional Office, Missoula, MT. These ARC macro-language (AML) routines are recorded on compact disks and are available through the junior author.

Principal Components Analysis

We used principal components analysis (Dunteman 1989) to assess which of the eight study metrics best explain the overall variability in landform relief and configuration across the 10 DEM quadrangles. This type of analysis has been used successfully in previous research (Mather and Doornkamp 1970, Cadigan et al. 1972) with similar objectives of determining which geomorphometrics best describe topography. In principal components analysis several to many uncorrelated multi-variate linear equations (components) are calculated to account for the observed variation in the parameters (geomorphometrics) being studied. The first component explains most of the variance. This is followed by the second and subsequent components, each of which accounts for progressively less variance. We examined relations from three principal components derived from eight geomorphometrics. Factor loadings were then calculated to represent correlations between individual components and the studied geomorphometrics. The squared value of a factor loading approximates the degree of variance accounted for by a particular geomorphometric and is analogous to the coefficient of determination (r^2) commonly reported in standard correlation analysis. Accordingly, parameters (geomorphometrics) with the highest loading on each principal component and their proportional reduction in the total geomorphometric complexity of a quadrangle were identified through this type of analysis, and those with the highest loading values are referred to below as the principal metrics.

RESULTS

For the 10 study area quadrangles, the first three principal components accounted for an average 75.0 percent of the total variance inherent in the geomorphometric data (Table 1). The lowest explained variance was 72.7 percent for the Widow Mountain quadrangle, whereas the highest was 77.1 percent for the Lozeau quadrangle. The proportion of variance accounted for by the first component ranged from 30.1 percent for the MacDonald quadrangle to 42.8 percent for the Glenn Creek quadrangle. The second principal component ranged from 20.8 percent for the Gable Peak quadrangle to 25.7 percent for the MacDonald quadrangle, and the third principal component ranged from 12.1 percent for the Lozeau quadrangle to 18.8 percent for the Widow Mountain quadrangle.

Analysis of coefficients of determination associated with principal metrics and components (Table 2) suggests

Table 1. The Principal Metrics Identified across 10 DEM Quadrangles Arrayed by Three Principal Components. Numbers Indicate the Quadrangle Count for which a Given Metric had the Highest Loading.

Metric	Principal Component 1	Principal Component 2	Principal Component 3
Aspect			8
Bumpiness			
Elevation	1 (Mount Haggin)		
Hypsometric Integral			1 (Widow Mountain)
Roughness	9		1 (MacDonald Pass)
Ruggedness			
Skyward Angle		9	
Slope		1 (Widow Mountain)	
Total Count	10	10	10

Table 2. Coefficients of Determination (r^2) Associated with Individual Principal Components and Land Form Metrics.

			Hypso.			Skyward		
	Aspect	Bump.	Elev.	Integral	Rough.	Rugged.	Angle	Slope
Principal Component 1								
Average	0.011	0.117	0.391	0.059	0.860	0.739	0.072	0.767
Std. Dev.	0.022	0.097	0.257	0.066	0.132	0.245	0.099	0.261
Principal Component 2								
Average	0.007	0.273	0.111	0.494	0.032	0.140	0.714	0.132
Std. Dev.	0.112	0.134	0.196	0.159	0.032	0.221	0.225	0.228
Principal Component 3								
Average	0.667	0.019	0.133	0.066	0.080	0.036	0.069	0.037
Std. Dev.	0.402	0.043	0.134	0.124	0.130	0.073	0.132	0.075

that roughness accounted for most of the explained variance ($r^2 = 0.86$) for the first principal component, followed by slope ($r^2 = 0.77$) and ruggedness ($r^2 = 0.74$). This is not surprising given the high degree of correlation between these three metrics. Skyward angle ($r^2 = 0.71$) explained the most variance in the second principal component, and aspect ($r^2 = 0.67$) accounted for the most variance in the third principal component. These three principal metrics (roughness, skyward angle, and aspect) accounted for an average of 67.0 percent of the total geomorphometric variability across all 10 quadrangles. The amount of variance explained by these principal metrics ranged from a low of 52.4 percent for MacDonald Pass to a high of 72.8 percent for Glenn Creek.

In Figures 2, 3, and 4 we present a six class, 30 m, raster-based classification for each of the three principal metrics described

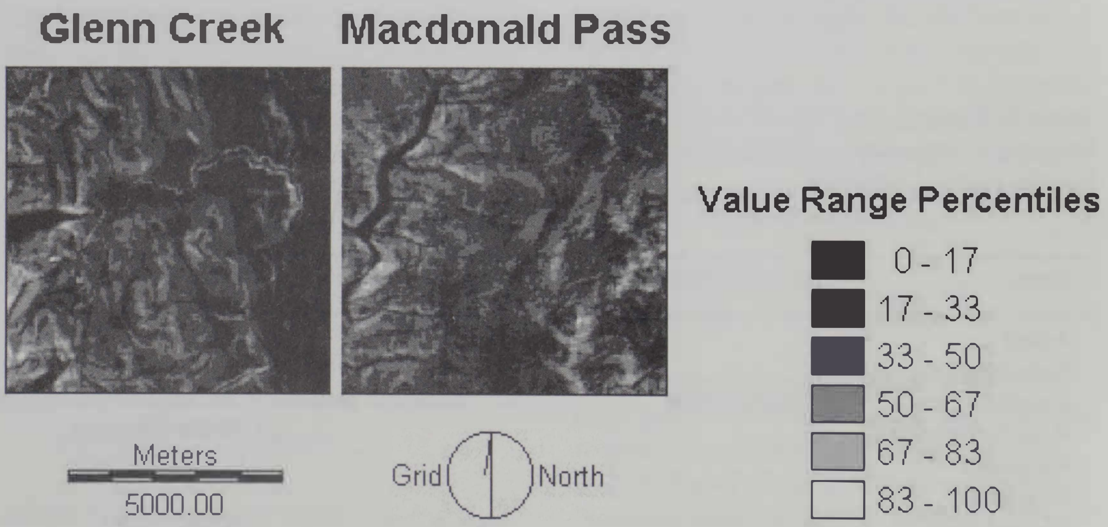

Figure 2. Six-class Representation of Landform Morphomerty Based on the First Principal Metric: Roughness

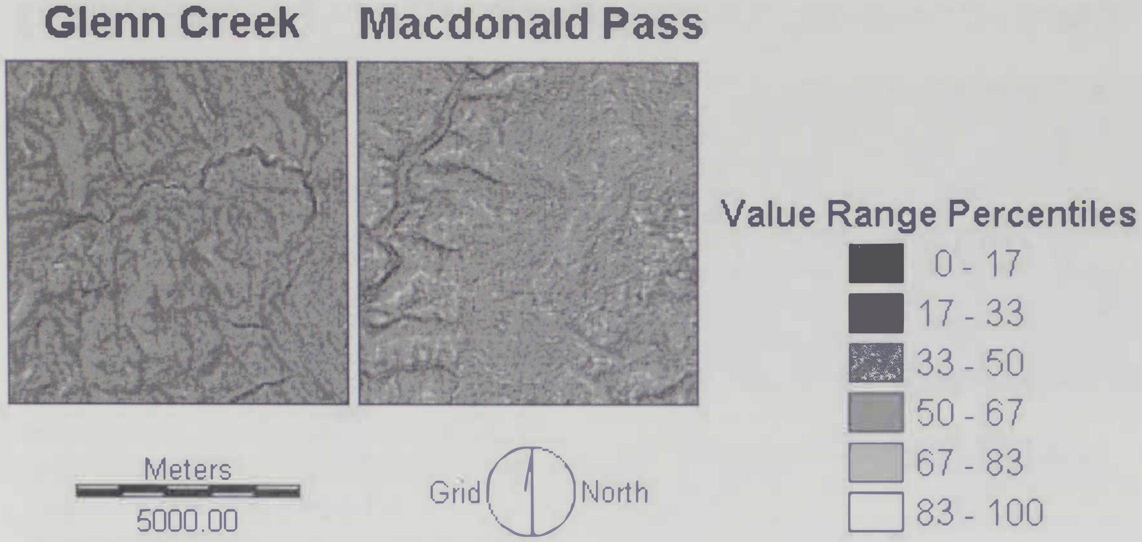

Figure 3. Six-Class Representation of Landform Morphometry Based on the Second Principal Metric: Skyward Angle

above. The two areas presented as examples are from Glenn Creek ($r^2 = 72.8$) and MacDonald Pass ($r^2 = 52.4$). The classes presented in these figures represent equal intervals of the principal metric value ranges. Figure 2 displays a classification of land surface form based on roughness, which represents differences in the vertical dimension of a terrain, i.e., low values indicate regular surfaces, whereas high values indicate irregular surfaces. Figure 3 displays skyward angle classes for the Glenn Creek and MacDonald Pass quadrangles with low values indicating relative concavity and high-values convexity. Figure 4 displays land form aspect which represents slope facing-directions and edges, such as divides and thalwegs (stream bottoms), where different aspect slopes intersect.

In Figure 5, we present composite maps of the Glenn Creek and MacDonald Pass quadrangles synthesized from roughness, skyward angle, and aspect. Six classes for

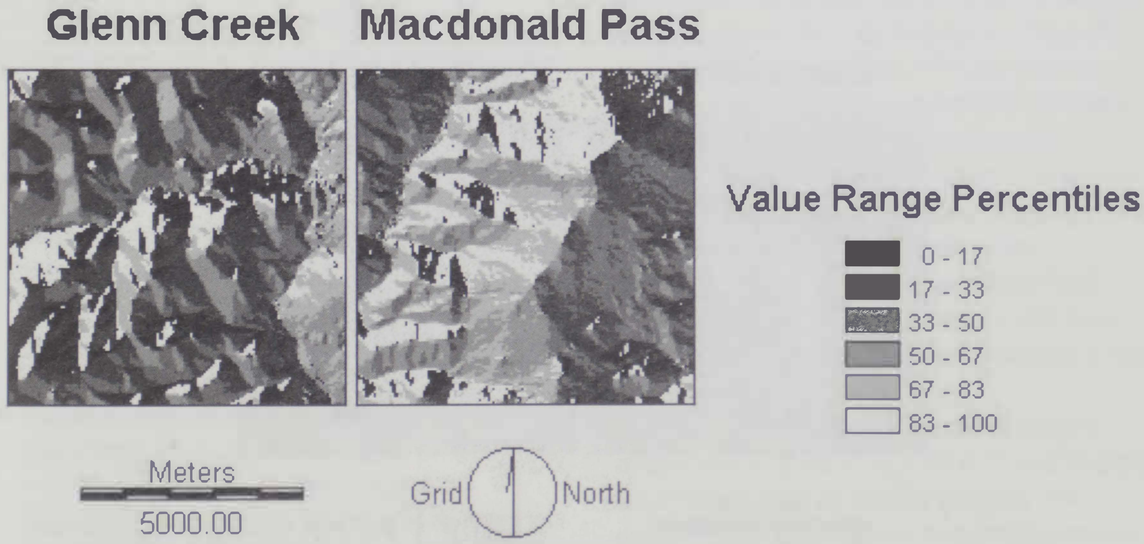

Figure 4. Six-Class Representation of Landform Morphometry Based on the Third Principal Metric: Aspect

Although topographic details in the shaded relief maps are poorly rendered by the composites (Fig 5) in some areas, medium and large components are reliably reproduced. The fact that topographic characteristics can be quantified and displayed on maps suggests that spatial correlations and other types of relations between topography and biophysical factors can be established and examined over comparatively broad areas. Much can be learned at the regional level, and such characterizations can be quite detailed because the metrics used may be represented by small ground cells, currently as small as 30m on a side. In this respect, topographic metrics match the scale of much current and past satellite imagery used by geographers, ecologists, land use managers, and others. In all likelihood, DEM resolutions will increase more or less in step with increases in satellite resolution.

Geomorphometrics convey considerable detail about land surface form nearly everywhere. In many places the form of the land surface discloses the presence of different types and structures of underlying bedrock and residual materials (Tator et al. 1960, Miller 1961). Place-to-place differences in wildland flora and fauna are commonly associated with differences in surface geometry and underlying materials (Howard and Mitchell 1985). Because of such relationships, geomorphometrics and their mapping can be important to the pre-mapping of ecological units or in the mapping of natural species habitats (Canon and Bryant 1997, Nellemann and Fry 1995, Koehler and Hornocker 1989). They also permit the quantitative description and classification of areas important to land managers (Hurley and Jensen 2001). Morphometrics also help provide insight into surface conditions and processes that have shaped such habitats. Much morphometric work has been devoted to geographical aspects of runoff and mass wasting processes and hazards (Quinn et al.1993, Pike 1988).

In the future, other metrics will likely be found to be more informative than those examined in this study. The three principal metrics (roughness, skyward angle, and aspect) identified in this study likely will be superseded but the meanings of the three principal components (vertical dimension, surface vertical curvature and slope face pattern) may not.

CONCLUSIONS

The following conclusions are drawn from this research:

(1) Relief is probably the most essential factor in quantitatively characterizing mountainous topography. The next most important factor may be surface curvature, followed by slope facing pattern;

(2) Mountainous topography can be reasonably characterized for geomorphometric mapping purposes by as few as three metrics: roughness, skyward angle and aspect; and

(3) New metrics may outperform traditional metrics as shown. This was the case for roughness and skyward angle in comparison to aspect, hypsometric integral, average elevation, and slope.

In the future, other metrics will likely be found to be more informative than those examined in this study. The three principal metrics (roughness, skyward angle, and aspect) identified here likely will be superseded, but the essential meanings of the three principal components (vertical dimension, surface vertical curvature and slope face pattern) may not.

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