Landform Characterization with Geographic Information Systems

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Abstract
The ability to analyze and quantify morphology of the surface of the Earth in terms of landform characteristics is essential for understanding of the physical, chemical, and biological processes that occur within the landscape. However, because of the complexity of taxonomic schema for landforms which include their provenance, composition, and function, these features are difficult to map and quantify using automated methods. The author suggests geographic information systems (GIS) based methods for mapping and classification of the landscape surface into what can be understood as fourth-order-of-relief features and include convex areas and their crests, concave areas and their troughs, open concavities and enclosed basins, and horizontal and sloping flats. The features can then be analyzed statistically, aggregated into higher-order-of-relief forms, and correlated with other aspects of the environment to aid fuller classification of landforms.

Introduction
The ability to analyze and quantify morphology of the surface of the Earth is essential for understanding the physical, chemical, and biological processes that occur within the landscape. The shape of terrain influences flow of surface water, transport of sediment and pollutants, climate both on local and regional scales, nature and distribution of habitats for plant and animal species, and migration patterns of many animal species. It is also an expression of geologic and weathering processes that have contributed to its formation. Knowledge of terrain morphology also is essential for any engineering or land-management endeavors that affect or disturb the surface of the land.

The primary science that deals with understanding, description, and mapping of the shape of terrain is geomorphology, defined in the *Random House Webster's Dictionary* as the study of the characteristics, origin, and development of the form or surface features of the Earth, i.e., landforms. Landforms are defined as specific geomorphic features on the surface of the Earth, ranging from large-scale features such as plains and mountain ranges to minor features such as individual hills and valleys. Geomorphology encompasses a spectrum of approaches to the study of landforms within two major interrelated conceptual frameworks: functional and historical. The functional approach tries to explain the existence of a landform in terms of the circumstances which surround it and allow it to be produced, sustained, or transformed such that the landform functions in a manner which reflects these circumstances, while the historical approach tries to explain the existing landform assemblage as a mixture of effects resulting from the vicissitudes through which it has passed (Chorley *et al.*, 1985). Taxonomic schemes for landforms therefore often include the way they were formed, their composition, and the environment in which they were formed.

The ability to map landforms is an important aspect of any environmental or resource analysis and modeling effort. Traditionally, mapping of the aspects of the environment has been accomplished through *in situ* surveys. The advent of aerial photography and satellite remote sensing have made surveys of large areas easier to accomplish, although this technology still requires *in situ* verification and ground-truthing. While remote sensing technology can provide tremendous amounts of information about the surface of the Earth, it is incapable of providing all of the data needed. The most complete approach to mapping the distribution of various environmental parameters requires an integrated approach that relies on remote sensing and geographically referenced field survey data, whether in cartographic or tabular format. By combining mapped data from various sources, it is often possible to make informed guesses about those characteristics of the environment that remain hidden to satellite sensors or aerial cameras. For example, through correlation of mapped information on vegetation types with data on local climate, topography, hydrology, geology, and general distribution of soils and through application of the knowledge of surface processes that relate to soil formation, detachment, and transport, it is possible to make relatively accurate predictions regarding distribution of different types of soils, something not currently possible using remote sensing data alone.

Traditionally, these types of studies have been performed using a manual overlay process that relies on maps hand-drawn on transparent velum. Currently, geographic information systems (GIS) permit integration of geographic data using computers. Surveyed information is entered into a GIS and preserved in digital format, where it can be combined with remote sensing images to generate new maps using various automated spatial data processing algorithms. The knowledge-based process that combines existing geographic data to generate new information is generally known as cartographic modeling. The component maps that show the geographic distribution of a single environmental parameter or a single category of parameters are known as geographic themes.

When a theme represents a category of information that consists of many data elements, it is possible to generate new maps from a single geographic theme by selectively displaying the elements. For example, a single soil mapping unit within a soils theme can have numerous attributes associated with it, such as data on the organic matter content, pH factor, salt content, percentages of silt and clay, erodibility, structure, and other information. Using a GIS, each kind of

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information can be selectively identified, displayed, and saved as an independent data layer for use within a cartographic model.

In the above example, a GIS functions mainly as a display or selection device for various soil attributes already known. However, a GIS also permits automated extraction of completely new information from an existing theme. This is particularly the case with topographic data traditionally available as elevation contour maps. From the contour map various types of information, such as watershed boundaries, steepest flow paths, slope gradients, slope aspects, and more, can be derived by a specialist through painstaking manual analysis of the shape of the contours and the distances between contour lines.

In digital format, elevation data are generally available as grids, where each grid cell represents a particular elevation above a certain vertical reference, such as the mean sea level. Geographic information systems include various algorithms that mathematically analyze the digital elevation data to automatically derive information that otherwise would take tremendous effort and amount of time to obtain. Typical terrain analysis algorithms in a GIS include methods for generating slope gradients, slope aspects, watershed boundaries, and flow paths. The added bonus of using these automated means is that new information is always calculated in precisely the same way, eliminating subjective judgement on the part of the analyst.

Automated extraction of new information from digital elevation models (DEMs) has many levels of complexity. Generation of slope and aspect maps is a relatively simple process, while delineation of watershed boundaries or steepest flow paths requires more complex calculations. Yet another level of complexity is reached when topographic parameters for physical processes are very closely associated with other parameters not directly related to elevations. For example, while movement of sediment across terrain is strongly dependent on topography, other factors such as the amount vegetation cover, type of soils, and intensity of rainfall govern sediment transport and interact in complex ways with the topographic factors. Analysis of elevation data to provide useful information for sediment transport modeling therefore requires a precise understanding of the contribution of topography to the movement of soils and an analysis of that contribution in isolation from other factors that influence movement of sediment across the landscape. Currently, much research is being performed to develop new terrain analysis algorithms to model such processes (Beven and Moore, 1993).

A similar issue arises in classification of landforms, although here it is mostly a question of definition and taxonomy. What do we understand a landform to be? To what extent can we think of landforms purely in terms of shapes in isolation from questions concerning their origin and composition? If so, is there a simple way to determine the shapes of landforms from elevation data?

This paper proposes a simple approach, based mostly on existing GIS capabilities, to extract meaningful information from digital elevation data that can ultimately lead to precise mapping of landforms independently of taxonomic schemes. While the methods described here cannot provide instant identification of the nature, probable origin, or composition of any particular landform, the information generated through them can be used as part of a more complex cartographic modeling process that will potentially accomplish that goal.

Classification of Landforms for GIS Processing

More specific definitions of the term landform than those quoted previously come from Belcher (1948) and Lueder (1959). According to Belcher, each landform presents separate and distinct soil characteristics, topography, rock materials, and groundwater conditions. He adds that the recurrence of the landform, regardless of the location, implies a recurrence of the basic characteristics of that landform (Belcher, 1948). Lueder, on the other hand, describes a unit landform as a terrain feature or terrain habit, usually of the third order, created by natural processes in such a way that it may be described and recognized in terms of typical features wherever it may occur, and which, when identified, provides dependable information concerning its own structure and either composition and texture or uniformity (Lueder, 1959). In identifying landforms as the third-order-of-relief features, Lueder narrows the definition down by placing landforms more in the context of shape of the land, and within the traditional orders-of-relief framework. In that framework, the first-order-of-relief is represented by continents and ocean basins; the second order by mountain ranges, plains, continental shelf, continental rise, and the abyssal plains; while the third order by the landscape features such as individual hills, mountains, and valleys. Of course, for the purposes of precise mapping, the question still remains, where to place the boundaries of features.

Lueder's definition serves as a departure point for analysis of landform characteristics based purely on elevation data. While it is unclear whether identification of the third-order-of-relief features will provide dependable information concerning the landform's own structure, composition, or texture, elevation data implicitly contains information on the shape, vertical order, and magnitude of relief features. However, because of problems with definition, it is very difficult to agree on the precise boundaries of third-order-of-relief features. It is much easier to identify and delineate portions of these features as related to the fact that they represent a part of a continuous surface. Each complex continuous surface can be said to consist of concave areas, convex areas, and flats. Convex areas can be further subdivided into crests and sideslopes. Concave areas can be subdivided into troughs, sideslopes, and open and enclosed basins. Flats can be divided into sloping flats and horizontal flats. In the context of terrain analysis, these subfeatures can be referred to as the fourth-order-of-relief features. Most or all of the fourth-order-of-relief features are always present in any terrain, and a digital surface representation of the terrain can be analyzed to identify discrete boundaries for these categories. The features can then be aggregated to form higher-order-of-relief categories using diverse definitions or taxonomic schema and multi-thematic support data.

Landform characterization maps where the continuous terrain surface is classified into fourth-order-of-relief features provide information on the shape, vertical order, and magnitude of the features. Shape refers to the two-dimensional and three-dimensional distribution pattern of any particular feature. Vertical order refers to the fact that, within its immediate neighborhood, a crest is the highest area on a convexity (e.g., a hill), a convexity is higher than a concavity, and a trough is the lowest area within a concavity (e.g., a depression). Magnitude refers to the actual elevations of the features, and the fact that some hills are higher than others and some depressions are deeper than others. Magnitude also includes any other characteristic that can be derived from elevation values for any particular feature, such as the average slope gradient of a crest or the areal extent and volume of an enclosed basin.

Analysis for Convexity, Concavity, and Flatness

Qualities of concavity and convexity are synonymous with whether a particular neighborhood or area on the surface of the Earth predominantly tends toward being a depression or a protrusion. Curvature is generally understood as a directional property. Some existing GIS systems offer methods to determine profile curvature, or curvature of a surface in the direction of slope, and planform curvature, or curvature of a surface perpendicular to the direction of slope, examplified by algorithms based on the work of Moore *et al.* (1991) and Zeverbergen and Thorne (1987). However, after several attempts to use these, the author found them to be insufficient for his purposes and it therefore became imperative to develop a different method. This method, although quite simple, is currently (to the best knowledge of the author) not available in any of the existing geographic information systems and has not been previously discussed in the literature. However, the method should be easy to program by those who are interested in using it.

The new approach is a modification of an existing method for calculation of the average percent slope gradient for a center cell within a neighborhood (matrix) the size of which is specified by the user. The existing algorithm calculates the values of the slopes between the center cell and neighborhood cells by taking the absolute value of the difference in elevations between the center cell and other cells in the neighborhood (rise) and dividing it by the horizontal distance between them calculated using the Pythagoranean theorem (run). It then takes the average of the positive fractional value thus obtained and multiplies it by 100 to derive a percent slope gradient value that is assigned to the central cell of the neighborhood. The entire grid is processed in that way by proceeding to the next cell in a row (line) and repeating the same procedure, and then moving to the next row in the elevation grid until the entire grid is processed.

To obtain information as to whether the center cell of a 3- by 3-cell neighborhood is part of a convexity, a concavity, or a flat, the average percent slope gradient algorithm was modified by the author in a simple way. The first step of this modification was to ensure that the calculation of the rise occurs through subtraction of the elevation value of the neighborhood cell from the elevation value of the center cell. The second step was to eliminate the absolute value function from the "rise" calculation, which resulted in either positive, negative, or zero values for the rise and therefore for the slope. Negative rise values indicate that the neighborhood cell lies above the center cell, positive values that the neighborhood cell lies below the center cell, while a zero value indicates equal elevations. Summation and averaging of these values results in a negative, a positive, or a zero value being assigned to the center cell. Positive values mean that the central cell is within a 3- by 3-cell neighborhood that has a predominantly convex shape, while negative values indicate a predominantly concave shape of the surface. Zero values indicate either a flat or an area where convex and concave curvatures cancel each other out, such as a saddlepoint. The method seems to work well in identifying convexities, concavities, and flats.

The method is partially based on the nine basic geometric forms of hillslopes (Chorley *et al.*, 1985) with each form represented using a 3- by 3-cell grid. Figure 1 shows some of the representative combinations of elevation values within the neighborhood. A graph is included with each example to show the relative impact of the positive and negative slopes calculated on the value of the center cell. The *y*-axis shows the elevation differences in the positive or negative directions, while the *x*-axis shows the positive distance from the center cell to any of the neighborhood cells. Because the magnitude of 1 is used for the width and height of the cells, the horizontal distance from the center cell to any of the adjacent cells is either 1 or (using the Pythagoranean theorem) the square root of 2, which is approximately 1.41. A line is extended from the center cell (the origin on the graph) to a point on the graph that represents the location of the neighborhood cell. The slope of the line is the slope gradient between the center and neighborhood cell. Each line is marked with a number ranging from 1 through 8, which represents to which of the neighborhood cells the line connects.

The graph is a visual way of showing how negative or positive slope gradient values within the matrix are used to evaluate whether the center cell lies within a generally convex, concave, or flat neighborhood. The algorithm calculates positive, zero, or negative slopes and then averages the values, assigning the result to the center cell. This is equivalent to adding all the slopes derived from the graph and dividing them by the number of neighbor cells, which in this example is equal to eight. If the elevation differences and slopes shown on the graph are predominantly negative both in magnitude and number, the center cell lies in a neighborhood that is generally concave; if positive, then it lies in a generally convex neighborhood. When the positive and negative elevation differences and slope magnitudes cancel each other out, the area is either flat, or represents equal amounts of convexity and concavity which cancel each other out. An example of the latter, as already mentioned, can be a saddlepoint, or an inflection point where the curvature of the slope changes from concave to convex.

Comparison of the shaded map that resulted from processing of a DEM using this algorithm, with its portrayal of convex, concave, and flat areas, to the contour map and the shape of the contours within any particular neighborhood, indicates that the method is accurate to the degree that the data are accurate. An example is provided in Figure 2, which shows convex, concave, and flat areas with elevation contours overlaid on top for a portion of the USGS 7.5-minute Sagebrush Hill quadrangle in Colorado.

The size of the neighborhood used for the analysis can currently be varied by the user from 3 by 3 cells to 31 by 31 cells. In a USGS 7.5-minute DEM with 30- by 30-m cell size, this means that in the first case positive, negative, and zero slopes are averaged over an area of 90m by 90m, while in the latter case over an area of 930m by 930m. In the first case this means that the longest horizontal distance (run) from the center cell to a neighborhood cell is 42.426 m, while in the latter case it is 636.396 m. The upper limit of 31 by 31 cells is not fixed and represents an arbitrary cutoff point.

For a neighborhood of any size within the current limits, the algorithm calculates slopes by directly evaluating the rise and run from the center cell to each of the neighborhood cells. The longer the run, the smaller the slope gradient value. Therefore, the value assigned to the center cell is a distance weighted average of all the slopes possible within a given neighborhood. For a 31- by 31-cell neighborhood using a 30-m by 30-m DEM, this means that 960 slope calculations are performed for cells as close as 30 m or as far as 636 m away, and the classification of a given cell as convex, concave, or flat is influenced by distant elevation values. This has the effect of generalizing or smoothing of information on trends in curvature of the landscape. For a 31- by 31-cell neighborhood, only if the entire 864,900-m^2 area considered by the algorithm exhibits average positive slopes can the center cell of that area be considered convex. Figure 3 shows the generalized convexities, concavities, and flats for the same area as Figure 2. Instead of highly fragmented mosaic, only the large trends in land curvature, such as ridge formations and valleys, are represented on the map. The flat areas appear mostly at the boundary between the generally convex and concave areas, indicating locations of inflection where the total weight of positive and negative slopes is in balance.

Further Classification of Digital Terrain Data

Additional information about the terrain can be extracted from DEMs using the surface hydrologic terrain analysis capa-

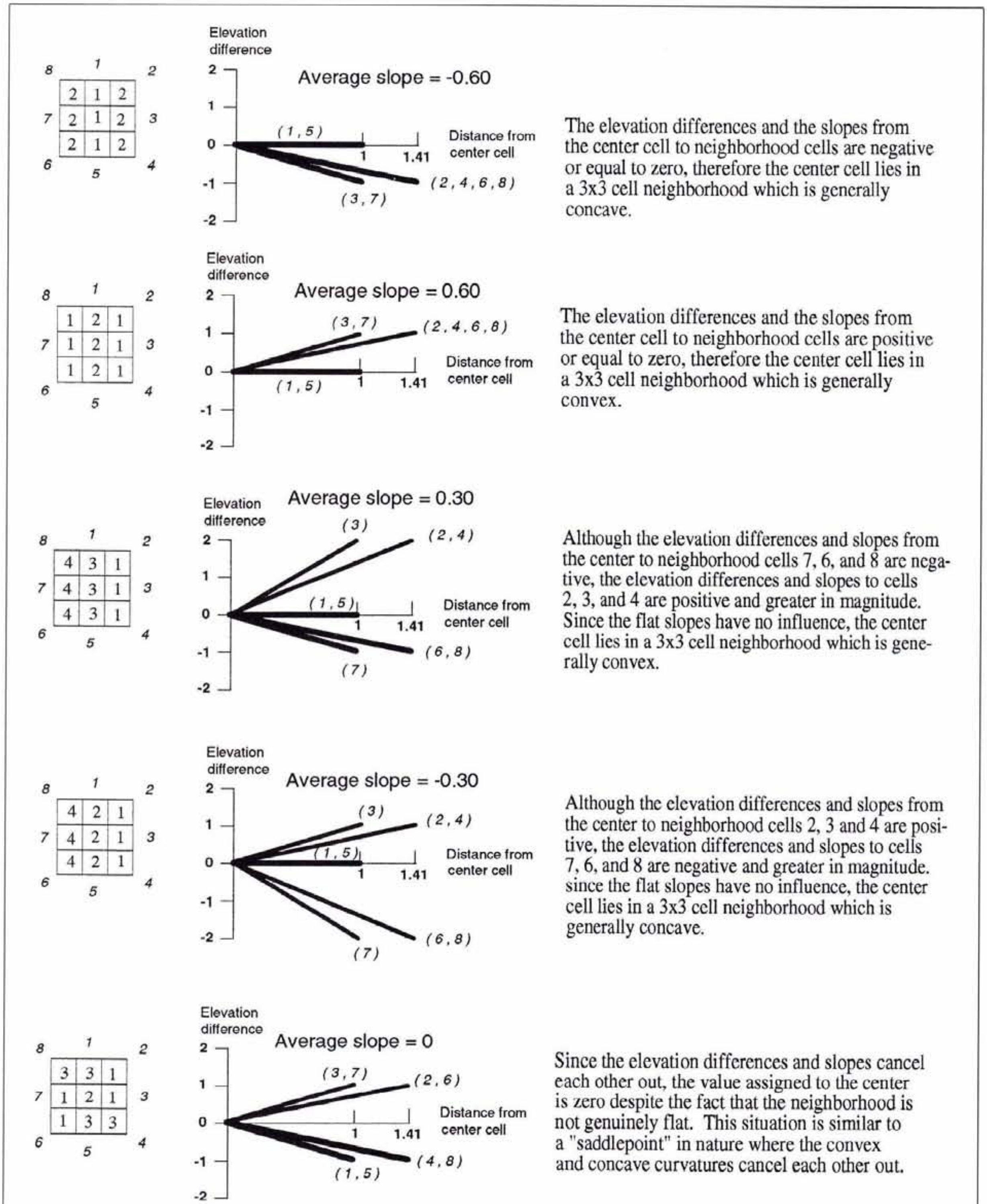


Figure 1. A graph depicting five different combinations of elevation values within a 3- by 3-cell neighborhood and vectors representing negative, positive, and zero value slopes between the center and neighborhood cells.

bilities developed by Jenson and Domingue (1988). The software was originally designed to delineate catchments and flow paths from digital elevation data.

As one of the first steps of processing to delineate catchments (watersheds), Jenson's software provides an algorithm for filling single-celled and multi-celled depressions in digital elevation models. This is important because, to calculate watershed boundaries, it is necessary to route the flow of water across the entire DEM, and therefore across surface depressions. Because most single-celled depressions in DEMs are a product of errors in generation of the models, the multi-celled depressions are of greater interest because they are more likely to represent actually existing enclosed basins on the surface of the Earth.

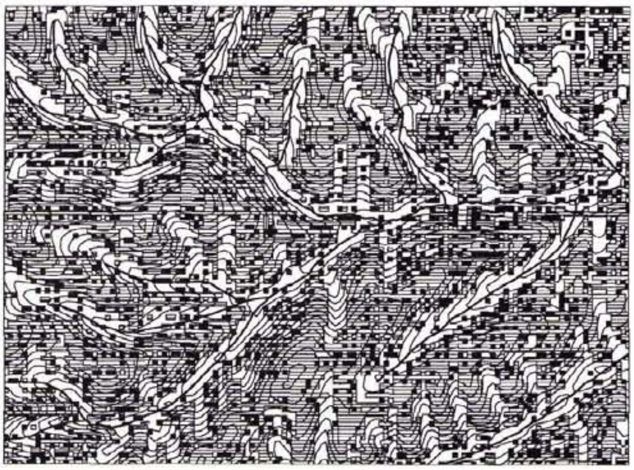


Figure 2. Convex (horizontal lines), concave (unshaded), and flat areas (dark shade) delineated using a 3- by 3-cell matrix for a portion of the USGS 7.5-minute Sagebrush Hill quadrangle in Colorado. Streams and elevation contours are also shown.

The algorithm for filling multi-celled depressions fills them to their pour point. Imagine a tilted bowl that is being filled with water. At some point in time, the water will start flowing out of the bowl at its pour location, which is the lowest point on the edge of the bowl. The area covered by the surface of water in the bowl (basin) as the water begins to flow out is equivalent to the areal extent of the enclosed basin in map view. To obtain a map that shows the areal extent of enclosed basins, it is necessary to subtract the original unfilled DEM from the filled DEM. Because the resultant digital map contains values that represent the depth of each basin, it is also easy to calculate the volume of each basin using standard GIS techniques.

As the next step toward deriving watershed boundaries from digital terrain data, Jenson's software contains algorithms to calculate flow directions from the filled DEM. The flow direction for a cell is the direction water will flow out of the cell along the steepest path. This is encoded in the flow direction map as a value that represents the orientation of flow toward one of the eight cells that surround it. The flow direction algorithm resolves the problem of routing potential water flow through the landscape by providing solutions for four possible conditions that determine flow direction.

The first condition occurs only if the algorithm is used on unfilled DEMs and will not be discussed here. (For a detailed discussion of these methods, see the original paper by Jenson and Domingue (1988) or the HTAS User's Manual, prepared by the author in 1993 and listed in the references.) The second condition occurs when the distance-weighted drop from the central cell is higher for one of the surrounding cells than for the other neighborhood cells. A flow direction value is assigned to the central cell of a 3 by 3 matrix in the direction of the cell where the drop (or the slope gradient) is the steepest.

In the third case, there are two or more cells that have the same steepest drop, and one has to be selected as the direction of flow. This is accomplished using a logical table look-up operation, where, for example, if three adjacent cells have the same steepest drop from the center cell, the middle one of these cells will be chosen for direction of flow. If two cells on opposite sides have an equal drop, then one of them is arbitrarily chosen.

In the fourth condition, the center cell is located in a flat area and all cells are equal (or greater) in elevation. The outflow point is not known. First, to determine flow direction, all of the cells belonging to the first, second, or third condition are resolved. Then, in an iterative process, cells are assigned to flow toward a neighbor if the neighbor has a defined flow direction that does not point back to the tested cell. In this way, the flow direction assignments grow into the flat area from the flat's outflow point until all of the cells have flow directions assigned.

From the flow direction map, it becomes possible to calculate flow accumulation for each cell. The flow accumulation map contains, for each of its cells, an integer value that represents how many other cells are "flowing" into any particular cell along steepest pathways. Because generation of a flow direction map from a filled DEM establishes paths across depressed and flat areas of the landscape, the cells having the flow accumulation value of zero (to which no other cells flow) should correspond to the pattern of crests of ridges. Another way to consider the crests is to realize that the zero flow accumulation areas consist of those cells that represent local elevation maxima (are at the top of a convexity), and where the slope gradient between them is less than the slope gradient between the cells in other portions of a convexity. To put it in yet another way, water is modeled as flowing away from the cells that represent a crest, because, in this definition, the crest is constituted of cells that have less of an elevation difference between themselves than there is between the cells of the crest and of the sideslopes.

How well will this definition hold for modeled landscapes and correspond to real landscapes? The best answer is that the current definition of crests is only adequate. While it applies in most cases, there are situations in which flow will occur along the identified crest. Better methods to deal with this problem will need to be developed in the future; however, the current methods might be adequate for a variety of modeling efforts.

The cells with values greater than zero in the flow accumulation data set made from a filled DEM delineate a fully

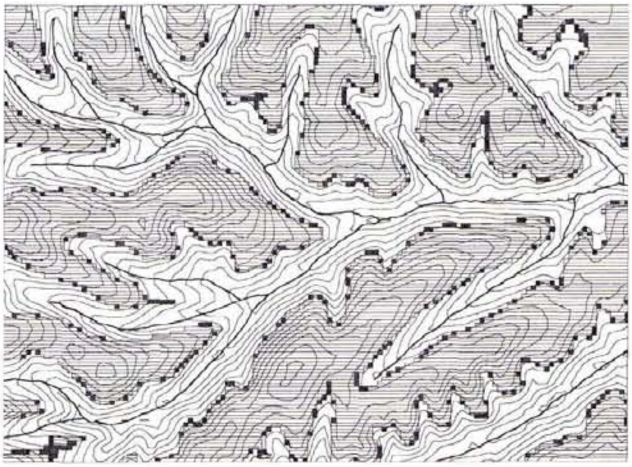


Figure 3. Convex (horizontal lines), concave (unshaded), and flat areas (dark shade) delineated using a 31- by 31-cell matrix for a portion of the USGS 7.5-minute Sagebrush Hill quadrangle in Colorado. Streams and elevation contours are also shown.

connected drainage network. If one selects ranges of flow accumulation values for display, then as the lowest value in this range is decreased, the density of the drainage network displayed will increase. This is because a greater number of smaller flow path tributaries are shown. Because the cells in the flow path are in an ordered relationship to each other, so that, in almost all cases, each consecutive cell has the lowest elevation of all the cells surrounding the previous cell, these flowpaths form a trough of a valley and represent a sequence of lowest points within an open basin.

Within a closed basin (a surface depression), a trough is essentially the point or points with lowest elevations within the basin. Geographic information systems permit analysis of groups of cells and extraction of statistical information about them, such as the minimum and maximum elevation values. Here, the minimum value in a group of cells that represents an enclosed basin is considered to be the trough. Figure 4 shows crests, troughs of open basins, and closed basins for a portion of the USGS 7.5-minute Sagebrush Hill quadrangle in Colorado.

Flats are extracted from the DEM using the curvature analysis method described in the previous section; however, this method does not provide a way to separate sloping from horizontal flats. To do so, it is necessary to apply the unmodified average percent slope gradient algorithm to the DEM, which results in a slope gradient map. Extraction of zero values from this map results in a map of horizontal flats that can then be displayed separately from the other flats, i.e., the ones that have a slope gradient greater than zero and are therefore not horizontal.

Figure 5 shows a simplified three-dimensional view of landform features draped over a portion of the digital elevation model for the USGS 7.5-minute Sagebrush Hill quadrangle in Colorado. Convexities and concavities in this illustration were derived using a 31 by 31 neighborhood.

Potential Enhancements of the Landform Characterization Method

The product of the procedures described in previous sections is either a digital or a hardcopy map that separates the landscape into concave and convex areas, crests and troughs, enclosed basins, sloping flats, and horizontal flats. The digital map of the features explicitly contains information on the shape, and implicitly on the vertical order and magnitude, of the features. Each discrete area has a specific shape in two-dimensional map view and in three dimensions. Vertical order is implicit in the identification of each feature as being a crest, a convexity, a concavity, or a trough. Within any particular local neighborhood, a crest is the highest area on a convexity, a convexity is higher than a concavity, and a trough is the lowest area of a concavity. The data on the magnitude of each feature is implicitly contained in the location of each cell on the map. To obtain actual values, the original DEM has to be available to serve as a reference data layer. The values can either be displayed as contours, or interactively queried within a GIS.

Extraction of discrete entities from a continuous elevation data set opens up possibilities for further statistical analysis of the morphology of individual features in isolation from other features. This can be accomplished by obtaining statistical summaries for each feature or group of cells using various GIS statistical operations. Such summaries can include, for example, the maximum, minimum, and average elevations, slope gradients, or slope aspects for any given area. Other types of summaries are also possible. The statistical data can then be placed as each feature's attribute in an attribute table.

One of the problems that might arise is that a particular feature, such as a ridge, can extend continuously through a large portion of the map to the point where statistical summaries became less meaningful. If that is the case, the map can be edited further. In raster format, it can be combined with an aspect map so as to separate the ridge into slopes facing in opposite directions. In vector format, a feature can be subdivided by placing or removing lines that represent feature boundaries to create new, more specific features. Features can also be aggregated using similar methods.

This type of analysis, while requiring user interaction in the edit stage, could be automated to the point that the statistics for each feature of the final product would be automatically displayed in a table format if the feature was pointed and clicked at with a cursor. Such an automated landform characterization system could become a module within a geographic information system and could include other methods of terrain analysis, e.g., methods for calculation of roughness factors, for fractal analysis, etc.

Once continuous terrain information is classified into discrete entities, it also becomes possible to analyze the variety of these entities using commands such as FOCALVARIETY or ZONALVARIETY available in ARC/INFO software. FOCALVARIETY analyzes the diversity of discrete features using a roving window of size specified by the user. It assigns a value that represents the number of distinct features found within a neighborhood to the center cell, and therefore the values in the resultant map indicate the variety of entities found within a certain distance from any point on the landform map. ZONALVARIETY works in a similar manner, except that it identifies a variety of features for areas defined by the extent of some other environmental parameters, such as soil or vegetation type. FOCALVARIETY can provide a way to compare various terrains by identifying diversity of features found within a neighborhood of certain size. ZONALVARIETY can be of help as a correlation device by providing a method to identify diversity of features found within the boundaries of unique mapping units that represent the spatial extent of some aspect of the environment. Using this command, it might be possible to correlate the diversity of landform features within a particular soil or vegetation type to the diversity found within other soil or vegetation types, or any other discrete areas that represent the extent of some environmental parameter.

Possible Applications of Fractal Analysis with the Landform Methods

The algorithm to determine convex, concave, and flat areas allows for analysis of the influence of elevation values at various distances from the center cell through changing of the size of the neighborhood used for calculations. Furthermore, ARC/INFO software permits various shapes of neighborhoods, including a wedge shaped windows oriented in directions specified by the user, and neighborhoods where each of the neighbor cells can be assigned some weighted factor value. These capabilities permit a variety of approaches to generalization, and therefore to analysis of the relationships between topographic trends and the shape of the fourth-order-of-relief features.

The following discussion concerns possible benefits that might be derived from analysis of terrain using a change in the size of a square neighborhood surrounding the center cell. A simple increase in the size of the window results in a decrease in fragmentation of the features and in the sinuosity of the boundaries of the features. Potentially in some landscapes this decrease is gradual, while in others there can be a sudden lessening in fragmentation and sinuosity at some threshold window size. The various patterns of these changes occur in dependence on the trends in shape of the terrain, and are presumably different for different landscapes.

One way to quantify the degree of fragmentation and

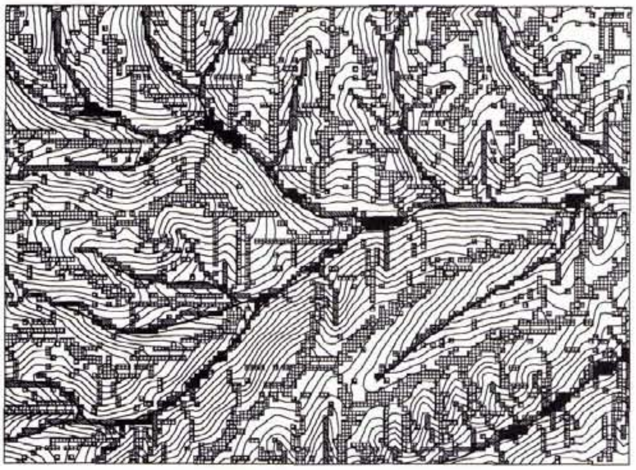


Figure 4. Crests of convexities (crosshatch), troughs (diagonal lines), and enclosed basins (dark shade) delineated for a portion of the USGS 7.5-minute Sagebrush Hill quadrangle in Colorado. Streams and elevation contours are also shown.

sinuosity for each window size would be to measure their fractal dimension. If the fractal dimensions show a clear and narrow range of values for each neighborhood size for a particular type of terrain, these values can be plotted against the window size. Such a graph could potentially reflect a unique "signature" for the particular landscape studied. The "signature" would be an expression of the influence of the shape of the landscape at various distances from the center cell on the landform feature fragmentation and shape. Figure 6 shows the changes in fragmentation of the features and sinuosity of the boundaries with changing window size for a portion of the USGS 7.5-minute Sagebrush Hill quadrangle in Colorado.

The next step would be to compare different types of landscapes to see if their "signatures" are adequately different and distinct to be of use in classifying terrains into similar groups. If such a pattern does exist, landform methods combined with fractal analysis can potentially be used to develop an index for various types of landscapes based on their morphology. From this information conclusions could potentially be drawn with respect to the nature and the geographical extent of morphic patterns for different terrains and the processes that have shaped them. Additionally, such an approach can provide a way to classify large areas into more general categories of similar terrains than is possible with the current methods.

Environmental and Resource Analysis Applications

The landform characterization methodology described in this paper is essentially a morphometric technique which permits objective classification of any digital surface. It allows for quick analysis of elevation data for vast tracks of land, eliminating the painstaking process of manual analysis of contoured representation of surfaces. In manual approaches the difficulties involved in contour interpretation introduce a level of subjective judgement that makes a precise comparison of various types of terrain from different locations difficult to accomplish. Because with automated methods terrain data are always analyzed in precisely the same way, the only source of error in such comparative studies arises from the difference in quality of digital elevation data from area to area.

A clear use of landform characterization methods is therefore a mapping tool which provides another way of representing terrain information that is complementary to con-

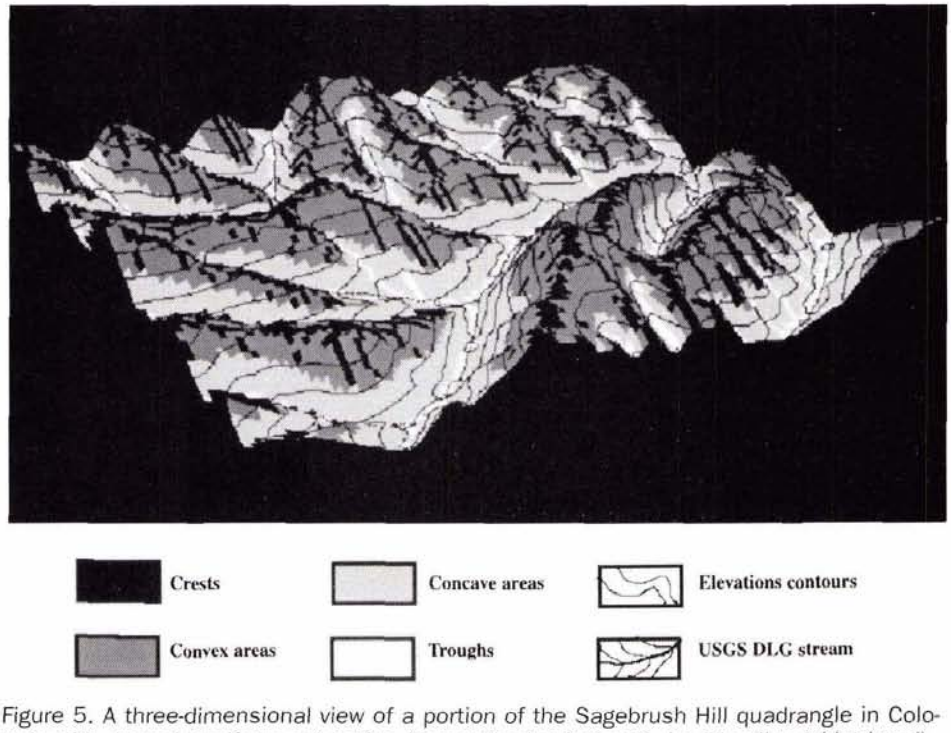
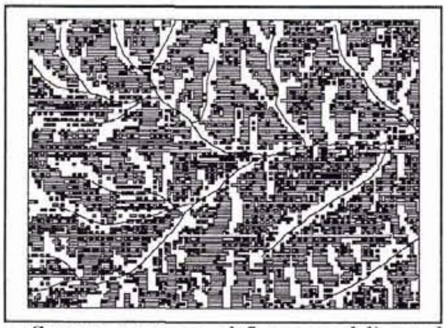
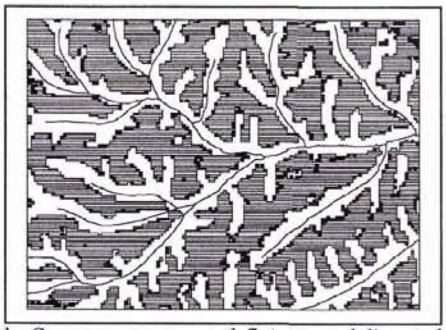


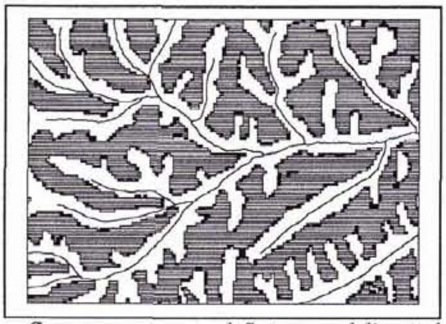
Figure 5. A three-dimensional view of a portion of the Sagebrush Hill quadrangle in Colorado with draped landform categories (generalized using a 31- by 31-cell neighborhood). Streams and elevation contours are also shown.



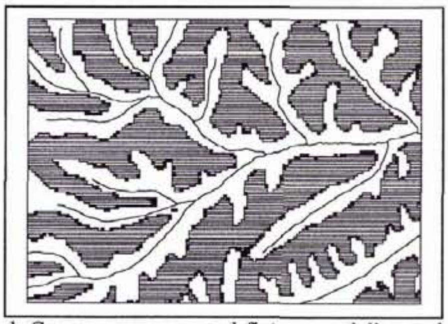
a. Convex, concave, and flat areas delineated using a 3x3 cell neighborhood.



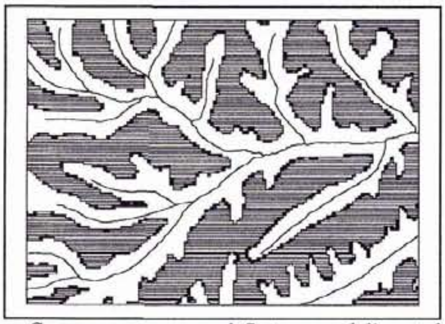
b. Convex, concave, and flat areas delineated using a 7x7 cell neighborhood.



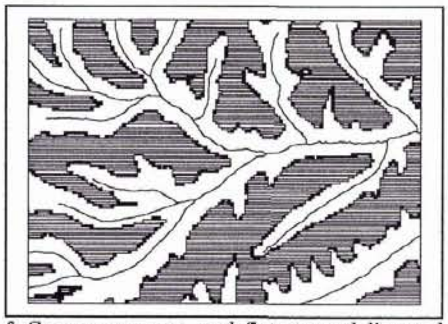
c. Convex, concave, and flat areas delineated using a 11x11 cell neighborhood.



d. Convex, concave, and flat areas delineated using a 19x19 cell neighborhood.



e. Convex, concave, and flat areas delineated using a 25x25 cell neighborhood.



f. Convex, concave, and flat areas delineated using a 31x31 cell neighborhood.

Figure 6. The effects of increasing the neighborhood size on fragmentation of features and sinuosity of boundaries delineated for a portion of the USGS 7.5-minute Sagebrush Hill quadrangle in Colorado.

touring. Because the tool classifies the continuous landscape surface into meaningful fourth-order-of-relief categories represented by areas with discrete boundaries, the resultant map permits aggregation of landform features into distinct geomorphological units. Each such unit can be developed to represent a unique set of geomorphic controls on the ecosystem processes in the landscape. Furthermore, similar units can be grouped together according to type so that large areas of land are represented by several distinct groups of units. Potentially, the results of intensive data collection, analysis, and modeling of the influence of geomorphic controls on environmental processes and patterns performed in representative units could be extrapolated to other units within the same group. This could lead to improved understanding of the influence of terrain characteristics on ecosystem processes for large regions and for a variety of environments.

The classification of continuous terrain surface into discrete and meaningful categories can also be of aid in mathematical analyses of terrain content and pattern of areas identified according to taxonomic schemes based on other aspects of the environment. For example, statistical summaries of landform feature content within a soil and vegetation unit, and comparison of the summaries between the units, may yield clear differences in feature distributions between this or that soil or vegetation type. Such methods can be easily automated and can permit statistical correlation between terrain morphology and other environmental parameters. Beyond that, fractal analysis of the shape of landform feature boundaries can provide additional data for this type of correlation.

The techniques for analysis of feature content and pattern can also be applied to digital elevation data for the same areas but at various resolutions and levels of detail. Comparison of the loss or increase in feature content and the difference or similarity in patterns with change in resolution could potentially lead to developing a better understanding of scaling relationships in terrain data, and in identifying the level of self-similarity for data at various scales. This approach could also be of benefit in quantifying sub-pixel microrelief for various types of landscapes.

Because the methods proposed here can provide an accurate description of the morphology of a three-dimensional feature, they can potentially be used to model processes that generated a particular feature. An example of such an approach can be provided in the context of the equilibrium theory of coastal landforms. From Tanner (1974), "the equilibrium idea is that an energetic wave system will establish in due time and barring too many complications, a delicately adjusted balance among activity, three-dimensional geometry, and sediment transport such that the system will tend to correct short or minor interference." To put it in another way, the energy input from waves results in sediment transport processes which cause morphological change. That change will continue indefinitely unless a landform is produced in which the energy is dissipated without any net sediment transport. Should the equilibrium concept be accurate and applicable to a variety of coastal landforms, the landform analysis methods proposed here can provide quantitative information on the three-dimensional geometry aspect of the equilibrium landform, potentially leading to development of models that account for sediment transport processes that determine its morphology in terms of the local wave energy regimes.

Correlation and interpretation of terrain characteristics with other data can permit detailed analysis of the interaction of landscape morphology with other aspects of the landscape. Interpretation of geologic and soil data in combination with landform data can aid in understanding of the provenance of landforms and provide a more complete picture of the geomorphology of an area. Landform maps can also provide one of the constituent data layers for soil survey enhancement and premapping prior to *in situ* soil survey efforts. Correlation and interpretation of landform data with vegetation, soil, climate, and geology data can lead to better understanding of the influence of terrain characteristics on vegetation distribution patterns in landscape ecological studies. Landform patterns can be useful in generating hydrologic response unit (HRU) maps important in various hydrologic models. The shape of terrain is also of relevance for habitat studies. Similar approaches can be utilized in studies of submarine geomorphology and distribution patterns of benthic communities, provided that the different nature of underwater sedimentation and biological dispersion processes is accounted for.

Summary

In general, the landform characterization methodology proposed here can serve as a useful mapping and analysis tool for a variety of resource and environmental studies performed on local or regional scales. The ability to classify the continuous terrain surface into meaningful and discrete features provides a way to describe, analyze, and quantify the characteristics of landscape morphology so that they can be logically related to other aspects of ecosystems. As such, it can be useful in any analysis and modeling efforts that consider the influence of terrain characteristics on landscape processes and patterns.

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