

INCORPORATING GRID-BASED TERRAIN MODELING INTO LINEAR INFRASTRUCTURE ANALYSIS

Joseph K. Berry

*Senior Consultant, New Century Software
Keck Scholar in Geosciences, University of Denver
Principal, Berry & Associates // Spatial Information Systems
2000 South College Avenue, Suite 300, Fort Collins, Colorado, 80525
Email: jberry@innovativegis.com — Website: www.innovativegis.com/basis/*

Nate Mattie

*GIS Developer, New Century Software
2627 Redwing Road, Suite 100, Fort Collins, Colorado 80526
Email: natem@newcenturysoftware.com — Website: www.newcenturysoftware.com*

<Paper presented at GITA Conference, Denver, Colorado, March 6-9, 2005>
<Click here> for a printer-friendly version (.pdf)

ABSTRACT

Grid-based map analysis is increasingly used to characterize conditions and impacts of infrastructure networks, such as pipe and power lines. “Off-line” concerns are driving new regulations for assessing potential impacts and consequences, as well as new demands by corporations for better portrayals of conditions along a linear asset. Terrain-modeling includes a variety of procedures for assessing surface configuration and flows that address these concerns. This paper describes the application of several techniques for determining micro-terrain characteristics (slope/aspect and surface inflection), elevation profile segmentation and characterization and overland flow modeling of spill migration. Particular attention is devoted to the interactions between discrete (vector) and continuous (raster) systems. Discussion is extended to considerations in the practical application of these techniques through several case studies.

INTRODUCTION

Linear infrastructure applications using Geographic Information Systems (GIS) technology traditionally have focused on linking information on asset characteristics and conditions to segments identifying the location of a linear feature. In most instances, traditional geo-referencing is through “stationing” that locates a base point followed by a series of offsets (planimetric distance and direction values) to define individual line segments forming a portion of a route. While this structuring is very efficient for characterizing a route, it is different from mainstream “vector-based” GIS technology that identifies individual segment end points by their geographic coordinates, such as longitude and latitude. “Raster-based” systems are even more different as they represent geographic space as a continuous grid and linear features as a set of adjoining grid cells along a route.

These differences go well beyond the technical aspects of geo-referencing; they identify differences in perspective of applications and business models defining the utility of geo-processing. The “stationing” approach is focused on the linear asset itself, while the “vector”

broadens the focus to other point, line and polygon features surrounding a route. However, both approaches treat geographic space as composed of set of discrete spatial objects analogous to puzzle pieces defining a project area.

“Raster” systems, on the other hand, treat geographic space as a continuum and extend point, line and polygon features to map surfaces. These gradients characterize the spatial distributions of continuous phenomena that continually change throughout geographic space. In addition, this grid-based structure expresses mapped data in a numerical context that supports an extensive set of mathematical and statistical operations for analyzing relationships within and among mapped data layers.

Most contemporary infrastructure software packages have fully integrated the stationing and vector approaches. This bundling provides a wide array of operations for geo-query of spatial databases and mapping the results. In addition, raster images can be geo-registered and used as a backdrop for display resulting in extremely useful systems for constructing, maintaining and querying infrastructure data.

However, applications involving grid-based analysis “off the lines” are less familiar to GIS professionals, managers and policy makers working in infrastructure applications. This paper demonstrates the utility of grid-based map analysis through several examples for determining micro-terrain characteristics, elevation profile segmentation and characterization and overland flow modeling of spill migration in the pipeline industry.

UNDERSTANDING GRID-BASED DATA

For thousands of years, points, lines and polygons have been used to depict map features. With the stroke of a pen a cartographer could outline a continent, delineate a highway or identify a specific building’s location. With the advent of the computer, manual drafting of these data has been replaced by the cold steel of the plotter.

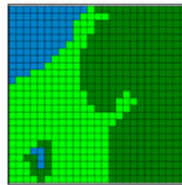
In digital form these spatial data have been linked to attribute tables that describe characteristics and conditions of the map features. Desktop mapping exploits this linkage to provide tremendously useful database management procedures, such as address matching, geo-query and routing. *Vector-based* data forms the foundation of these techniques and directly builds on our historical perspective of maps and map analysis.

Grid-based data, on the other hand, is a relatively new way to describe geographic space and its relationships. Weather maps, identifying temperature and barometric pressure gradients, were an early application of this new data form. In the 1950s computers began analyzing weather station data to automatically draft maps of areas of specific temperature and pressure conditions. At the heart of this procedure is a new map feature that extends traditional points, lines and polygons (discrete objects) to continuous surfaces.

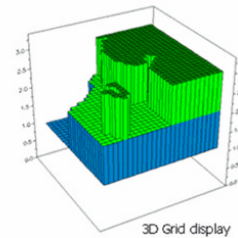
Figure 1 outlines the major differences between discrete and continuous mapped data. **Discrete** maps identify mapped data with independent numbers forming sharp abrupt

boundaries, such as a Covertypes map. **Continuous** maps, on the other hand, contain a range of values that form spatial gradients, such as an Elevation surface.

Covertypes map— values are independent and represent discrete categories (*independent numbers*); map values form sharp abrupt boundaries in geographic space (*abrupt boundaries*)



2D Grid display

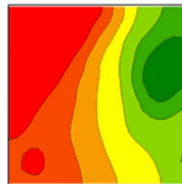


3D Grid display

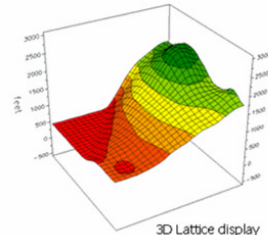
Numeric distribution
Geographic distribution

Discrete	Continuous
<i>independent numbers</i>	<i>range of values</i>
<i>abrupt boundaries</i>	<i>spatial gradient</i>
Discrete	Continuous

Elevation map— values form a continuous range with an absolute reference (*range of values*); map values form a continuous gradient in geographic space (*spatial gradient*)



2D Lattice display



3D Lattice display

Figure 1. Visualizing the differences between discrete and continuous representations of mapped data.

Note that the 3D display of a Covertypes map as a surface is inappropriate as the map values (1= water, 2= meadow and 3= forest) have no numerical relationship with one another and that each feature has a sharp boundary. A surface view of the Elevation map, however, is appropriate as the data is constantly changing. Its 2D contour display is inappropriate as it generalizes the spatial variability into a few broad classes forming polygons that contain a wide range of individual elevation values.

Forcing a continuous spatial variable (surface) into its vector-based representation oversimplifies the spatial pattern and severely limits further analytical processing. The following examples of surface analysis focuses on characterizing terrain conditions and flows as applied in contemporary pipeline industry applications.

MICRO-TERRAIN CHARACTERISTICS

A terrain surface is organized as a rectangular "analysis grid" with each cell containing an elevation value. The upper-left inset in Figure 2 shows a smoothed lattice-display of the elevation surface with its 2D contour lines projected onto the floor of the 3D plot. The larger plot is a grid-display each cell to the relative height of its elevation value.

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").

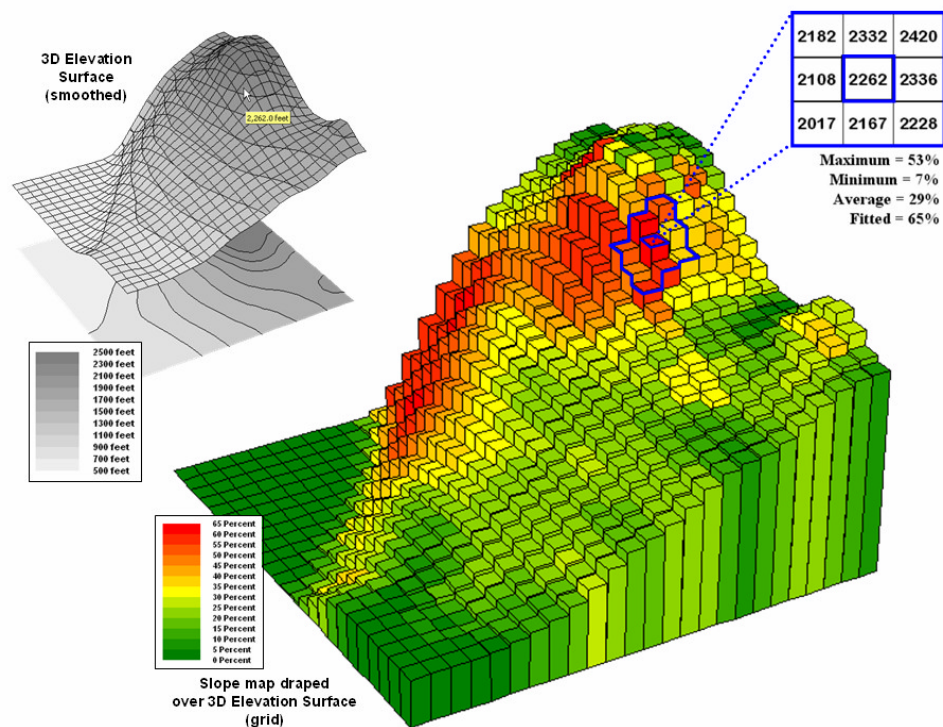


Figure 2. Elevation surface with its slope map graphically overlaid.

In calculating slope, a 3x3 window is used to identify elevation values surrounding an individual grid location as shown on the left side of figure 2. An individual slope value from the center cell can be calculated for each one of the eight adjacent cells. 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 ($328 * 1.414 = 464$).

Note that the sign of the eight individual slope values 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 (to be discussed in the last section on overland flow), the flow away from the cell will take the steepest downhill slope—southwest flow in the example.

The eight slope values can be used to identify the Maximum and Minimum slope as reported in the figure. Note that the large difference between the maximum and minimum slope values ($53 - 7 = 46$) suggests that the overall slope around the center cell is fairly variable.

In addition, the eight individual slopes can be used to calculate transverse and longitudinal slope for locations along a linear feature, such as a proposed pipeline route. In this instance,

the 3x3 window moves along the cells defining the route and separately averages the individual slopes containing the route (longitudinal) and those outside the route (transverse).

An estimate of the overall slope for a location is derived by averaging all eight individual slopes. However, the simple Average can be misleading. It is supposed to indicate the overall slant 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 value is 65%—more than the maximum individual slope.

The 3D grid plot in Figure 2 shows the results derived by "fitting a plane" to the nine elevation values surrounding each map location. Note that larger slope values (reds) align with the steeper areas of the surface, while lower values (greens) align with gentle slopes and flat areas.

The use of a fitted plane for calculations also provides a procedure for calculating aspect (directional orientation at each cell location comprising the surface). The technique uses a bit trigonometry by calculating the “direction cosines” of the fitted plane to identify its orientation as an azimuth value between 0 (north) and 360. For the example location, the azimuth is 221 degrees (SW bearing).

ELEVATION PROFILE SEGMENTATION

Slope is a critical factor in both siting and operating a pipeline. In general, crossing areas of steep slopes are avoided whenever possible when designing new routes. Once a proposed route has been identified slope plays a dominant role in determining the location of compressor facilities along the route.

It is imperative that a meaningful terrain profile is generated. The line segments defining the profile cannot contain elevation values that are significantly higher or lower than the end points or the calculated slope length will be too inaccurate for determining compressor location.

Neither “stationing” nor “vector-based” approaches are aware of the full continuum of elevation values throughout a project area. A “raster-based” system, on the other hand, is fully aware of subtle elevation differences for identifying the peaks and valleys in an elevation surface.

Figure 3 outlines a frequently used technique that involves subtracting a “smoothed elevation” value from the actual elevation value at a given location. A window is used to average the elevations over a several-cell reach in both directions of a route location under consideration. This has the effect of “smoothing” the elevation to its trend line. Subtracting the trend value from the actual elevation determines the type and magnitude of a terrain deflection —positive difference values indicate “convex features” protruding above the surface’s trend line; negative values indicate “concave features.” The magnitude of the difference indicates the relative height (or depth) of the micro terrain feature.

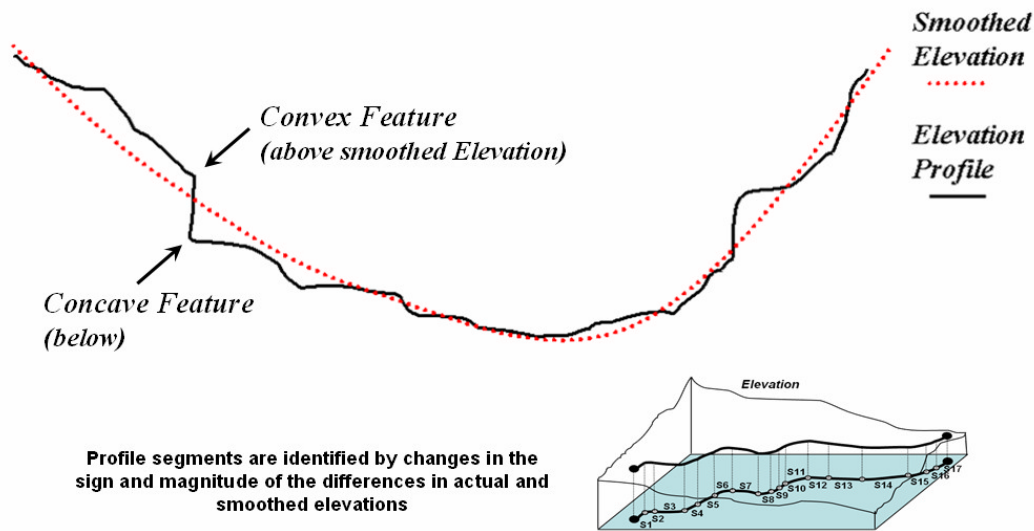


Figure 3. Identifying Convex and Concave features by deviation from the terrain's trend.

In segmenting the terrain along a proposed route, a change in sign indicates an inflection point that can be used as an end point for terrain segments. If the change in sign isn't significant (small value) then a break is not warranted. The schematic at the bottom of figure 3 illustrates the variable length of segments defined by coincidence of a proposed route with major inflection points along an elevation surface.

OVERLAND FLOW MODELING

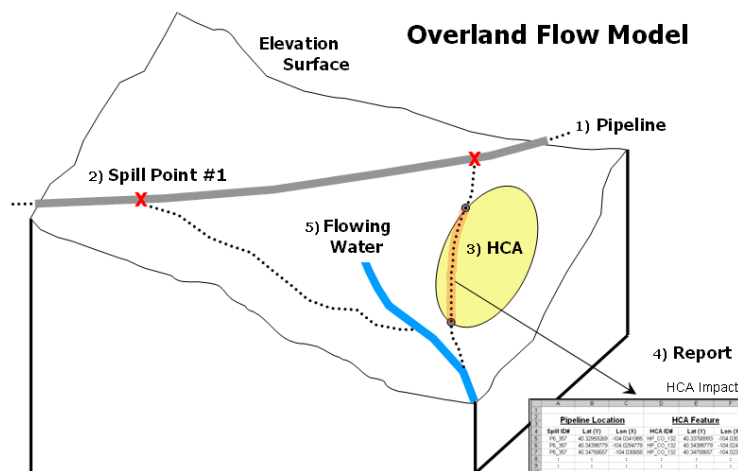
Now consider a far more complex terrain analysis problem. The pipeline industry has been mandated to determine the flows that would occur if a release were to happen at any location along a pipeline route. Figure 4 outlines the major steps of an "Overland Flow" model that tracks potential spill migration. The first step positions a pipeline on an elevation surface. Then a spill point along the pipeline is identified and its overland flow path (downhill) identified. In an iterative fashion, successive spill points and their paths are identified.

High Consequence Areas (HCAs) are delineated on maps prepared by the Office of Pipeline Safety. These include areas such as high population concentrations, drinking water supplies and critical ecological zones. The HCAs impacted by individual spills are identified and recorded in a database table. The final step identifies where paths enter streams or lakes and passes the information to a Channel Flow module.

Developing a realistic model of overland flow is complex and needs to consider differences in terrain slopes, product types and intervening conditions. In addition, information on the timing and quantity of flow as the path progresses is invaluable in spill migration planning.

At the heart of the solution is the ability to identify path flow. As mentioned in the previous discussion on calculating slope, the sign of the eight individual slopes surrounding a grid location on an elevation surface identifies the direction of flow with negative values

indicating flows away from the center cell. The magnitude of the slope value indicates how steep the step is.



- 1) The *Pipeline* is positioned on the *Elevation* surface
- 2) Flow from *Spill Points* along the pipeline are simulated
- 3) *High Consequence Areas* (HCA) are identified
- 4) A *Report* is written identifying flow paths that cross HCA areas
- 5) Overland flow is halted when Flowing Water is encountered (Channel Flow Model)

Figure 4. Spill mitigation for pipelines identifies high consequence areas that could be impacted if a spill occurs anywhere along a pipeline.

Figure 5 illustrates two downhill paths over a terrain surface. A starting point on the surface is identified and the computer simulates the downhill route by selecting “the steepest downhill path” at each step along the grid surface.

As shown in the enlarged inset on the right side of the figure, a location along the path could potentially flow to any of its neighboring cells. Uphill possibilities with larger elevation values are immediately eliminated. The steepest downhill step is determined and path flow moves to that location. The process is repeated over and over to identify the steps along the steepest downhill path.

This procedure works nicely until reality sets in. What happens when a flat area is encountered? No longer is there a single steepest downhill step because all surrounding elevation values are equal or larger. Obviously the flow doesn’t stop; it simply spreads out into the flat area. In this instance the algorithm must incorporate code that continues spreading as shown in the figure. The “steepest downhill path, then stop at flat areas” approach is not sufficient. Nor is a path that simply shoots a straight line across a flat area a realistic solution.

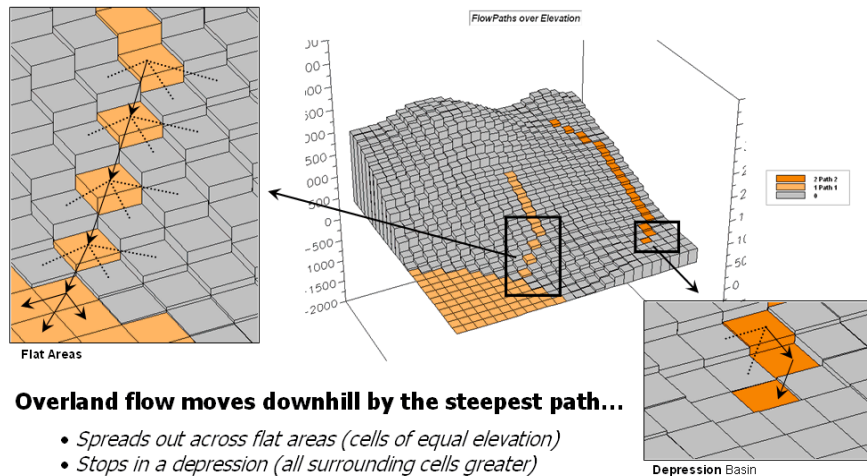


Figure 5. Surface flow takes the steepest downhill path whenever possible but spreads out in flat areas and pools in depressions.

However, realistic flow modeling is even more subtle than that. Areas of very gentle slope but not perfectly flat tend to exhibit sheet flow and spread out to all of the slight downhill locations. Figure 6 depicts the different conditions for path, sheet and flat flow.

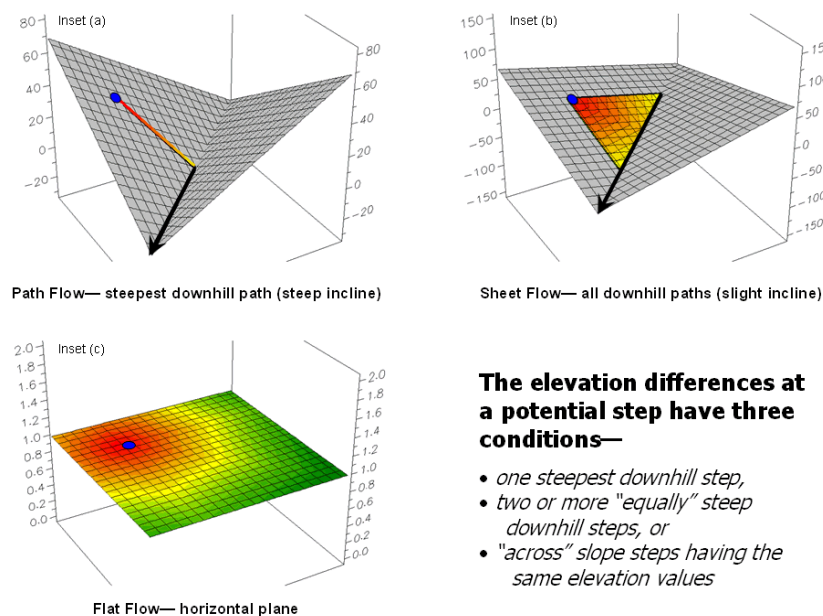


Figure 6. Surface inclination and liquid type determine the type of surface flow—path, sheet or flat.

Incorporating sheet flow into the algorithm inserts a test that determines if the steepest downhill step is less than a specified angle—if so, then steps to all of the downhill locations are taken. Another confounding condition occurs when there are equally steep downhill possibilities. In this instance both steps are taken and the flow path broadens or splits.

By far the trickiest flow for a computer to simulate is pooling. Figure 7 shows a path that seemingly stops when it reaches a depression. In this instance, all of the elevation values around it are larger and there are no downhill or across steps to take. As flow continues the depression fills. When the quantity reaches the height of the smallest elevation surrounding the depression the flow moves into it.



When overland flow encounters a depression...

- "Rising <value>" incrementally increases the elevation of the depression spreading to adjoining elevations with each increase
- Tests to see if there if a new downhill/across step is reached
- Continues downhill path if the depression lip is breached
- Or stops when the "Rising" value is reached (pooling quantity)

Figure 7. Pooling of surface flow occurs when depressions are encountered.

This is the same procedure the computer algorithm uses. It searches the neighboring cells for the smallest elevation, fills to that level, and then steps to that location. The procedure of filling and stepping is repeated until the lip of the depression is breached and downhill flow can resume.

Another possibility is that the quantity of flowing liquid is exhausted and the path terminated at a pooling depth that fails to completely fill the depression. The idea of tracking flow quantity, as well as elapsed time, along a flow path is an important one, particularly when modeling pipeline spill migration. If a stream channel is encountered, the spill quantity and timing for the entry point is automatically transferred to a vector-based channel flow module and continues along the stream network for a specified distance or time.

Figure 8 shows real-world results from the Spill Migration AnalystTM module to ArcGIS by New Century Software, Incorporated. The user supplies information about pipeline characteristics, product type and spill simulation locations or spacing. The software moves along the pipeline stopping at a specified location and then generates a simulated overland spill path and channel flow if a stream is encountered. The primary map out is an alignment sheet identifying the HCA's impacted by sections of the pipeline.

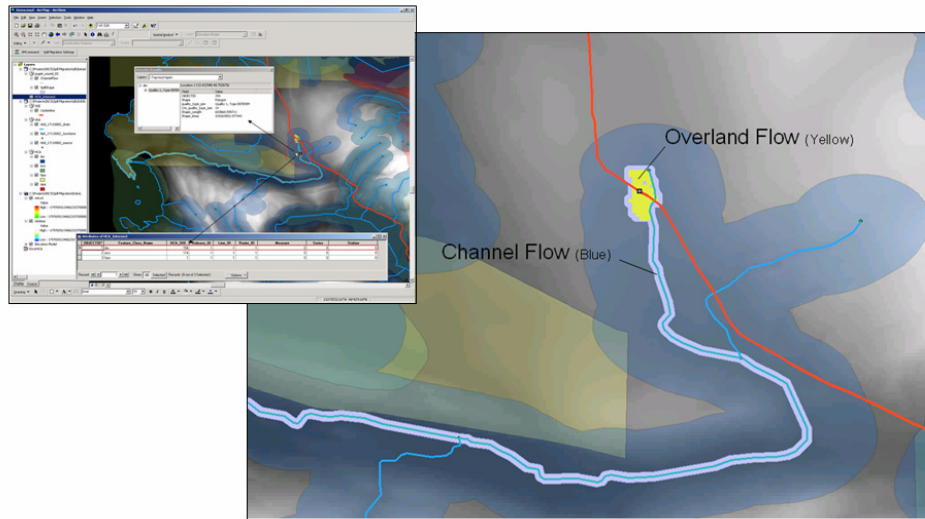


Figure 8. Example output from Spill Migration AnalystTM.

The spill migration output can be integrated into an alignment sheet format identifying the HCA's impacted by sections of the pipeline. In addition, grid-based maps are generated that identify the maximum quantity and minimum time to reach all locations impacted by at least one simulated flow path. HCA's that are coincident with the overland and channel flow paths are identified in a tabular report. A report is generated identifying the geographic coordinates, elapsed time and quantity remaining for the entry and exit points. This information can be summarized into standard and custom reports.

CONCLUSION

Grid-based map analysis procedures provide a wealth of capabilities for incorporating terrain information surrounding linear infrastructure. Although the procedures described have important practical applications, a hidden agenda of the discussions was to get readers 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).

ONLINE REFERENCES

See the online book Map Analysis by Joseph K. Berry (BASIS Press) that is posted at www.innovativegis.com/basis

Select the following topics for more information on grid-based map analysis and procedures for analyzing terrain conditions and flows (listed in order of discussion this paper):

- Topic 18, Understanding Grid-based Data
- Topic 11, Characterizing Micro Terrain Features
- Topic 20, Surface Flow Modeling
- Topic 19, Routing and Optimal Paths

Paper with full color figures is posted online at www.innovativegis.com/basis/Present/GITA_Denver05/