Topic 6

Applying Effective Distance

6.1 Calculating Hiking-Time

Travel-time maps are most often used within the context of a road system connecting people with places via their cars. Network software is ideal for routing vehicles by optimal paths that account for various types of roads, one-way streets, intersection stoppages and left/right turn delays. The routing information is relatively precise and users can specify preferences for their trip—shortest route, fastest route and even the most scenic route.

In a way, network programs operate similar to the grid-based travel-time procedure discussed in the last two columns. The cells are replaced by line segments, yet the same basic concepts apply—absolute barriers (anywhere off roads) and relative barriers (comparative impedance on roads).

However, there are significant differences in the information produced and how it is used. Network analysis produces exact results necessary for navigation between points. Grid-based travel-time analysis produces statistical results characterizing regions of influence (i.e., effective buffers). Both approaches generate valid and useful information within the context of an application. One shouldn't use a statistical travel-time map for routing an emergency vehicle. Nor should one use a point-to-point network solution for site location or competition analysis within a decision-making context.

Neither does one apply on-road travel-time analysis when modeling off-road movement. Let's assume you are a hiker and live at the ranch depicted in figure 6-1. The top two "floating" map layers on the left identify *Roads* and *Cover_type* in the area that affect off-road travel. The *Locations* map positions the ranch and a nearby cabin.

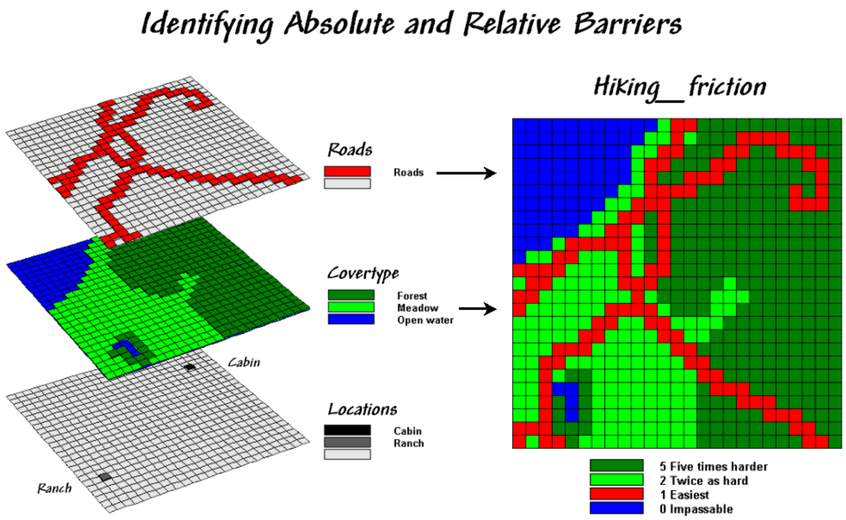


Figure 6-1. Maps of Cover Type and Roads are combined and reclassified for relative and absolute barriers to hiking.

In general, walking along the rural road is easiest and takes about a minute to traverse one of the grid cells. Hiking in the meadow takes twice as long (about two minutes). Hiking in the dense forest, however is much more difficult, and takes about five minutes per cell. Walking on open water presents a real problem for most mortals (absolute barrier) and is assigned zero in the *Hiking_friction* map on the right that combines the information.

Now the stage is set for calculating foot-traffic throughout the entire project area. Figure 2 shows the result of simulating hiking from the *Ranch* to everywhere using the “splash” procedure described in the previous two columns. The *distance waves* move out from the ranch like a “rubber ruler” that bends, expands and contracts as influenced by the barriers on the *Hiking_friction map*—fast in the easy areas, slow in the harder areas and not at all where there is an absolute barrier.

The result of the calculations identifies a travel-time surface where the map values indicate the hiking time from the *Ranch* to all other map locations. For example, the estimated time to slog to the farthest point is about 62 minutes. However, the quickest hiking route is not likely a straight line to the ranch, as such a route would require a lot of trail-whacking through the dense forest.

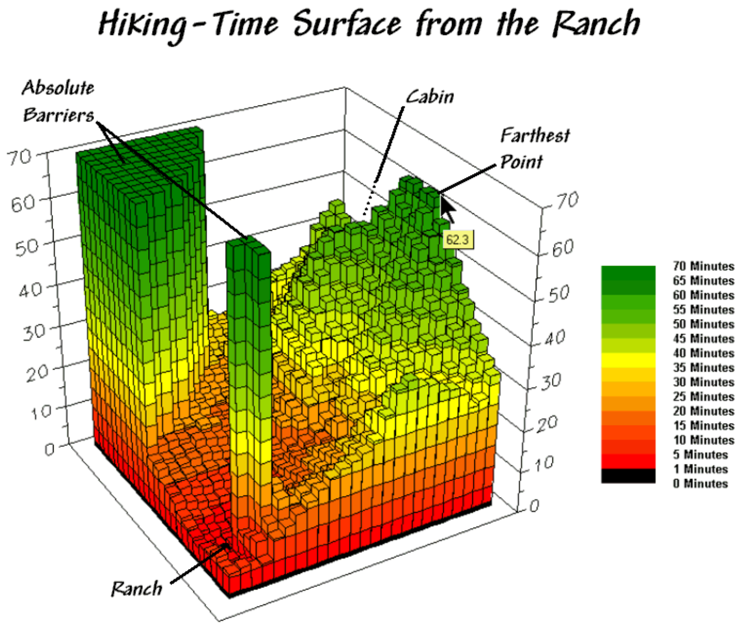


Figure 6-2. The hiking-time surface identifies the estimated time to hike from the Ranch to any other location in the area. The protruding plateaus identify inaccessible areas (absolute barriers) and are considered infinitely far away.

The surface values identify the shortest hiking time to any location. Similarly, the values around a location identify the relative hiking times for adjacent locations. “Optimal” movement from a location toward the ranch chooses the lowest value in the neighborhood—one step closer to the ranch.

The “not-necessarily-straight” route that connects any location to the ranch by the quickest pathway is determined by repeatedly moving to the lowest value along the surface at each step—the steepest downhill path. Like rain running down a hillside, the unique configuration of the surface guides the movement. In this case, however, the guiding surface is a function of the relative ease of hiking under different *Roads* and *Cover_type* conditions.

Actually, the optimal path retraces the effective distance wave that got to a location first—the quickest route in this case. The 3D display in figure 6-3 isolates the optimal path from the ranch to the cabin. The surface value (36.5) identifies that the cabin is about a 36-minute hike from the ranch.

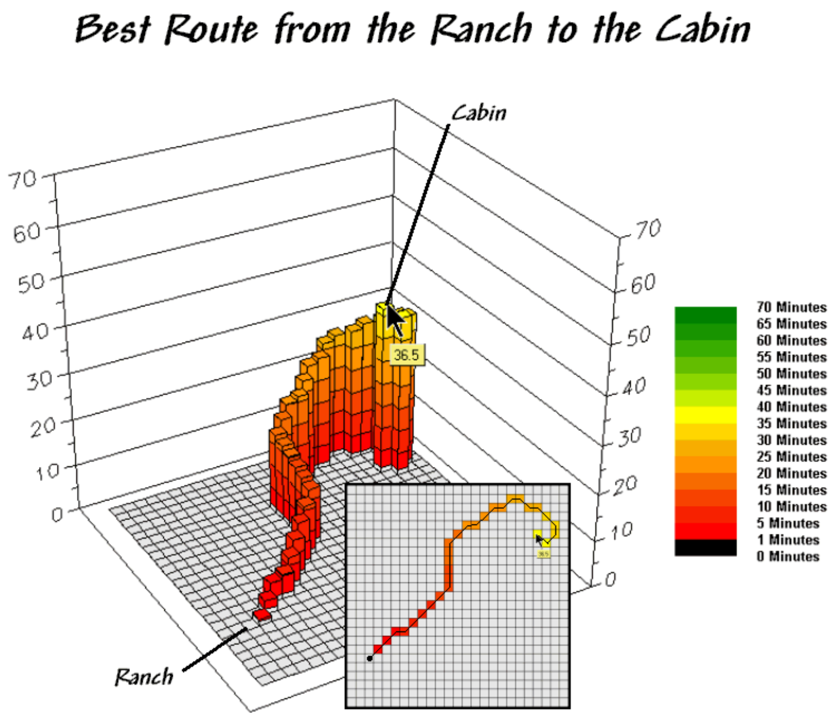


Figure 6-3. The steepest downhill path from a location (Cabin) identifies the "best" route between that location and the starter location (Ranch).

The 2D map depicts the route and can be converted to X,Y coordinates that serve as waypoints for GPS navigation. The color zones along the route show estimated hiking times for each "cell-step"… -ideal for answering that nagging question, "Are we there yet?" Next time we'll take the analysis a step further to investigate the effects of other friction surfaces and the concept of "optimal path density." See you then.

6.2 Incorporating Effective Distance

"It's the second mouse that gets the cheese." While effective proximity and travel-time procedures have been around for years, it is only recently that they are being fully integrated into GIS applications. So why is there a time lag from the innovator's use to the current "born again" use? Two factors seem most likely—the new generation of software makes the procedures much easier, and a growing consciousness of new ways of doing things.

Distance measurement as the "shortest, straight line between two points" has been with us for thousands of years. The application of the Pythagorean Theorem for measuring distance is both conceptually and mechanically simple. However in the real world, things rarely conform to the simplifying assumptions that all movement is between two points and in a straight line.

Last section described a procedure for calculating a hiking-time map. The approach eliminated the assumption that all measurement is between two points and evolved the concept of distance to one of ***proximity***. The introduction of absolute and relative barriers addressed the other assumption that all movement is in a straight line and extended the concept a bit further to that of ***effective proximity***. The discussion ended with how the hiking-time surface is used to identify an ***optimal path*** from any location to the starting location—the shortest but not necessarily straight route.

Now the stage is set to take the concept a few more steps. The top right map in figure 6-4 is the friction map used last time in deriving the hiking-time surface. It assumes that it takes 1 minute to hike across a road cell, 2 minutes for a meadow cell, and 3 minutes for a forested one. Open water is assigned 0 as you can't walk on water and it takes zero minutes to be completely submerged. But what about slope? Isn’t it harder to hike on steep slopes regardless of the land cover?

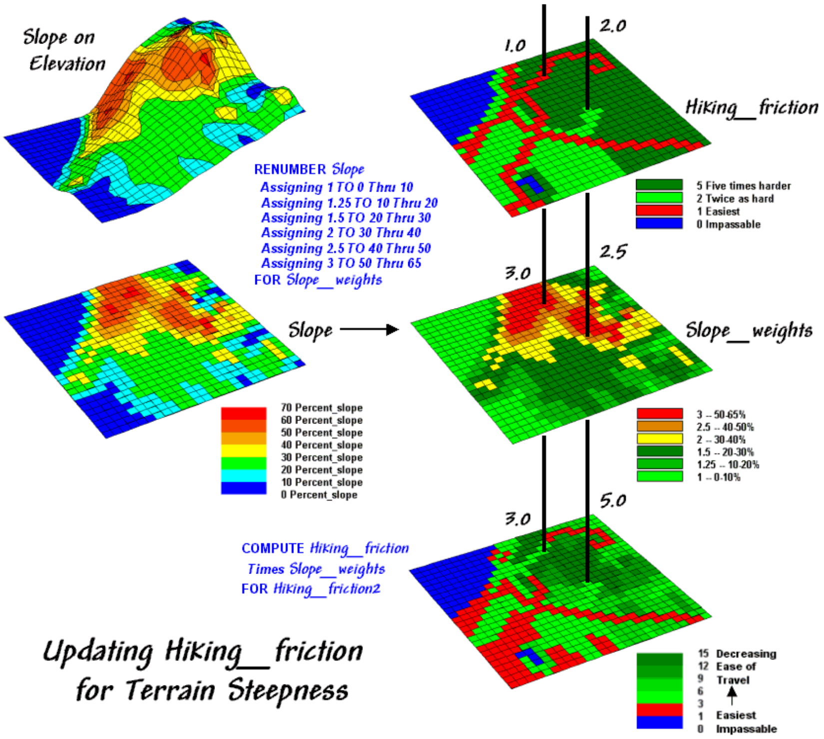


Figure 6-4. Hiking friction based on Cover Type and Roads is updated by terrain slope with steeper locations increasing hiking friction.

The slope map on the left side of the figure identifies areas of increasing inclination. The “Renumber” statement assigns a weight (figuratively and literally) to various steepness classes— a factor of 1.0 for gently sloped areas through a factor 3.0 for very steep areas. The “Compute” operation multiplies the map of *Hiking_friction* times the *Slope_weights* map. For example, a road location (1 minute) is multiplied by the factor for a steep area (3.0 weight) to increase that location’s friction to 3.0 minutes. Similarly, a meadow location (2 minutes) on a moderately step slope (2.5 weight) results in 5.0 minutes to cross.

The effect of the updated friction map is shown in the top portion of figure 6-5. Viewing left to right, the first map shows simple friction based solely on land cover features. The second map shows the slope weights calibrated from the slope map. The third one identifies the updated friction map derived by combining the previous two maps.

The 3D surface shows the hiking-time from the ranch to all other locations. The two tall pillars identify areas of open water that are infinitely far away to a hiker. The relative heights along the surface show hiking-time with larger values indicating locations that are farther away. The farthest location (highest hill top) is estimated to be 112 minutes away. That’s nearly twice as long as the estimate using the simple friction map presented last month—those steep slopes really take it out of you.

The lower set of maps in figure 6-5 reflects an entirely different perspective. In this case, the weights map is based on aesthetics with good views of water enhancing a hiking experience. While the specifics of deriving a “good views of water” map are reserved for next month, it is sufficient to think of it as analogous to a slope map. Areas that are visually connected to the lakes are ideal for hiking, much like areas of gentle terrain. Conversely, areas without such views are less desirable comparable to steep slopes.

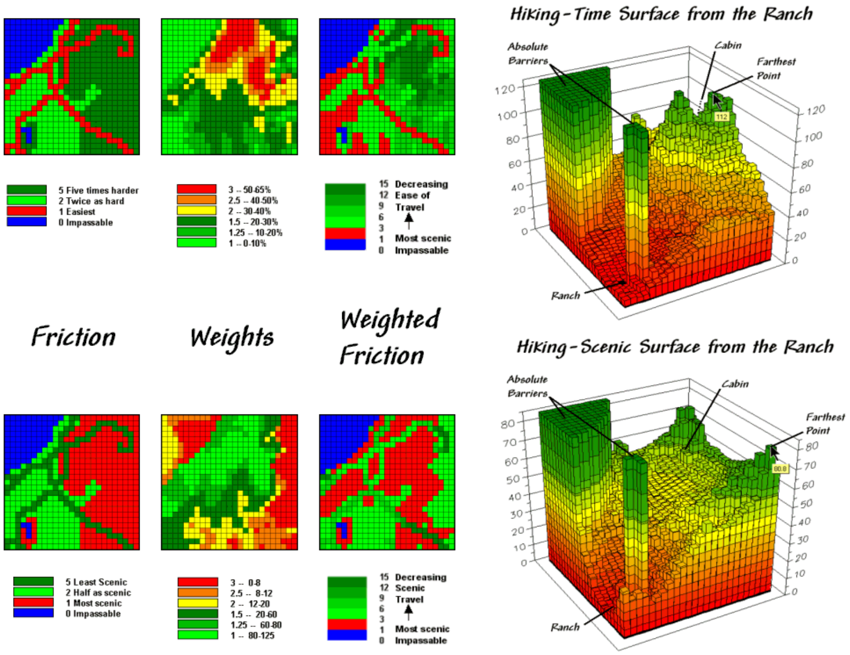
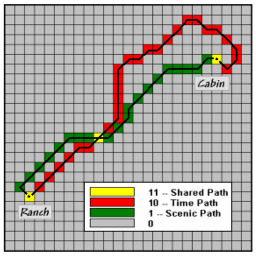
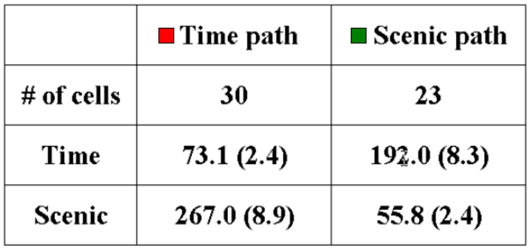


Figure 6-5. Hiking movement can be based on the time it takes move throughout a study area, or a less traditional consideration of the relative scenic beauty encountered through movement.

The map processing steps for considering aesthetics are identical—calibrate the visual exposure map for a *Beauty_weights* map and multiply it times the basic *Hiking_friction* map. The affect is that areas with good views receive smaller friction values and the resulting map surface is biased toward more beautiful hikes. Note the dramatic differences in the two effective proximity surfaces. The top surface is calibrated in comfortable units of minutes. But the bottom one is a bit strange as it implies accumulated scenic beauty while respecting the relative ease of movement in different land cover.

The pair of hiking paths depicted in figure 6-6 identifies significantly different hiking experiences. Both represent an optimal path between the ranch and the cabin; however the red one is the quickest, while the green one is the most beautiful. As discussed last month, an optimal route is identified by the "steepest downhill path" along a proximity surface. In this case the surfaces are radically different (time vs. scenic factors) so the resulting paths are fairly dissimilar.





	🟥 Time path	🟩 Scenic path
# of cells	**30**	**23**
Time	**73.1 (2.4)**	**192.0 (8.3)**
Scenic	**267.0 (8.9)**	**55.8 (2.4)**

Figure 6-6. The "best" routes between the Cabin and the Ranch can be compared by hiking time and scenic beauty.

The table in the figure provides a comparison of the two paths. The number of cells approximates the length of the paths—a lot a longer for the "Time path" route (30 vs. 23 cells). The estimated time entries, however, show that the "Time path" route is much quicker (73 vs. 192 minutes). The scenic entries in the table favor the "Scenic path" (267 vs. 56). The values in parentheses report the averages per cell.

But what about a route that balances time and scenic considerations? A simple approach would average the two weighting maps, and then apply the result to the basic friction map. That would assume that time loss in very steep areas is compensated by gains in scenic beauty. Ideally, one would want to bias a hike toward gently sloping areas that have a good view of the lakes.

How about a weighted average where slope or beauty is treated as more important? What about hiking considerations other than slope and beauty? What about hiking trail construction and maintenance concerns? What about seasonal effects? …that's the beauty of GIS modeling—it starts small then expands.

6.3 Basics of Surface Flow

The previous section focused on effective distance and connectivity. This section expands on the techniques to characterize surface flows over a digital terrain surface. It is common sense when hiking that steeper slopes result in faster downhill movement—particularly when falling.

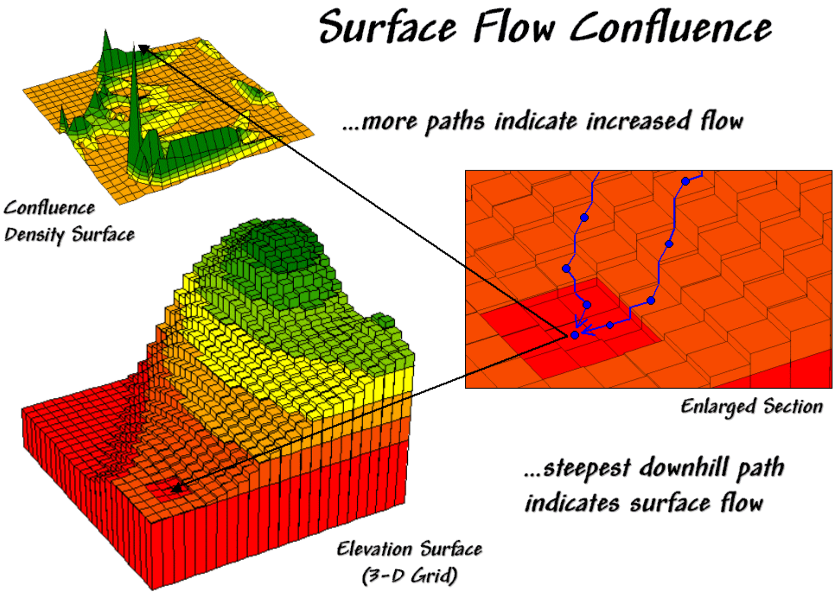


Figure 6-7. Map of surface flow confluence.

Water has a similar vantage point of the slopes it encounters, except that when given its head water will take the steepest downhill path (sort of like an out-of-control skier). Figure 6-7 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.

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 6-8. 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.

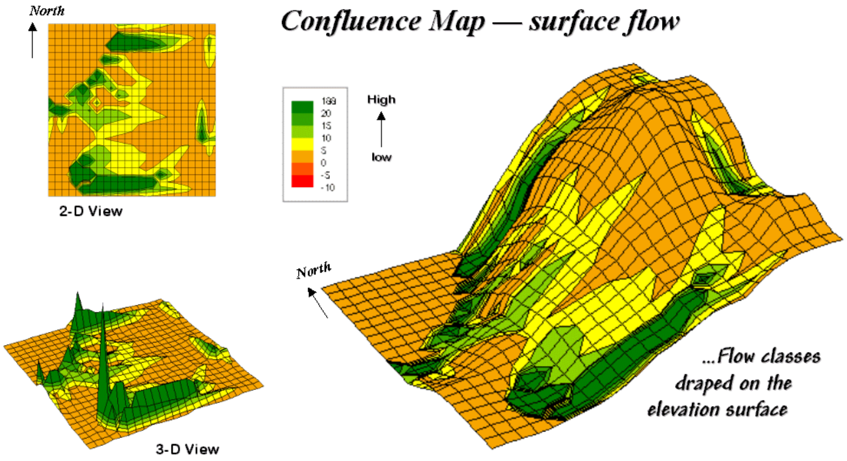


Figure 6-8. 2-D, 3-D and draped displays of surface flow confluence.

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.

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.

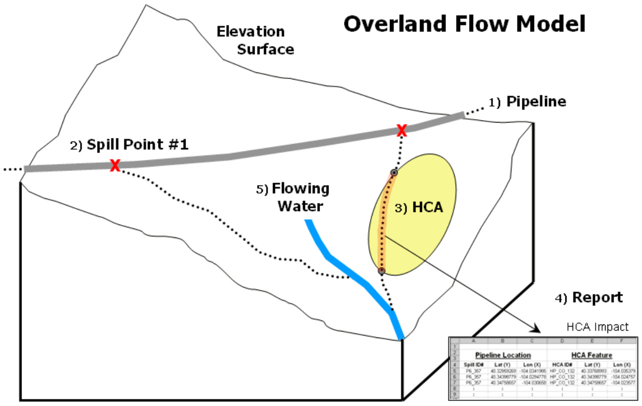
The more important limitation is intellectual. For decades, manual measurement, photo interpretation and process modeling approaches have served as input for decision-making involving terrain conditions. Instead of using GIS to simply automate the existing procedures our science needs to consider the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

6.4 Characterizing Overland Flow

Common sense suggests that “water flows downhill” however the corollary is “…but not always the same way.” Similarly, overland flow modeling in a GIS is a bit more complicated than simply choosing the steepest downhill path.

The liquid 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—that could be from Wyoming to Missouri or Texas. However, the GIS solution, in many ways, is as challenging from a modeling perspective as it is from its awesome geographic breadth.

Figure 6-9 outlines the major steps of an *Overland Flow* model for tracking 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.



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 6-9. Spill mitigation for pipelines identifies high consequence areas that could be impacted if a spill occurs anywhere along a pipeline.

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 (subject for future discussion).

The centerline of the pipeline usually is stored as a series of vector lines in an existing corporate database. USGS's National Elevation Data (NED) data set is available for the entire U.S. as 30-meter grid of elevation values. Merging the data sets involves vector to raster conversion of the pipeline to form a consistent 30-meter database for analysis. Keep in mind that this is a bit of a task as thousands of miles of pipeline often are involved. Developing a database design that seamlessly traverses gigabytes of grid cells in an efficient manner is quite a challenge.

Developing a realistic model of overland flow is just as challenging. Real world flows are complex and need 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.

The top portion of figure 6-10 shows the spill patterns for three different locations along a pipeline assuming perfectly flat terrain. The jagged edges of the patterns result from approximating circles through grid-based proximity analysis. The progressively larger rings are analogous to slowly dripping coffee on your desk …first a small spill, then growing a little larger and a little larger, etc.

Now let's add a bit reality. The middle series of maps identify the elevation surface for the area. The insets on the right show the downhill locations from each of the three spill points. The colored bands identify increasing distance with red tones identifying locations close to a spill.

A final bit of reality recognizes that not all downhill locations affect flow in the same manner. The *Flow Impedance* map at the lower left incorporates the effects of terrain slope on flow velocity. In flat or gently sloped areas (<2% slope), flow is gradual and can take several minutes to traverse a 30 meter cell. In steep areas, on the other hand, the same distance can take far less than a minute.

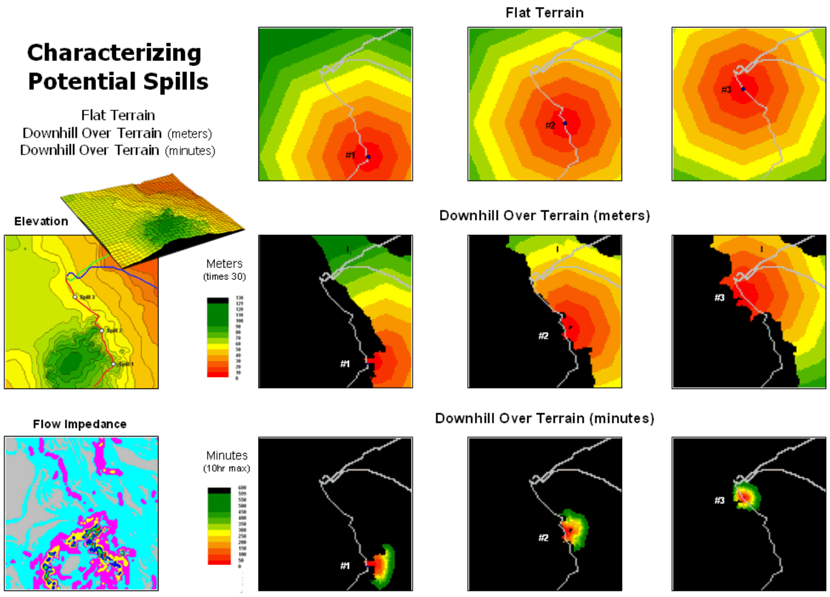
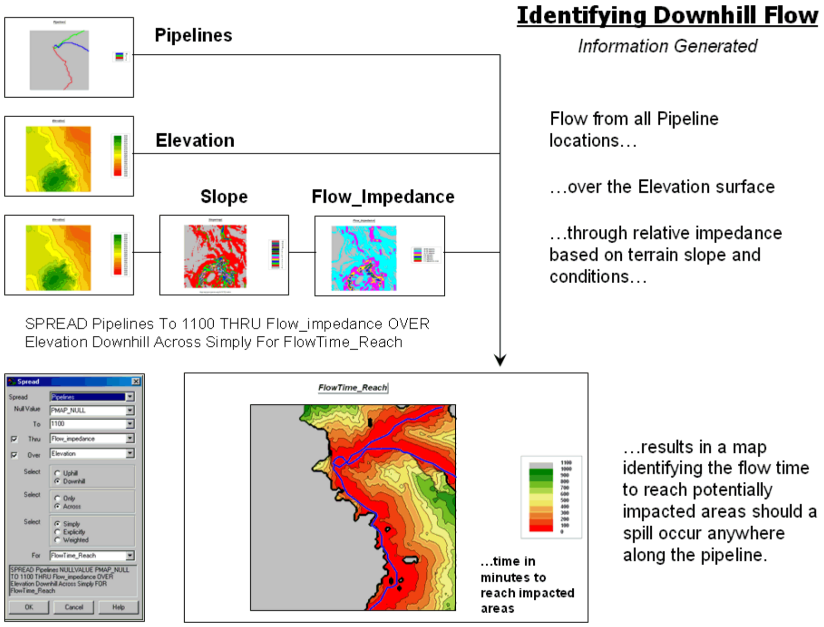


Figure 6-10. Overland flow can be characterized as both distance traveled and elapsed time.

This information is taken into account to generate maps at the bottom-right of figure 6-8. The results show a downhill flow “reach” of several hours for the three simulated spill points. Note that most of the flow occurs on very gentle slopes (cyan and light grey on the Flow Impedance map) so progress isn’t very fast or far.

Figure 6-11 depicts the processing flowchart and results for simulating overland flow from all locations defining the pipeline. The procedure is analogous to tossing a stick shaped like the pipeline into a pond. Ripples move outward indicating increasing distance. However in this instance, the waves can’t go uphill and the shortest elapsed time to reach any location is calculated.

The grey areas on the resultant map identify uphill locations (infinitely far away). The red tones identify areas that are relatively close to the pipeline. They progress to green tones identifying locations that are several hours away.



```
SPREAD Pipelines To 1100 THRU Flow_impedance OVER
Elevation Downhill Across Simply For FlowTime_Reach
```

```
SPREAD Pipelines NULLVALUE PMAP_NULL
TO 1100 THRU Flow_impedance OVER
Elevation Downhill Across Simply FOR
FlowTime_Reach
```

Figure 6-11. Effective downhill proximity from a pipeline can be mapped as a variable-width buffer.

As we’ll see in the next section, things get even more complex as various terrain conditions (path, sheet, flat flow and pooling) and product properties (viscosity, release amount, etc.) come into play. The bottom line is that the traditional approach of choosing just the steepest downhill path for characterizing overland flow doesn’t hold water.

6.5 Constructing Realistic Downhill Flows

The instinct of a herd of rain drops is unwavering. As soon as they hit the ground they start running downhill as fast as they can. But not all downhill options are the same. Some slopes are extremely steep and call the raindrops like a siren. Other choices are fairly flat and the herd tends to spread out. Depressions in the terrain cause them to backup and pool until they can break over the lip and start running downhill again.

In overland flow modeling these conditions are termed path, sheet, flat and pooling flows. Figure 6-12 depicts two downhill paths over a terrain surface that is displayed in its raw form as grid cells raised to the relative height of their elevation values. A starting point on the surface is identified and the computer simulates the downhill route.

As shown in the enlarged inset on the right, a location along the *path flow* could potentially move to any of its neighboring cells. Uphill possibilities with larger elevation values are immediately eliminated (educated raindrops). 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.

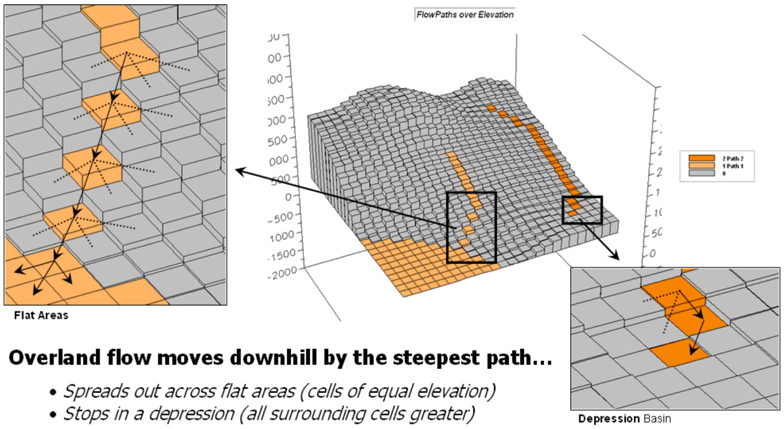


Figure 6-12. Surface flow takes the steepest downhill path whenever possible but spreads out in flat areas and pools in depressions.

This procedure works nicely until reality sets in. What happens when flat areas are 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 follow the raindrop's lead and incorporate code that continues spreading as shown in the figure. The "steepest downhill path, then stop" approach isn't sufficient. Nor is a path that simply shoots a straight line across the flat area a realistic solution.

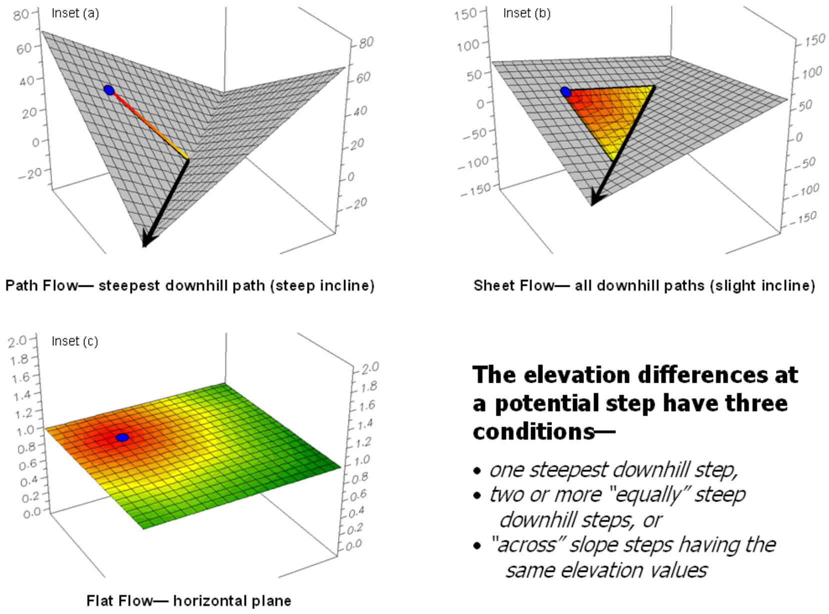


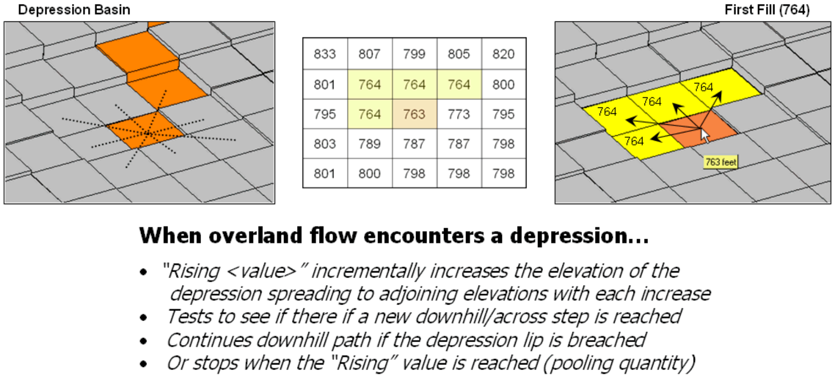
Figure 6-13. Surface inclination and liquid type determine the type of surface flow—path, sheet or flat.

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 6-13 depicts the different conditions for path, sheet and flat flow.

The upper-left inset (a) shows the steepest downhill path in areas of steep terrain. Inset (b) shows the sheet flow widening to all downhill locations when inclination is slight.

Inset (c) depicts the *flat flow* going in all directions on perfectly flat terrain. As an empirical test, the next time you are doing the dishes hold a cutting board under the faucet and watch the water pattern change as you tilt the board from horizontal to steeper inclinations—flat, sheet then increasingly narrow path flows.

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 subtle 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.



833	807	799	805	820
801	764	764	764	800
795	764	763	773	795
803	789	787	787	798
801	800	798	798	798

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 6-14. Pooling of surface flow occurs when depressions are encountered.

By far the trickiest movement for a computer to simulate is *pooling flow.* Figure 6-14 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 more and more raindrops backup in confusion they start filling the depression. When they reach the height of the smallest elevation surrounding them they flow into it.

That 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 flow downhill can resume.

Another possibility is that the quantity of flowing liquid is exhausted and the path is 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. That discussion is reserved for next month.

6.6 Calculating Flow Time and Quantity

The last couple of sections have investigated overland flow modeling with a GIS. The basic approach was introduced and some of the extended procedures needed to simulate realistic flows were discussed. While the steepest downhill path is a raindrop's first choice, *path* flow becomes *sheet* flow when inclination is minimal and *flat* flow in perfectly flat terrain.

A fourth type of flow—*pooling*—occurs when a depression is encountered. In this instance flow continues rising until it fills the depression and can proceed further downhill or the available quantity of liquid is trapped.

The introduction of flow quantity and timing are important concepts in modeling pipeline spill events. It's common sense that a 100 barrel release won't travel as far as a 1000 barrel release from the same location. Similarly, a "gooey" liquid takes longer to flow over a given distance than a "watery" one.

So how does the computer track retained quantity and elapsed time along a spill path? Several factors come into play involving cell size, properties of the liquid, terrain configuration and intervening conditions. Viscosity and specific gravity determine the “gooeyness” of flowing liquid and the effective depth of the flow.

This, plus the steepness of the terrain, determines the amount of liquid that is retained on the surface at each location. Add an infiltration factor for seepage into the soil and you have a fairly robust set of flow equations. In mathematical terms, this relationship can be generalized as—

Quantity Retained = fn [cellsize, flow depth, slope angle, soil permeability]

Flow Velocity = fn [viscosity, specific gravity, flow depth, slope angle]

Implementing the cascading flow in a GIS requires map-ematically solving fully defined equations at each step along the path. The user specifies the physical properties of the product, the local soil map determines the permeability and the elevation surface is used to calculate the slope angles.

In terms of pipeline spill mitigation, the quantities of jet fuel (thin) or crude oil (thick) that are retained along a flow path can be dramatically different. Equally striking are the differences in quantities that seep into dissimilar soil types. Also, if the spill occurs when the soil is saturated or frozen, infiltration will be minimal with nearly all of the quantity continuing along the path. Coding for all of these contingencies is what makes a spatially-specific model particularly challenging.

Figure 6-15 shows the overland flow from a simulated spill. It is a conservative estimate as the simulation assumes sheet/flat flow at minimal inclinations, no soil infiltration and an unlimited quantity of liquid. In addition, the flow is measured in units of time by successively adding the time to cross each grid cell (time= cell length / flow velocity) as the flow proceeds.

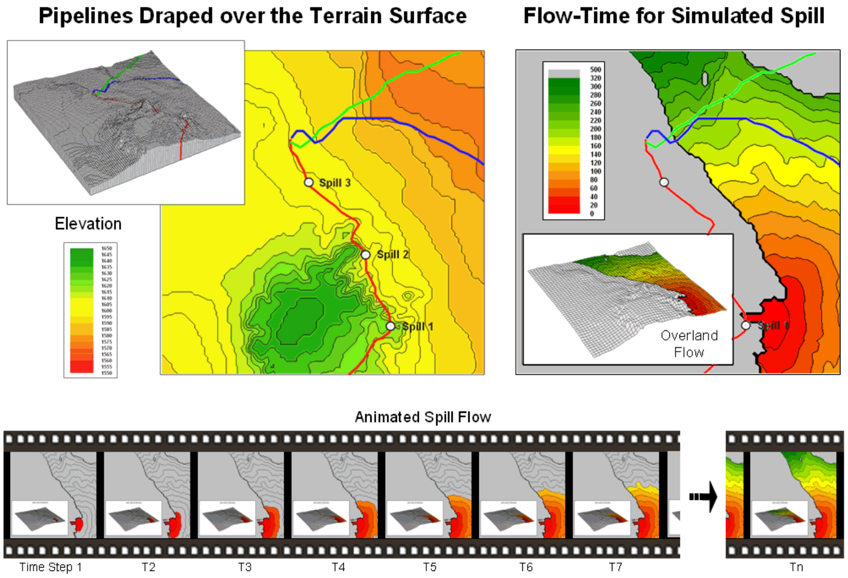


Figure 6-15. Overland flow is calculated as a series of time steps traveling downhill over an elevation surface.

The lower inset in the figure depicts an animation series of flow progress in 20 minute time steps. Note that the simulated release starts in relatively steep terrain of about 6 percent but quickly fans out as more gentle terrain is encountered. The maximum extent within the project area occurs at the northern portion and is reached in a little over five hours.

Figure 6-16 compares the flow times for two different liquid types over the same terrain. Louisiana crude oil (right side) is more viscous than water (left side) and only travels about two-thirds of the path distance in the same five hour period. Also note the differences in the shape of the wave fronts with a much smoother appearance for the more viscous flow of crude oil.

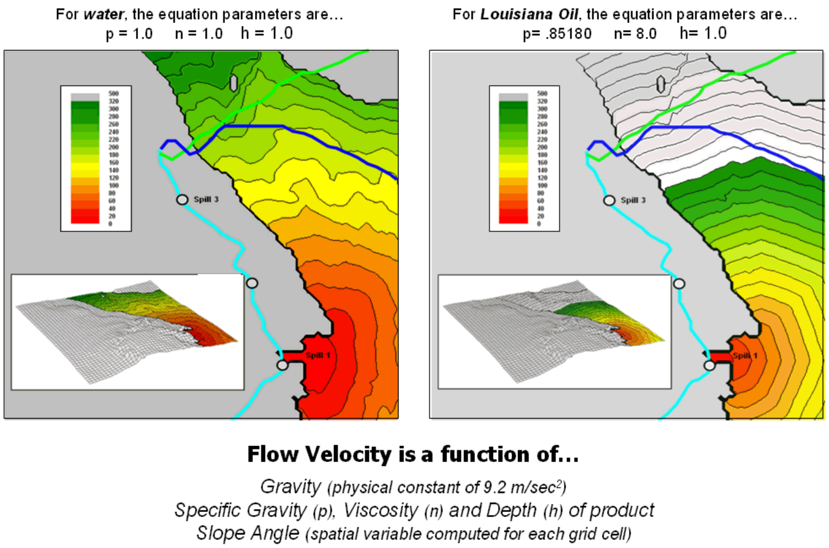


Figure 6-16. Flow velocity is dependent on the type of liquid and the steepness of the terrain.

In Mr. Wizard terms, it means if you pour a cup of water on a tilted cutting board most of it runs off almost instantly. However, if you pour a cup of honey on the same board it takes much longer to flow down the board and a relatively larger portion sticks to it.

The quantity and velocity equations quantitatively account for these common sense characteristics of overland flow. While neither the equations nor the data are perfect, the extension of the cutting board example to the grid cell element provides a radically new approach to modeling overland flow.

Research into the equations has been ongoing for decades. However, in real-world applications the effects of slope angle could not be adequately modeled until the advent of map analysis tools and an extensive data set. Today, we have seamless elevation data for the contiguous fifty states (National Elevation Dataset) that can be purchased for about $1500. The pieces are in place—equations, technology and data—for realistic modeling of overland flow. As we'll see next month the same holds for modeling channel flow.

6.7 Determining Spill Impacts

Overland flow careens downhill and across flat areas in a relentless pursuit of beach front property. Previous discussion has focused on the important factors in the flow mechanics (*path*, *sheet*, *flat* and *pooling*) and major considerations (*quantity* and *velocity*) behind the calculations. The characteristics of the liquid (*viscosity* and *specific gravity*) and the terrain (*slope angle* and *soil type*) are the dominant influences on the velocity of flow and the quantity retained at each location.

The ability to effectively model overland flow is critical to understanding the impacts of potential pipeline spills. For example, an *Impact Buffer* can be generated that identifies the minimum time for a spill to reach any impacted location. The process involves aggregating the results from repeated simulation of release points (left side of figure 6-17).

Each spill point generates a path identifying the elapsed time to reach locations within its impacted area. The stack of simulated flow maps is searched for the minimum time at each grid location. The result is an overall map of the effected area comprised of a series of red to green contours that how close each location is in terms of flow time. Such a map can be invaluable in emergency response planning.

In a similar manner, the individual simulation maps can be summarized to identify the estimated quantity retained or the portions of the impacted area that are affected by specific sections of the pipeline. For example, the small inset in the figure identifies the spill numbers for each impacted location (blue for just spill 3; yellow for spills 2 and 3; red for spills 1, 2, and 3). Such a map can be useful in characterizing pipeline risk.

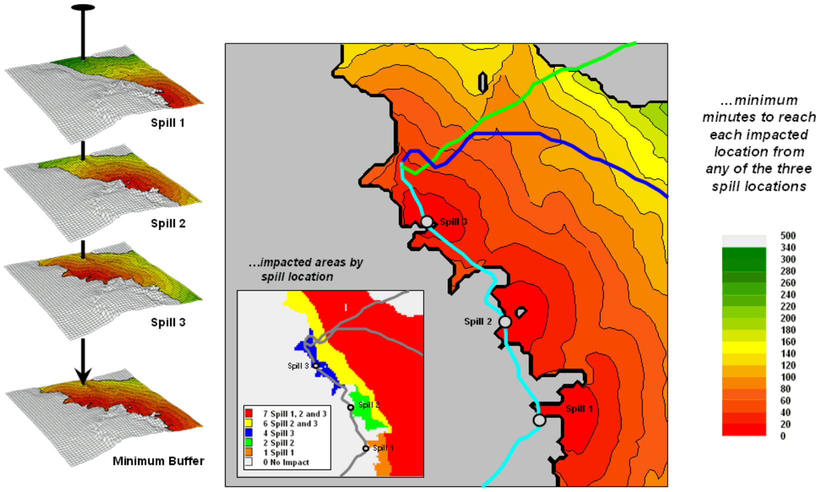


Figure 6-17. An Impact Buffer identifies the minimum flow time to reach any location in the impacted area—areas that are effectively close to the pipeline.

Another important component in risk assessment is the occurrence of high consequence areas within the impacted area. It is like the age old question "If a tree falls in the forest and no one is around to hear it, does it make a sound?" If a spill occurs and doesn't impact high consequence areas then, while the spill hazard might be great, the risk is relatively small for various sections of the pipeline.

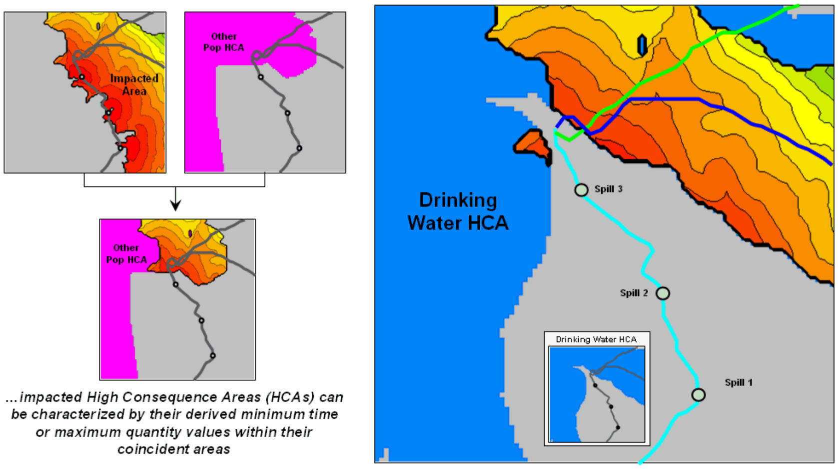
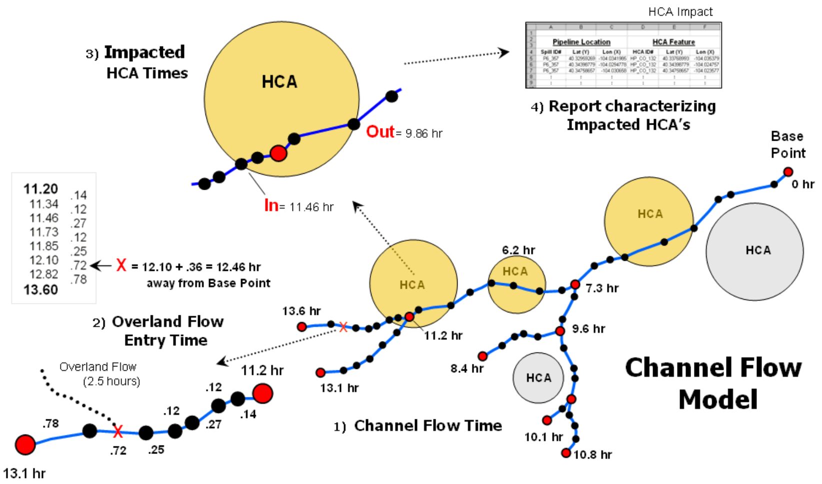


Figure 6-18. Identification of High Consequence Areas (HCAs) impacted by a simulated spill is automatically made when a flow path encounters an HCA.

The left side of figure 6-18 shows the spatial coincidence between the impacted area and a map identifying the Other Populations HCA. The top two insets identify the input maps and the bottom one depicts their coincidence as the extreme northern portion of the impacted area. The map on the right shows a much larger portion of the impact area occurs within the Drinking Water HCA. Tabular statistics relating potential spill locations and HCA's are generated and can be used to characterize risk along the entire length of the pipeline.

However, overland flow is only part of the total solution. When the path encounters flowing water entirely different processes take over and the GIS solution changes from raster to vector. Figure 6-19 outlines the four basic steps in *Channel Flow* modeling.



1) *Channel Flow* along stream network segments is added

2) *Overland Flow* time and quantity at entry is noted

3) Impacted *High Consequence Areas* (HCA) are identified

4) A *Report* is written identifying flow paths that cross HCA areas

Figure 6-19. Channel flow identifies the elapsed time from the entry point of overland flow to high consequence areas impacted by surface water.

The first step involves structuring the stream network so each line segment reflects the flow time it takes to traverse it. In most applications this is calculated as the flow velocity based on the stream size multiplied times the segment length. Stationing along the network is established by beginning at a base point and accumulating flow times for each vertex moving toward the head waters.

The second step links the overland flow time and remaining quantity to the entry point in the stream network. In the example in the figure the entry point time is proportioned between 12.10 and 12.82 hours and set as 12.46 hours from the base point.

The next step determines the entry and exit times for impacted HCA's. This is derived by subtracting the HCA entry time from overland flow entry time to calculate the flow time along the stream (12.46 – 11.46 = 1.0 hours). The final step adds the stream flow time to the overland flow time for the total elapsed time from the spill to the HCA (1.0 + 2.5 = 3.5 hours).

The procedure is repeated for all of the impacted HCA's along the channel flow route. Implementation is very fast as all of the information on coincidence and accumulated flow time is stored predefined tables. Spatial intersection of streams and HCA's is computed just once with all subsequent processing involving only table manipulation.

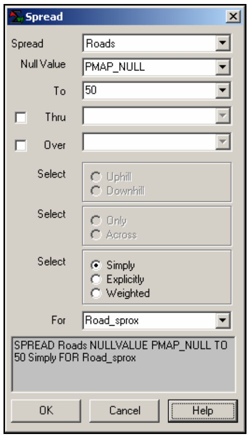
The result of spill migration modeling identifies and characterizes all of the potentially effected HCA's by both overland and channel flows. That's quite a feat when analyzing a hundreds of miles of pipeline. But that's what GIS is supposed to do—not simply inventory physical features but to provide information within the context of complex spatial issues.

6.8 Exercises

Access MapCalc using the *Tutor25.rgs* data set by selecting **Start** à **Programs** à **MapCalc Learner** à **MapCalc Learner** à **Open existing map set** à **NR_MapCalc Data** à **Tutor25.rgs**. The following set of exercises utilizes this database.

12.8.1 Calculating Simple Proximity

Press the **Map Analysis** button to access the analytical operations, select **Distance** à **Spread** and complete the dialog box shown below.



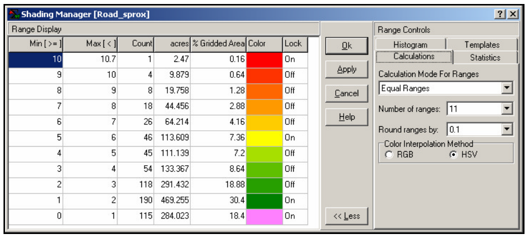
Spread
Spread: Roads
Null Value: PMAP_NULL
To: 50
☐ Thru:
☐ Over:
Select: ○ Uphill ○ Downhill
Select: ○ Only ○ Across
Select: ● Simply ○ Explicitly ○ Weighted
For: Road_sprox

```
SPREAD Roads NULLVALUE PMAP_NULL TO
50 Simply FOR Road_sprox
```

SPREAD Roads NULLVALUE PMAP_NULL TO 50 Simply FOR Road_sprox

Double-click on the map legend and set the Shading Manager options as—

Ranges = 11
Violet to the range 0 to 1 cells away
Green to the range 1 to 2
Yellow to the range 5 to 6
Red to the range 10 to 10.7

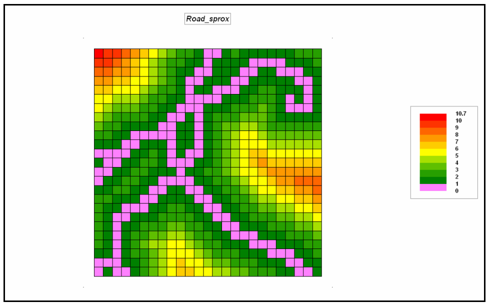


Shading Manager [Road_sprox]

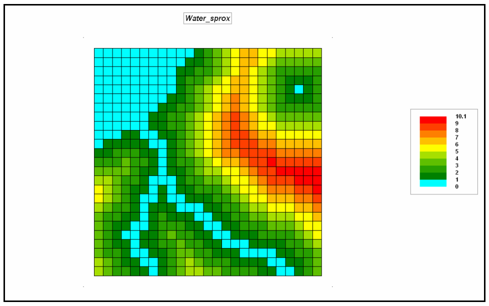
Range Display

Min [>=]	Max [<]	Count	acres	% Gridded Area	Color	Lock
10	10.7	1	2.47	0.16	🟥	On
9	10	4	9.879	0.64	🟥	Off
8	9	8	19.758	1.28	🟧	Off
7	8	18	44.456	2.88	🟧	Off
6	7	26	64.214	4.16	🟧	Off
5	6	46	113.609	7.36	🟨	On
4	5	45	111.139	7.2	🟩	Off
3	4	54	133.367	8.64	🟩	Off
2	3	118	291.432	18.88	🟩	Off
1	2	190	469.255	30.4	🟩	On
0	1	115	284.023	18.4	🟪	On

Range Controls
Calculation Mode For Ranges: Equal Ranges
Number of ranges: 11
Round ranges by: 0.1
Color Interpolation Method: ○ RGB ● HSV



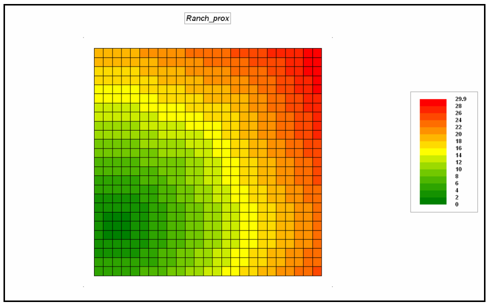
Repeat the processing using the Water map.



Calculate the simple proximity from the Ranch using the following commands--

Reclassify à **Renumber**
RENUMBER Covertype ASSIGNING 0 TO 1 ASSIGNING 2 TO 2 ASSIGNING 5 TO 3 FOR Hiking friction

Distance à **Spread**
SPREAD Ranch NULLVALUE PMAP_NULL TO 50 Simply FOR Ranch_prox



Displayed as # Ranges = 15, Green 0 to 2, Yellow 14 to 16 and Red 28 to 29.9

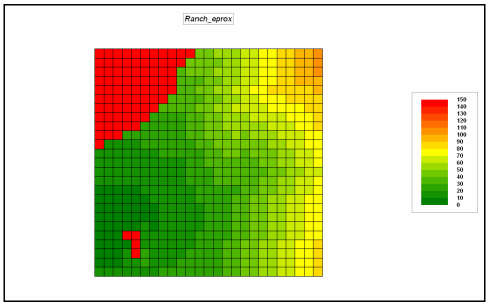
12.8.2 Calculating Effective Proximity

The first step in calculating effective proximity is to establish the relative and absolute barriers to movement. In this example, the Covertype map is renumbered to identify Open Water as 0 (absolute barrier), Meadow as 2 (two minutes to cross a cell) and Forest as 5 (five minutes).

Reclassify à Renumber
RENUMBER Covertype ASSIGNING 0 TO 1 ASSIGNING 2 TO 2 ASSIGNING 5 TO 3 FOR Hiking friction

The cover type based friction map is used to guide the effective proximity calculations.

Distance à Spread
SPREAD Ranch NULLVALUE PMAP_NULL TO 150 THRU Hiking friction Simply FOR Ranch_eprox



Displayed as # Ranges = 15, Green 0 to10, Yellow 70 to 80 and Red 140 to150

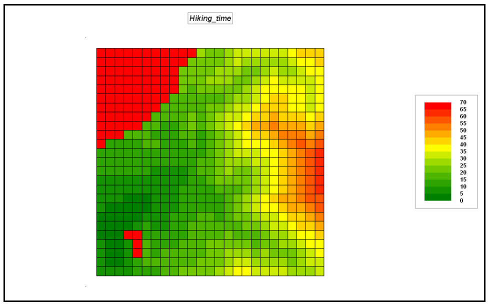
The friction map can be updated to reflect easiest (one minute) hiking along roads—

Reclassify à Renumber
RENUMBER Roads ASSIGNING 1 TO 1 THRU 43 FOR Road_friction

Overlay à Cover
COVER Hiking friction WITH Road_friction IGNORE 0 FOR Hiking_friction2

The updated friction map is used to calculate the effective distance from the ranch considering the relative ease of movement in different cover types and along the road.

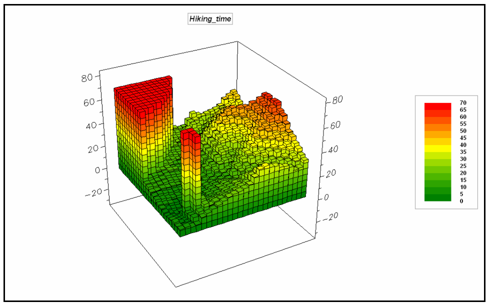
Distance à Spread
SPREAD Ranch NULLVALUE PMAP_NULL TO 70 THRU Hiking_friction2 Simply FOR Hiking_time



Displayed as # Ranges = 14, Green 0 to 5, Yellow 35 to 40 and Red 65 to 70

3D 3D Toggle button (toggles between 2D and 3D views)

▦ Use Cells button (toggles between Lattice and Grid display types)



3D view (grid)

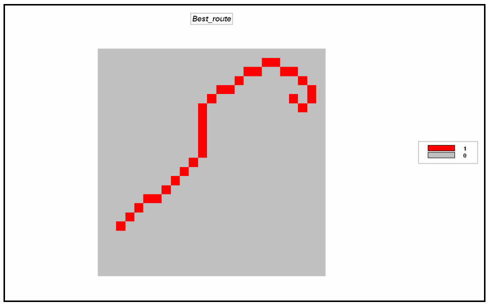
12.8.3 Identifying Optimal Paths

Create a map of just the cabin by—

Reclassify à Renumber
RENUMBER Locations ASSIGNING 0 TO 1
ASSIGNING 0 TO 3 THRU 5 FOR Cabin

Establish the best route (Least Cost Path) between the Ranch and the Cabin considering the relative ease of movement in different cover types and along the road.

Distance à Stream
STREAM Cabin OVER Hiking_time Simply Steepest Downhill Only FOR Best_route

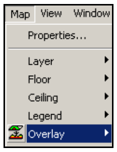


The optimal path can be "draped" over the hiking time surface to help visualize the "steepest downhill" path solution.

Use the View button to display the Hiking_time map.

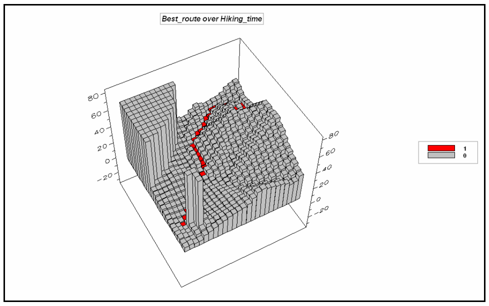
Use the 3D Toggle button to view in 3D.

Use the Use Cells button for a grid display.



From the Main menu, select **Map à Overlay à Best_route**.

Use the Rotate button to rotate the 3D view.



12.8.4 Extending the Analysis

The analysis can be extended to include consideration of terrain steepness and visual exposure to water through the use of weighting factor maps.

Create a weighting map of slope by entering the following command that weights increases the hiking friction values three times for the steepest locations (weighting factor = 3.0). Gentle slopes from 0 to 10% have no effect (weighting factor = 1.0) on the original friction values.

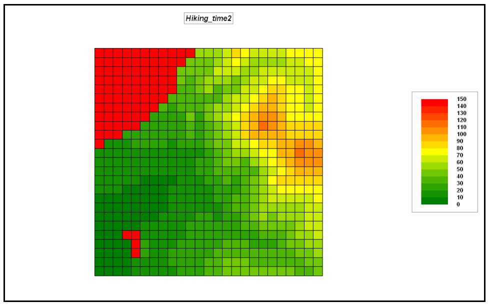
Reclassify à Renumber
RENUMBER Slope
ASSIGNING 1 TO 0 THRU 10
ASSIGNING 1.25 TO 10 THRU 20
ASSIGNING 1.5 TO 20 THRU 30
ASSIGNING 2 TO 30 THRU 40
ASSIGNING 2.5 TO 40 THRU 50
ASSIGNING 3 TO 50 THRU 65
FOR Slope_weights

Multiply the weighting factor map times the original friction map…

Overlay à Compute
COMPUTE Hiking_friction2 Times Slope_weights FOR Hiking_friction_steepness

…then calculate a new hiking time map.

Distance à Spread
SPREAD Ranch NULLVALUE PMAP_NULL TO 150 THRU Hiking_friction_steepness Simply FOR Hiking_time2



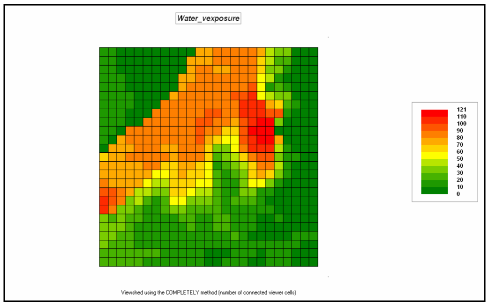
Displayed as # Ranges = 15, Green 0 to10, Yellow 70 to 80 and Red 140 to150

The same approach can be used for weighting distance as a function of the beauty of the hike as represented by the amount of water visible from each map location (visual exposure).

First create a map of visual exposure to water locations for every location in the project area. (see Topic 4 for review).

Distance à Radiate

```
RADIATE Water OVER Elevation TO 50 AT 1
NULLVALUE 0 Completely FOR
Water_vexposure
```

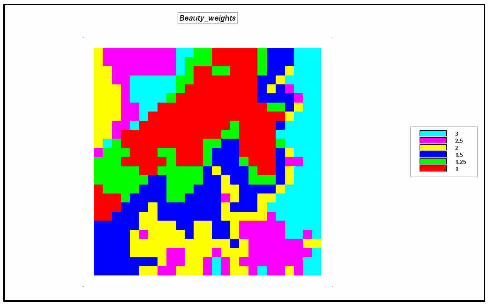


Displayed as # Ranges = 12, Green 0 to10, Yellow 50 to 60 and Red 110 to120

Create a weighting map of visual exposure to water by entering the following command that weights increases the hiking friction values three times for the least visually exposed locations (weighting factor = 3.0 to 0 through 8 times seen) and decreasing to no effect for locations seeing lots of water (weighting factor = 1.0 to 80 through 125). The weighting factors .

Reclassify à Renumber

```
RENUMBER Water_vexposure
ASSIGNING 3 TO 0 THRU 8
ASSIGNING 2.5 TO 8 THRU 12
ASSIGNING 2 TO 12 THRU 20
ASSIGNING 1.5 TO 20 THRU 60
ASSIGNING 1.25 TO 60 THRU 80
ASSIGNING 1 TO 80 THRU 125
FOR Beauty_weights
```



Multiply the weighting factor map times the original friction map…

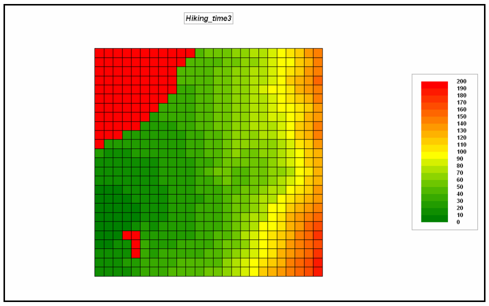
Overlay à Compute

```
COMPUTE Hiking friction Times
Beauty_weights FOR Hiking_friction_vexpose
```

…then calculate a new hiking time map.

Distance à Spread

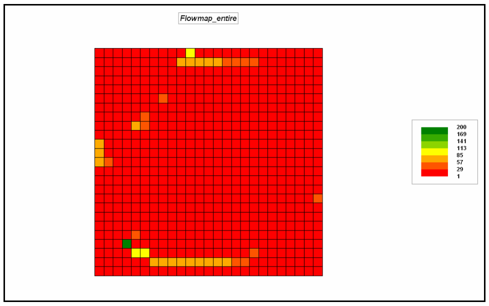
```
SPREAD Ranch NULLVALUE PMAP_NULL
TO 200 THRU Hiking_friction_vexpose Simply
FOR Hiking_time3
```



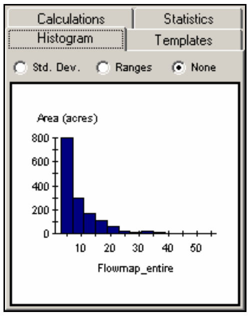
Displayed as # Ranges = 20, Green 0 to10, Yellow 90 to 100 and Red 190 to200

12.8.4 Surface Flow Analysis

Create a map that identifies the accumulated surface flow over the terrain indicating the number of uphill locations for every location in the entire project area.

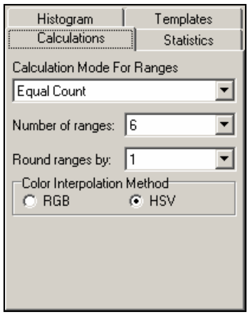


Note that the flow values range from 1 to 200 uphill locations contributing surface flow. However the default map display is not appropriate as the distribution of the data is skewed to the lower values. Double-click on the map legend and select the Histogram Tab to view the distribution of the data.



○ Std. Dev. ○ Ranges ● None

This data is best displayed using the Equal Count calculation mode with six ranges.

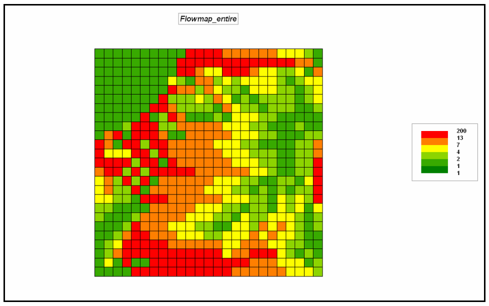


Calculation Mode For Ranges: Equal Count

Number of ranges: 6

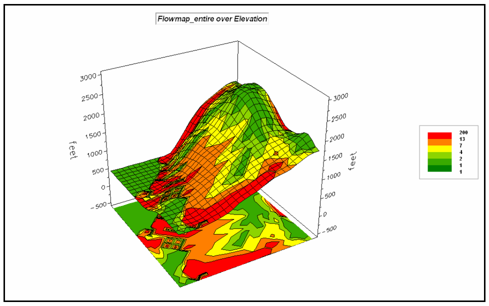
Round ranges by: 1

Color Interpolation Method: ○ RGB ● HSV



Displayed as Equal Count, # Ranges = 6, Green 0 to1, Yellow 4 to 7 and Red 13 to200

Display the flow map draped over the elevation surface by first using the View button (binocular icon) and choosing the Elevation map and displaying as a 3D lattice plot, and then selecting from the Main Menu, **Map à Overlay à Flowmap_entire**.

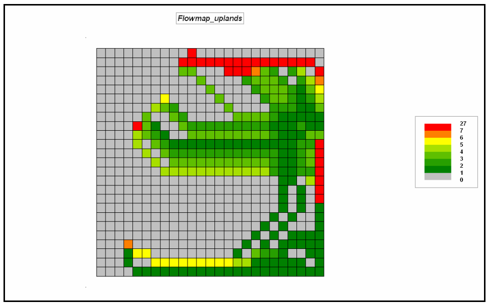


Note the concentration of flow (confluence) occurring in the 'creases" in the terrain surface. Use the Rotate button to spin the plot for better viewing.

Repeat the analysis to identify the flow from just the upland soils.

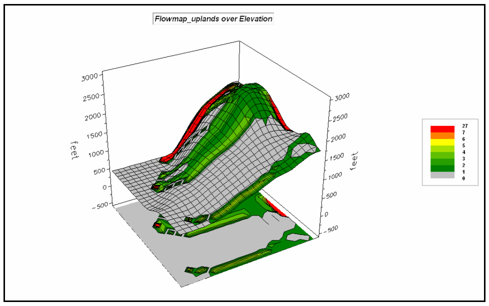
Reclassify à Renumber
RENUMBER Soils ASSIGNING 0 TO 1 THRU 3 ASSIGNING 1 TO 4 FOR Upland_areas

Distance à Drain
DRAIN Upland_areas OVER Elevation Simply Steepest FOR Flowmap_uplands



Displayed as User defined ranges, # Ranges = 8 and the following interval and specifications--
0 to 1 = light grey lock on
1 to 2 = green lock on
2 to 3
3 to 4
4 to 5
5 to 6 yellow lock on
6 to 7
7 to 27 = red lock on

Display this map draped over the Elevation surface.



Note that the downhill flow confluence is identified for just the locations of the upland soil category.