From “Digital Mapping Techniques ‘09—Workshop Proceedings”
U.S. Geological Survey Open-File Report 2010–1335
http://pubs.usgs.gov/of/2010/1335/

Semiautomated Mapping of Surficial Geologic Deposits from Digital Elevation Models (DEMs) and Hydrologic Network Data

By Pete Chirico

U.S. Geological Survey
12201 Sunrise Valley Drive
MS 926A, National Center
Reston, VA 20192
Telephone: (703) 648-6950
email: *pchirico@usgs.gov*

Introduction

Unconsolidated materials lying above the bedrock are here defined as being surficial materials. These materials often have economic or environmental value. For example, surficial material deposits in alluvial valleys often contain mineral deposits in the form of industrial sands and gravels, metals, or gemstones that have been sorted and concentrated by flowing water. Surficial deposits also often serve as shallow aquifers for groundwater. In addition, alluvial materials deposited in valleys often function as productive agricultural areas because of fertile soils and available water supplies.

Mapping the location, extent, and characteristics of surficial materials has been the focus of several overlapping realms of science. Specifically, surficial materials mapping has been pursued in geology, geography, pedology, and geomorphology. Surficial materials have been classified, mapped, and grouped in a variety of different ways depending on the discipline and purpose of mapping. The mapping of *regolith*, which has been an especially active part of Australian research, has sought to characterize the in situ weathered materials as well as transported materials lying above solid bedrock and is perhaps the most integrative of the surface material disciplines (Scott and Pain, 2008).

In geologic mapping, surficial materials are classified according to their geologic age (for example, to the Neogene Period and Holocene and Pleistocene Epochs), or according to their lithology, or even according to the depositional environment (Maltman, 1998). While the geologic disciplines generally are unconcerned with the organic content of surface materials, surficial geologists often refer to soil maps as a guide or reference to surficial geologic map units (Kite and others, 1995).

When mapping soil associations, soil scientists pay close attention to the landscape and topographic forms, and the organic material present in the soil. The *catena* concept helped to define the understanding that soil map units were inherently linked to topographic processes (Milne, 1935). Soil science is concerned with the underlying geologic materials only to the extent that parent material is one of several soil forming factors; however, geologic maps are an important data source used in the compiling and understanding of soil associations.

Gellert (1972) recognized geomorphologic mapping as a subdiscipline of many related fields of science that are primarily concerned with deriving relief and surface landforms, but also incorporate the qualitative and quantitative observation of the forms as well as the processes which have developed the form. This definition helped to formalize efforts in geomorphological mapping but still failed to unify the methods or purpose of the many different fields contributing to the discipline.

So, the history and tradition of surficial materials mapping has led to differing approaches and to subjectivity in mapping and interpretation. Regardless of discipline, the traditional approach to mapping surficial materials would be field based, but this practice is expensive, and remote field locations pose logistical challenges to effective and efficient mapping. Many disciplines already rely on topographic maps, aerial photographs, and interpretation by professionals to map surficial deposits, yet these interpretations result in highly subjective interpretation and are not easily repeatable methodologies. The lack of repeatability limits the applicability of individual studies over larger areas and often prevents the transfer of a methodology from one field area to another field area where a different terrain may be encountered. Subjectivity in classification and the cost of field mapping require that we develop quantitative and easily replicable scientific methods to map and characterize surficial materials. One way of developing a quantitative approach to surficial material mapping is through geographic information systems (GIS) and digital elevation modeling techniques.

Automated Mapping Review

Automated mapping techniques are based on numerical data, are repeatable, and are quantitatively based. Also, the process is typically implemented in a GIS environment where the results are easily integrated with other datasets and can be iteratively edited and processed with other GIS layers (Longley and others, 2005). The mathematical or morphological definition of particular landforms remains problematic, as semantic definitions vary among the disciplines and no defined standards exist for deriving a landform from an elevation model. This has led to revision and adaptations of models across disciplines and is still an active area of research (Dehn and others, 2001).

The various surficial material disciplines have all contributed studies and research that utilize GIS, remote sensing, and elevation modeling techniques to automate or improve mapping techniques. There has been a broad range of work undertaken to apply different classification techniques, technology, satellite sensors, and models to map surficial materials within each of the related disciplines but often little coordination or sharing of methods across discipline lines.

Geomorphometry or quantitative geomorphology has experienced a resurgence in the form of digital elevation modeling and digital terrain modeling, due to the improved computing power of personal computers, GIS software, and the wide availability of digital elevation models (DEMs) (Pike, 2000). Pike (2000) provides a review of many of the geomorphometric studies completed in soil-landscape relations, landslide hazards, dune mapping, landscape ecology, and other fields. Several studies attempting to map alluvial soils, alluvial plains, and valley bottom settings have been undertaken within several individual disciplines and using different methodologies.

Landform Classification

Hammond (1954, 1964) classified landforms using local relief as the primary means of examining landforms at continental and regional scales. Dikau (1989) extended this methodology, classifying landforms by relief units consisting of slope, local relief, and profile type, to further define forms and facets of the landform. Subsequently, Dikau and others (1991) tested this classification using a digital elevation dataset in a study in New Mexico, thereby automating Hammond's process and recognizing that with available DEMs, countries or large regions could easily be classified through this system.

Wood (1996) used slope, planform curvature, and profile curvature to delineate the morphology of geomorphic signatures into six classes: ridge, channel, plane, peak, pass, and pit. Further analysis showed that geomorphologic units are made up of collections of those morphometric forms and that those forms indicate geomorphic processes at work within the landform classes (Bolongaro-Crevenna and others, 2005).

Williams and others (2000) developed an integrated DEM and vector-based geometric approach to delineating valley bottoms. This study was based on the assumption that valley bottom settings could be distinguished by change in rate of slope from valley bottom to hillslope along the river course. This was a computationally intense process of automatically deriving cross-section statistics along a vector hydrographic network.

Prima and others (2006) used a 50-meter (m) resolution DEM and classified mountains, hills, volcanoes, alluvial plains, and alluvial fans using multidirection slope calculations from a neighborhood of elevation cells and a function of topographic openness which used a line-of-sight principle to determine if a neighborhood of cells is enclosed or open. This work used supervised classification techniques and produced good results for the geomorphology of volcanic mountain ranges in northern Honshu Island, Japan.

An object-oriented classification of landforms and processes associated with mountainous geomorphology realized a high degree of correlation between previously mapped geomorphic units and those predicted using a high-resolution digital terrain model (DTM) derived from Lidar (van Asselen and Seijmonsbergen, 2006). The derived classes included fluvial terraces and alluvial fans as well as shallow and deeply incised channels.

Soil-Landscape Research

Soil-landscape studies have been productive in the use and application of geomorphometric techniques to assess and map the hydromorphic zones and to delineate alluvial soils. McBratney and others (2003) provided a thorough summary and review of the various methods and approaches to digital soil mapping in a GIS environment as well as discussion of the GIS datasets used in the different methods. Park and others (2001) proposed a process-based methodology called the Terrain Characterization Index (TCI) to map the extent of nine soil landscape units in glaciated Wisconsin. Penizek and Boruvka (2008) evaluated three different methodologies for the delineation of alluvial soils from a DEM; the TCI method (originally proposed by Park and others, 2001), the Compound Topographic Index (CTI), and a method using drainage area and height above watercourse. They compared the predicted alluvial soil layers to those on a soil map. Their results indicated that the CTI method underpredicts alluvial soil extent by 43 percent; Park's method underestimated alluvial soil extent by 24.5 percent; and the drainage area and height above watercourse method underestimated soil extent by only 22 percent.

Mourier and others (2008) used the CTI method coupled with the stream-ordering technique proposed by Strahler (1964) to map hydromorphic soil zones in a river catchment in western France. Their findings showed that CTI was a reliable predictor of waterlogged soils in stream orders 1 through 3, but CTI was a less reliable predictor in higher order streams. This was particularly true for orders 6 and 7, owing to the wider and flatter valley floor topography.

Research Goal

The goal of this research is to test two complementary digital terrain-processing techniques for mapping fluvial geomorphology and surficial geologic map units. The study relies on DEM processing and compares the results to two study areas where recent surficial geologic mapping has been completed.

Methodology

Study Areas

Two separate study areas and control datasets were used in this study. The first is the 1:24,000-scale U.S. Geological Survey (USGS) Stanardsville quadrangle in Virginia. Bedrock and surficial geology of the Stanardsville quadrangle was mapped by Southworth and others (2009). Previous surficial mapping of the quadrangle was completed by Eaton and others (2001). Geologic map units representing alluvium, terraces, and debris flows are mapped in each dataset. Both of these maps are also available as digital geologic map databases in the form of ArcInfo layers and shapefiles.

The second study area chosen for this project was the Big Spring quadrangle in Missouri. The geology of the Big Spring quadrangle was mapped by Weary and McDowell (2006) and includes alluvium and terrace deposits mapped along the Current River and its tributaries running from northwest to southeast throughout the study area.

The alluvium mapped in each of the study areas consists of gravel, sand, and clay lying along the bed and active floodplain of the stream valleys. Terrace deposits consist of larger materials from cobble to sand-sized particles deposited on relatively flat areas flanking but above the seasonal floodplain (Weary and McDowell, 2006).

Elevation Source Data

One-third arc-second elevation models for this study were downloaded from the USGS Seamless data server (*http://seamless.usgs.gov*). Each DEM has a nominal horizontal resolution of 10 m and an estimated vertical resolution of ± 7 m. The National Elevation Dataset (NED) DEM data are gridded elevation values interpolated from the original topographic map contour data. The original contour data for the Stanardsville quadrangle was 40 feet (ft) and the contour interval for the Big Spring quadrangle was 20 ft. Each DEM was downloaded in its native unprojected geographic coordinate system and reprojected into a UTM projection. Each NED dataset was then clipped to the 1:24,000-scale USGS quadrangle boundaries.

DEM Data Preprocessing

NED data were reprocessed in order to prepare each dataset for the path distance function and relative relief modeling. First, each DEM was "filled" to remove pits and spikes in the data and to enforce hydrological flow across the surface of the DEM. Next, flow direction was calculated and a flow accumulation analysis was performed. Flow direction determines the cardinal direction of flow from an upslope cell to its downslope cell neighbor. Flow accumulation then determines the number of upslope cells which drain or flow into each subsequent cell. The flow accumulation result grid is classed into categories. All cells with an accumulation value of 1,000 or greater are classified as a flowpath or "synthetic stream line." The value of 1,000 cells is based in part on the work of Tarboton and others (1991), but has been adjusted to account for a higher resolution DEM (10 m) as compared to the 30-m DEMs used in the earlier study. Cells with a value of less than 1,000 were classed as 'NoData'. Strahler stream orders were calculated for each flow path segment (fig. 1). Strahler stream orders 1 and 2 were removed, leaving only orders three and higher for the alluvial modeling. Watersheds were derived for all flow paths in the study areas based on the remaining Strahler streams. Finally, the minimum elevation of the watershed for each flow path was determined by intersecting the watersheds layer with the DEM data and finding the minimum value per watershed area.

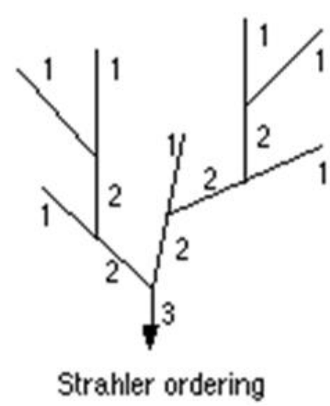

Figure 1. Diagram showing Strahler (1964) stream ordering scheme for orders 1, 2, and 3.

In this study, a path-distance function and relative relief model were used in combination to model the likelihood that fluvial surficial materials were deposited in a given area. The path-distance method presented here calculates the likelihood of alluvial material deposition in proximity to hydrological flowpaths. The flowpaths were each attributed with the Strahler stream order for the model. Based on previous studies in reviewed literature, a determination was made to only calculate alluvial material deposition in Strahler streams with an order of 3 or higher. The following formula is the simple description of the path-distance calculation:

Path-distance = Surface_distance * Cost Raster

Path-Distance Function

Path-distance GIS modeling is a type of cost-distance operation in GIS. Cost-distance operations model the "cost" of movement or travel from a source grid cell in a raster dataset to all other cells in the raster dataset. The cost is determined by both the distance from the source to the other grid cells as well as a numerical "cost" value modeled by a cost-raster layer. Cost rasters numerically model a variety of phenomenon such as the flammability of wildfire fuels, the likelihood of soil erosion or deposition, or the vehicular cost of overland travel or any other type of movement. The cost-raster layers may be numerically stored in a particular type of cost unit such as the financial cost in dollars, or it may be dimensionless and represented as a relative expression of the cost of travel through cells in the raster layer. For this study, the calculated slope of the elevation surface was used as the cost raster (see fig. 2).

Path-distance modeling in GIS extends the cost-distance model to include the complexity of traveling over a surface rather than the more simple Euclidean distance from cell to cell. Typical surfaces used in path-distance modeling are elevation surfaces that represent the terrain of the land surface. Movement over an elevation model surface is a more realistic metric to determine the true distance traveled and its cost. Travel from point A to point B over a flat surface modeled simply as a plane will yield one distance. However, based on the Pythagorean Theorem, travel from point A to point B over a series of hills and valleys modeled by a surface raster grid yields the true distance of traveling over the surface (fig. 3). Figure 4 shows a progression of the simulated raster surface for this study with the path-distance calculated for each cell using the slope values as the cost raster.

Relative Relief Model

The second part of the alluvial deposition model is a relative relief model. Relief is the difference between the highest elevation in a given area and the lowest elevation in the same area (fig. 5). Measures of relief are useful in geomorphometric modeling because they can help to show the complexity and patterns of elevation variation. One problem with using typical relief measures is that they compare elevation values to other elevation values within an analysis window. This is a drawback when the goal of geomorphic modeling is to determine the topographic position of one grid cell to other features, such as base level of a river or the elevation of a ridge upslope of the cell. These features very often will be located outside of the local analysis window and so are not readily compared. Therefore, a different approach needs to be taken to model the relationship of the topographic relief to cells in the grid.

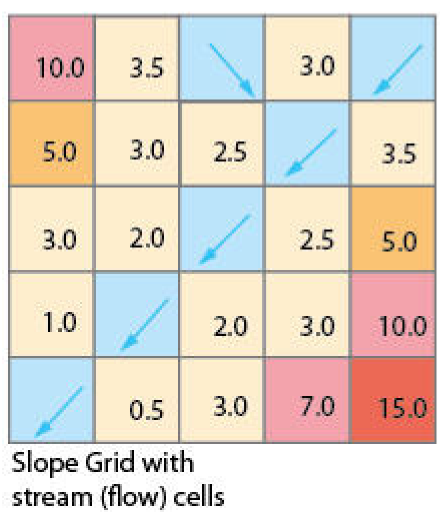

Figure 2. Diagram of simulated raster showing percent slope values derived from DEM and hydrological flow path cells (in blue) with arrows indicating downstream flow direction.

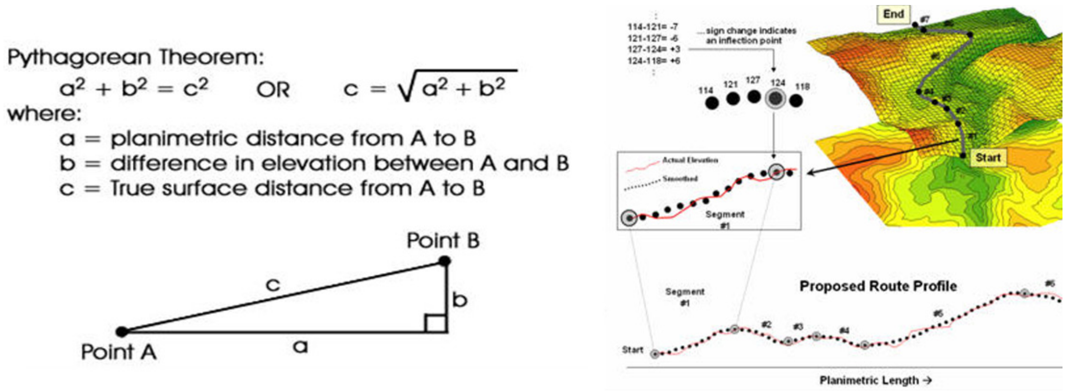

Figure 3. Diagram showing the Pythagorean Theorem (at left) and its implementation in the Path Distance GIS operation on a raster elevation surface (at right).

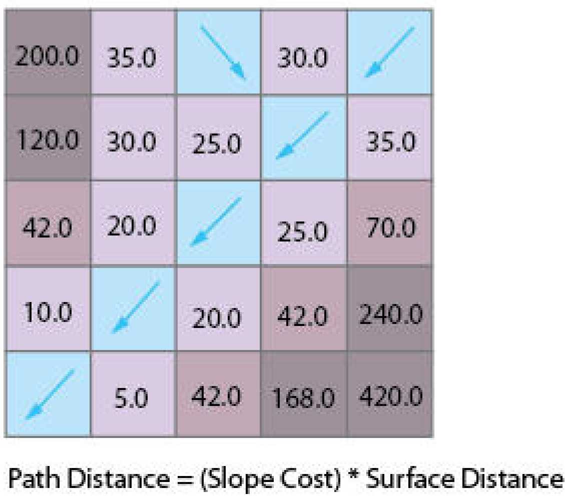

Figure 4. Simulated raster showing the values of grid cells for the path-distance calculation.

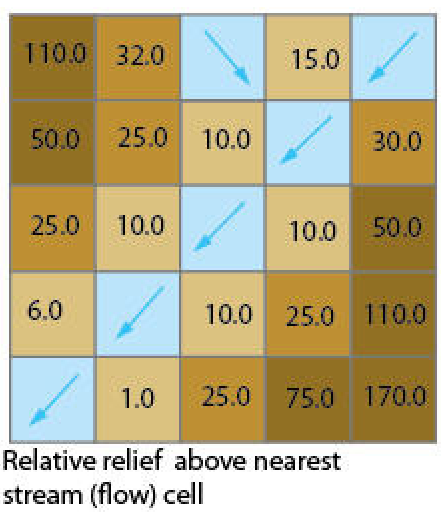

Figure 5. Simulated raster showing the values of grid cells for the relative-relief calculation.

To modify this measure, elevation values were compared to the minimum elevation of the closest flowpath (or stream) grid cell. This measures the relative relief of every cell in the dataset to the minimum value in its local watershed or basin, or to the local baseflow elevation. The benefit of this method is that elevation differences are related to a local, common elevation of the hydrologic network, and thus comparisons can be made more easily from one stream reach to another. This is of particular importance when measuring and comparing alluvial landforms. Figure 5 shows the calculated values for the relative relief parameter for the simulated raster.

In this study, a slope grid is used as the cost raster. Addition modifiers for the relative erosivity of the geologic parent material can be added to this model as well but have been omitted for simplicity. For this study, a uniform erosivity is modeled for parent material layers.

Combination

Once the path-distance model and the relative relief model have been calculated, each resultant dataset was classified into the categories shown in table 1.

Table 1. Classification values from path-distance and relative-relief models for overall alluvial deposition model results.

Path-Distance Model Reclass Values	
0	Stream Channel
0 - 15	Al 1
15 - 50	Al 2
50 - 100	Al 3
100 +	NoData
Relative-Relief Model Reclass Values	
0 - 5	Alluvium
5 - 15	Qt 1 (Terrace)
15 -25	Qt 2 (High Terrace)
25 +	NoData

After each dataset is classified, the two datasets are combined to yield the final alluvial deposition model (fig. 6). The classified results and subsequent combination allow for some interpretation by the analyst as to the values, class widths, and the resultant surficial geologic map units represented by the numerical modeling.

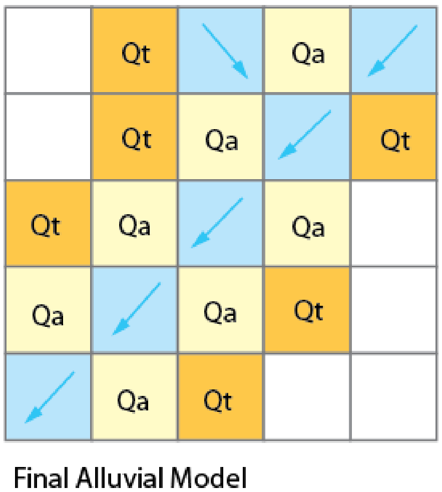

Figure 6. Final results of the path-distance and relative-relief models shown for the simulated raster model, which now represent alluvium and terrace deposits.

Results

Stanardsville

Figure 7 shows the spatial results of the alluvial landform modeling with the mapped units from Southworth and others (2009). Visually, the results appear to be similar, showing a general trend of alluvial materials mapped and predicted in the major river and stream valleys. The alluvial landform modeling results predicted more alluvial map units than what were actually mapped by Southworth. In particular, more alluvium or alluvial terrace deposits were predicted in several of the smaller tributaries.

Statistical correlation coefficient results for both study areas are presented in table 2. The statistical results show that the mapped and the modeled Qa correlate over 38.7 percent of the area. However, when Qa and Qt units are grouped together, the alluvial model showed a correlation of 64.7 percent.

Big Spring

The results for the Big Spring quadrangle show a visual similarity between the alluvial landform model and the mapped surficial geologic units (fig. 8). The alluvial model appears to have predicted more alluvial and terrace material accumulation in several very small streams and tributaries than was previously mapped, yet there is a strong correlation overall between the amounts of material mapped by the alluvial landform model and the amounts mapped by Weary and McDowell (2006).

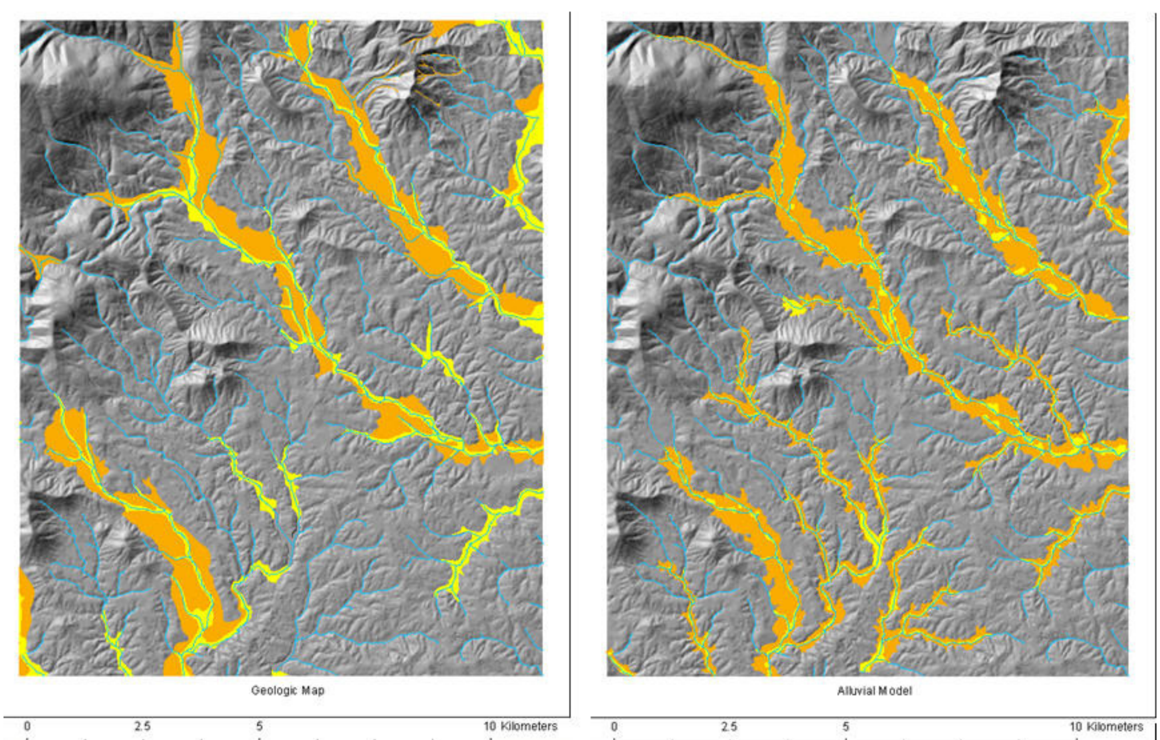

Figure 7. Graphical results of the geologic map (left) and the alluvial deposition model (right) for the Stanardsville quadrangle.

Table 2. Results showing correlations of the mapped and modeled alluvium and terrace deposits, for the Stanardsville and the Big Spring quadrangles.

Study Area	Dataset 1	Dataset 2	Correlation
Stanardsville			
	Mapped Qa	Modeled Qa	38.70%
	Mapped Qa and Qt	Modeled Qa and Qt	64.70%
Big Spring			
	Mapped Qa	Modeled Qa	48.50%
	Mapped Qa and Qt	Modeled Qa and Qt	83.10%

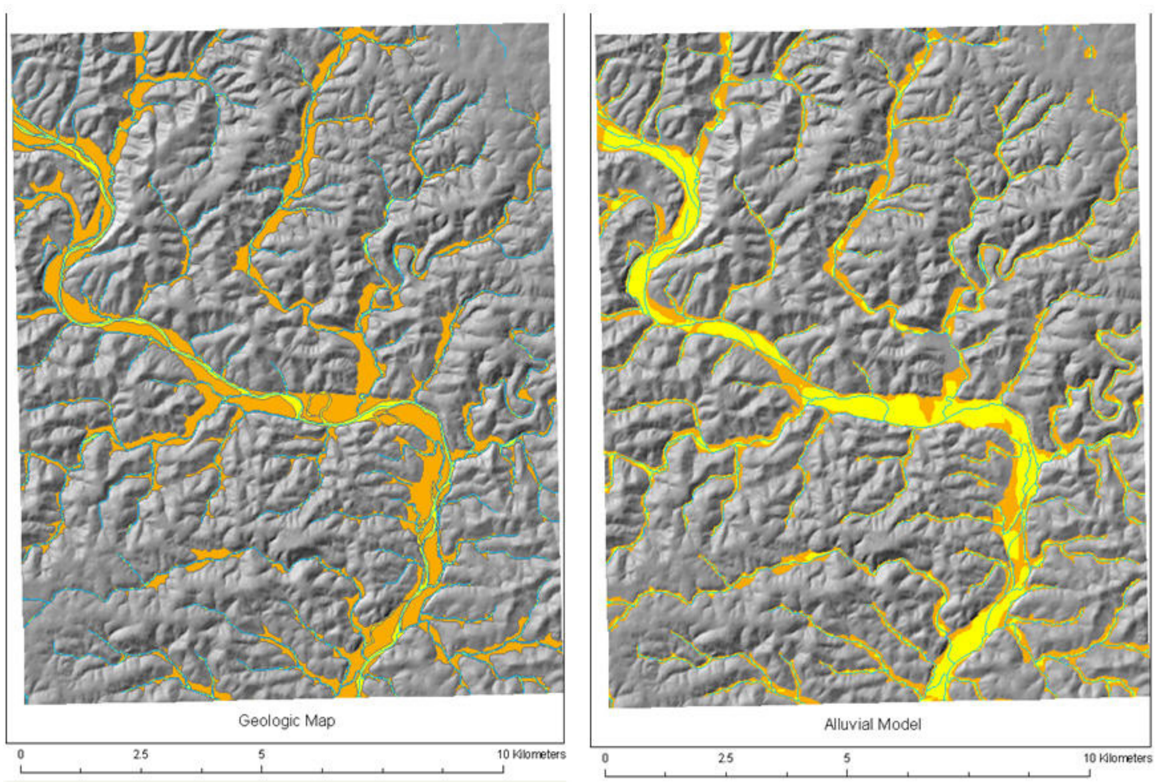

Figure 8. Graphical results of the geologic map (left) and the alluvial deposition model (right) for the Big Spring quadrangle.

The spatial correlation results show that the mapped and modeled Qa units correlate 48.5 percent of the time. When Qa and Qt units are grouped and treated singularly as alluvial materials, the correlation between mapped and modeled results increased to 83.1 percent (Table 2).

Discussion

The results show a cartographic similarity in mapped and modeled alluvium and terrace deposits in both study areas. Overall, there is a general trend of agreement in the determination of alluvial material deposition in proximity to rivers and streams between the terrain modeling approach and the geologic map control data. The difficulty in comparing results lies in the subjectivity of mapping and classifying surficial materials as either alluvium or terrace deposits. Different geologists may choose to classify the units stratigraphically, lithologically, or by depositional environment. Therefore, it may be better to seek a more comprehensive surficial control dataset by which to compare modeled results.

The terrain modeling results show that in both study areas, determining the difference between mapped alluvium and alluvial terrace deposits is difficult. However, when Qa and Qt are combined and viewed as a single alluvial material deposit, the correlation improves significantly. This shows that the alluvial model presented here is an accurate predictor of the deposition of alluvium and terrace deposits. One limiting factor may be the vertical resolution of the DEM data. Since alluvial terrace deposits are typically mapped based on their vertical elevation above the current floodplain, obtaining elevation data that are able to discern fine scale differences in elevation is important. In both cases, the vertical resolution of the DEM data used in this study (+/- 7 m) is greater than the 1- or 2-m difference in elevation between the alluvial flat and the terrace deposits. This indicates that higher vertical resolution DEM data may better be able to distinguish between alluvial deposits and the low terrace deposits which lie a few meters in relief above the flats.

Research using the alluvial model presented here, but using higher vertical resolution elevation data, would be a productive avenue for future studies, especially if validation of fieldwork could be done in order to compare modeled results to conventionally prepared geologic maps.

References

Bolongaro-Crevenna, Andrea, Torres-Rodriguez, Vincent, Sorani, Valentino, Frame, Dawn, and Ortiz, M.A., 2005, Geomorphometric analysis for characterizing landforms in Morelos State, Mexico: Geomorphology, v. 67, p. 407-422.

Dehn, Martin, Gärtner, Holger, and Dikau, Richard, 2001, Principles of semantic modeling of landform structures: Computers & Geosciences, v. 27, no. 8, p. 1005-1010.

Dikau, Richard, 1989, The application of a digital relief model to landform analysis in geomorphology, *in* Raper, J.F. (ed.), Three dimensional applications in geographical information systems: London, Taylor and Francis, p. 51-77.

Dikau, Richard, Brabb, E.E., and Mark, R.M., 1991, Landform classification of New Mexico by computer: U.S. Geological Survey Open-File Report 91-634, 15 p.

Eaton, L.S., Morgan, B.A., and Blair, J.L., 2001, Surficial geology of the Fletcher, Madison, Stanardsville, and Swift Run Gap, 7.5-minute quadrangles, Madison, Greene, Albemarle, Rockingham, and Page Counties, Virginia: U.S. Geological Survey Open-File Report 01-92, scale 1:24,000.

Gellert, J.F., 1972, The nature and aims of detailed geomorphological mapping, *in* Demek, Jaromir, Embleton, C., Gellert, J.F., and Verstappen, H.T. (eds.), Manual of detailed geomorphological mapping: International Geographical Union Commission on Geomorphological Survey and Mapping, Prague, Academia, p. 15-17.

Hammond, E.H., 1954, Small scale continental landform maps: Annals of the Association of American Geographers, v. 44, p. 32-42.

Hammond, E.H., 1964, Analysis of properties in landform geography—An application to broadscale landform mapping: Annals of the Association of American Geographers, v. 4, p. 11-19.

Kite, J.S., Behling, R.E., Davis, E.N., Cenderelli, D.A., Springer, G.S., Elmes, G.A., Mastrorocco, T., Warner, T.A., and Fedorko, N., 1995, Geological aspects of a GIS-based approach to mapping surficial geology in the Central Appalachians [abs.]: Geological Society of America Abstracts with Programs, v. 26, p. 66-67.

Longley, P.A., Goodchild, M.F., Maguire, D.J., and Rhind, D.W., 2005, Geographic information systems and science (2d ed.): Chichester, UK, John Wiley & Sons, 517 p.

Maltman, Alex, 1998, Geological maps—An introduction (2d ed.): Chichester, UK, John Wiley & Sons, 260 p.

McBratney, A.B., Mendonca-Santos, M.L., and Minasny, B., 2003, On digital soil mapping: Geoderma, v. 117, no. 1-2, p. 3-52.

Milne, G., 1935, Some suggested units of classification and mapping, particularly for east African soils: Soil Research, v. 4, p. 183-198.

Mourier, Brice, Walter, Christian, and Merot, Philippe, 2008, Soil distribution in valleys according to stream order: Catena, v. 72, p. 395-404.

Park, S.J., McSweeney, Kevin, and Lowery, Birl, 2001, Identification of the spatial distribution of soils using a process-based terrain characterization: Geoderma, v. 103, p. 249-272.

Penizek, V., and Boruvka, L., 2008, The Digital Terrain Model as a tool for improved delineation of alluvial soils, *in* Hartemink, A.E., McBartney, A.B., and Mendonca-Santos, M.L. (eds.), Digital soil mapping with limited data: New York, Springer Publishers, p. 319-326.

Pike, R.J., 2000, Geomorphometry – diversity in quantitative surface analysis: Progress in Physical Geography, v. 24, no. 1, p. 1-20.

Prima, O.D., Echigo, Ayako, Yokoyama, Ryuzo, and Yoshida, Takeyoshi, 2006, Supervised landform classification of northeast Honshu from DEM-derived thematic maps: Geomorphology, v. 78, p. 373-386.

Strahler, A.N., 1964, Quantitative geomorphology of drainage basins and channel networks, *in* Chow, V.T. (ed.), Handbook of applied hydrology: New York, McGraw-Hill, p. 4-40.

Scott, K.M., and Pain, C.F., 2008, Regolith science: Victoria, Australia, CSIRO, p. 461.

Southworth, Scott, Aleinikoff, J.N., Bailey, C.M., Burton, W.C., Crider, E.A., Hackley, P.C., Smoot, J.P., and Tollo, R.P., 2009, Geologic map of the Shenandoah National Park region Virginia: U.S. Geological Survey Open-File Report 2009–1153, 96 p., 1 plate, scale 1:100,000.

Tarboton, D.G., Bras, R.L., and Rodriguez-Iturbe, Ignacio, 1991, On the extraction of channel networks from digital elevation data: Hydrological Processes, v. 5, p. 81–100.

van Asselen, Sanneke, and Seijmonsbergen, A.C., 2006, Expert-driven semi-automated geomorphological mapping for a mountainous area using a laser DTM: Geomorphology, v. 78, p. 309-320.

Weary, D.J., and McDowell, R.C., 2006, Geologic map of the Big Spring quadrangle, Carter County, Missouri: U.S. Geological Survey Scientific Investigations Map 2804, scale 1:24,000.

Williams, W.A., Jensen, M.E., Winne, J.C., and Redmond, R.L., 2000, An automated technique for delineating and characterizing valley-bottom settings: Environmental Monitoring and Assessment, v. 64, no. 1, p. 105-114.

Wood, J.D., 1996, The geomorphological characterisation of digital elevation models: Leicester, UK, University of Leicester, Ph.D. dissertation.