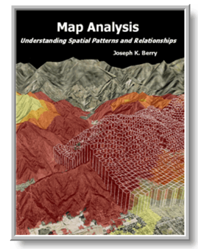
Beyond Mapping III

Topic 11: Characterizing Micro-Terrain Features



Map Analysis book with companion CD-ROM for hands-on exercises and further reading

Note: The processing and figures discussed in this topic were derived using MapCalc™ software. See www.innovativegis.com to download a free MapCalc Learner version with tutorial materials for classroom and self-learning map analysis concepts and procedures.

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Use Data to Characterize Micro-Terrain Features

(GeoWorld January, 2000; "" pg. 22)

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The past several columns investigated surface modeling and analysis. The data surfaces derived in these instances weren't the familiar terrain surfaces you walk the dog, bike and hike on. None-the-less they form surfaces that contain all of the recognizable gullies, hummocks, peaks and depressions we see on most hillsides. The "wrinkled-carpet" look in the real world is directly transferable to the cognitive realm of the data world.

However, at least for the moment, let's return to terra firma to investigate how micro-terrain features can be characterized. As you look at a landscape you easily see the changes in terrain with some areas bumped up (termed convex) and others pushed down (termed concave). But how can a computer "see" the same thing? Since its world is digital, how can the lay of the landscape be transferred into a set of drab numbers?

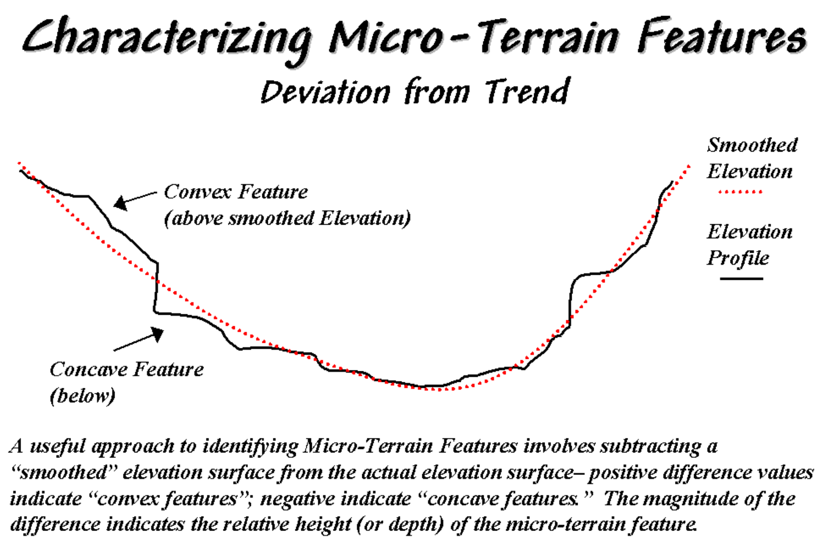

Figure 31-1. Identifying Convex and Concave features by deviation from the trend of the terrain.

One of the most frequently used procedures involves comparing the trend of the surface to the actual elevation values. Figure 31-1 shows a terrain profile extending across a small gully. The dotted line identifies a smoothed curve fitted to the data, similar to a draftsman's alignment of a French curve. It "splits-the-difference" in the succession of elevation values—half above and half below. Locations above the trend line identify convex features while locations below identify the concave ones. The further above or below determines how pronounced the feature is.

In a GIS, simple smoothing of the actual elevation values derives the trend of the surface. The left side of fig. 31-2 shows the actual and smoothed surfaces for a project area. The flat portion at the extreme left is an area of open water. The terrain rises sharply from 500 feet to 2500 feet at the top of the hill. Note the small "saddle" (elevation dips down then up) between the two hilltops. Also note the small depression in the relatively flat area in the foreground (SW) portion.

In generating the smoothed surface, elevation values were averaged for a 4-by-4 window moved throughout the area. Note the subtle differences between the surfaces—the tendency to pull-down the hilltops and push-up the gullies.

While you see (imagine?) these differences in the surfaces, the computer quantifies them by subtracting. The difference surface on the right contains values from -84 (prominent concave feature) to +94 (prominent convex feature). The big bump on the difference surface corresponds to the smaller hilltop on elevation surface. Its actual elevation is 2016 while the smoothed elevation is 1922 resulting in 2016 - 1922 = +94 difference. In micro-terrain terms, these areas are likely drier than their surroundings as water flows away.

The other arrows on the surface indicate other interesting locations. The "pockmark" in the foreground is a small depression (764 - 796 = -32 difference) that is likely wetter as water flows into it. The "deep cut" at the opposite end of the difference surface (539 - 623 = -84) suggests a prominent concavity. However representing the water body as fixed elevation isn't a true account of terra firma configuration and misrepresents the true micro-terrain pattern.

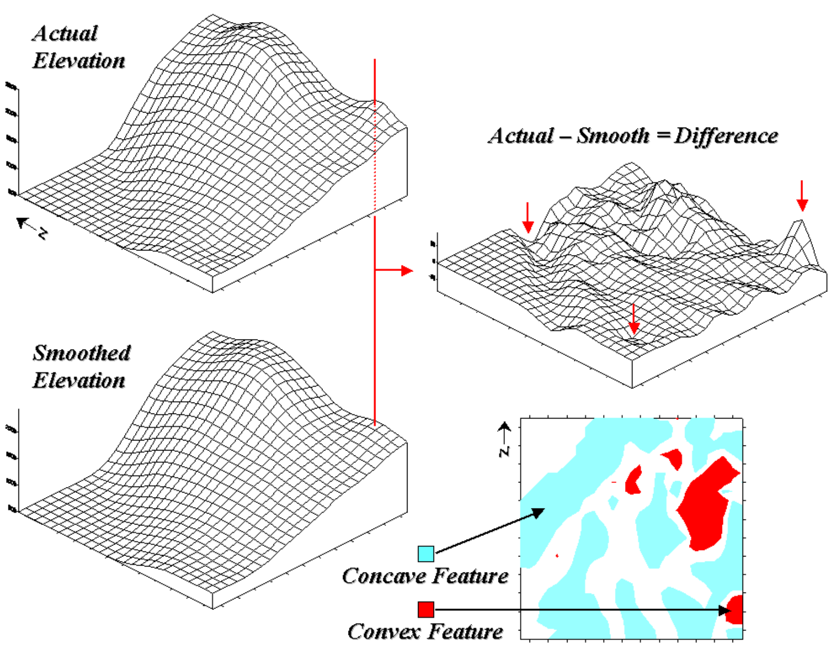

Figure 31-2. Example of a micro-terrain deviation surface.

In fact the entire concave feature in the upper left portion of 2-D representation of the difference surface is suspect due to its treatment of the water body as a constant elevation value. While a fixed value for water on a topographic map works in traditional mapping contexts it's insufficient in most analytical applications. Advanced GIS systems treat open water as "null" elevations (unknown) and "mirror" terrain conditions along these artificial edges to better represent the configuration of solid ground.

The 2-D map of differences identifies areas that are concave (dark red), convex (light blue) and transition (white portion having only -20 to +20 feet difference between actual and smoothed elevation values). If it were a map of a farmer's field, the groupings would likely match a lot of the farmer's recollection of crop production—more water in the concave areas, less in the convex areas.

A Colorado dryland wheat farmer knows that some of the best yields are in the lowlands while the uplands tend to "burn-out." A farmer in Louisiana, on the other hand, likely see things reversed with good yields on the uplands while the lowlands often "flood-out." In either case, it might make sense to change the seeding rate, hybrid type, and/or fertilization levels within areas of differing micro-terrain conditions.

The idea of variable rate response to spatial conditions has been around for thousands of years as indigenous peoples adjusted the spacing of holes they poked in the ground to drop in a seed and a piece of fish. While the mechanical and green revolutions enable farmers to cultivate much larger areas they do so in part by applying broad generalizations of micro-terrain and other spatial variables over large areas. The ability to continuously adjust management actions to unique spatial conditions on expansive tracks of land foretells the next revolution.

Investigate the effects of micro-terrain conditions goes well beyond the farm. For example, the Universal Soil Loss Equation uses "average" conditions, such as stream channel length and slope, dominant soil types and existing land use classes, to predict water runoff and sediment transport from entire watersheds. These non-spatial models are routinely used to determine the feasibility of spatial activities, such as logging, mining, road building and housing development. While the procedures might be applicable to typical conditions, they less accurately track unusual conditions clumped throughout an area and provide no spatial guidance within the boundaries of the modeled area.

GIS-based micro-terrain analysis can help us be more like a "modern ancient farmer"—responding to site-specific conditions over large expanses of the landscape. Calculation of a difference surface simply scratches the surface of micro-terrain analysis. In the next few columns we'll look other procedures that let us think like a raindrop while mapping the micro-terrain.

Characterizing Localized Terrain Conditions

(GeoWorld, February 2000, pg. 26)

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Last month's column described a technique for characterizing micro-terrain features involving the difference between the actual elevation values and those on a smoothed elevation surface (trend). Positive values on the difference map indicate areas that "bump-up" while negative values indicate areas that "dip-down" from the general trend in the data.

A related technique to identify the bumps and dips of the terrain involves moving a "roving window" (termed a spatial filter) throughout an elevation surface. The profile of a gully can have micro-features that dip below its surroundings (termed concave) as shown on the right side of figure 31-3.

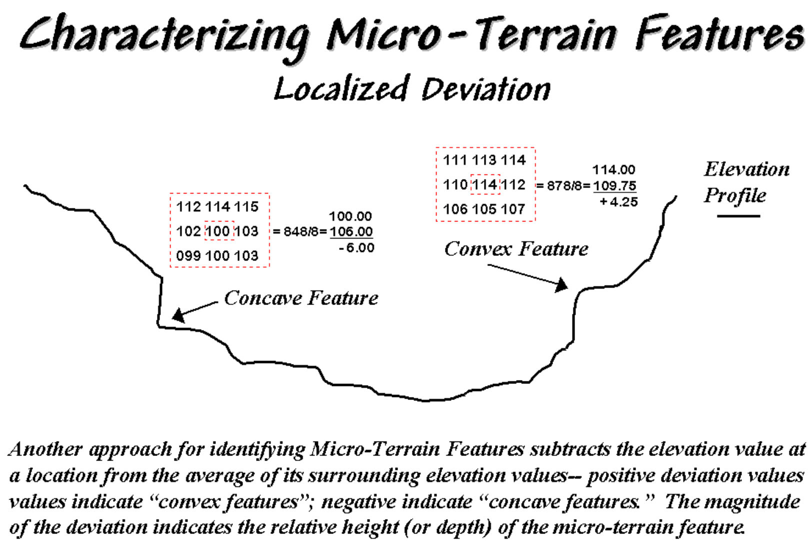

Figure 31-3. Localized deviation uses a spatial filter to compare a location to its surroundings.

The localized deviation within a roving window is calculated by subtracting the average of the surrounding elevations from the center location's elevation. As depicted in the example calculations for the concave feature, the average elevation of the surroundings is 106, that computes to a -6.00 deviation when subtracted from the center's value of 100. The negative sign denotes a concavity while the magnitude of 6 indicates it's fairly significant dip (a 6/100= .06). The protrusion above its surroundings (termed a convex feature) shown on the right of the figure has a localized deviation of +4.25 indicating a somewhat pronounced bump (4.25/114= .04).

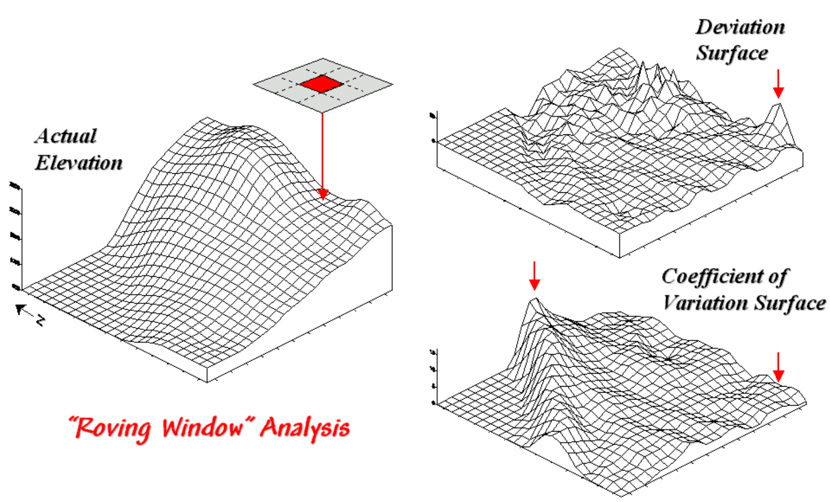

Figure 31-4. Applying Deviation and Coefficient of Variation filters to an elevation surface.

The result of moving a deviation filter throughout an elevation surface is shown in the top right inset in figure 31-4. Its effect is nearly identical to the trend analysis described last month--comparison of each location's actual elevation to the typical elevation (trend) in its vicinity. Interpretation of a Deviation Surface is the same as that for the difference surface discussed last month—protrusions (large positive values) locate drier convex areas; depressions (large negative values) locate wetter concave areas.

The implication of the "Localized Deviation" approach goes far beyond simply an alternative procedure for calculating terrain irregularities. The use of "roving windows" provides a host of new metrics and map surfaces for assessing micro-terrain characteristics. For example, consider the Coefficient of Variation (Coffvar) Surface shown in the bottom-right portion of figure 31-4. In this instance, the standard deviation of the window is compared to its average elevation—small "coffvar" values indicate areas with minimal differences in elevation; large values indicate areas with lots of different elevations. The large ridge in the coffvar surface in the figure occurs along the shoreline of a lake. Note that the ridge is largest for the steeply-rising terrain with big changes in elevation. The other bumps of surface variability noted in the figure indicate areas of less terrain variation.

While a statistical summary of elevation values is useful as a general indicator of surface variation or "roughness," it doesn't consider the pattern of the differences. A checkerboard pattern of alternating higher and lower values (very rough) cannot be distinguished from one in which all of the higher values are in one portion of the window and lower values in another.

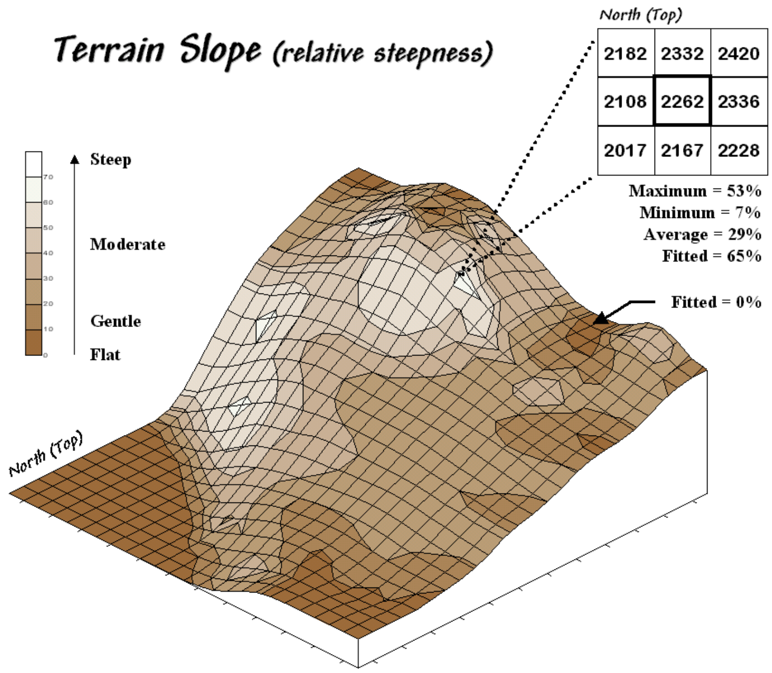

Figure 31-5. Calculation of slope considers the arrangement and magnitude of elevation differences within a roving window.

There are several roving window operations that track the spatial arrangement of the elevation values as well as aggregate statistics. A frequently used one is terrain slope that calculates the "slant" of a surface. In mathematical terms, slope equals the difference in elevation (termed the "rise") divided by the horizontal distance (termed the "run").

As shown in figure 31-5, there are eight surrounding elevation values in a 3x3 roving window. An individual slope from the center cell can be calculated for each one. For example, the percent slope to the north (top of the window) is ((2332 - 2262) / 328) * 100 = 21.3%. The numerator computes the rise while the denominator of 328 feet is the distance between the centers of the two cells. The calculations for the northeast slope is ((2420 - 2262) / 464) * 100 = 34.1%, where the run is increased to account for the diagonal distance (328 * 1.414 = 464).

The eight slope values can be used to identify the Maximum, the Minimum and the Average slope as reported in the figure. Note that the large difference between the maximum and minimum slope (53 - 7 = 46) suggests that the overall slope is fairly variable. Also note that the sign of the slope value indicates the direction of surface flow—positive slopes indicate flows into the center cell while negative ones indicate flows out. While the flow into the center cell depends on the uphill conditions (we'll worry about that in a subsequent column), the flow away from the cell will take the steepest downhill slope (southwest flow in the example… you do the math).

In practice, the Average slope can be misleading. It is supposed to indicate the overall slope within the window but fails to account for the spatial arrangement of the slope values. An alternative technique fits a “plane” to the nine individual elevation values. The procedure determines the best fitting plane by minimizing the deviations from the plane to the elevation values. In the example, the Fitted slope is 65%… more than the maximum individual slope.

At first this might seem a bit fishy—overall slope more than the maximum slope—but believe me, determination of fitted slope is a different kettle of fish than simply scrutinizing the individual slopes. Next time we'll look a bit deeper into this fitted slope thing and its applications in micro-terrain analysis.

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Author's Note: An Excel worksheet investigating Maximum, Minimum, and Average slope calculations is available online at the "Column Supplements" page at http://www.innovativegis.com/basis.

The Long and Short of Slope

(GeoWorld, July 2007, pg. 18-19)

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Recall from the past sections dealing with slope calculation that the nine elevation values in a 3x3 window are generally used. There are two basic approaches for characterizing relative steepness—surface fitting and individual slope statistics.

Surface fitting aligns a plane to the elevation values that minimizes the deviations from the plane to the values. If all of the values are the same, a horizontal plane is fitted and the slope is zero.

However as the values on one side of the window increase and the values on the other decrease, the fitted plane tilts indicating increasing terrain steepness.

The surface fitting algorithm first establishes the 3x3 window, then identifies the nine elevation values, fits the plane and records the slope for the center cell in the window. The "roving window" shifts to the next adjacent location and repeats the process until all of the cells in a project area have been evaluated.

The algorithm for summarizing individual slopes also utilizes a 3x3 window, but instead of fitting a plane it calculates the slopes formed by the center location and each of its eight neighbors. The minimum, maximum or average of the individual slope values is recorded for the center cell and the window advanced.

Both slope techniques result in a continuous map surface indicating the relative steepness throughout a project area. Sometimes, however, slope along a linear feature, such as a pipeline, is sought (figure 1). In this case, only three cells are involved—the center cell and its input and output neighbors at each location along the pipeline.

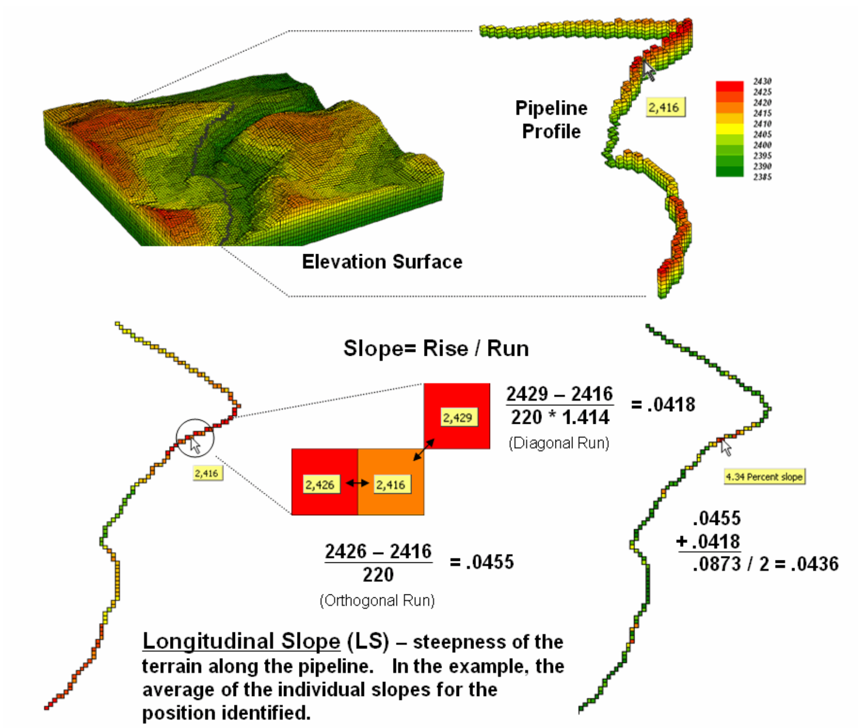

Figure 1. Longitudinal slope calculates the steepness along a linear feature, such as a pipeline.

Longitudinal Slope (LS) requires isolating just the route's elevation values. In grid-based modeling this means first creating a "masking map" of the route where the cells defining the pipeline are assigned the value 1 and the non-pipeline cells are assigned a special value of Null (or No Data). This map is multiplied by the elevation surface having the effect of retaining the elevation values along the route but all other locations are assigned Null.

Most map analysis packages have been "trained" to recognize a Null value and simply skip over these locations when processing. The effect in this case is to calculate slope using just the three aligned elevation values in the 3x3 roving window—either fitted or maximum/minimum/average.

A simple extension to the algorithm, *Directional Slope (DS)*, enables a user to enter a starting location and the direction of flow, and then it calculates individual slopes for each step along the route using just the input and center cell. This technique characterizes where gravity is helping or hindering flow and is useful in determining draw-down if the pipe is ruptured.

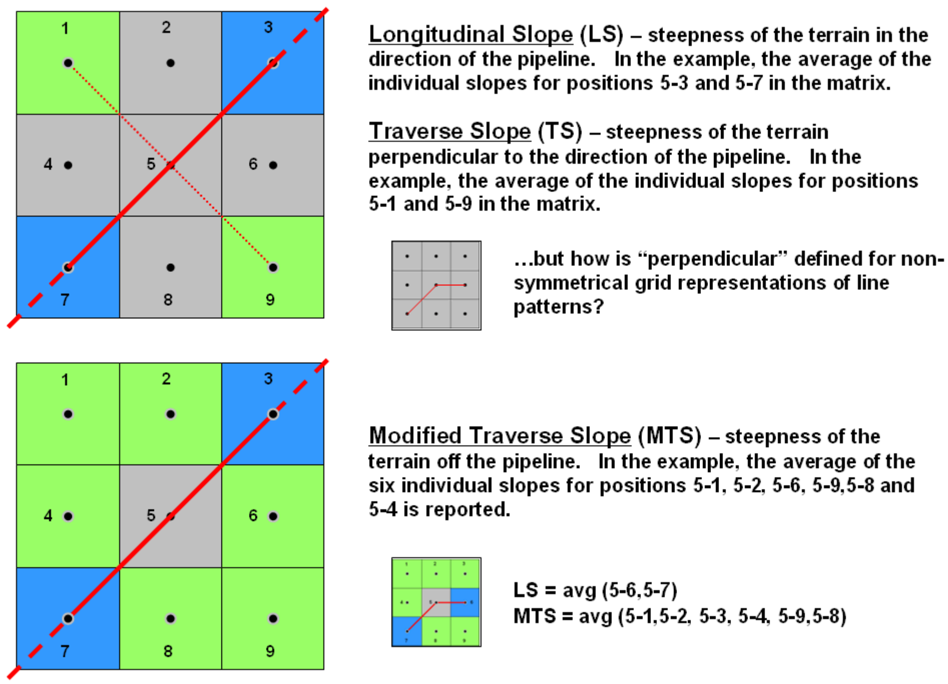

Figure 2. Modified transverse slope is calculated as the average of off-route slopes surrounding a location.

A more radical extension considers the off-route cells in calculating *Transverse Slope (TS)*. Traditionally, transverse slope was manually calculated by estimating the slope of a line perpendicular to the route. For example in the upper portion of figure 2, the slopes from the center cell (5) to the NE (5-3) and SW (5-7) cells identify the longitudinal slope along the route while the slopes to the NW (5-11) and SE (5-9) cells indicate the transverse slope.

The perpendicular approach works for any orthogonal and diagonal transect of the window. The elevation grid, however, can take an oblique bend involving diagonal and orthogonal directions as shown and there isn't a true perpendicular. In this instance, GIS-derived transverse slope requires a new definition.

Modified Transverse Slope (MTS) calculates slope for the off-route cells, regardless of the linear shape. In the lower-left portion of figure 2 all of green cells (1, 2, 4, 6, 8 and 9) are considered in calculating terrain steepness surrounding the pipeline. Ideally, routes with fairly gentle modified transverse slopes are preferred as subsidence risks are lower.

These fairly innocuous extensions for calculating slope point to a bigger issue in map analysis—mainly that our grid-based analytical toolbox and GIS modeling expressions are a long way from complete. Most of the development occurred in the 1970s and 80s and coding of new capabilities in flagship systems have languished. As a result, solution providers are encoding specialized tools for their clients and running them outside the GIS or hooking them in as objects or add-ins.

What I find interesting is that this is where GIS was in the 1970s and early 80s—a collection of disparate proprietary systems. With all that you hear about data standards, open systems and GIS community access it's peculiar that map analysis seems to be moving in the opposite direction.

Generating Mountains and Molehills from Field Sampled Data

(GeoWorld, August 2013)

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Geotechnology has revolutionized the dogma, development and dissemination of spatial information—duh. Today's youth is growing up in an increasingly cyber-based society with instantaneous connection to the world about them, and like Peter Pan they can be whisked-away by Google Earth to distant lands in the blink of an eye.

But what if they are interested in detail beyond the maximum level of the zoom slider bar? Or they want to simulate localized surface flow paths, convergence and path density? Or identify subtle hummocks and depressions? Or model subsurface moisture regimes? Or relate any of these characteristics to the spatial relationships with vegetative patterns?

That's the dilemma of many aspiring scientists who want to go beyond simply visualizing a landscape to investigating system interactions that are spatially driven. But their data analysis quiver is primarily full of non-spatial analytic tools that rely on assessing and comparing the central tendencies of field collected data without consideration of the spatial distributions inherent in the data.

Two major obstacles stand in their way— appropriate spatial data and spatially aware analysis tools. Most readily downloadable data is too course for detailed scientific study, and even if it were available, most potential users are unacquainted with the quantitative analysis procedures involved.

Let's consider the data limitation hurdle first and then see how its practical solution can spark spatial reasoning among non-GIS'ers. Suppose a budding grad student wants to develop a micro-terrain surface for a project area. Unless there is a Lidar over flight or total station survey of the area available, they will need to construct a detailed elevation surface from scratch.

First impulse is to use an inexpensive GPS unit (or Google's GPS Surveyor app for Smartphones) to capture XYZ measurements throughout a project area. But alas, it is soon discovered that precision of the coordinates is insufficient for detailed mapping. The vertical precision in a GPS unit is characteristically less than half of that of the horizontal precision which in itself is plus or minus several meters—hardly the precision required for surface modeling.

Another possibility is to acquire sophisticated surveying equipment (transit, theodolite, laser rangefinder or GPS total station), but their costs are far too high both in terms of a tight budget and a demanding learning curve. A Dumpy level, tripod, graduated staff and a couple of meter tapes form a far more practical option (they are likely buried in an old storeroom on campus).

Dumpy levels work by precisely measuring vertical distances in a horizontal plane about a base location (figure 1). A bubble level is used to establish a horizontal plane in each quarter-circle to make sure it is level throughout the entire 360 degree swing of the instrument. An operator looks through the eyepiece of the telescope, while an assistant slowly rocks a graduated staff at a sample location and the maximum reading on the staff is recorded. Subtracting the Staff Reading from the Base Height determines the relative elevation of any measured point to a fraction of centimeter.

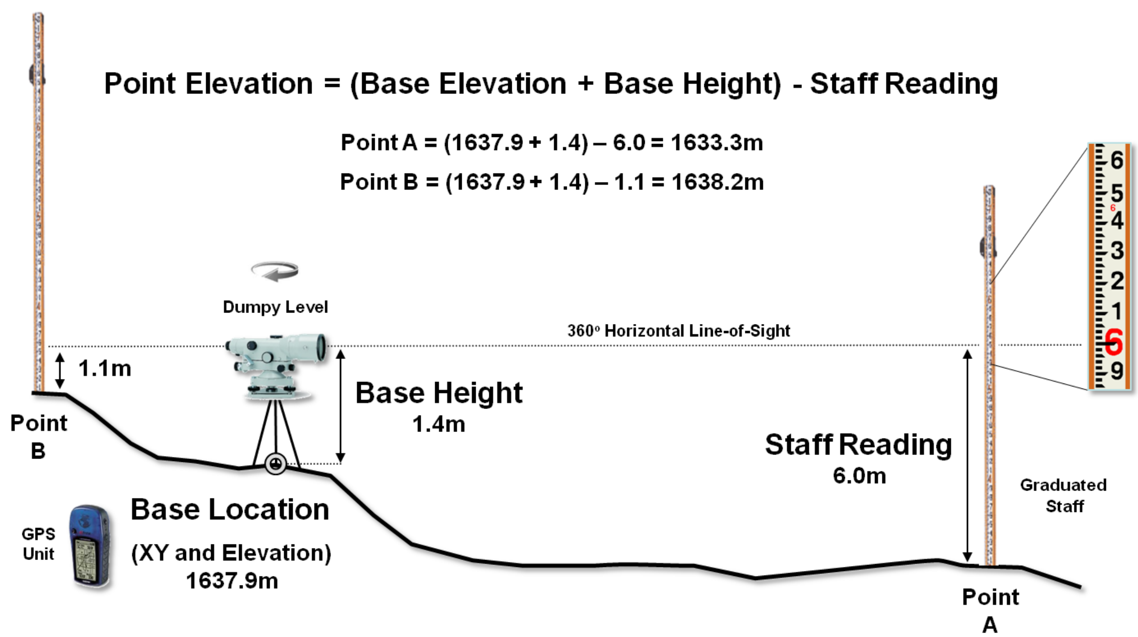
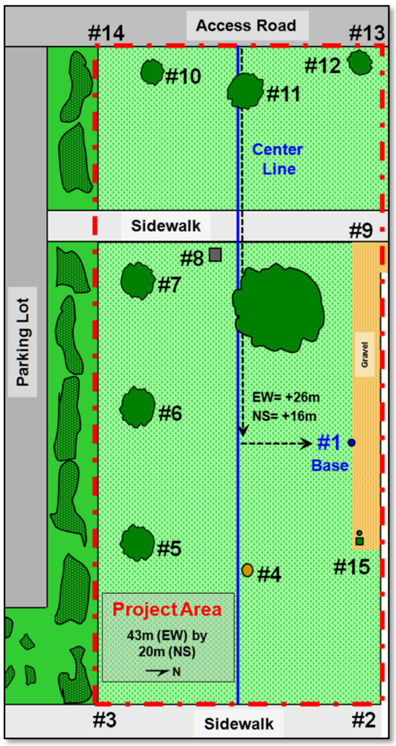


Figure 1. A Dumpy level establishes a horizontal plane to measure the relative elevation differences throughout a project area.

To establish real-world positioning, an inexpensive GPS unit can be used. The average of several readings taken throughout the day provides a “reasonable estimate” of the Base Location’s earth position (top-right portion of figure 2).

Sketch Map



Base Station Setup

A	B	C	
Base Station Setup			
#1	**Elevation Reading**	**Longitude (X)**	**Latitude (Y)**
	1639.00	104.963161	39.674158
	1637.00	104.963159	39.674159
	1638.00	104.963163	39.674158
	1636.00	104.963161	39.674160
	1639.00	104.963160	39.674157
	1640.00	104.963162	39.674159
	1636.00	104.963160	39.674157
Average-->	**1637.86**	**104.963161**	**39.674158**

Real-world coordinates for the base station is established using an inexpensive GPS unit. Several readings are made by walking away from the location, returning and noting the longitude, latitude and elevation readings (XYZ). The averages of the readings form a “reasonable estimate” of the base station’s earth position.

Measuring Sample Points

A	B	C	D	E	
Measuring Sample Points					
Sample #	**Description**	**Staff Reading**	**Elevation**	**Relative X Position**	**Relative Y Position**
#1	Base	-------	1637.9	26.0	17.0
2	NE Corner	0.2	1637.7	43.0	20.0
3	SE Corner	0.5	1637.4	43.0	0.0
4	Stump	0.7	1637.2	32.5	10.5
5	Small Tree	4.7	1633.2	31.0	5.0
6	Small Tree	5.6	1632.3	24.0	5.0
7	SmallTree	5.7	1632.2	15.5	5.0
8	Lamp Post	7.9	1630.0	13.0	12.5
9	Sidewalk	10.9	1627.0	12.0	20.0
10	Small Tree	6.9	1631.0	4.0	6.0
11	Small Tree	7.2	1630.7	6.0	11.5
12	Small Tree	7.1	1630.8	3.5	19.0
13	NW Corner	7.0	1630.9	0.0	20.0
14	SWCorner	6.8	1631.1	0.0	0.0
15	Building SW	10.2	1627.7	14.5	20.0

Locations of other points in a project area are measured relative to the base station’s location within a working coordinate system. Differential vertical values are read from the graduated staff and differential horizontal values are read as perpendicular deflections from the center line.

Figure 2. The XYZ coordinates of sample points are easily derived from field data.

Before the staff is moved to another location, the distance along a center line is measured (EW as the X axis in the example) and the perpendicular deflection to the point is measured (NS as the Y axis). The result is a record of relative horizontal location and elevation difference that is easily evaluated for XYZ coordinates within a working coordinate system (bottom-right portion of figure 2) or relative to the base station’s Lat/Lon real-world coordinates.

The final step involves surface modeling software to complete the 3-dimentional surface by “spatially interpolating” the elevation values for all of the grid cells within the project area. Figure 3 shows the result using the powerful yet inexpensive Surfer software package (by Golden Software). The derived terrain surface can be exported to ArcGIS, MapCalc or other map analysis package, as well as to Google Earth as contour lines or a color-shaded raster image.

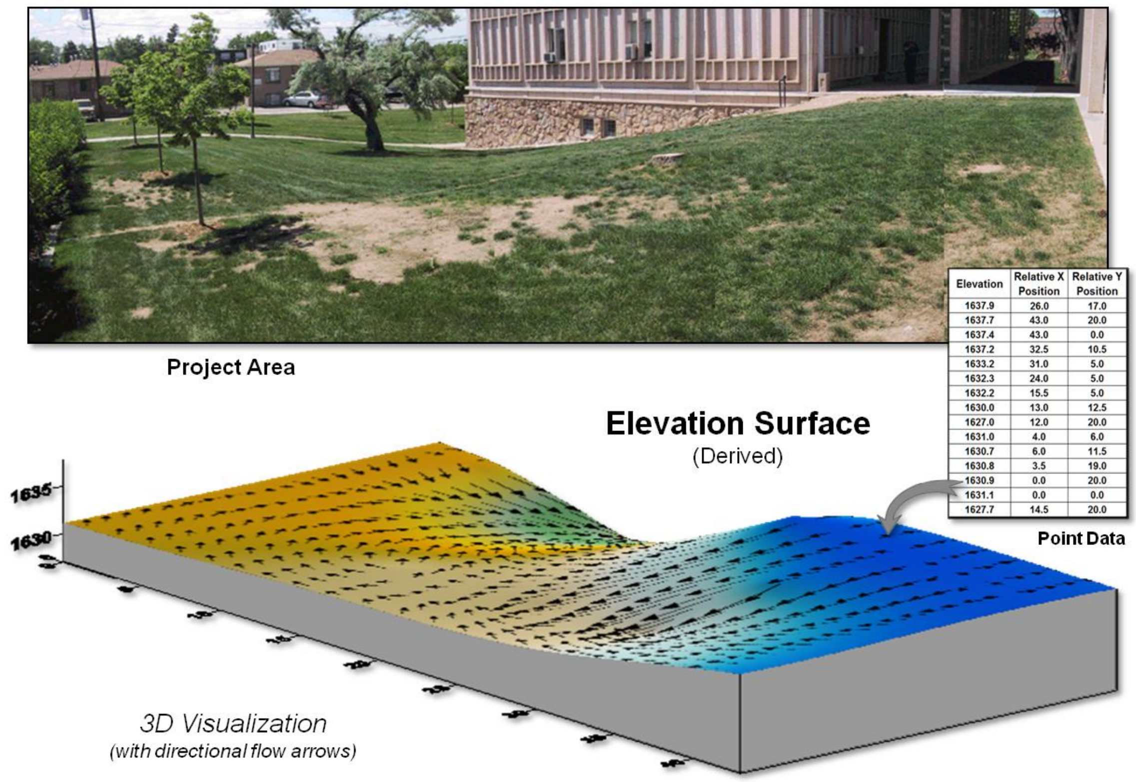


Figure 3. A detailed elevation surface is generated using inexpensive surface modeling software.

I have presented this 3-hour workshop in various forms to numerous GIS and non-GIS students and professionals since the 1980s. The practical fieldwork coupled with easy-to-use software encourages dialog about the inherent spatial nature ingrained in most field collected data.

Discussion quickly extends to data other than elevation—the "Z values" could easily be relative concentrations of an environmental variable; or disease occurrences in an epidemiological study; or relative biomass or stem density measurements of a plant species; or crime incidences for mapping pockets of crime in a city; or point of sales values for a particular product; or questionnaire response levels in a social survey; etc.

The peaks and valleys in any map surface characterize the spatial distribution of that mapped variable— identifying where the relative highs and lows occur in geographic space. And since a map surface is a spatially organized set of numbers, mathematical and statistical analysis tools can be applied (see Author's Note).

The bottom line is that many (most?) field-based mapped data contain useful information about the spatial distribution/pattern inherent in the data. While the ability to surface map this characteristic is well-known within the GIS community, it is less familiar and woefully underutilized in the applied sciences. A simple experience in surface mapping terrain elevation can be useful in crossing this conceptual chasm and often serves as a Rosetta stone in stimulating cross-discipline discussion and recognition of "maps as data" awaiting quantitative analysis— as opposed to traditional "graphic images" for human viewing and interpretation.

Author's Note: for more discussion on math/stat analytics for mapped data, see the online book Beyond Mapping III, Topic 30 "A Math/Stat Framework for Map Analysis" posted at www.innovativegis.com/basis/MapAnalysis/.

Segmenting Our World

(GeoWorld, June 2007, pg. 18-19)

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Dividing geographic space into meaningful groupings is the basis of all mapping. This holds for abstract maps like customer propensity clusters for purchasing a product or animal habitat suitability, as well as more traditional mapping applications such as vegetation maps, ownership parcels, highways and pipeline routes. Further divisions of the patterns in a base map often involve segmentation.

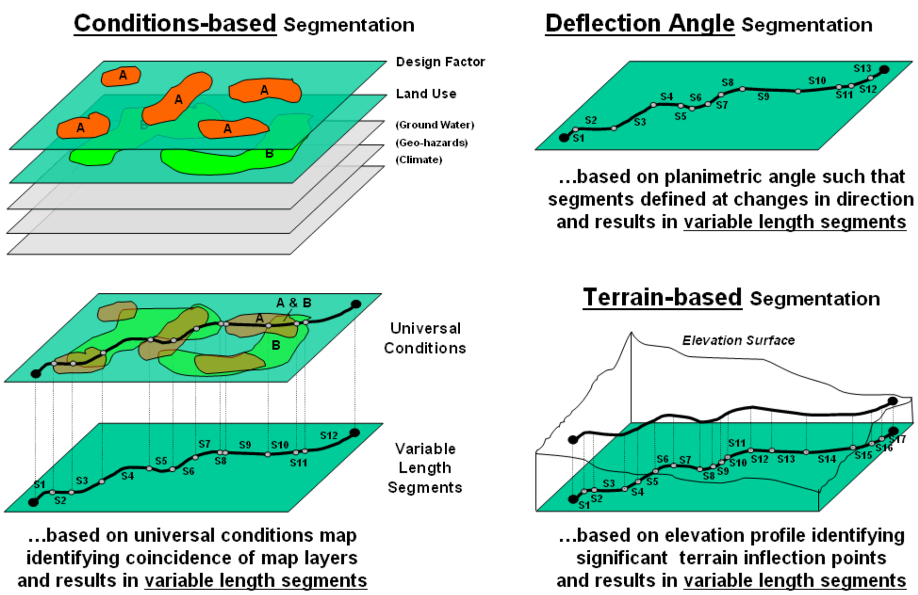

Figure 1. Basic approaches used in route segmentation.

For example, a pipeline is frequently divided into "stationing coordinates" that partitions a serpentining route into uniform linear distances along a pipeline (*Uniform* segmentation). Alternatively, the route can be segmented by identifying a point at each major change in direction as shown in the top right portion of figure 1. The result divides the route into a set of variable length segments responding to planimetric orientation of straight line sections (*Deflection Angle* segmentation).

A more complex form of segmentation is often referred to as "dynamic segmentation." This approach uses changes in conditions on other map layers to subdivide a route. The *Conditions-based* segmentation procedure first derives a "universal conditions" map by overlaying a set of map layers to establish individual coincident polygons containing the same combination of conditions throughout their interiors (left side of figure 1). A route is intersected with the universal conditions map and "broken" into a series of line segments at the entry and exit of each universal condition polygon.

The result is a series of variable length line segments with uniform conditions throughout their length. The line segment set is written to a table containing x, y and z coordinates followed by fields identifying the combination of conditions along each segment. In addition, the table can report "crossing counts" that note the number of intersections of the derived line segments and other linear features, such as river and road crossings.

Another advanced form of segmentation involves breaking a route into segments considering elevation changes along a terrain surface as shown in the bottom right portion of figure 1. *Terrain-based* segmentation divides the route into segments representing similar terrain configuration as determined by major inflection points and slope conditions.

The first step is to establish the elevation profile of the route by "masking" the terrain surface with the route. To eliminate subtle changes, the elevation values are smoothed to characterize the overall trend of the terrain. This is done by passing a moving-average window along the elevation profile resulting in a smoothed profile.

The width of the smoothing window is critical because if it is too large the smoothing will eliminate potentially important inflection points; if it is too small there will be a multitude of insignificant segment breaks. The dilemma is similar to choosing an appropriate angular change factor in Deflection-angle segmentation and is as much art as it is science. Experience for liquid pipelines suggests an 11 to 15-cell diameter window on a 10 meter digital elevation model (DEM) works fairly well.

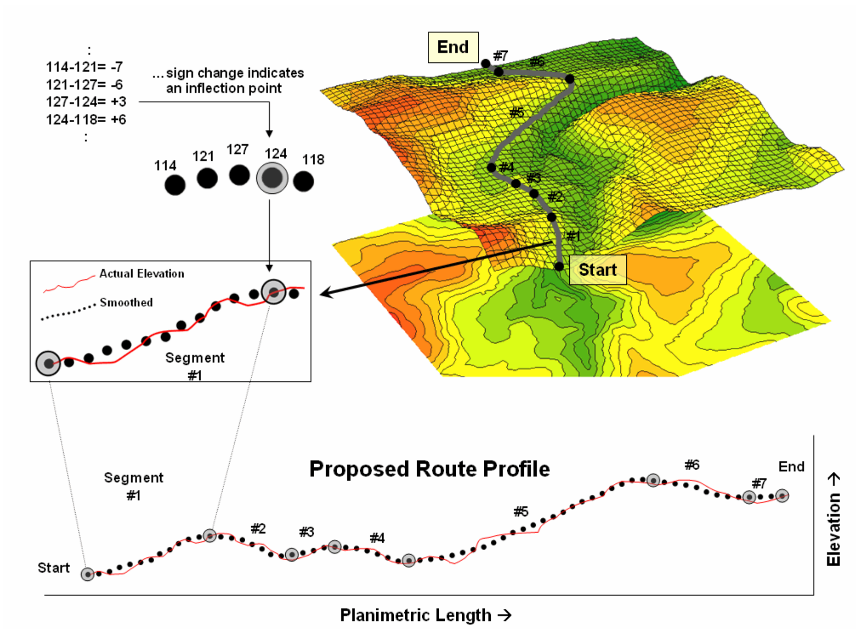

Figure 2. Analyzing the slope differences along a proposed route.

Figure 2 illustrates the final step in the procedure. The tool evaluates the smoothed elevation values by subtracting the current value from the previous location's value as the solution progresses left-to-right along the smoothed profile. If the sign is the same, a continuous "running slope" is indicated. A negative difference indicates an upward incline; a negative difference indicates a downward descent; zero difference indicates no change (flat portion). A location where the sign of the difference changes (negative to positive; positive to negative) identifies an inflection point. The coordinates and elevation value for the location that changed sign is written to a Segments Table.

For example, the calculations in the upper left portion of figure 2 show a continued upward incline until the elevation point of 124 is encountered. At this location the sign of the difference changes indicating the start of a downward descent (from a negative to a positive difference).

A refinement to the approach avoids storing and processing the entire elevation profile of actual values by calculating and comparing the moving average values (smoothed elevation) on-the-fly. This approach is much more efficient and greatly improves performance. In this application a 1x15 cell window is used to smooth the actual elevation profile and store the information in a temporary table with just two records—previous and current average.

The difference is calculated and tested for a change in sign; if different, the coordinates and elevation value for the current location is written to the Segments Table. The window is advanced and the old previous average is replaced and a new smoothed value for the current location is considered. The sequence of steps of 1) replace, 2) calculate, 3) compare and 4) write if sign change is repeated until the entire profile of a route has been evaluated.

The result is a set of map segments with consistent terrain configuration. Summarizing the average slope along the segmented file provides important information for assessing the hydraulics along a pipeline and pump-station positioning and design required for anticipated product flows …a big step beyond simply mapping a pipeline route.

Characterizing Terrain Slope and Roughness

(GeoWorld, March 2000, pg. 23-24)

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The past few columns discussed several techniques for generating maps that identify the bumps (convex features), the dips (concave features) and the tilt (slope) of a terrain surface. Although the procedures have a wealth of practical applications, the hidden agenda of the discussions was to get you to think of geographic space in a less traditional way—as an organized set of numbers (numerical data), instead of points, lines and areas represented by various colors and patterns (graphic map features).

A terrain surface is organized as a rectangular "analysis grid" with each cell containing an elevation value. Grid-based processing involves retrieving values from one or more of these "input data layers" and performing a mathematical or statistical operation on the subset of data to produce a new set numbers. While computer mapping or spatial database management often operates with the numbers defining a map, these types of processing simply repackage the existing information. A spatial query to "identify all the locations above 8000' elevation in El Dorado County" is a good example of a repackaging interrogation.

Map analysis operations, on the other hand, create entirely new spatial information. For example, a map of terrain slope can be derived from an elevation surface and then used to expand the geo-query to "identify all the locations above 8000' elevation in El Dorado County (existing data) that exceed 30% slope (derived data)." While the discussion in this series of columns focuses on applications in terrain analysis, the subliminal message is much broader—map analysis procedures derive new spatial information from existing information.

Now back to business. Last month's column described several approaches for calculating terrain slope from an elevation surface. Each of the approaches used a "3x3 roving window" to retrieve a subset of data, yet applied a different analysis function (maximum, minimum, average or "fitted" summary of the data).

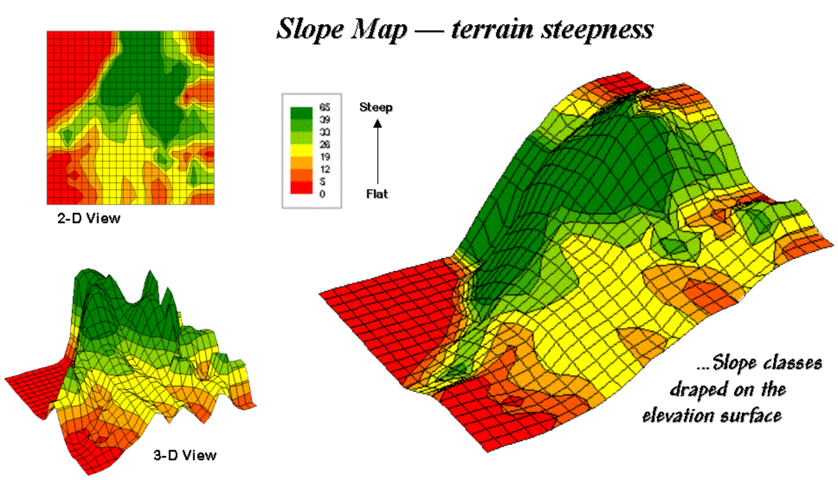

Figure 31-6. 2-D, 3-D and draped displays of terrain slope.

Figure 31-6 shows the slope map derived by "fitting a plane" to the nine elevation values surrounding each map location. The inset in the upper left corner of the figure shows a 2-D display of the slope map. Note that steeper locations primarily occur in the upper central portion of the area, while gentle slopes are concentrated along the left side.

The inset on the right shows the elevation data as a wire-frame plot with the slope map draped over the surface. Note the alignment of the slope classes with the surface configuration—flat slopes where it looks flat; steep slopes where it looks steep. So far, so good.

The 3-D view of slope in the lower left, however, looks a bit strange. The big bumps on this surface identify steep areas with large slope values. The ups-and-downs (undulations) are particularly interesting. If the area was perfectly flat, the slope value would be zero everywhere and the 3-D view would be flat as well. But what do you think the 3-D view would look like if the surface formed a steeply sloping plane?

Are you sure? The slope values at each location would be the same, say 65% slope, therefore the 3-D view would be a flat plane "floating" at a height of 65. That suggests a useful principle—as a slope map progresses from a constant plane (single value everywhere) to more ups-and-downs (bunches of different values), an increase in terrain roughness is indicated.

Figure 31-7 outlines this concept by diagramming the profiles of three different terrain cross-sections. An elevation surface's 2nd derivative (slope of a slope map) quantifies the amount of ups-and-downs of the terrain. For the straight line on the left, the "rate of change in elevation per unit distance" is constant with the same difference in elevation everywhere along the line—slope = 65% everywhere. The resultant slope map would have the value 65 stored at each grid cell, therefore the "rate of change in slope" is zero everywhere along the line (no change in slope)—slope2 = 0% everywhere.

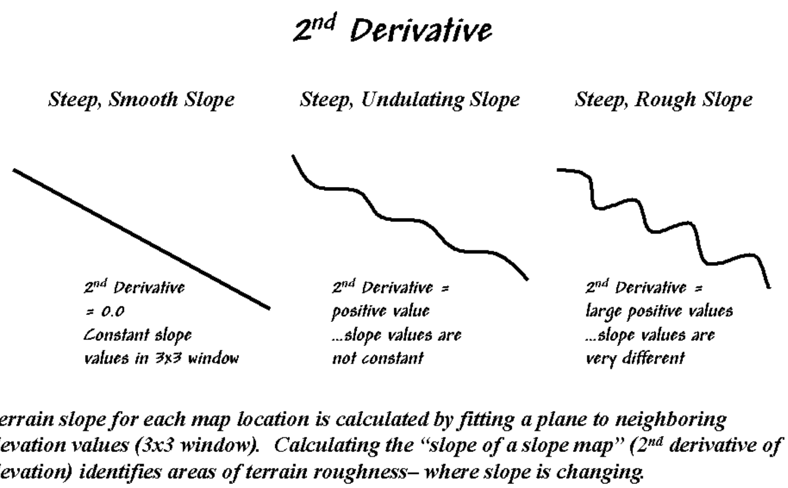

Figure 31-7. Assessing terrain roughness through the 2nd derivative of an elevation surface.

A slope2 value of zero is interpreted as a perfectly smooth condition, which in this case happens to be steep. The other profiles on the right have varying slopes along the line, therefore the "rate of change in slope" will produce increasing larger slope2 values as the differences in slope become increasingly larger.

So who cares? Water drops for one, as steep smooth areas are ideal for downhill racing, while "steep 'n rough terrain" encourages more infiltration, with "gentle yet rough terrain" the most.

Figure 31-8 shows a roughness map based on the 2nd derivative for the same terrain as depicted in Figure 31-6. Note the relationships between the two figures. The areas with the most "ups-and-downs" on the slope map in figure 31-6 correspond to the areas of highest values on the roughness map in figure 31-8. Now focus your attention on the large steep area in the upper central portion of the map. Note the roughness differences for the same area as indicated in figure 31-8—the favorite raindrop racing areas are the smooth portions of the steep terrain.

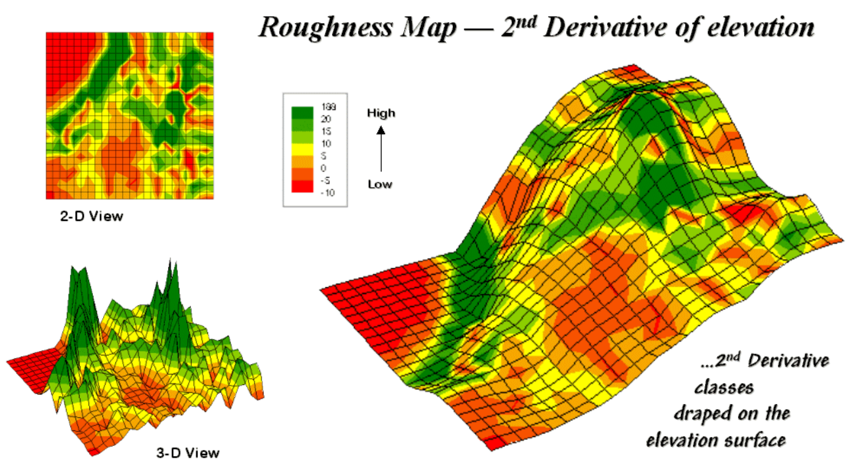

Figure 31-8. 2-D, 3-D and draped displays of terrain roughness.

Whew! That's a lot of map-ematical explanation for a couple of pretty simple concepts—steepness and roughness. Next month we'll continue the trek on steep part of the map analysis learning curve by considering "confluence patterns" in micro terrain analysis.

Confluence Maps Further Characterize Micro-terrain Features

(GeoWorld, April 2000, pg. 22-23)

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Last section's discussion focused on terrain steepness and roughness. While the concepts are simple and straightforward, the mechanics of computing them are a bit more challenging. As you hike in the mountains your legs sense the steepness and your mind is constantly assessing terrain roughness. A smooth, steeply-sloped area would have you clinging to things, while a rough steeply-sloped area would look more like stair steps.

Water has a similar vantage point of the slopes it encounters, except given its head, water will take the steepest downhill path (sort of like an out-of-control skier). Figure 31-91 shows a 3-D grid map of an elevation surface and the resulting flow confluence. It is based on the assumption that water will follow a path that chooses the steepest downhill step at each point (grid cell "step") along the terrain surface.

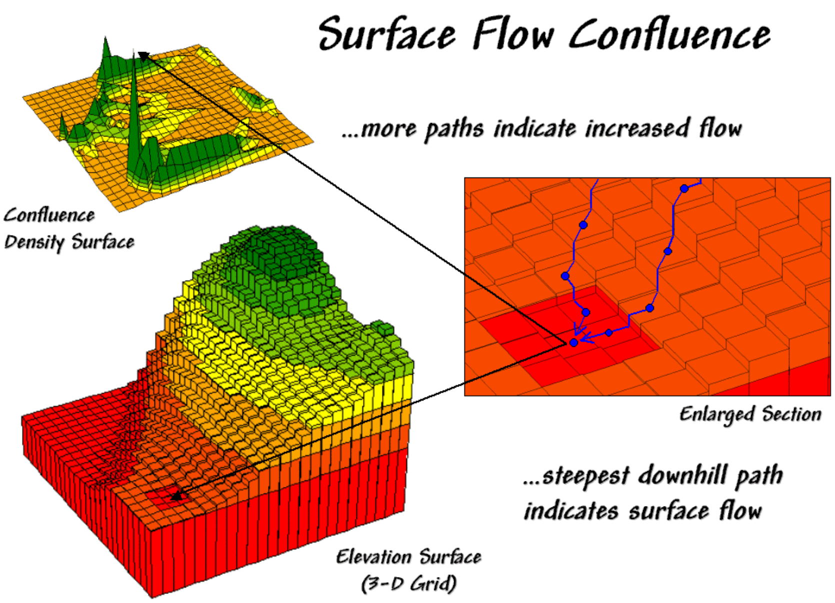

Figure 31-9. Map of surface flow confluence.

In effect, a drop of water is placed at each location and allowed to pick its path down the terrain surface. Each grid cell that is traversed gets the value of one added to it. As the paths from other locations are considered the areas sharing common paths get increasing larger values (one + one + one, etc.).

The inset on the right shows the path taken by a couple of drops into a slight depression. The inset on the left shows the considerable inflow for the depression as a high peak in the 3-D display. The high value indicates that a lot of uphill locations are connected to this feature. However, note that the pathways to the depression are concentrated along the southern edge of the area.

Now turn your attention to figure 31-10. Ridges on the confluence density surface (lower left) identify areas of high surface flow. Note how these areas (darker) align with the creases in the terrain as shown on the draped elevation surface on the right inset. The water collection in the "saddle" between the two hills is obvious, as are the two westerly facing confluences on the side of the hills. The 2-D map in the upper left provides a more familiar view of where not to unroll your sleeping bag if flash floods are a concern.

The various spatial analysis techniques for characterizing terrain surfaces introduced in this series provide a wealth of different perspectives on surface configuration. Deviation from Trend, Difference Maps and Deviation Surfaces are used to identify areas that "bump-up" (convex) or "dip-down" (concave). A Coefficient of Variation Surface looks at the overall disparity in elevation values occurring within a small area. A Slope Map shares a similar algorithm (roving window) but the summary of is different and reports the "tilt" of the surface. An Aspect Map extends the analysis to include the direction of the tilt as well as the magnitude. The Slope of a Slope Map (2^{nd} derivative) summarizes the frequency of the changes along an incline and reports the roughness throughout an elevation surface. Finally, a Confluence Map takes an extended view and characterizes the number of uphill locations connected to each location.

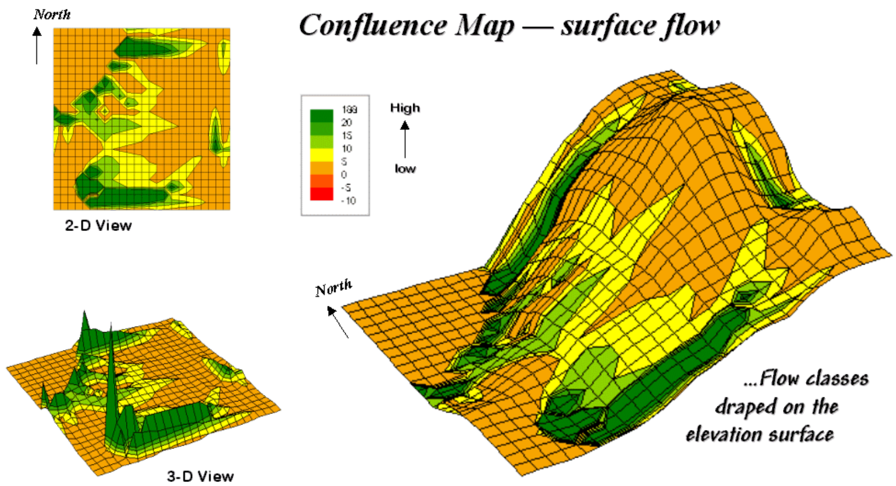

Figure 31-10. 2-D, 3-D and draped displays of surface flow confluence.

The coincidence of these varied perspectives can provide valuable input to decision-making. Areas that are smooth, steep and coincide with high confluence are strong candidates for gully-washers that gouge the landscape. On the other hand, areas that are rough, gently-sloped and with minimal confluence are relatively stable. Concave features in these areas tend to trap water and recharge soil moisture and the water table. Convex features under erosive conditions tend to become more prominent as the confluence of water flows around it.

Similar interpretations can be made for hikers, who like raindrops react to surface configuration in interesting ways. While steep, smooth surfaces are avoided by all but the rock-climber, too gentle surfaces tend too provide boring hikes. Prominent convex features can make interesting areas for viewing—from the top for hearty and from the bottom for the aesthetically bent. Areas of water confluence don't mix with hiking trail unless a considerable number of water-bars are placed in the trail.

These "rules-of-thumb" make sense in a lot of situations, however, there are numerous exceptions that can undercut them. Two concerns in particular are important— conditions and resolution. First, conditions along the surface can alter the effect of terrain characteristics. For example, soil properties and the vegetation at a location greatly effects surface runoff and sediment transport. The nature of accumulated distance along the surface is also a determinant. If the uphill slopes are long steep, the water flow has accumulated force and considerable erosion potential. A hiker that has been hiking up a steep slope for a long time might collapse before reaching the summit. If that steep slope is southerly oriented and without shade trees, then exhaustion is reached even sooner.

In addition, the resolution of the elevation grid can effect the calculations. In the case of water drops the gridding resolution and accurate "Z" values must be high to capture the subtle twists and bends that direct water flow. A hiker on the other hand, is less sensitive to subtle changes in elevation. The rub is that collection of the appropriate elevation is prohibitively expensive in most practical applications. The result is that existing elevation data, such as the USGS Digital Terrain Models (DTM), are used in most cases by default. Since the GIS procedures are independent of the gridding resolution, inappropriate maps can be generated and used in decision-making.

The recognition of the importance of spatial analysis and surface modeling is imperative, both for today and into the future. Its effective use requires informed and wary users. However, as with all technological things, what appears to be a data barrier today, becomes routine in the future. For example, RTK (Real Time Kinematic) GPS can build elevation maps to centimeter accuracy— it's just that there are a lot of centimeters out there to measure.

The more important limitation is intellectual. For decades, manual measurement, photo interpretation and process modeling approaches have served as input for decision-making involving terrain conditions. Instead of using GIS to simply automate the existing procedures our science needs to consider the new micro-terrain analysis tools and innovative approaches they present.

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Author's Note: The figures presented in this series on "Characterizing Micro-Terrain Features" plus several other illustrative ones are available online as a set of annotated PowerPoint slides at the "Column Supplements" page at http://www.innovativegis.com/basis.

Modeling Erosion and Sediment Loading

(GeoWorld, May 2000, pg. 22-23)

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Previous discussions suggested that combining derived maps often is necessary for a complete expression of an application. A simple erosion potential model, for example, can be developed by characterizing the coincidence of a Slope Map and a Flow Map (see the previous two columns in this series). The flowchart in the figure 31-11 identifies the processing steps that form the model— generate slope and flow maps, establish relative classes for both, then combine.

While a flowchart of the processing might appear unfamiliar, the underlying assumptions are quite straightforward. The slope map characterizes the relative "energy" of water flow at a location and the confluence map identifies the "volume" of flow. It's common sense that as energy and volume increases, so does erosion potential.

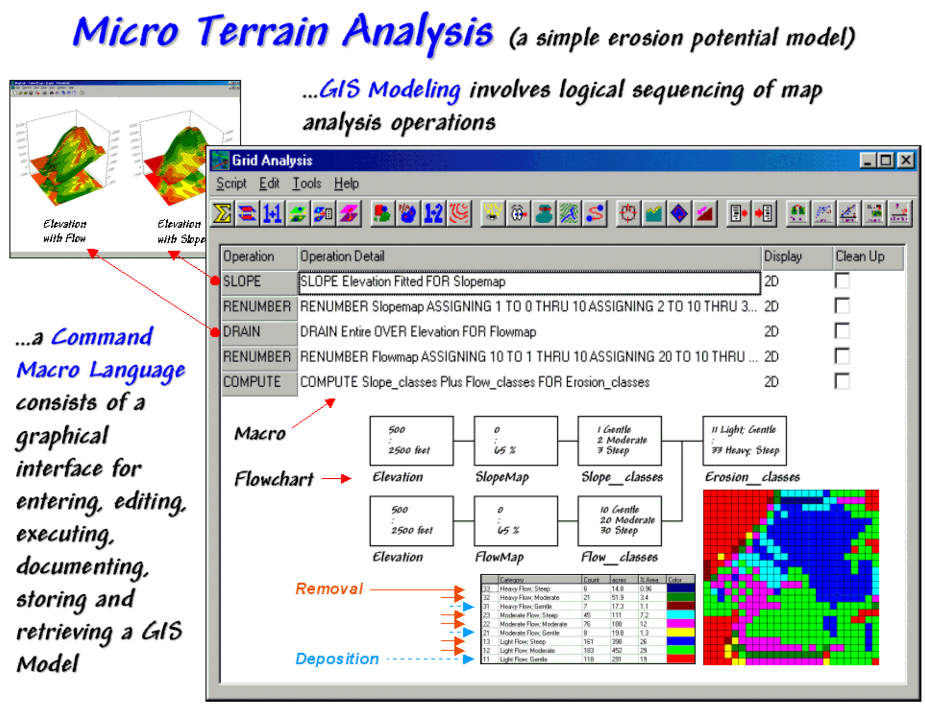

Figure 31-11. A simple erosion potential model combines information on terrain steepness and water flow confluence.

The various combinations of slope and flow span from high erosion potential to deposition conditions. On the map in the lower right, the category "33 Heavy Flow; Steep" (dark blue) identifies areas that are steep and have a lot of uphill locations contributing water. Loosened dirtballs under these circumstances are easily washed downhill. However, category "12 Light Flow; Moderate" (light green) identifies locations with minimal erosion potential. In fact, deposition (the opposite of erosion) can occur in areas of gentle slope, such as category "11 Light Flow; Gentle" (dark red).

Before we challenge the scientific merit of the simplified model, note the basic elements of the GIS modeling approach— flowchart and command macro. The flowchart is used to summarize the model's logic and processing steps. Each box represents a map and each line represents an analysis operation. For example, the first step depicts the calculation of a SlopeMap from a base map of Elevation. The actual command for this step, "Slope Elevation for SlopeMap," forms the first sentence in the command macro (see author's note).

The remaining sentences in the macro and the corresponding boxes/lines in the flowchart complete the model. The macro enables entering, editing, executing, storing and retrieving the individual operations that form the application. The flowchart provides an effective means for communicating the processing steps. Most "GIS-challenged users" are baffled by the detailed code in a command macro but readily relate to flowchart logic. In developing GIS applications, the user is the expert in the logic (domain expertise) while the developer is the expert in the code (GIS expertise). The explicit linkage between the macro and the flowchart provides a common foothold for communication between the two perspectives of a GIS application.

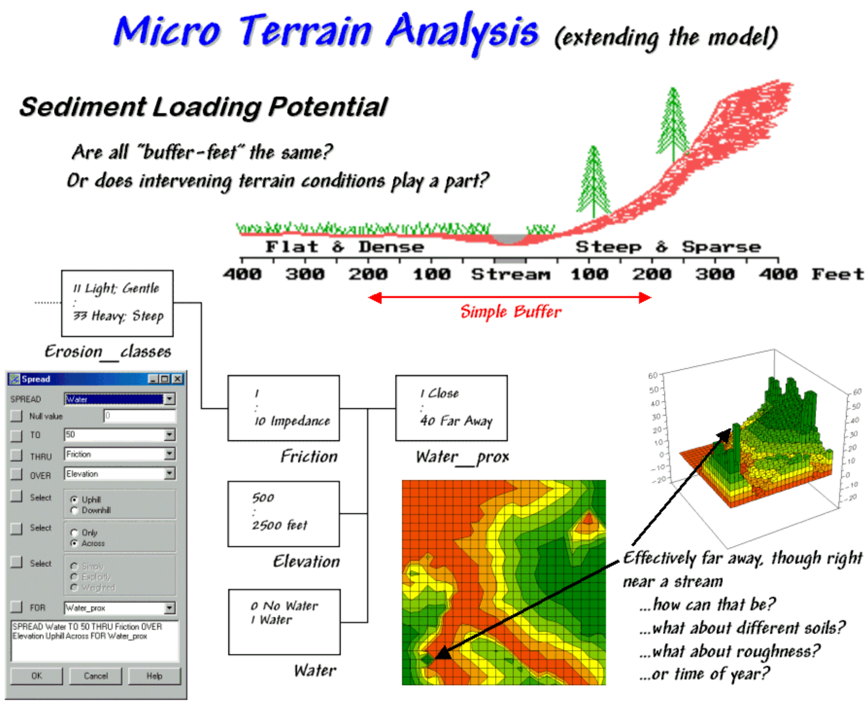

Figure 31-12. Extended erosion model considering sediment loading potential considering intervening terrain conditions.

It provides a starting place for model refinement as well. Suppose the user wants to extend the simple erosion model to address sediment loading potential to open water. The added logic is captured by the additional boxes/lines shown in figure 31-12. Note that the upper left box (Erosion_classes) picks up where the flowchart in figure 31-11 left off.

A traditional approach would generate a simple buffer of a couple of hundred feet around the stream and restrict all dirt disturbing actives to outside the buffered area. But are all buffer-feet the same? Is a simple geographic reach on either side sufficient to hold back sediment? Do physical laws apply or merely civil ones that placate planners?

Common sense suggests that the intervening conditions play a role. In areas that are steep and have high water volume, the setback ought to be a lot as erosion potential is high. Areas with minimal erosion potential require less of a setback. In the schematic in figure 31-12, a dirt disturbing activity on the steep hillside, though 200 feet away, would likely rain dirtballs into the stream. A similar activity on the other side of the stream, however, could proceed almost adjacent to the stream.

The first step in extending the erosion potential model to sediment loading involves "calibrating" the intervening conditions for dirtball impedance. The friction map identified in the flowchart ranges from 1 (very low friction for the 33 Heavy Flow: Steep condition) to 10 (very high friction for 11 Light Flow; Gentle). A loose dirtball in an area with a high friction factor isn't going anywhere, while one in an area of very low friction almost has legs of its own.

The second processing step calculates the effective distance from open water based on the relative friction. The command, "SPREAD Water TO 50 THRU Friction OVER Elevation Uphill Across For Water_Prox," is entered simply by completing a dialog box. The result is a variable-width buffer that reaches farther in areas of high erosion potential and less into areas of low potential. The lighter red tones identify locations that are effectively close to water from the perspective of a dirtball on the move. The darker green tones indicate areas effectively far away.

But notice the small dark green area in the lower left corner of the map of sediment loading potential. How can it be effectively far away though right near a stream? Actually it is a small depression that traps dirtballs and can't contribute sediment to the stream— effectively infinitely far away.

Several other real-world extensions are candidates to improve model. Shouldn't one consider the type of soils? The surface roughness? Or the time of year? The possibilities are numerous. In part, that's the trouble with GIS— it provides new tools for spatial analysis that aren't part of our traditional procedures and paradigms. Much of our science was developed before we had these spatially-explicit operations and is founded on simplifying assumptions of spatial independence and averaging over micro conditions. But now the "chicken or egg" parable is moot. Spatial analysis is here and our science needs updating to reflect the new tools and purge simplifying assumptions about geographic relationships.

Identify Valley Bottoms in Mountainous Terrain

(GeoWorld, November 2002, pg. 22-23)

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On occasion I am asked how I come up with ideas for the Beyond Mapping column every month for over a dozen years. It's easy—just hang around bright folks with interesting questions. It's also the same rationale I use for keeping academic ties in GIS for over three decades—bright and energetic students.

For example, last section's discussion on "Connecting Riders with Their Stops" is an outgrowth of a grad student's thesis tackling an automated procedure for routing passengers through alternative public transportation (bike, bus and light rail). This month's topic picks up on another grad student's need to identify valley bottoms in mountainous terrain.

The upper-left inset in figure 1 identifies a portion of a 30m digital elevation model (DEM). The "floor" of the composite plot is a 50-meter contour map of the terrain co-registered with an exaggerated 3D lattice display of the elevation values. Note the steep gradients in the southwestern portion of the area.

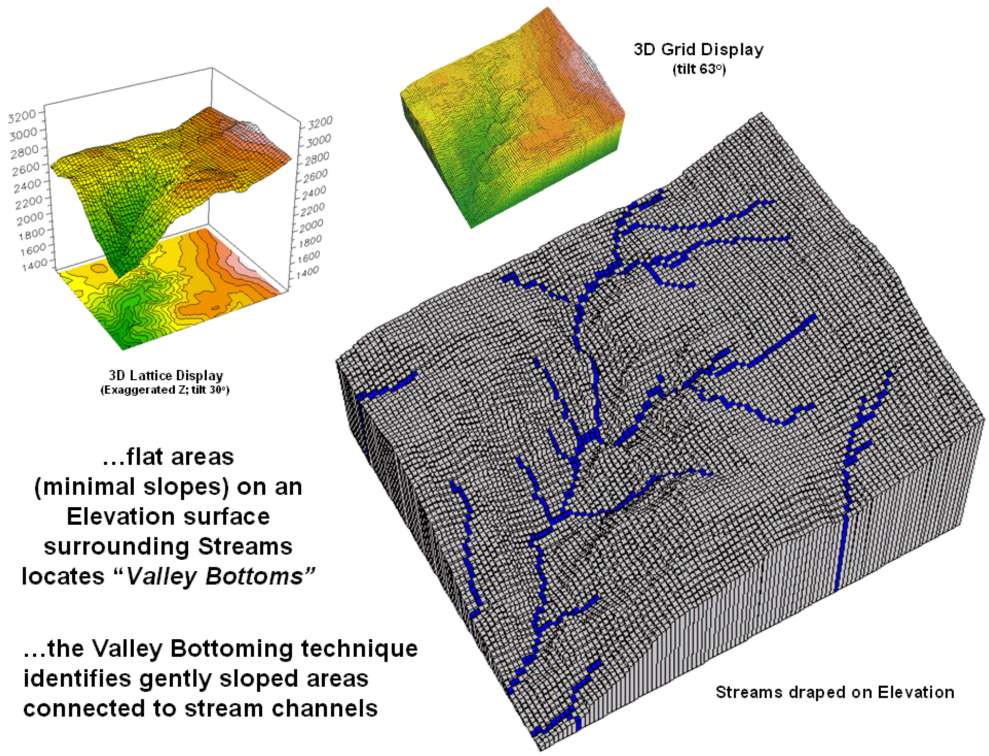

Figure 1. Gentle slopes surrounding streams are visually apparent on a 3D plot of elevation.

The enlarged 3D grid display on the right graphically overlays the stream channels onto the terrain surface. Note that the headwaters occur on fairly gentle slopes then flow into the steep canyon. While your eye can locate areas of gentle slope surrounding streams in the plot, an automated technique is needed to delineate and characterize the valley bottoms for millions of acres. In addition, a precise rule set is needed to avoid inconsistencies among subjective visual interpretations.

Like your eye, the computer needs to 1) locate areas with gentle slopes that are 2) connected to the stream channels. In evaluating the first step the computer doesn't "see" a colorful 3D plot like you do. It "sees" relative elevation differences—rather precisely—that are stored in a matrix of elevation values. The slope algorithm retrieves the elevation value for a location and its eight surrounding values then mathematically compares the subset of values. If the nine elevation values were all the same, a slope of zero percent (flat) would be computed. As the elevation values in one portion of the 3x3 window get relatively large compared to another portion, increasing slope values are calculated. You see a steep area on the 3D plot; the computer sees a large computed slope value.

Figure 2 shows the slope calculation results for the project area. The small 3D grid plot at the top identifies terrain steepness from 0 to 105% slope. Gently sloped areas of 0-6% are shown in green tones with steeper slopes shown in red tones. The gently sloped areas are the ones of interest for deriving valley bottoms, and as your eye detected, the computer locates them primarily along the rim of the canyon. But these areas only meet half of the valley bottom definition—which of the flat areas are connected to stream channels?

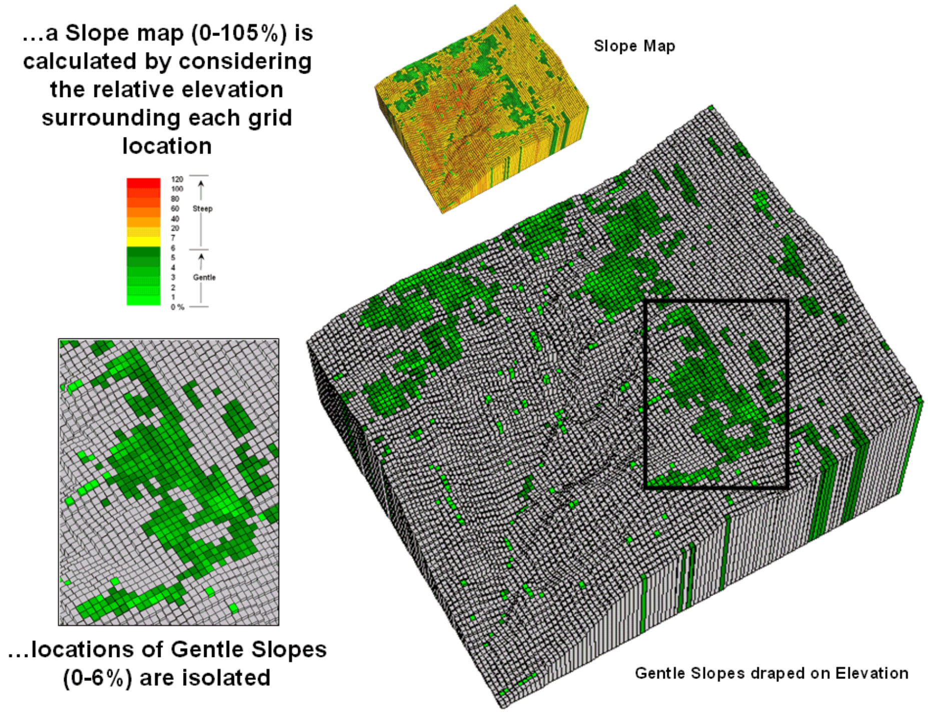

Figure 2. Slope values for the terrain surface are calculated and gently sloped areas identified.

Figure 3 identifies the procedure for linking the two criteria. First the flat areas are isolated for a binary map of 0-6% slope=1 and greater slopes=0. Then an effective distance operation is used to measure distance away from streams considering just the areas of gentle slopes. The enlarged inset shows the result with connected valley bottom as far away as 900 meters.

While the prototype bottoming technique appears to work, several factors need to be considered before applying it to millions of areas. First is the question whether the 30 meter DEM data supports the slope calculations. In figure 2 the horizontal stripping in the slope values suggests that the elevation data contains some inconsistencies. In addition what type of slope calculation (average, fitted, maximum, etc) ought to be used? And is the assumption of 0-6% for defining valley bottoms valid? Should it be more or less? Does the definition change for different regions?

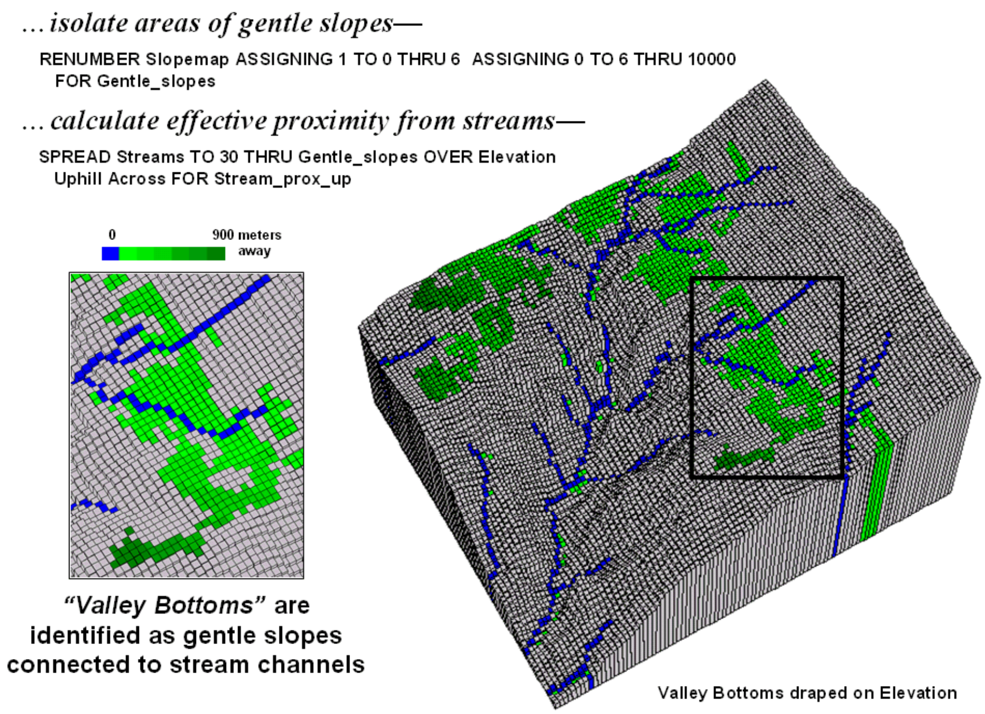

Figure 3. Valley bottoms are identified as flat areas connected to streams.

Another concern involves the guiding surface used in determining effective proximity—distance measurement uphill/downhill only or across slopes? Do intervening soil and vegetation conditions need to be considered in establishing connectivity? A final consideration is designing a field methodology for empirically evaluating model results. Is there a strong correlation with riparian vegetation and/or soil maps?

That's the fun of scholarly pursuit. Take a simple idea and grind it to dust in the research crucible—only the best ideas and solutions survive. But keep in mind that the major ingredient is a continuous flow of bright and energetic minds.

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Author's Note: Sincerest thanks to grad students Jeff Gockley and Dennis Staley with the University of Denver-Geography for inspiration…the icing is easy but the pound cake of research awaits.

Use Surface Area for Realistic Calculations

(GeoWorld, December 2002, pg. 22-23)

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The earth is flat …or so most GIS maps contend. I am not referring to concern about the curvature of the earth but to the undulations of local terrain. Once projection adjustments are made, a flattened world is assumed—*planimetric* representation. But what happened to the up-and-down wrinkles of the real world? What about actual surface areas and lengths of map features that are clinging to sides of slopes in a real landscape?

Common sense suggests that if you walk up and down in steep terrain you will walk a lot farther than the planimetric length of your path. While we have known this fact for thousands of years, surface area and length calculations were practically impossible to apply to paper maps. However, map-ematical processing in a GIS easily handles the calculations.

In a vector-based system, area calculations use plane geometry equations. In a grid-based system, ***planimetric area*** is calculated by multiplying the number of cells defining a map feature times the area of an individual cell. For example, if a forest cover type occupies 500 cells with a spatial resolution of 1 hectare each, then the total planimetric area for the cover type is 500 cells * 1ha/cell = 500ha.

However, the actual surface area of each grid cell is dependent on its inclination (slope). ***Surface area*** increases as a grid cell is tilted from a horizontal reference plane (planimetric) to its three-dimensional position in a digital elevation surface (see figure 1).

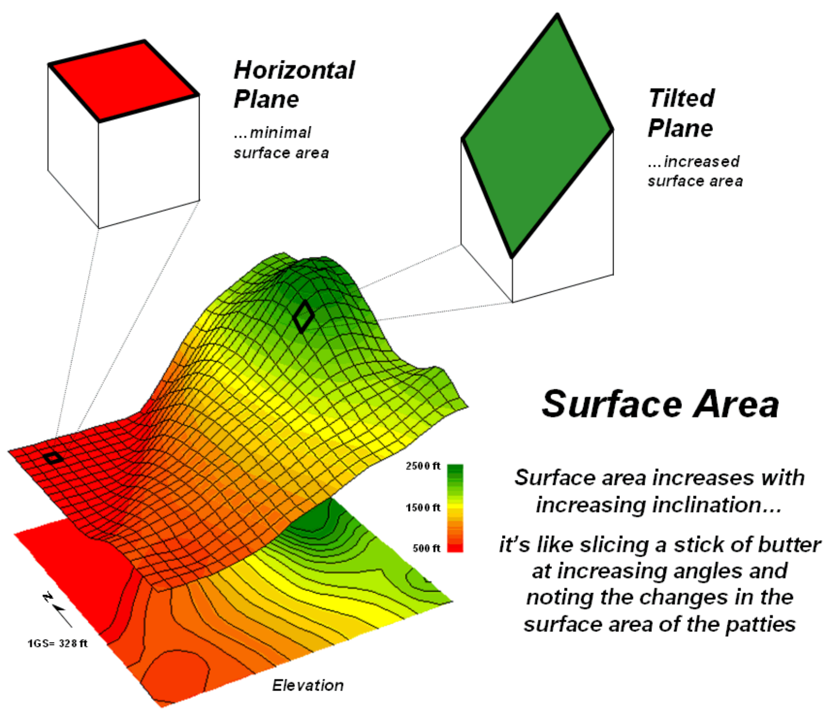


Figure 1. Surface area increases with increasing terrain slope.

Surface area can be calculated by dividing the planimetric area by the cosine of the slope angle (see Author's Note). For example, a grid location with a 20 percent slope has a surface area of 1.019803903 hectares based on solving the following sequence of equations:

Tan_Slope_Angle = 20 %_ slope / 100 = .20 slope_ratio
Slope_Angle = arctan (.20 slope_ratio) = 11.30993247 degrees
Surface_Area_Factor = cos (11.30993247 degrees) = .980580676
Surface_Area = 1 ha / .980580676 = 1.019803903 ha

The table in figure 2 identifies the surface area calculations for a 1-hectare gridding resolution under several terrain slope conditions. Note that the column ***Surface_Area_Factor*** is independent of the gridding resolution. Deriving the surface area for a cell on a 5-hectare resolution map, simply changes the last step in the 20% slope example (above) to *5 ha / .9806 = 5.0989 ha Surface_Area*.

%Slope	*Tan_Slope_Angle*	*Slope_Angle*	*Surface_Area_Factor*	*Surface_Area (1ha)*
0	0.00	00.0000	1.0000	1.0000 ha
20	0.20	11.3099	0.9806	1.0198 ha
40	0.40	21.8014	0.9285	1.0770 ha
80	0.80	38.6598	0.7809	1.2806 ha
100	1.00	45.0000	0.7071	1.4142 ha
150	1.50	56.3099	0.5547	1.8028 ha
200	2.00	63.4349	0.4472	2.2361 ha
300	3.00	71.5650	0.3163	3.1623 ha
infinity	infinity	90.0000	0.0000	infinity

Figure 2. Surface areas for selected terrain slopes.

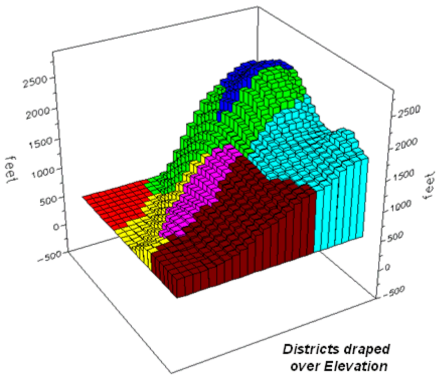
For an empirical test of the surface area conversion procedure, I have students cut a stick of butter at two angles— one at 0 degrees (perpendicular) and the other at 45 degrees. They then stamp an imprint of each patty on a piece of graph paper and count the number of grid spaces covered by the grease spots to determine their areas. Comparing the results to the calculations in the table above confirms that the 45-degree patty is about 1.414 larger. What do you think the area difference would be for a 60-degree patty?

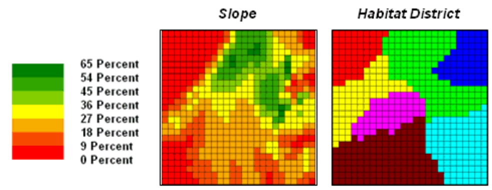
In a grid-based GIS things are a bit less messy. A slope map is derived from an elevation surface then used to map-ematically solve the set of equations for each grid cell. In the MapCalc system, the set of commands calculating surface area for each habitat districts in a project area is…

Step 1) **SLOPE ELEVATION FOR SLOPE_MAP**
Step 2) **CALCULATE (COS ((ARCTAN (SLOPE_MAP / 100)))) FOR SURFACE_AREA_FACTOR_MAP**
Step 3) **CALCULATE 1.0 / SURFACE_AREA_FACTOR_MAP FOR SURFACE_AREA_MAP**
Step 4) **COMPOSITE HABITAT_DISTRICT_MAP TOTAL WITH SURFACE_AREA_MAP FOR HABITAT_SURFACE_AREA_MAP**

The command macro is scaled to a 1-hectare gridding resolution project area by assigning the value 1.0 (ha) in the third step. If a standard DEM (Digital Elevation Model with 30m resolution) surface is used, the GRID_RES would be set to .09 hectare (30m * 30m= 900m$^{2;}$ 900m^2/10,000m^2= .09ha). If the gridding resolution is available in the metadata with the data base, this factor can be automatically set. A similar procedure can be developed for ArcGIS Spatial Analyst or other grid-based map analysis software.

A region-wide, or zonal overlay procedure (Composite), is used to sum the surface areas for the cells defining any map feature—habitat districts in this case. Figure 2 shows the planimetric and surface area results for the districts considering the terrain surface. Note that District 2 (light green) aligns with most of the steep slopes on the elevation surface. As a result, the surface area is considerably greater (9.62%) than its simple planimetric area.





	District	# Cells	Planimetric Area(ha)	Surface Area (ha)	% Difference
(red)	1	58	58.0	58.0	0.00
(green)	2	135	135.0	148.0	9.62
(blue)	3	59	59.0	61.9	4.91
(yellow)	4	76	76.0	78.4	3.16
(magenta)	5	56	56.0	57.9	3.39
(cyan)	6	102	102.0	105.0	2.94
(dark red)	7	139	139.0	141.0	1.44

Figure 3. Planimetric vs. surface area differences for habitat districts.

Surface length of a line also is affected by terrain. In this instance, azimuth as well as slope of the tilted plane needs to be considered as it relates to the direction of the line. If the grid cell is flat or the line is perpendicular to the slope of a tilted plane, there is no correction to the planimetric length of a line—from orthogonal (1.0 grid space to diagonal (1.414 grid space) length. If the line is parallel to the slope (same direction as the azimuth of the cell) the full cosine correction to its planimetric projection takes hold. The geometric calculations are a bit more complex and reserved for online discussion (see Author's Note below).

So who cares about surface area and length? Suppose you needed to determine the amount of pesticide needed for weed spraying along an up-down power-line route or estimating the amount of seeds for reforestation or are attempting to calculate surface infiltration in rough terrain. Keep in mind that "simple area/length calculations can significantly under-estimate real world conditions." Just ask a pooped hiker that walked five planimetric-miles in the Colorado Rockies.

Author's Note: For background theory and equations for calculating surface area and length… see ***www.innovativegis.com/basis****, select "Column Supplements."*

Beware Slope's Slippery Slope

(GeoWorld, January 2003, pg. 22-23)

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If you are a skier it's likely that you have a good feel for terrain slope. If it's a steep double-diamond run, the timid will zigzag across the slope while the boomers will follow the fall-line straight down the hill.

This suggests that there are myriad slopes—uphill, across and downhill; N, E, S and West; 0-360 azimuth—at any location. So how can a slope map report just one slope value at each location? Which slope is it? How is it calculated? How might it be used?

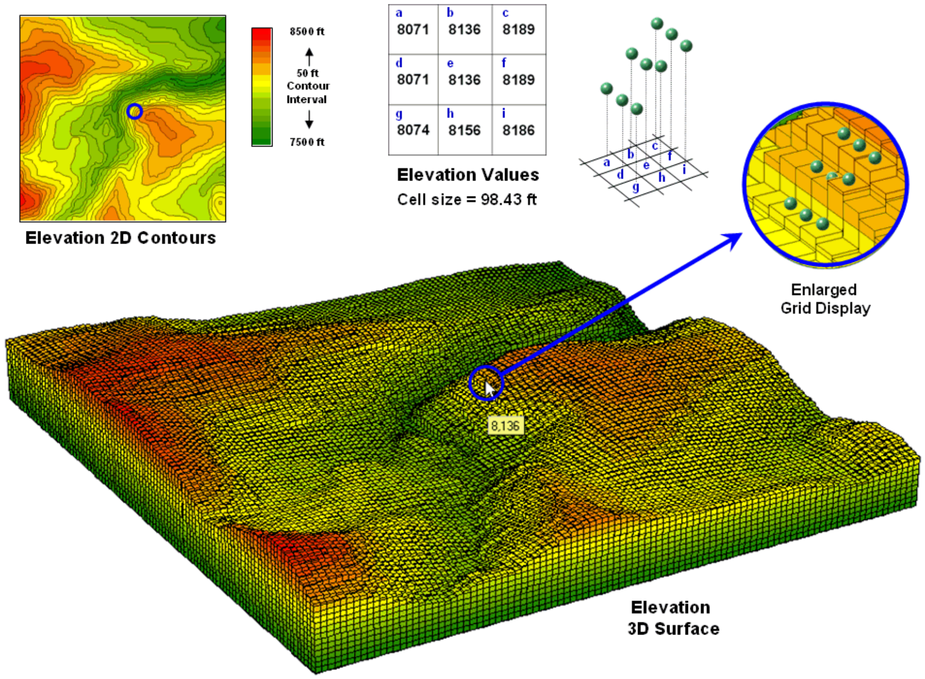

Figure 1. A terrain surface is stored as a grid of elevation values.

Digital Elevation Model (DEM) data is readily available at several spatial resolutions. Figure 1 shows a portion of a standard elevation map with a cell size of 30 meters (98.43 feet). While your eye easily detects locations of steep and gentle slopes in the 3D display, the computer doesn't have the advantage of a visual representation. All it "sees" is an organized set of elevation values—10,000 numbers organized as 100 columns by 100 rows in this case.

The enlarged portion of figure 1 illustrates the relative positioning of nine elevation values and their corresponding grid storage locations. Your eye detects slope as relative vertical alignment of the cells. However, the computer calculates slope as the relative differences in elevation values.

The simplest approach to calculating slope focuses on the eight surrounding elevations of the grid cell in the center of a 3-by-3 window. In the example, the individual percent slope for *d-e* is change in elevation (vertical *rise*) divided by change in position (horizontal *run*) equals [((8071 ft – 8136 ft) / 98.43 ft) * 100] = -66%. For diagonal positions, such as *a-e*, the calculation changes to [((8071 ft – 8136 ft) / 139.02 ft) * 100] = -47% using an adjusted horizontal run of SQRT(98.43**2 + 98.43**2) = 139.02 ft.

Applying the calculations to all of the neighboring slopes results in eight individual slope values yields (clockwise from *a-e*) 47, 0, 38, 54, 36, 20, 45 and 66 percent slope. The ***minimum*** slope of 0% would be the choice the timid skier while the boomer would go for the ***maximum*** slope of 66% provided they stuck to one of the eight directions. The simplest calculation for an overall slope is an arithmetic ***average*** slope of 38% based on the eight individual slopes.

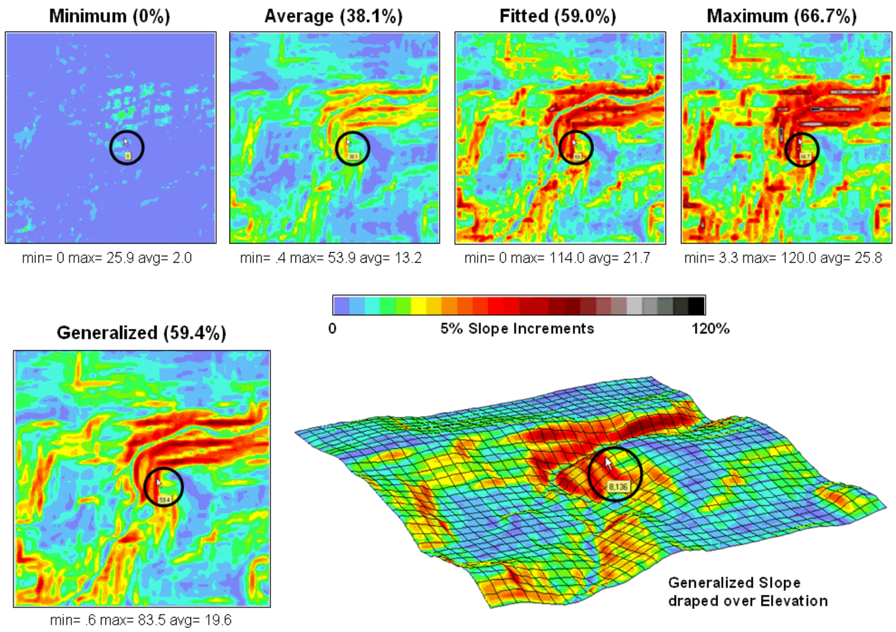

Figure 2. Visual comparison of different slope maps.

Most GIS systems, however, offer more sophisticated solutions for characterizing the overall slope for a grid location. One approach summarizes the relative changes in rise to run for x and y-directions in the 3x3 window (***generalized***). Another fits a plane to the nine elevation values (***fitted***) then computes the slope of the plane.

The equations and example calculations for the advanced techniques are beyond the scope of this column but are available online (see author's note). The bottom line is that grid-based slope calculators use a roving window to collect neighboring elevations and relate changes in the values to their relative positions. The result is a slope value assigned to each grid cell.

Figure 2 shows several slope maps derived from the elevation data shown in figure 1 and organized by increasing overall slope estimates. The techniques show somewhat similar spatial patterns with the steepest slopes in the northeast quadrant. Their derived values, however, vary widely. For example, the *average* slope estimates range from .4 to 53.9% whereas the *maximum* slope estimates are from 3.3 to 120%. Slope values for a selected grid location in the central portion are identified on each map and vary from 0 to 59.4%.

So what's the take-home on slope calculations? Different algorithms produce different results and a conscientious user should be aware of the differences. A corollary is that you should be hesitant to download a derived map of slope without knowing its heritage. The chance of edge-matching slope maps from a variety of systems is unlikely. Even more insidious is the questionable accuracy of utilizing a map-ematical equation calibrated using one slope technique then evaluated using another.

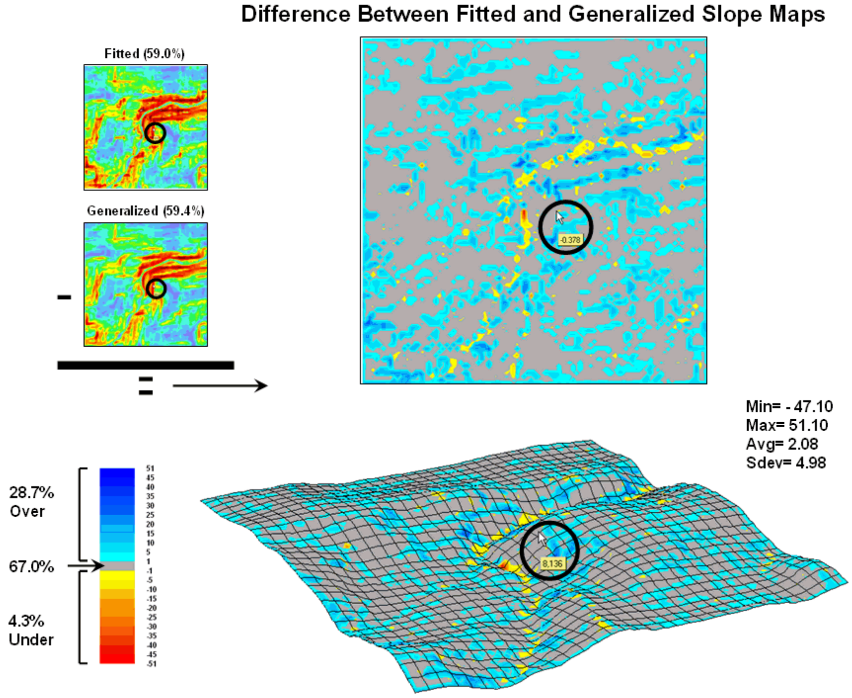

Figure 3. Comparison of Fitted versus Generalized slope maps.

The two advanced techniques result in very similar slope estimates. Figure 3 "map-ematically" compares the two maps by simply subtracting them. Note that the slope estimates for about two-thirds of the project area is within one percent agreement (grey). Disagreement between the two maps is predominantly where the *fitted* technique estimates a steeper slope than the *generalized* technique (blue-tones). The locations where *generalized* slopes exceed the *fitted* slopes (red-tones) are primarily isolated along the river valley.

Shedding Light on Terrain Analysis

(GeoWorld, April 2008,)

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A lot of GIS is straightforward and mimics our boy/girl scout days wrestling with paper maps. We learned that North is at the top (at least for us in the northern latitudes) and red roads and blue streams wind their way around green globs of forested areas. However, the brown concentric rings presented a bit more of a conceptual challenge.

When the contour lines formed a fairly small circle it was likely a hilltop; or a depression, if the line sprouted whiskers. Sharp "V-shaped" contour lines pointed upstream when a blue line was present; and somewhat rounded V's pointed downhill along a ridge. Once these and a few other subtle nuances were mastered and you survived a day or so in the woods, a merit badge and sense power over geography was attained.

Your computer is devoid of such a nostalgic experience. All it sees are organized sets of colorless numbers. In the case of vector systems, these number sets identify lines defining discrete spatial features in a manner fairly analogous to traditional mapping. On the surface, direction measurement fundamentals remain the same and your fond memory of the 0-360^o markings around a compass ring holds for most GIS mapping applications.

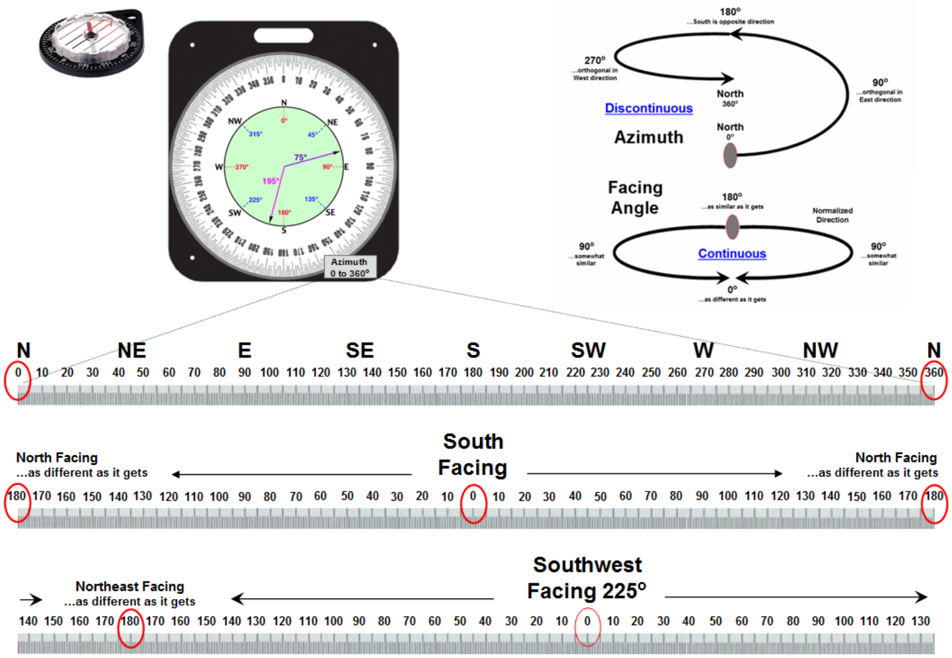

Figure 1. Azimuth is a discontinuous numeric scale as it wraps around on itself; Facing Angle is a continuous gradient indicating relative alignment with a specified direction.

The upper-left portion of figure 1 unfolds the compass ring into a continuum of azimuth from 0^o (north) to 360^o (north). Whoa …you mean north is at both ends of the continuum? As azimuth increases, it becomes less north-like for awhile and then more north-like until 0 = 360. Now that's enough to really mess-up a numeric bean-counter like a computer. Actually, azimuthal direction is termed a discontinuous number set as it wraps around on itself (spiral in the top-right side of figure 1).

The lower scales in figure 1 transform direction into a more stable continuous number set that indicates the relative alignment with a specified direction. A *Facing Angle* utilizes the concept of a back azimuth to indicate an orientation as different as it gets—180^o is completely opposite; and 0^o is exactly the same direction.

For a south facing location the continuum starts at 0 (South) and progresses "less south-like" in both the East and West directions until the orientation "is 180 degrees off" at due North. The importance of the consistency of this continuous scale might be lost on humans, but it means the world to a computer attempting to statistically analyze a set of directional data. The procedure normalizes terrain data for any given facing angle into a consistent scale of 0 to 180 indicating the degree of orientation similarly throughout an entire project area.

Figure 2 summarizes the geometry between Azimuth and Facing angles. Also it introduces the concept of a *Horizontal* angle that takes direction from 2D planar to 3D solid geometry. The "Hillshade" map of Mount St. Helens on the right shows the relative brightness of the terrain assuming a sun position from 225^o azimuth (SSW) and 35^o above the horizon; the brightest areas directly face the sun.

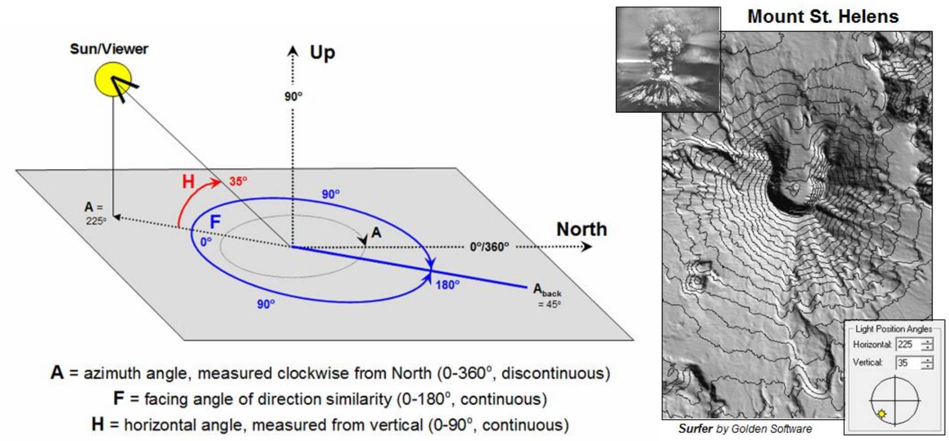

Figure 2. A Hillshade map identifies the relative brightness at every grid location in a project area.

Figure 3 expresses the relationship between the azimuth and horizontal angle gradients derived from aspect and slope maps. Each grid cell (30x30 meters in this example) can be thought of as a tilted plane in three-dimensional space. In the case of the brightest location, it identifies a grid cell that is perpendicular to the sun—like a contented lizard or sunbather positioned to absorb the most rays. All other possible orientations of the grid cell facets are some combination of the facing and horizontal angle gradients.

However, the "superstar *map*-ematicians" among us know that things are a bit more complex than an independent peek at each grid cell. A grid cell could be directly oriented toward the sun but on a small hill in the shadow of a much larger hill. To account for the surrounding terrain configuration one needs to solve the angles using solid geometry algorithms involving direction cosines to connect the grid cell to the sun and test if there is any intervening terrain blocking connection.

So what's the take-home from all this discussion? Actually three points should stand out. First, that GIS technology encompasses our paper map thinking (e.g., discontinuous azimuthal direction), but the digital map enables us to go beyond mapping. Secondly, that a map is an organized set of numbers first, and a picture later; we must understand the nature of the data (e.g., continuous facing angle) to fully capitalize on the potential of map analysis.

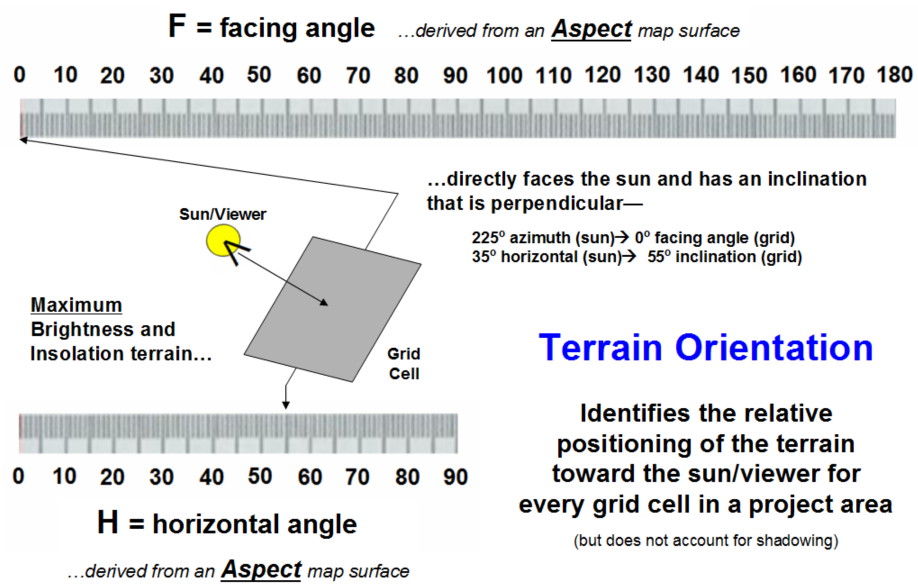

Figure 3. Terrain orientation combines azimuthal and horizontal angles for each grid cell facet.

Finally, the new map-*ematical* expression of maps supports radically new applications. For example, one can integrate a series of brightness maps over a day for a map of solar influx (insolation) that drives a wealth of spatial systems from wildlife habitat to global warming. In addition, these data can be statistically analyzed for insight into spatial patterns, relationships and dependencies that were beyond discovery a few years ago. In short, GIS is ushering in a new era of decision-making, not simply keeping track of where is what.

Author's Note: *related discussion on Terrain Analysis is in Topic 6, Summarizing Neighbors in the book Map Analysis (Berry, 2007; GeoTec Media,* ***www.geoplace.com/books/MapAnalysis****) and Topic 11 in the online Beyond Mapping III compilation (****www.innovativegis.com/basis/MapAnalysis****).*

Correction: *the following letter (5/25/08) outlined some concerns about the discussion of Azimuth.*

Joseph—In the many years of Beyond Mapping I've never had a serious disagreement. In the May column it seems as though your slant on angles is a bit off course. I'm no map-ematician but azimuth is not discontinuous; rather it is a cyclic attribute type that continuously wraps around (and around). If we thought of phase angles as discontinuous we would have a hard time using sines and cosines to compute mean wind directions slope aspects or buoy longitudes east of New Zealand. You say too that the brightest areas in a hillshade image face the sun. Those slopes that exactly face the sun reflect light back to the sun's incident angle, not the viewer. When the angle of incidence from surfaces oblique to the sun angle cause the angle of reflection to return to the viewer "overhead" the surface is brightest. One more thing if you will allow me. Your Mount St. Helens is lit from 225 degrees, putting the "shadows" to the north-east. This violates the remote sensing custom of putting the "shadows" to the south-east to avoid the terrain inversion phenomenon that results from the pseudoscopic effect. Many folks will see your Mt. St. Helens, as a depression with a small Mound St. Helens at the bottom. That of course is why the Surfer default is 335 degrees.

Best wishes**, Peter H. Dana**, Ph.D., Research Fellow and Lecturer, Department of Geography, University of Texas at Austin, pdana@mail.utexas.edu

Peter—right on …excellent points well taken. Azimuth is not "discontinuous" and your classification of "cyclical" is a good one. The bottom line is that azimuth isn't your normal numerical gradient and being a bit whacko one can't simply utilize raw azimuth values in spatial data mining. My use of the term "brightest areas" was misleading …I was referring to surface illumination intensity (amount of sunlight impacting a location as contained in the facing angle) not the relative brightness in the image which is dependent on viewer angle as well as solar angle as compounded by the unique lay of the terrain. Your recounting of the imaging interpretation rule also holds true for interpreting the graphic. My point however was less on the interpretation of the map graphic as on the ability to track solar insolation …mapped data versus visualization. The bottom line is that I am delighted that someone out there actually reads the column, particularly with your level of interest and expertise. The dialog is much appreciated and I stand corrected. Thank you. Joe

Identifying Upland Ridges

(GeoWorld, May 2009)

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The good news is that there is a tsunami of mapped data out there; the bad news is that there is a tsunami of mapped data out there. Rarely is it as simple as downloading and displaying the ideal map for decision-making. More often than not the base data that is available is just that—a base for further exploration and translation into meaningful information for solutions well-beyond a basic wall decoration.

Digital Elevation Models (DEMs) are no exception. While there is an ever increasing wealth of elevation data at ever increasing detail, most applications require a translation of the ups and downs into decision contexts. For example, suppose you are interested in identifying upland ridges in mountainous terrain for wildfire considerations, wind power location or animal corridors. Downloading and displaying a set of DEMs provides a qualitative glimpse at the topography but most human interpretation becomes overwhelmed by the sheer magnitude of the possibilities and the inability to apply a consistent definition.

A topographic ridge can be defined as a long narrow upper section or raised crest of elevation formed by the juncture of two sloping planes. While the definition of a ridge is straightforward, its practical expression is a bit murkier. Figure 1 outlines a commonly used grid-based map analysis procedure for identifying ridges. The first step involves "smoothing" the surface to eliminate subtle and often artificial elevation changes. This is accomplished by moving a small "roving window" over the surface that averages the localized elevation values in the vicinity of each map location (*1 Scan*).

The next step simulates water falling across the entire project area and moving downhill by the steepest path (*2 Drain*). The computer keeps track of how many uphill locations contribute water to each grid location to generate the flow accumulation map draped over the smoothed elevation surface shown in the upper-left portion of the figure. Note that lower values (grey tones) indicate locations with minimal uphill contributors and align with the elevation crests.

The third step reclassifies the flow map to isolate the locations containing just one runoff path—candidate ridges (*3 Renumber*). However note the cluttered pattern of the map in the upper-right that confuses a consistent and practical definition of a ridge. The final step in the figure uses another roving window operation to assign the majority value in the vicinity of each map location thereby eliminating the "salt and pepper" pattern of the raw ridges (*4 Scan*). If most of the values in the window are 0 (not a potential ridge) then the location is assigned 0. However if there is a majority of potential ridges in the window then a 1 is assigned. The draped display in the lower-left confirms the alignment of the derived ridges with the terrain surface.

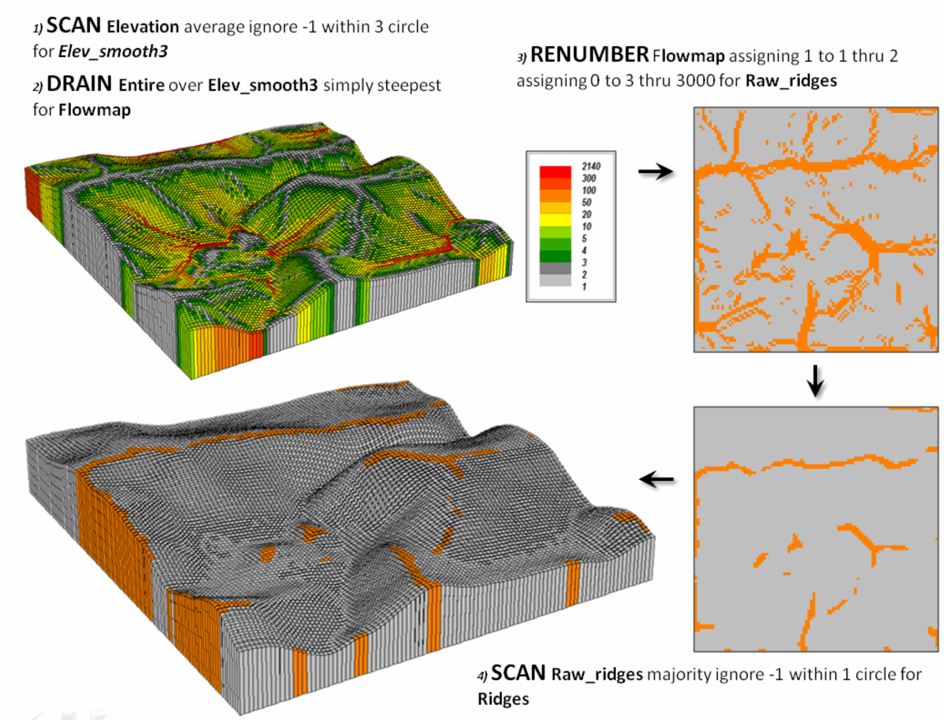

Figure 1. Accumulated surface flow is used to identify candidate ridges.
(MapCalc™ software commands are indicated to illustrate processing options)

Figure 2 continues the processing to identify just the upland ridges. Contiguous ridge locations are individually identified (*5 Clump*) and then the average elevation for each ridge grouping is determined (*6 Composite*). Note the low average elevation of the three small ridges in the center portion of the project area. The final step in the figure (*7 Renumber*) eliminates candidate ridges that are below the average elevation of the project area thereby leaving only the high ridge locations (black).

Figure 3 illustrates the processing steps for expanding the ridges as a function of terrain steepness. A slope map is generated (*8 Slope*) and calibrated to isolate areas of gentle slopes of 0 to 5 percent (*9 Renumber*). In turn, these areas are processed to eliminate the "salt and pepper" pattern (*10 Scan*) leaving relatively large expanses of gentle slopes.

The lower-right map identifies the upland ridges (black) superimposed on the gently sloped areas (red). An effective distance operation (*11 Spread*) is used to extend the ridges considering the non-gently sloped locations (grey) as absolute barriers. The warmer tones in the proximity map draped on the elevation surface indicate increasing distance from a ridge into the surrounding relatively flat areas. Depending on the application the upland ridge expansion could be reclassified from the full extent to just the immediate surrounding areas (green).

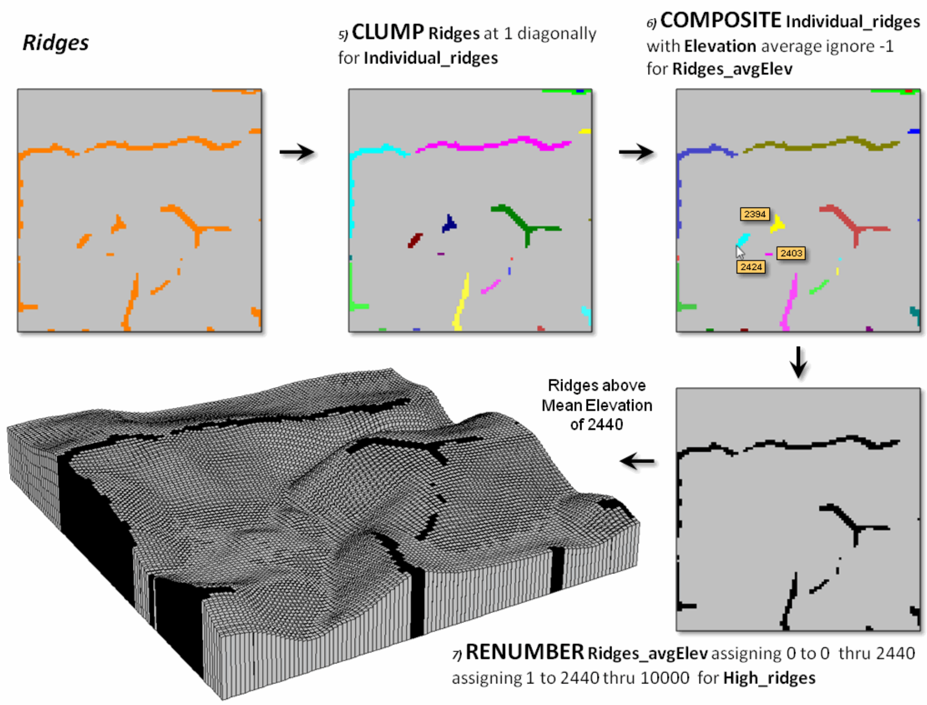

Figure 2. Low ridges are identified and eliminated.

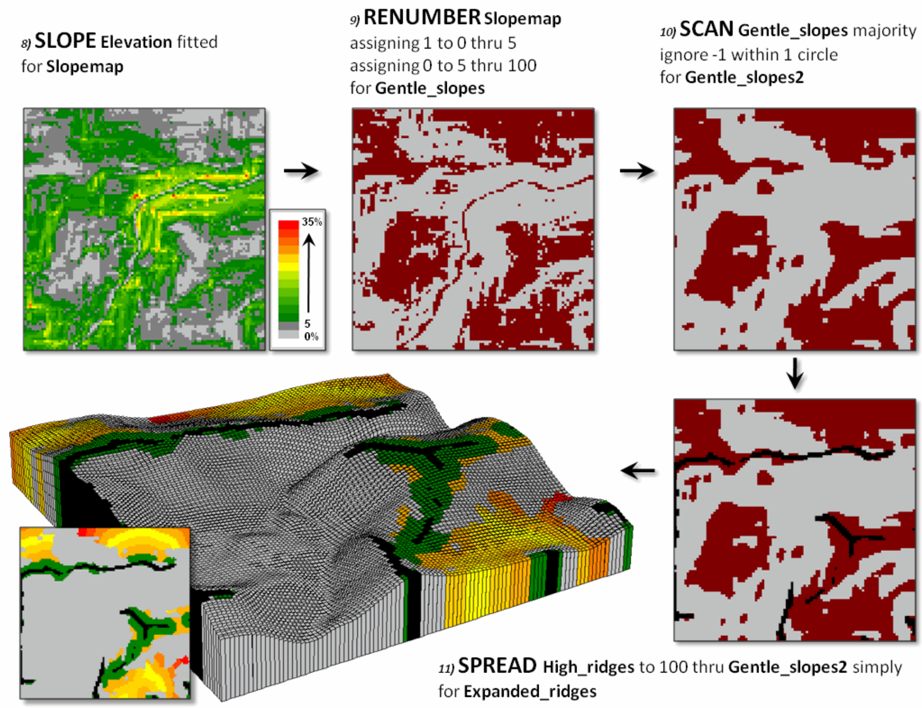

Figure 3. The ridges are extended into surrounding gently sloped areas to identify effective upland ridges.

The simple model may be extended to characterize conditions within the derived ridges. For example, an aspect map can be combined with the extended ridges to indicate their overall terrain orientation or precise azimuth each grid location defining the upland ridges to consider for prevailing wind direction or solar exposure. Another extension could generate an overland travel-time or a road construction surface to consider relative access potential of the ridges.

The bottom line is that it takes a bit of spatial reasoning to translate base maps into decision contexts …it's the analytic nature of GIS that moves it beyond mapping.

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Author's Note: *see the online book Beyond Mapping III, Topic 11, Characterizing Micro Terrain Features at www.innovativegis.com/basis/MapAnalysis/ for additional terrain analysis techniques.*

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