ANALYSIS OF MULTI-TEMPORAL GEOSPATIAL DATA SETS TO ASSESS THE LANDSCAPE EFFECTS OF SURFACE MINING[1]

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Abstract. Geospatial data sets, especially digital elevation data, have proven useful for characterizing and analyzing land surface conditions. Digital elevation models are routinely used for describing the morphology of the land surface in terms of slope gradient and aspect. Additionally, the elevation data are useful for deriving parameters that describe the local drainage conditions such as watersheds and stream channels. When the element of time is added to the analysis through the use of multi-temporal topographic data, the effects of changes to the physical shape of the land surface may be studied. Such is the case with analysis of historical (pre-mining) and recent (post-mining) topographic and other geospatial data sets, including land cover maps derived from remote sensing. Nationwide geospatial data sets now exist with the required spatial and temporal resolution that allow for assessment of the effects of surface mining operations. Changes to the local landscape morphology are readily identified, and the effects to the surface drainage features are quantifiable, such as changes to local relief and drainage pattern and the total length of affected streams. Additionally, the visual impact of the movement of rock and soil materials may be assessed through viewshed analysis. Examples in both Appalachian and Western coalfields show the usefulness of analyzing detailed historical and recent geospatial data sets to better map and describe the effects of surface mining.

Additional Key Words: geospatial data, digital elevation model, change detection, multi-temporal analysis, surface hydrology.

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Introduction

Changes to the shape and form of the land surface are primary effects of surface mining operations. Among the human induced transformations of the landscape, surface mining accounts for a substantial amount of displaced earth materials (Hooke, 1994; Hooke, 1999). Geospatial data in the form of digital elevation models (DEMs) often are used in studies of the morphology of the land surface and landscape processes. Digital elevation data routinely are used to analyze natural geomorphic conditions, but they also are useful for characterizing landscapes resulting from human activity. Multi-temporal elevation data collected before and after the human activity are useful for characterizing the effects of the changes to the physical shape of the land surface.

In addition to the basic elevation data that usually consist of a grid of sampled elevations at a regular interval, derived parameters also are used to describe land surface conditions. Two of the most common elevation derivatives are slope gradient and aspect, or azimuth (Maune et al., 2001). These parameters are derived by analyzing local differences among adjacent elevation values. Because slope gradient and aspect are such basic land surface characteristics that control many physical processes, they are used in many studies and are easily generated in all popular geospatial data processing software packages.

Surface drainage characteristics of the landscape are directly controlled by the distribution of elevations, thus digital elevation data are used extensively to derive parameters used to model and study hydrologic conditions. Watersheds and stream channels (flow paths) are the most commonly derived parameters among the many drainage attributes that can be derived directly from elevation data (Wilson and Gallant, 2000). Derivation of surface drainage parameters from multi-temporal elevation data collected before and after a landscape disturbance allows for a determination of the effects of the topographic surface change on local hydrologic conditions.

This paper describes the analysis of multi-temporal geospatial data sets to assess the landscape effects of surface mining. Analyses of Appalachian and Western coalfields are used to demonstrate the applicability of using historical and recent geospatial data sets to better map and describe the effects of surface mining.

Data Sources

Geospatial data, especially satellite and aerial remote sensing images, have been used extensively to detect and analyze landscape changes; specifically land use and land cover changes. Nationwide geospatial data sets now exist with the required spatial and temporal resolution for detecting and analyzing topographic surface change, or the vertical component of landscape transformation. Because surface mining operations affect the topographic form and shape of the land surface, these multi-temporal data sets are useful for assessing the effects of the mining activity. The data sources used in analyses to characterize the landscape effects of surface mining are described below.

National Elevation Dataset

The National Elevation Dataset (NED) produced by the U.S. Geological Survey (USGS) provides seamless coverage of the “best available” elevation data of the United States (Gesch et al., 2002). The NED is a multi-resolution data set, with national coverage (except Alaska)

available at 1-arc-second resolution (approximately 30 meters), large portions of the country available at 1/3-arc-second resolution (approximately 10 meters), and selected local areas available at 1/9-arc-second resolution (approximately 3 meters). The source data for the NED primarily are the USGS 7.5-minute DEMs that are based on the 1:24,000-scale topographic quadrangle maps (Osborn et al., 2001). Nearly 55,000 of these quadrangle-based DEMs have been processed and assembled to produce the NED for the conterminous United States. The NED is regularly updated on a monthly cycle, incorporating recent elevation data collections from both USGS and non-USGS sources, so that the data set reflects the best (publicly) available elevation data in an application ready format. The NED data used for this study are the 1-arc-second data available as of June 2003, which were produced entirely from USGS 30-meter and 10-meter resolution 7.5-minute DEMs. Thus, the NED derived from the standard USGS topographic map series represents the historical (pre-mining) data set for multi-temporal analysis.

Shuttle Radar Topography Mission

The Shuttle Radar Topography Mission (SRTM), a joint project of the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA), was flown aboard the Space Shuttle Endeavour in February 2000. The mission collected a near-global digital elevation data set unprecedented in its coverage and resolution (Farr and Kobrick, 2000). The mission used a technique called interferometric synthetic aperture radar to collect data that would eventually be used to produce 1-arc-second resolution elevation data for more than 80 percent of the Earth's land surface. One of the unique characteristics of the SRTM data set is that it was collected during an 11-day period, and thus provides a recent topographic "snapshot" of the shape and condition of the land surface. As such, the SRTM data serve as the end member of a set of multi-temporal elevation data that is useful for assessing the effects of topographic surface modifications like surface mining.

National Land Cover Dataset

The USGS has produced several national land cover products that also are useful when assessing the landscape effects of surface mining operations. The National Land Cover Dataset (NLCD), which is derived from Landsat multispectral satellite data on a nominal 10-year mapping cycle, provides national coverage of basic land cover information at a 30-meter spatial resolution. The NLCD 1992 version (Vogelmann et al., 2001) was derived from early-1990s Landsat data. The mapping work for the NLCD 2001 version (Homer et al., 2004) is ongoing and is based on early 2000s Landsat data. The use of land cover data derived from remote sensing along with multi-temporal elevation data allows for a more full assessment of the effects of mining because land cover change often corresponds with the physical transformation of the land surface relief.

Analysis Methods

The NED and SRTM data sets form a unique pair of elevation data sets that can be used to detect and analyze topographic surface changes in the United States. Both the NED and SRTM have a nominal spatial resolution of 1-arc-second (approximately 30 meters), and each is managed as a seamless data set for easy access and manipulation. Each data set has the requisite metadata to aid in determining the time interval over which changes may be identified. Because the NED is derived from the elevation information in the USGS 7.5-minute topographic map series, the date of the source data varies from 1923 to 1999, reflecting the highly variable survey

and compilation dates for the map series. All the SRTM data were collected in February 2000, so any detected surface changes reflect the conditions present at that time.

Change Detection

Change detection procedures are well developed for remote sensing multispectral images. Similar procedures can be used for topographic change detection with multi-temporal elevation data; however, analyzing elevation changes presents some unique challenges (Chirico and Epstein, 2000; Shank, 2003). After accounting for any reference frame differences (horizontal and vertical datums), the first step in detecting topographic surface change is to simply calculate the vertical difference between the elevation data sets, in this case subtracting the NED elevation from the SRTM elevation. In this manner, positive values in the difference data set reflect areas where the SRTM elevations are higher than NED, and negative values represent areas where SRTM elevations are lower than NED. In terms of topographic surface change, the positive differences may indicate areas of filling, and the negative differences may indicate areas of excavation. Local site conditions, namely the presence of vegetation or built structures, often must be taken into consideration to determine if the detected differences represent real geomorphic change.

The next step is to threshold the difference grid to determine which of the detected differences actually reflect significant surface changes. Thresholding is common in change detection techniques. The thresholding methodology incorporates the inherent absolute vertical accuracy of each data set, as determined from an accuracy assessment against an independent reference geodetic control point data set. Previous studies using multi-temporal elevation data have shown that the accuracy of the input elevation data sets must be accounted for to attain reliable results (Etzelmuller, 2000; Jaw, 2001).

DEM Accuracy Assessment. To effectively threshold the elevation difference grid to detect real vertical changes, the vertical accuracy of the input multi-temporal elevation data sets must be known. The vertical accuracies of the NED and SRTM data were calculated based on a comparison against a national set of GPS benchmarks from the National Geodetic Survey (NGS). The 13,305 control points used in the comparison are distributed throughout the conterminous United States, and they represent the high precision survey points used by NGS in their gravity and geoid modeling (National Geodetic Survey, 2003). The absolute vertical accuracy of the NED, expressed as the root mean square error (RMSE), is 2.44 meters. The absolute vertical accuracy of the corresponding SRTM data is 3.53 meters (RMSE).

DEM Differencing and Thresholding. The individual absolute accuracy for each elevation data set is used to determine the threshold with a formula based on a change detection method suggested by Jaw (2001). The threshold, *T*, is defined by:

$$T = \pm 3\left(\sqrt{\left(RMSE_{SRTM}\right)^2 + \left(RMSE_{NED}\right)^2}\right)$$

Using the RMSE values of 3.53 meters for SRTM data and 2.44 meters for the NED, the threshold for significant change is set at ±12.87 meters. When applied to the difference data set, this means that the difference has to be greater than 12.87 meters, or less than –12.87 meters, for an area to be labeled as significant topographic change. In recognition of the fact that the values in the tails of the distribution of difference values represent the likely topographic changes, the root sum of squares is multiplied by a factor of three. The assumption here is that the differences

follow a Gaussian distribution, and the threshold represents values three standard deviations above and below the mean difference value (Figure 1). By combining the measured RMSE for each data set into a root sum of squares and multiplying by three, the thresholding approach effectively states that differences with an absolute value less than the threshold may be due solely to the combined inherent vertical error (uncertainty) of the NED and SRTM data. Stated alternatively, differences with an absolute value less than the threshold may be areas of real surface change, but there is no way to be statistically certain because the NED and SRTM data may each be in error by an amount that, when combined, would show up as a difference.

Terrain Analysis

The detected areas of topographic change may be analyzed in numerous ways. The common elevation derivatives, especially slope and aspect, as well as topographic relief, can be calculated from the pre-mining data set and from the post-mining data set to quantify the effects of the surface change. Basic statistics for elevation and slope values, such as minimum, maximum, and average values, as well as histograms of the distribution of values, calculated from pre- and post-mining data sets will reveal the types and magnitude of changes made to the land surface. Because the change detection is done using geospatial data sets, it is straightforward to determine the area of the disturbed surface and the volume of displaced material using standard GIS tools.

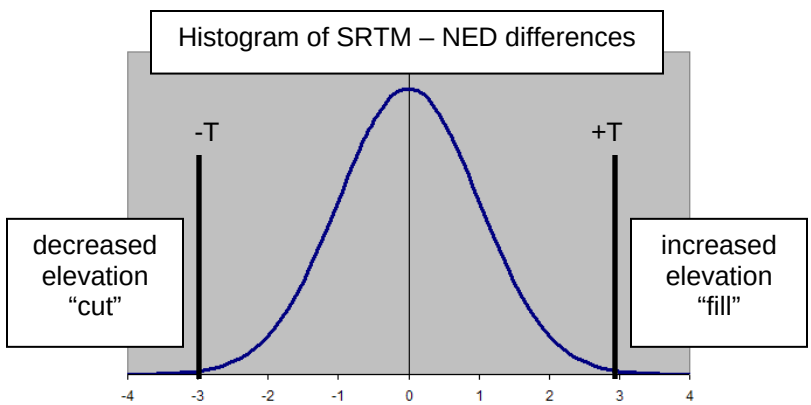

Figure 1. Statistically based topographic change detection threshold.

Surface Drainage Analysis

Surface drainage analysis is an effective means of assessing the effects of surface mining operations. Standard hydrologic derivative products calculated from both pre- and post-mining data sets allow for quantification of landscape changes, specifically changes to the shape and area of individual watersheds (stream reach catchments) and stream channel drainage patterns. Flow direction is a basic parameter calculated directly from the gridded elevation data, and it subsequently can be processed to derive watersheds and flow paths (stream channels) across the landscape. Upslope contributing area and downslope flow direction can be determined for any point on the landscape. Tools for generating hydrologic derivatives from elevation data (Jenson and Domingue, 1988) have long been standard capabilities in most GIS analysis software packages, and they are arguably the most commonly used DEM analysis tools. After the hydrologic derivatives have been produced, numerous metrics can be calculated to characterize the effects of the mining-related landscape alteration, including the total length of stream

channels covered by a valley fill, the contributing area above a fill, and the percentage of watershed area affected by cut and fill operations.

Viewshed Analysis

In his comparison of natural geomorphic agents with human activity altering the land surface, Hooke (1994) concluded that the visual impact of human geomorphic activity generally is greater than that of natural processes, but the impact is difficult to quantify. With the ability to detect specific areas of topographic surface change from multi-temporal elevation data sets, and the analysis and visualization capabilities available in GIS software packages, progress is being made on better understanding the visual effects of significant landscape disturbances, such as surface mining. Perspective views of an area derived from pre- and post-mining elevation data are a simple method of presenting the visual effects of the land transformation. Viewshed, or intervisibility, analysis also is a common GIS technique used to quantify spatially the nature of how terrain may be perceived by an observer on the ground. A viewshed identifies the areas on the landscape that can be seen from specific locations. For assessing the effects of surface mining, the relative size of the viewshed of the disturbed area is one way to quantify the impact of the earth moving operations. For instance, a large amount of material may be displaced during surface mining, but if the operation occurs in a rugged high-relief area, the viewshed for the disturbed area may be relatively small (the mine area can only be seen by observers close to it because of adjacent high-relief terrain). Alternatively, if surface mining occurs on an isolated upland area surrounded by flat ground, its viewshed can be large, even if the actual amount of displaced material is relatively small.

Example Results

Analyses of two example coalfield areas in the United States are used to demonstrate the applicability of using geospatial data sets to determine the effects of surface mining. The results are presented for Appalachian coalfields in eastern Kentucky and Western coalfields near Gillette, Wyoming.

Eastern Kentucky

The Appalachian coalfields provide many examples of the usefulness of analyzing multi-temporal elevation data sets to map and describe the landscape effects of surface mining. An area north of the city of Hazard in Perry County, Kentucky (Fig. 2) is used here to demonstrate the types of geospatial data analyses that can be done to assess the extent of landscape transformation.

Topographic Surface Changes. Fig. 3 shows the NED for the Perry County, Kentucky, study area, and the corresponding SRTM data for the area. The NED for the area is derived from topographic maps compiled based on 1952 source data. The elevation data are portrayed as color-coded shaded relief images, with the colors ranging from blue for the lower elevations to red for the higher elevations. The areas altered by surface mining operations are clearly visible.

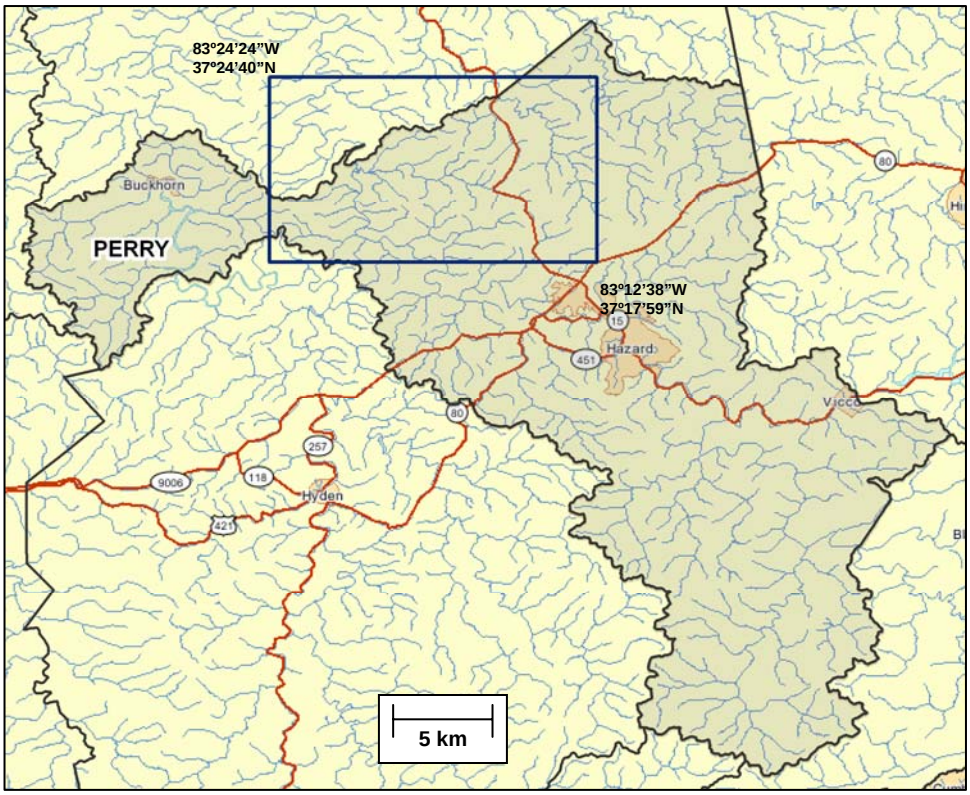

Figure 2. Eastern Kentucky (Perry County) study area (blue box) used for example illustrations.

Fig. 4 shows the results of the elevation differencing operation (subtracting NED elevations from SRTM elevations). The results are displayed with a color scheme ranging from blue for large negative differences to green for zero difference to red for large positive differences. In this case, the differences range from –99 meters to +118 meters. With this color scheme, areas of significantly decreased elevation ("cut") appear as dark blue, and areas of significantly increased elevation ("fill") appear as dark red. Also shown in Fig. 4 is the difference grid after the topographic change detection threshold has been applied, leaving only those areas that are statistically certain to represent true elevation changes. Note that the areas portrayed in the range of colors from cyan to green to yellow in the original difference image have been eliminated because those difference values fall within the bounds of statistical uncertainty. In this area of mountaintop mining, the red areas indicate valley fills, where the elevations have generally increased by 40 to 60 meters. The blue areas indicate where ridge tops have been removed and elevations generally have decreased by 50 to 75 meters. Note that the area between adjacent cuts and fills shows up as an area of "no change." These "no change" areas are obviously contained within the area disturbed by mining operations, however the elevation change was not great enough to exceed the change detection threshold. This pattern of adjacent cuts and fill fills separated by a thin band of "no change" is a characteristic signature of mountaintop mining in Appalachia.

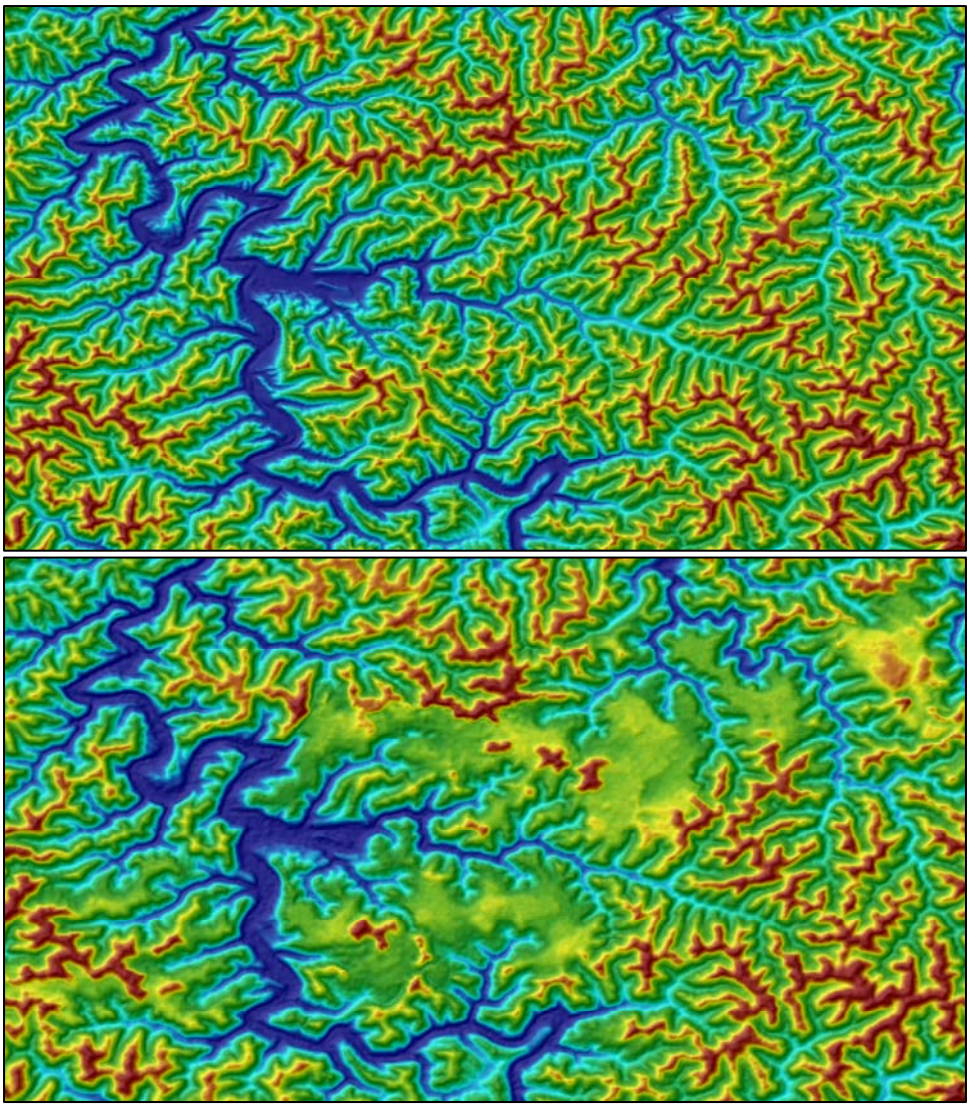

Figure 3. Multi-temporal elevation data illustrating the effects of surface mining in Perry County, Kentucky. The NED (top) is derived from 1952 source data. The SRTM data (bottom) is derived from 2000 source data.

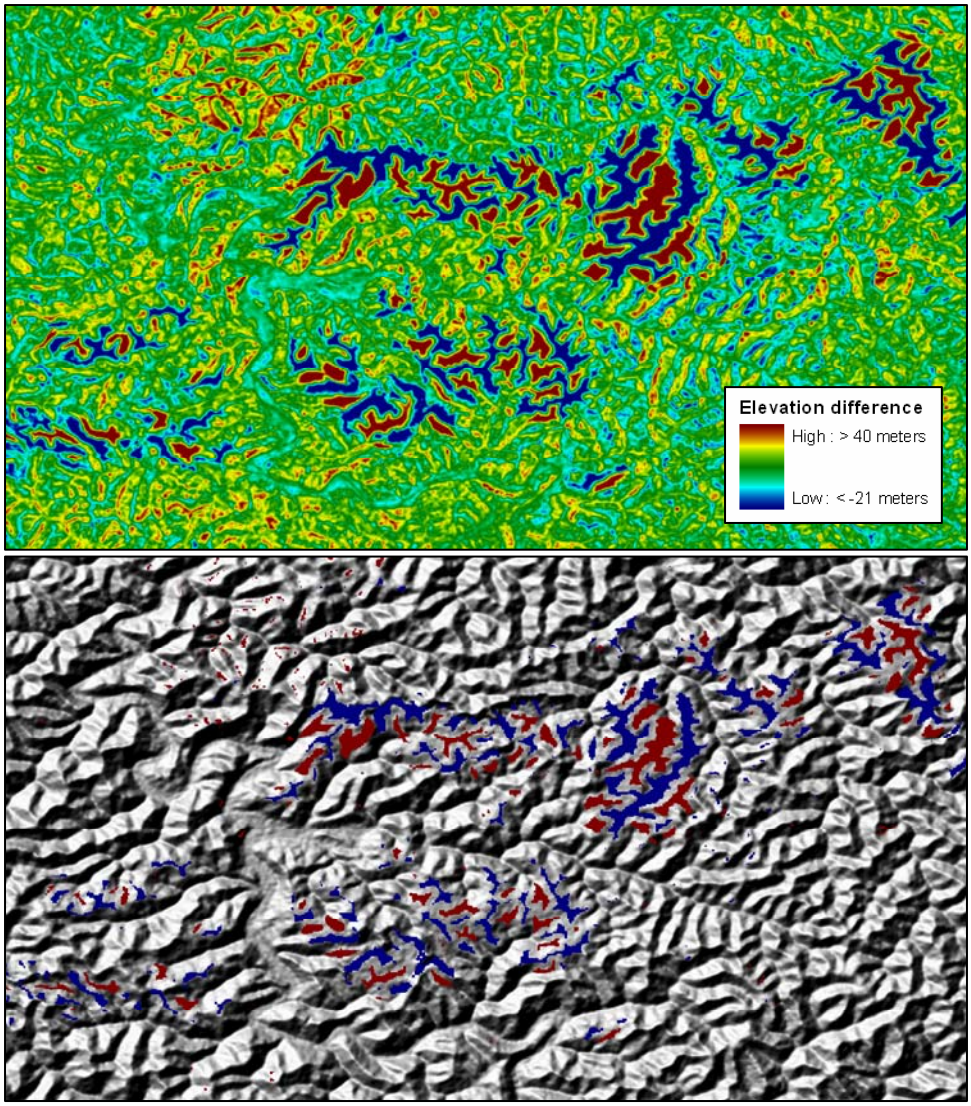

Figure 4. Difference grid (top) calculated by subtracting SRTM elevations (post-mining) from the NED elevations (pre-mining). Areas of increased elevation ("fill") are represented by red, whereas areas of decreased elevation ("cut") are represented by blue. Areas of significant elevation change overlaid on grayscale SRTM shaded relief (bottom).

Fig. 5 illustrates how land cover change often corresponds with a topographic surface change. Selected land cover classes from NLCD 1992 and NLCD 2001 are displayed (green: deciduous forest; gray: barren land/mining areas; yellow: grassland). Although the NLCD 1992 does not pre-date mining operations, comparison of the multi-temporal land cover maps does show the significant expansion of mining operations in this area, as well as reclamation of previously mined areas, which are now classified as grassland cover type.

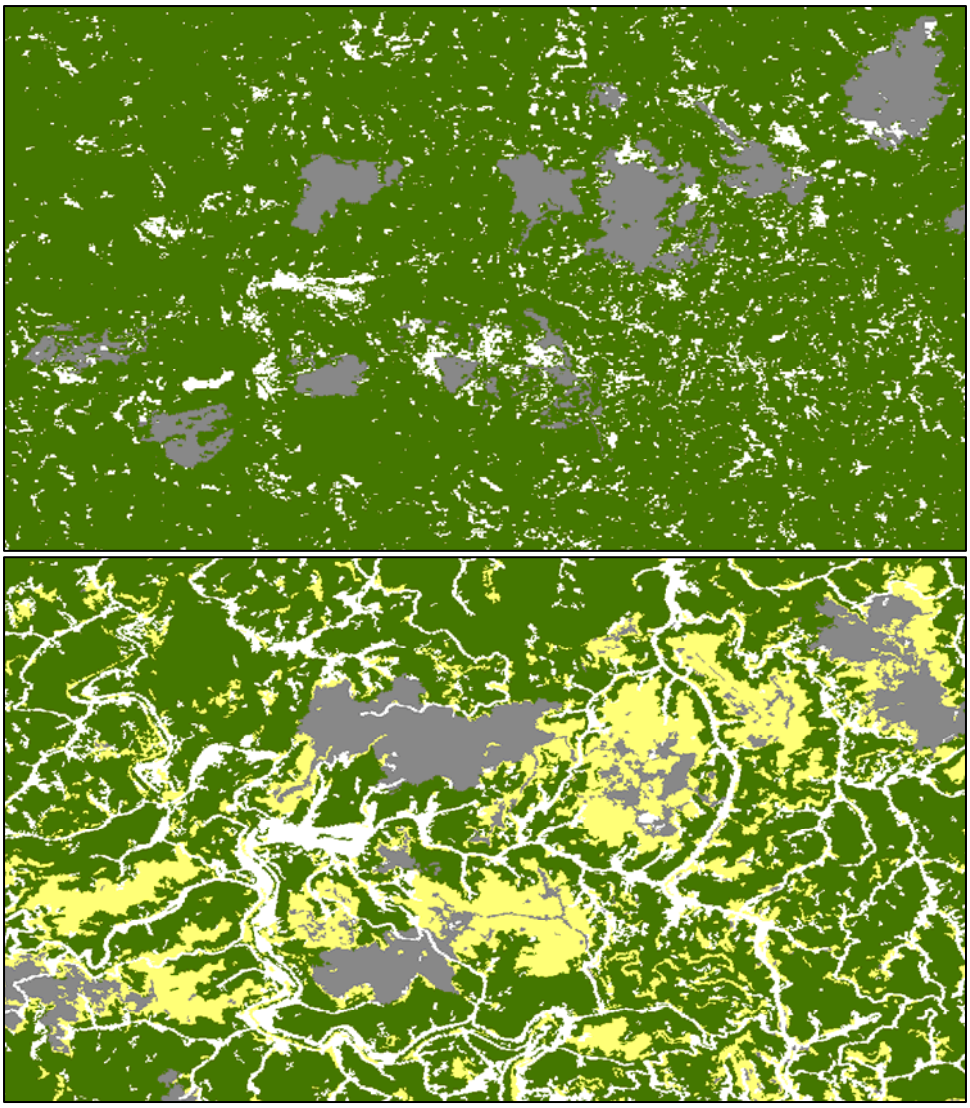

Figure 5. Landsat derived multi-temporal land cover data that show the land cover changes associated with expanded mining and reclamation activities. Selected land cover classes are from NLCD 1992 (top) and NLCD 2001 (bottom). Deciduous forest is green, barren land/mining is gray, and grassland is yellow.

Surface Hydrology Changes. Fig. 6 demonstrates how the local surface drainage features have been altered as a result of surface mining. Standard hydrologic analysis tools were used to delineate watersheds and flow lines from pre- and post-mining elevation data for four adjacent watersheds covering a mined area on the Perry County border, just east of the study area shown above. Note how the locations of the local drainage divides have been modified and how some upslope areas now drain through a different stream network than in the original condition.

Visual Impacts. Figure 7 depicts a qualitative visualization of the visual impact seen in a surface mining area. Multi-temporal land cover data have been draped over perspective view renderings of the NED and SRTM data. The Landsat derived land cover data are from an ongoing USGS study of the status and trends of the Nation's land cover (Loveland et al., 2002) that is using a

statistical sampling scheme to monitor land cover over time within 10- by 10-kilometer blocks. One of the sampling blocks falls within the Perry County study area. Note that ridge top removal and valley fill areas are clearly seen when comparing the images. Also note that some areas classified as mining in the earlier land cover map have been classified as grassland on the later land cover map, most likely indicating reclamation areas that have been re-vegetated. The major stream running through the area is the North Fork Kentucky River, the same stream seen in the western portion of Figure 3.

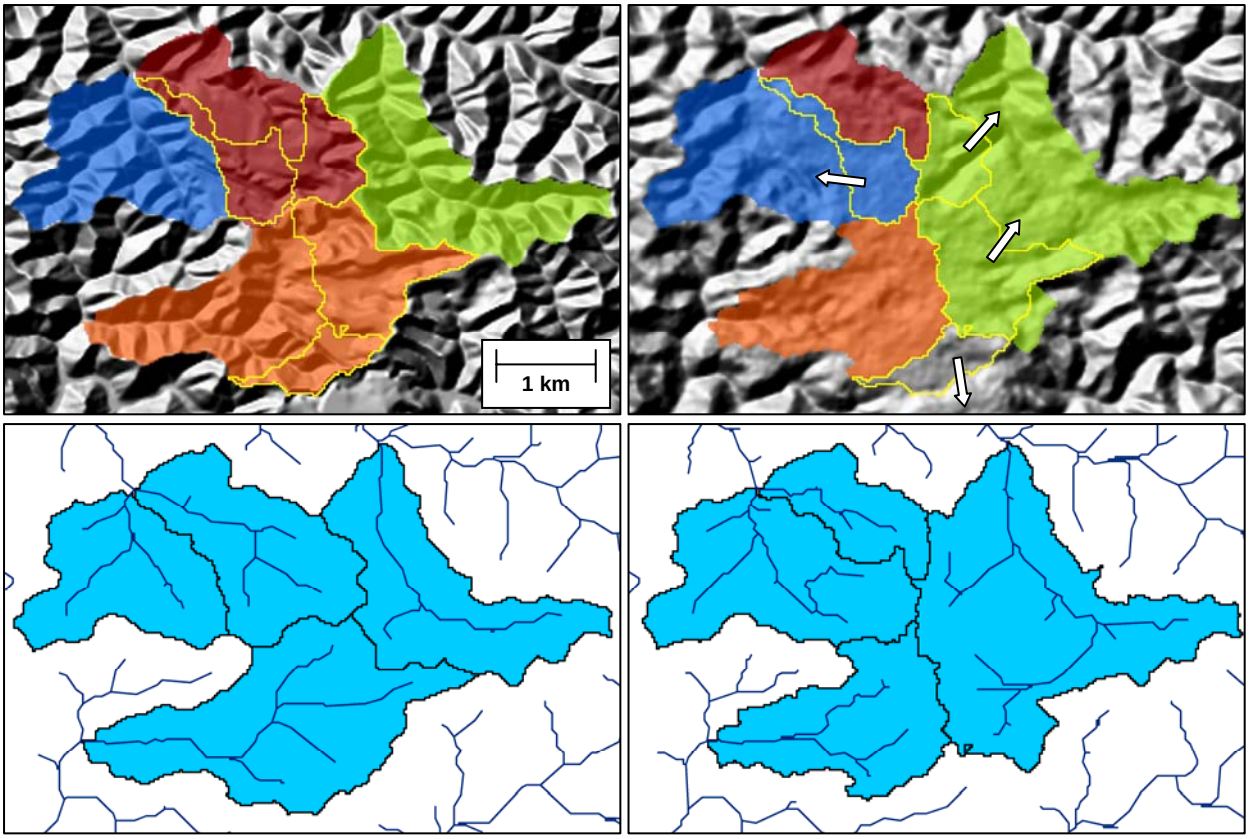

Figure 6. Alterations to the local drainage pattern resulting from surface mining. Watersheds and stream channels derived from pre-mining elevation data (NED) are on the left. Watersheds and stream channels derived from the post-mining elevation data (SRTM) are on the right. The areas outlined in yellow indicate the upslope areas that have changed watersheds and now drain through a different stream network (the arrows indicate the new general flow direction).

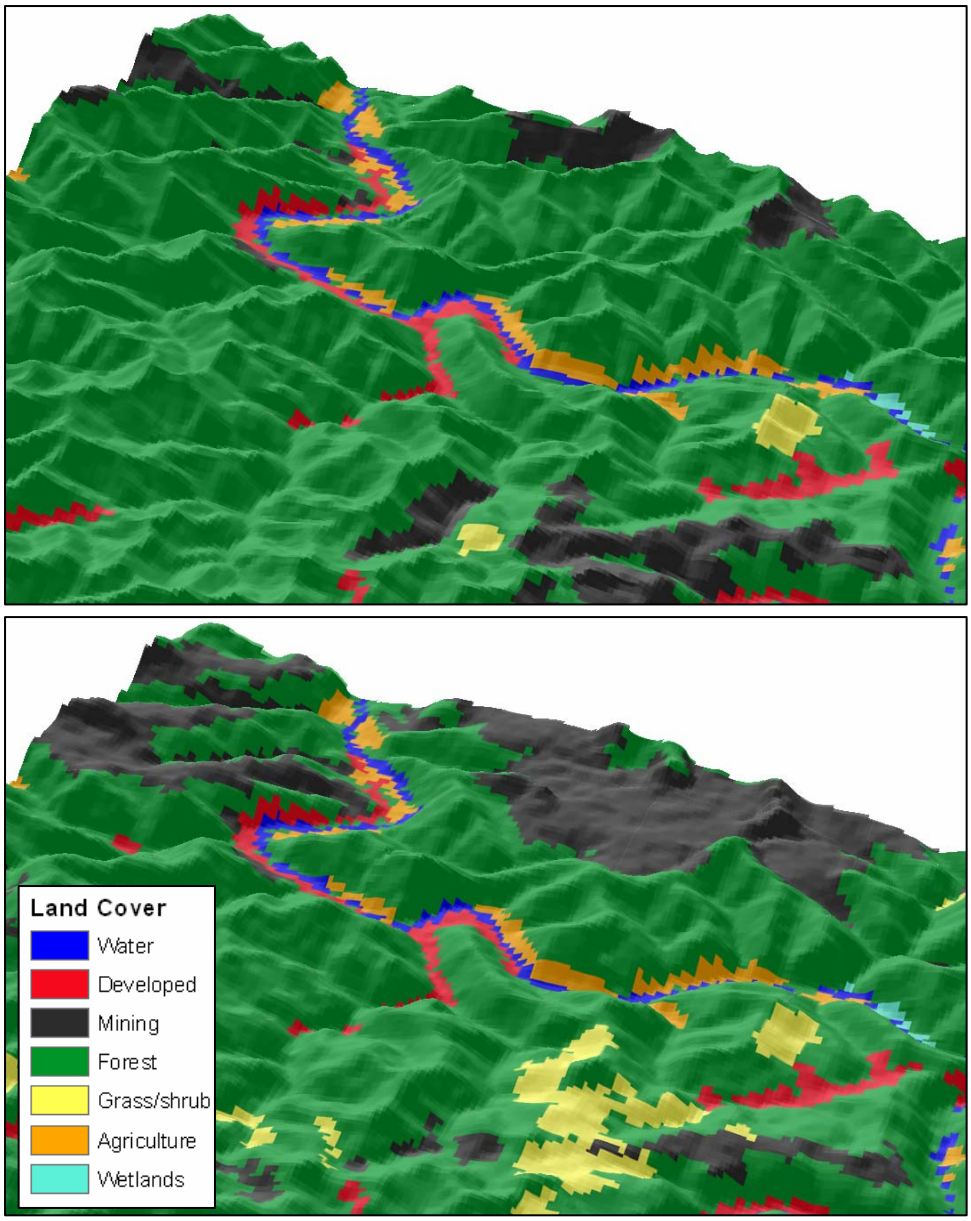

Figure 7. Perspective view renderings that illustrate the visual impacts of mountaintop mining in eastern Kentucky. Land cover classes derived from 1974 Landsat data are draped over the NED (top), and land cover classes derived from 1999 Landsat data are draped over SRTM data (bottom).

Wyoming

The topographic change detection and analysis techniques are effective in depicting the landscape effects of surface mining in settings other than Appalachian coalfields. Fig. 8 shows the signature of surface mining in the Western U.S. coalfields near Gillette, Wyoming.

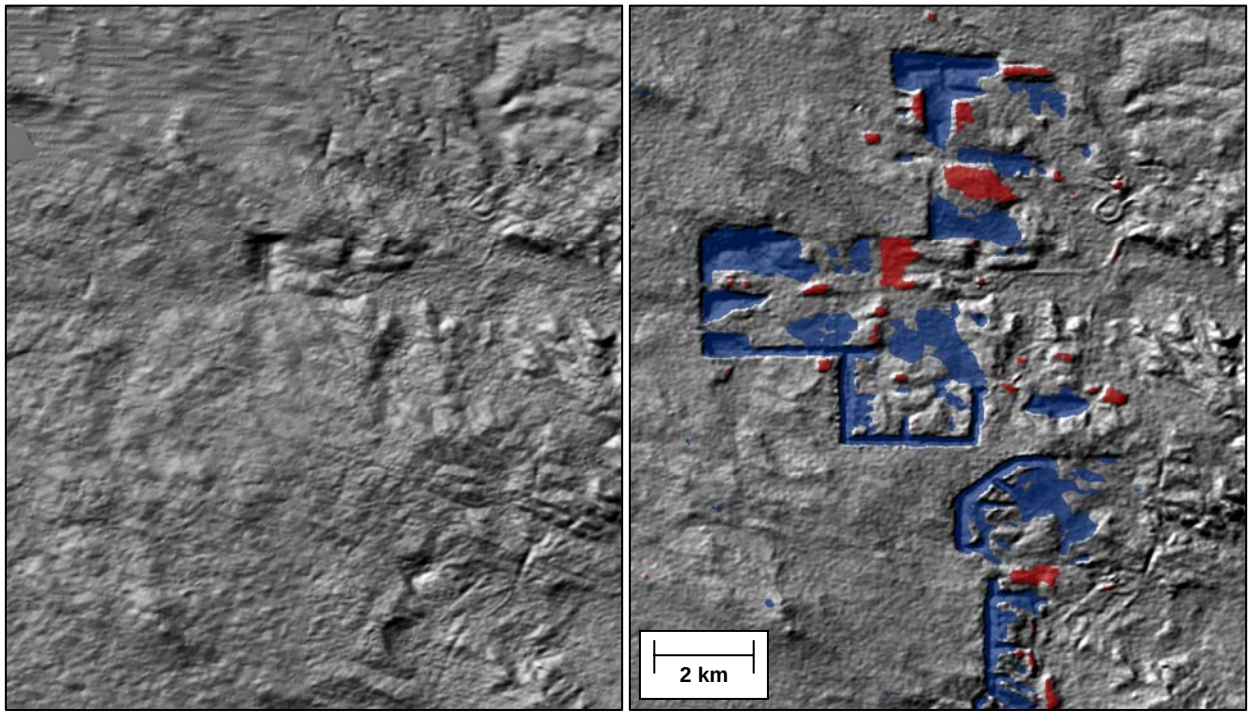

Figure 8. Historical (left) elevation data (the NED, derived from 1970 source material) and recent (right) elevation data (SRTM, 2000 source material) illustrating surface mining near Gillette, Wyoming. Significant elevation increases (fill) are indicated in red, and significant elevation decreases (cut) are indicated in blue.

Other Types of Surface Mines

The topographic change detection and analysis techniques are equally effective for characterizing the effects of surface mining for extraction of other minerals as they are for surface coal mining. Fig. 9 depicts a surface mining operation in the iron range of northern Minnesota. Topographic changes at open pit mines near Silver City, New Mexico (Fig. 10) and in southern Arizona (Fig. 11) also are readily identified. Fig. 12 shows that the change detection techniques work fairly well even in low relief settings, such as this area of phosphate extraction in central Florida.

Discussion and Conclusions

The availability of multi-temporal elevation data facilitates detection and analysis of topographic surface changes resulting from surface mining operations. Terrain and hydrologic analysis tools commonly available in GIS packages can be used effectively to generate elevation derivative products that help document and quantify the effects of surface mining on the landscape. One of the challenges in using multi-temporal elevation data for change analysis is that the user generally does not have a choice of source dates, as would be the case for aerial or satellite images used for land cover change analysis. In the case of using the NED as the historical, or pre-mining, data set, the source date is inherited from the original topographic map compilation, and often it will not align well with the start date of the mining operations. Also, in

most cases, only two elevation data sets are available, so although topographic surface changes may be detected, conclusions cannot be drawn about when the changes actually occurred or the annual rate of land transformation.

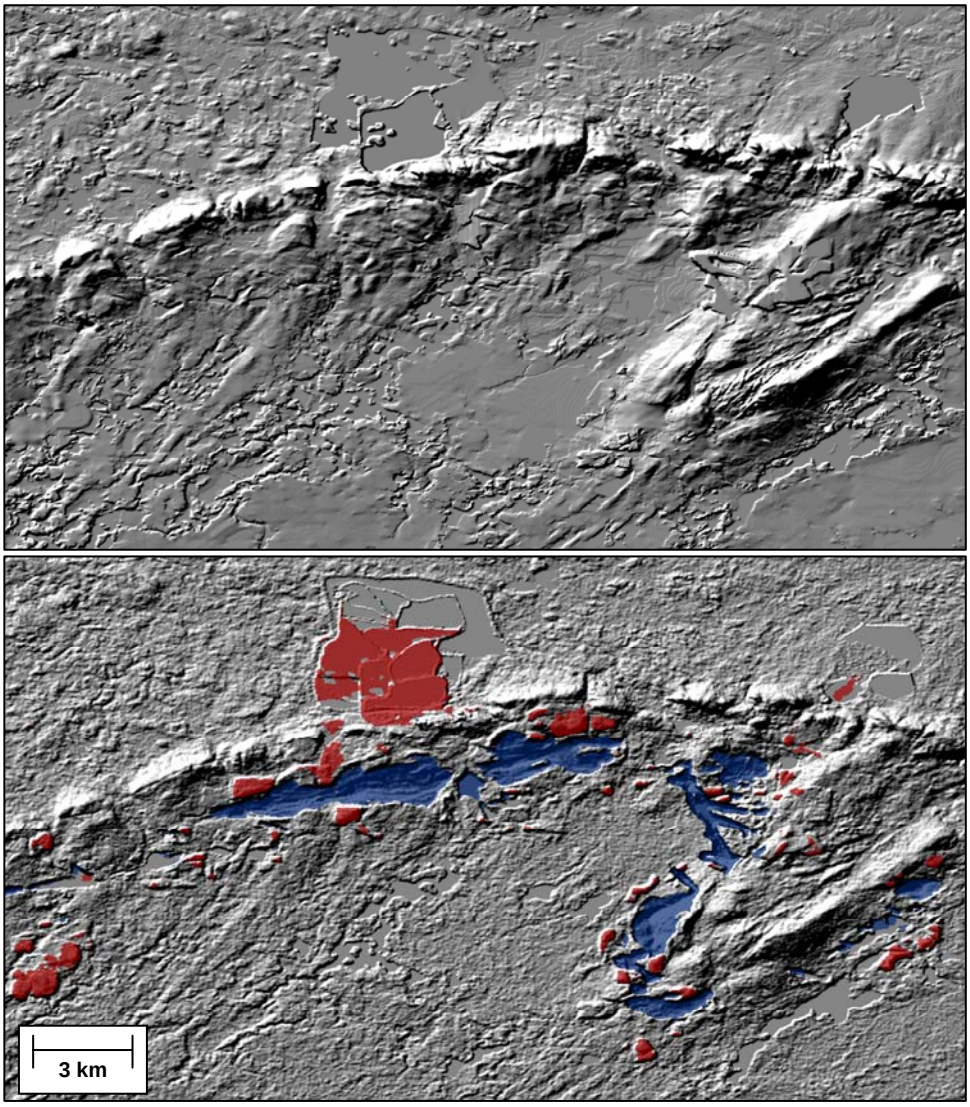

Figure 9. Historical (top) elevation data (the NED, derived from 1983 source material) and recent (bottom) elevation data (SRTM, 2000 source material) illustrating surface mining in the iron range of northern Minnesota. Significant elevation increases (fill) are indicated in red, and significant elevation decreases (cut) are indicated in blue.

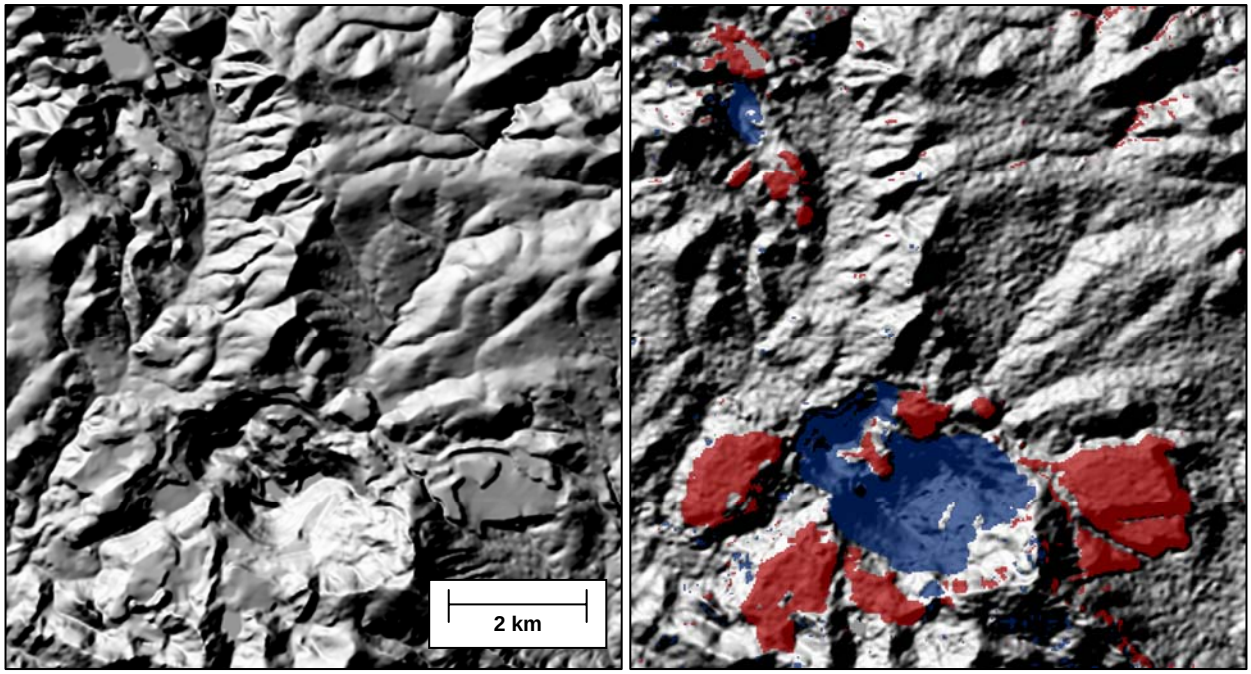

Figure 10. Historical (left) elevation data (the NED, derived from 1987 source material) and recent (right) elevation data (SRTM, 2000 source material) illustrating surface mining near Silver City, New Mexico. Significant elevation increases (fill) are indicated in red, and significant elevation decreases (cut) are indicated in blue.

The analytic techniques demonstrated here could be applied to other higher resolution, higher accuracy multi-temporal elevation data. Such an analysis would allow a description of very fine scale surface changes and corresponding environmental effects. The results of the national topographic change study using medium resolution (30-meter) NED and SRTM data are useful for determining areas where a higher resolution analysis may be useful. For example, such an analysis might be useful in verifying compliance with valley fill permits in terms of location and volume of the fill, and measures to mitigate surface drainage impacts.

The change detection described in this paper can be modified for analysis of specific areas. Namely, the threshold for detecting significant changes could be modified to be less restrictive, thus including more of a disturbed surface area in a labeling of change. The threshold demonstrated here is being used in an ongoing national inventory and assessment of topographic change, and the goal in that study is to focus on the most significant changes across the landscape. Thus the more restrictive threshold is used to eliminate smaller areas of possible change. The other types of surface change, in addition to mining, that often are detected include earth moving associated with construction of roads, buildings, and reservoirs. The topographic change detection work is a part of a larger collection of USGS projects in terrestrial monitoring.

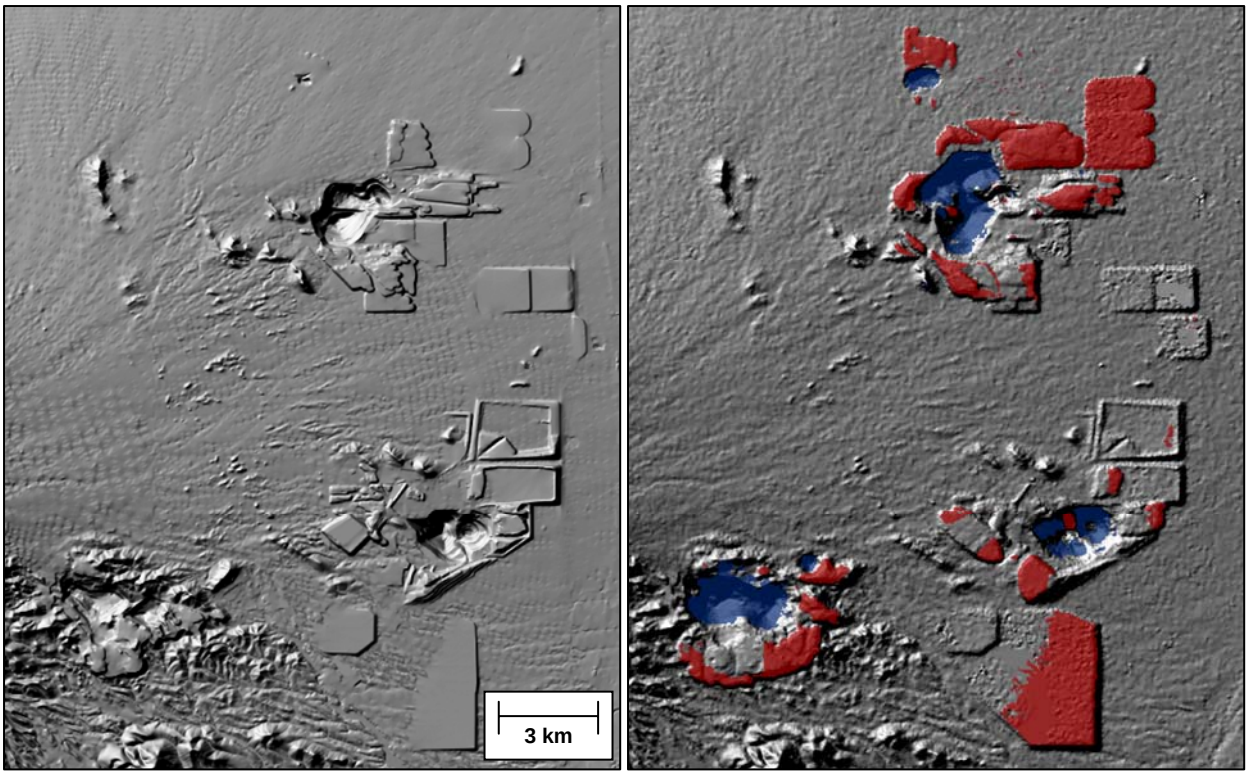

Figure 11. Historical (left) elevation data (the NED, derived from 1966 and 1975 source material) and recent (right) elevation data (SRTM, 2000 source material) illustrating surface mining in southern Arizona. Significant elevation increases (fill) are indicated in red, and significant elevation decreases (cut) are indicated in blue.

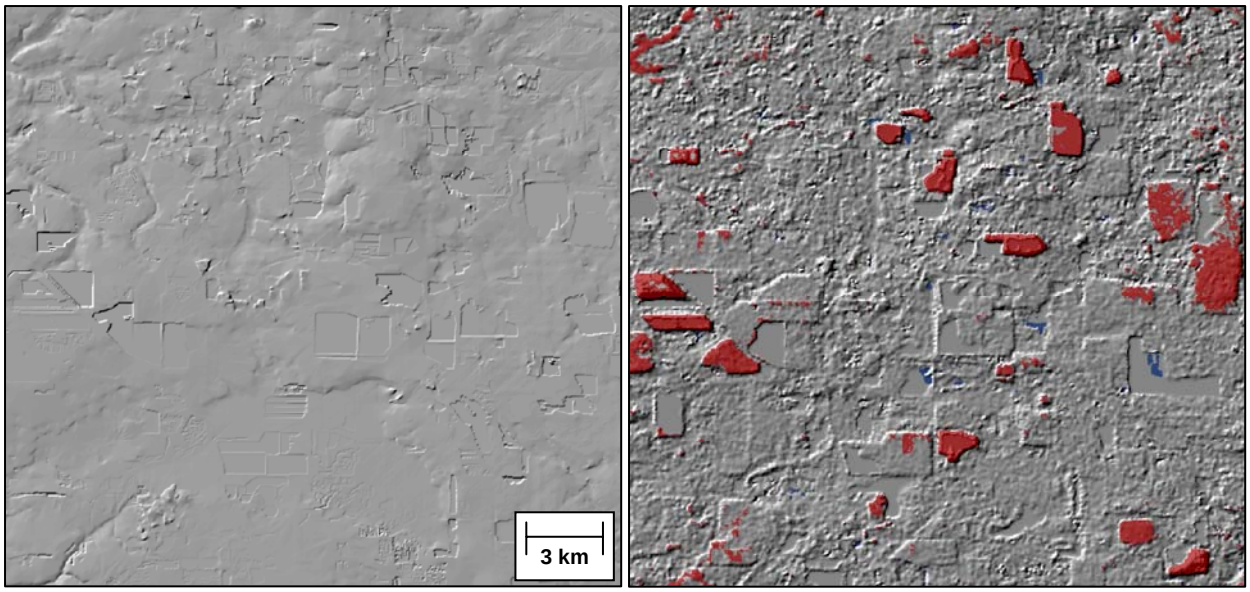

Figure 12. Historical (left) elevation data (the NED, derived from 1987 and 1993 source material) and recent (right) elevation data (SRTM, 2000 source material) illustrating surface mining in central Florida. Significant elevation increases (fill) are indicated in red, and significant elevation decreases (cut) are indicated in blue.

Acknowledgements

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