Automated Detection of Mining Valley Fills From Multi-Date Elevation Data

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Introduction

Change detection techniques are well established in the remote sensing community for monitoring processes over time. However, change detection using multi-date elevation data is still relatively uncommon. This could be because adequate data has not been available, or because in many areas the topography simply doesn't change that much. One exception is the coal mining region of Appalachia, which is undergoing radical alterations to its physical landscape. Surface mining techniques have advanced to the point where entire mountaintops can be systematically removed. During this process, overburden material is pushed into adjacent valleys, forming features known as valley fills (Figure 1). Concern over the environmental impacts of valley fills and mountaintop removal mining has resulted in a federal lawsuit and a court-directed environmental impact statement, the draft of which was released in May of 2003.

Figure 1. A typical valley fill. Note across-face terraces and rock drain along the side. Many fills also have a center drain. The original stream bed emerges at the toe of the fill in the lower right.

Central to the task of managing and studying valley fills is developing an accurate inventory of their location. However, this apparently simple task has proven surprisingly difficult. Fill inventories created from permit maps are incomplete and cannot determine which fills have actually been constructed. And while valley fills often are visible on high-resolution images if one knows where to look, manually searching a large area is tedious and prone to errors of omission. However, if sufficiently accurate elevation data were available for pre-mining and contemporary time periods, it should be possible to extract potential fills automatically.

Data

The availability of GIS data has risen dramatically in the last several years, so that it is not uncommon for a GIS shop to possess multiple elevation datasets for a single area. The original 30-meter digital elevation model from the USGS has been supplemented with hypsography (contour) data from 7.5' quadrangle maps, LIDAR, and radar products. Hypsography data can provide a viable 'before' image for topographical changes dating back 30 years or more, provided the magnitude of change is significantly larger than the error and resolution of the source data. Newer techniques such as LIDAR and IFSAR will likely become the new baseline for comparing subsequent changes, with all the associated benefits of finer resolution and accuracy. LIDAR to LIDAR comparisons could reasonably be expected to detect changes of one-half meter vertically.

To study the potential for detecting valley fills, hypsography data for Wyoming County, West Virginia (Figure 2) was interpolated to a regular grid with a 10-meter cell size. The source date for the hypsography ranged from 1957-69, pre-dating most valley fill activity. Contemporary elevation data was obtained in the form of a LIDAR mosaic originally acquired by FEMA for flood plane analysis. This data was resampled to a 10-meter cell size to match the first data set.

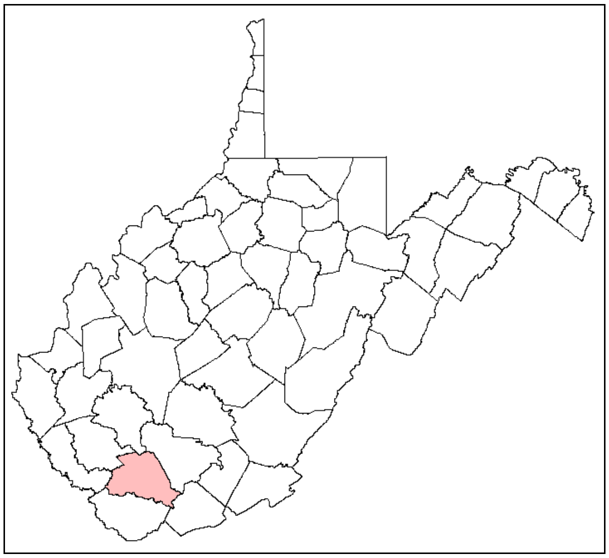

Figure 2. Study area—Wyoming County, W.Va.

Analysis

Change detection using multi-date elevation grids proceeds from the simple idea that the difference of the two grids (t_2 -t_1) results in positive values indicating fills and negative values indicating cuts. However, error present in the source data tends to muddle the results. One way to reduce noise in the result is to reclassify differences less than a selected threshold value as null values, leaving just large magnitude changes. A reasonable value for this threshold would be the sum of the error standards for the source datasets. For this analysis, however, a larger value was used—40', or one contour interval—after visual inspection of the results. Thresholding produced patches of positive and negative values that could be grouped into uniquely identified candidate regions. At this point very small areas less than 1 acre in size were eliminated from the data.

Many regions that were obvious error artifacts from the original datasets remained after the threshold operation, so that additional analysis was required to select actual fills. Three metrics were developed to evaluate whether a candidate region was a fill:

1) Regions representing valley fills should exhibit a relatively large elevation difference variance. That is, differences in elevation between elevation grids t_1 and t_2 for all of the grid cells in the prospective region should show a wide degree of variation (Figure 3). This is because fill depths would be large at the center of the fill, and become continually shallower toward the sides and back. In contrast, a region that is an error artifact might be expected to vary much less, as it is produced by the relatively gentle convergence and divergence of their respective surfaces.

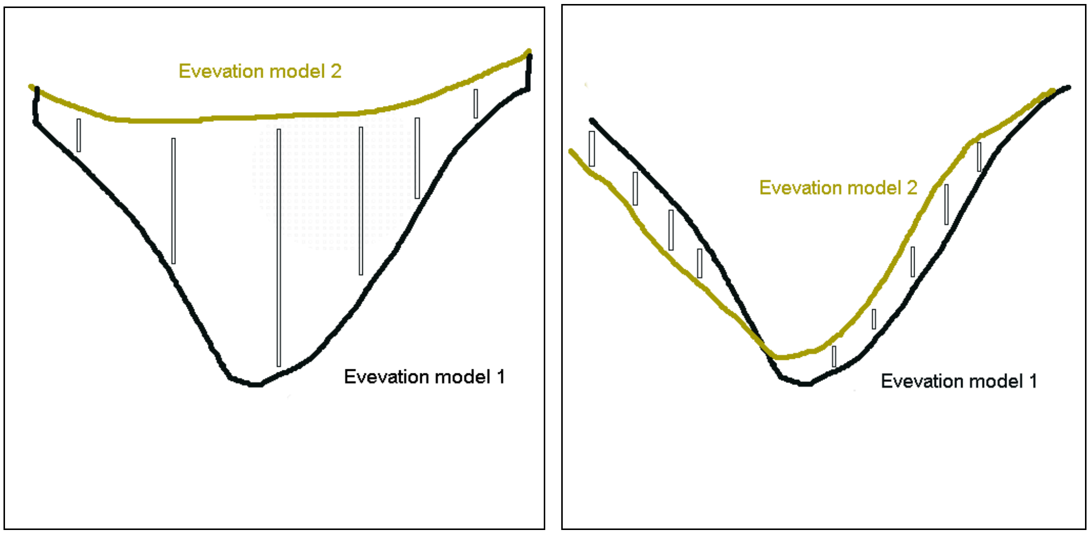

Figure 3. elevation differences for valley fills would be expected to exhibit a large amount of variance (left) while error artifacts might be expected to contain much less (right).

2)) Valley fills often occur adjacent to large cut operations, because hauling overburden any significant distance is expensive. Therefore, if a way could be found to delineate large cuts, a buffer operation could be performed to select nearby potential fills. Large cuts could be delineated using the variance method described above, because differences in elevation would be much greater in the center of the cut (where the ridge top used to be), diminishing toward the outer edges, where the coal originally outcropped.

3) Valley fills should have a single point of drainage occurring at the toe of the fill. Therefore, the entire fill should be reasonably contained within a watershed calculated upstream from that point. To evaluate this characteristic, the point of maximum flow accumulation can be determined for each candidate region. This point then can be used to calculate a watershed. If a candidate region were a typical fill, a large percentage of the fill would be expected to fall inside the calculated watershed. If the candidate region were an error artifact, occurring along the side of a ridge, for example, it is less likely that the entire region would be contained within a single drainage. While this characteristic drainage pattern applies to completed fills, exceptions occur in cases where a partially completed fill is proceeding down two adjacent valleys and have not yet converged to form a single fill. In these cases, while the fill is under construction, there are actually two distinct points of drainage, and the metric will fail.

A subset of 15 candidate regions, known to correspond to existing valley fills, was used to determine cutoff values and buffer distances associated with the three metrics. Each metric was calculated for the candidate regions and applied to a simple function (Figure 4), then summed into a single composite score. Scores ranged from 0 to 4, where anything greater than 2 was identified as a potential fill.

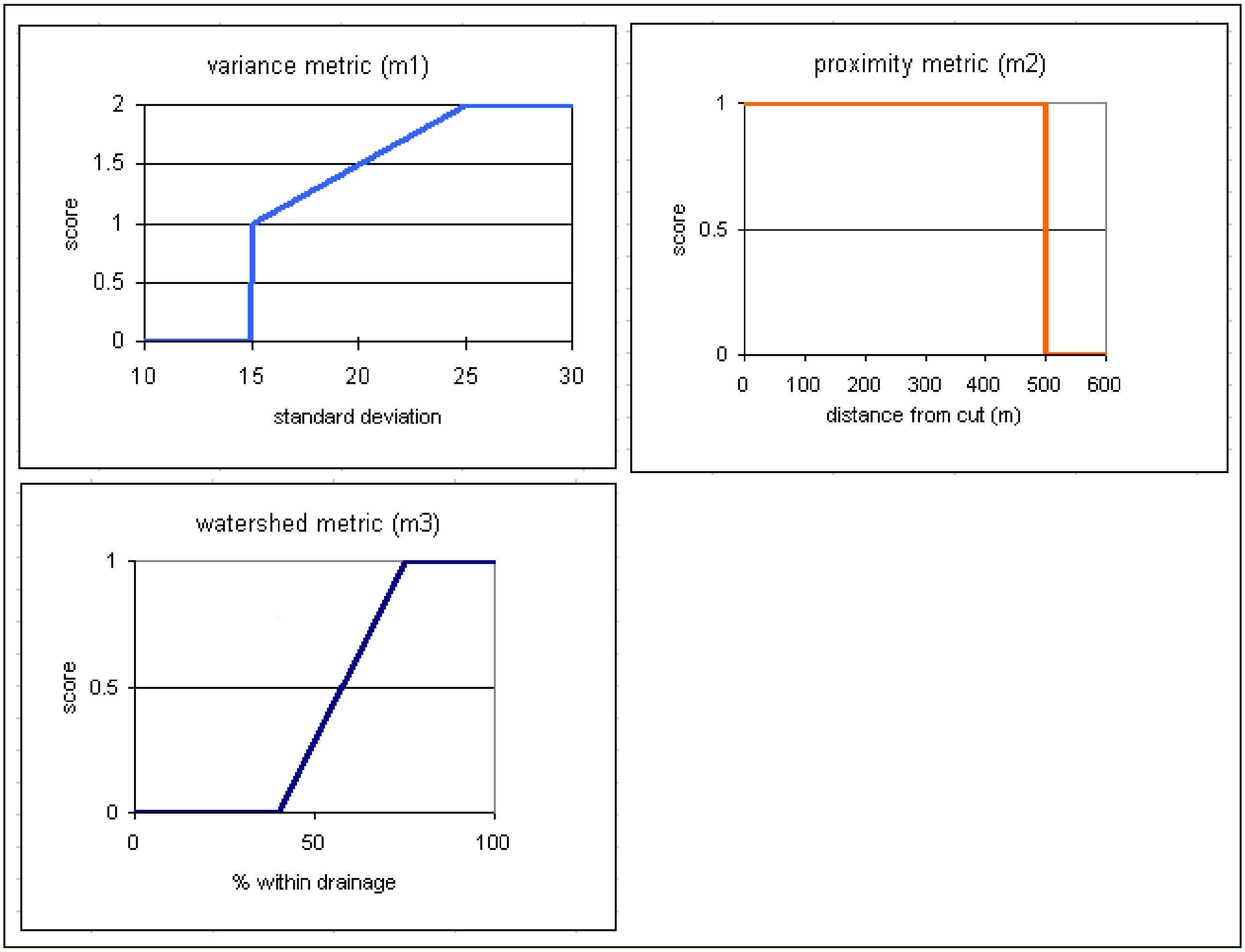

Figure 4. Functions applied to candidate region's metrics to arrive at a composite score.

The effectiveness of the variance metric became apparent during the course of the analysis and was given double the potential weight of the other two measures. The buffer and drainage measures allowed the selection of some shallow fills, perhaps under construction, that might otherwise not have been selected. At the same time, a candidate region having an exceptionally high standard deviation could be selected as a candidate fill based on this metric alone, which contributed to the identification of many refuse impoundments and older fills not associated with mountaintop operations. Overall, an effort was made to bias the combined score so as to not omit an actual fill, even if some error artifacts were selected as potential fills. In other words, errors of omission were considered less tolerable than errors of commission.

Results

Several data sources were used to evaluate the actual presence of fills at the candidate sites, including digital aerial photography from 1996, SPOT panchromatic images from 2000, and digitized valley fill outlines from mining permit maps. Results are shown in Table 1. Of the 161 potential fills, 119 were determined to represent fills related to mining, 28 showed no evidence of disturbance, 5 were judged to be fills not related to mining, and 9 could not be determined. Of the fills identified as related to mining, not all were classic valley fills, but also included refuse dumps and slurry impoundments. Non-mining fills included road fills, an industrial site, and a large reservoir.

Mining-related fills	120
Non-mining Fill	5
Not a fill	28
Couldn’t be determined	8
Total	161

Table 1. Final classification of candidate regions.

Table 2 shows a comparison between the analysis results and a fill inventory compiled from permit maps. The fill inventory consisted of 110 fills, of which 57 were detected as built/in progress by the analysis. 42 showed no evidence of construction. 11 fills in the inventory *did* exist and were not detected by the analysis. Eight of these undetected fills were not detectable even when the threshold of the elevation difference grid was set to 20’, indicating that the fills were very shallow. Three of the non-detected fills did produce candidate regions, but the metrics did not produce a sufficient score for them to be selected. This ordinarily would have been considered a significant problem with the analysis. However, the non-detected fills were typically quite small and correspondingly shallow—the median size of the undetected fills was only 2.75 acres, whereas the median size for the entire permit inventory was 17.7 acres. Visually, only one of the missed fills exhibited the typical look of a valley fill, with a terraced face and rock drainage ditches.

Fills in permit inventory	110
Permitted fills detected by analysis	57
Not detected, but confirmed to exist	11
Not detected, do not exist	42

Table2. Comparison of analysis results with permitted fill inventory.

An additional factor to consider in evaluating results of the analysis is the fact that some structures may have already existed at the time when the hypsography was compiled. While the initial focus of the study has been on valley fills, other coal waste structures, particularly impoundments, are of interest for a variety of safety and environmental reasons. Figure 5 shows what was initially classified as “couldn’t be determined” because its shape did not match existing structures depicted on aerial photography. However, an examination of the hypsography, and the topographical map source, indicated that most of the fill had been constructed by the time the map was compiled, with the exception of a depression in one corner that was subsequently filled, and detected, by the analysis. The source map photography was flown in 1968, making it one of the latest historical sources used in the analysis.

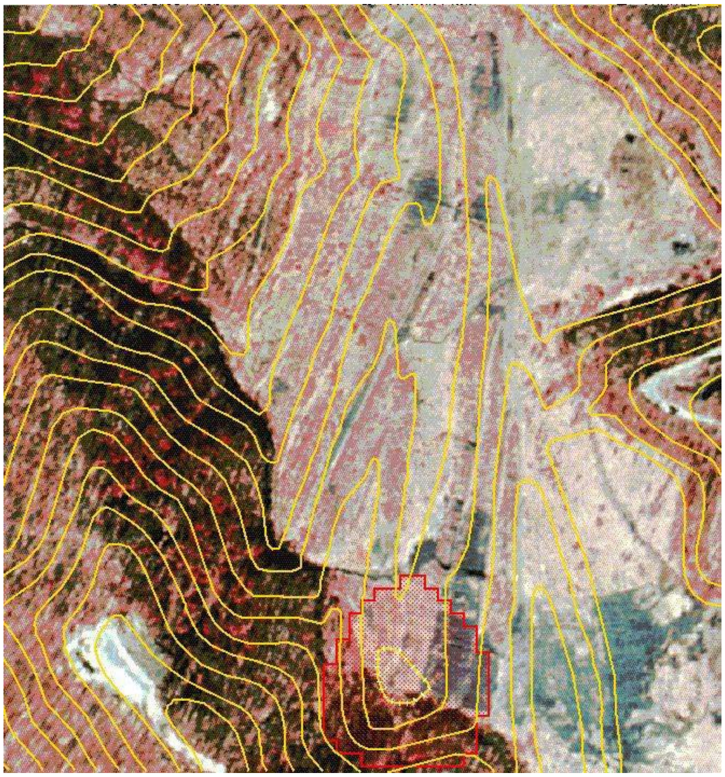

Figure 5. Historical contours show this fill was nearly complete when the source map was compiled, with the exception of a depression at the bottom center, which was subsequently filled and detected by the analysis.

The potential for improving the accuracy and usefulness of the existing valley fill inventory is illustrated in figure 6. Permitted fills are shown in green, while detected fills are red. Features depicted include cuts (a), permitted fills that where not constructed (b), permitted fills that were confirmed to exist (c), fills that were not a part of the inventory (d), and a fill that was partially completed (e).

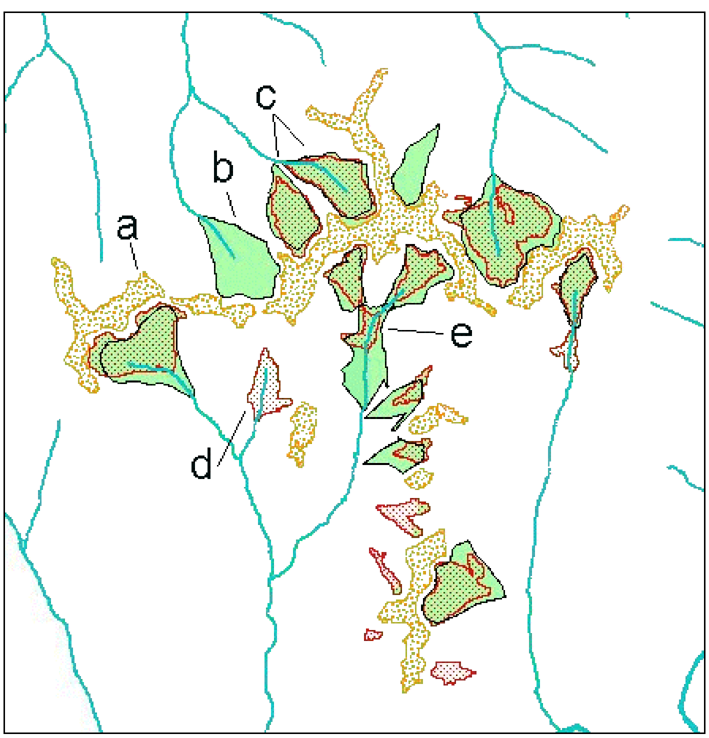

Figure 5. Comparison of permitted fill inventory with (green) with fills detected by the analysis (red). Cuts are yellow.

Figure 7 demonstrates that permit maps sometimes did not delineate the entire fill. The two center fills are represented only by the face (black triangles) in the permit inventory, whereas the actual fills were quite larger.

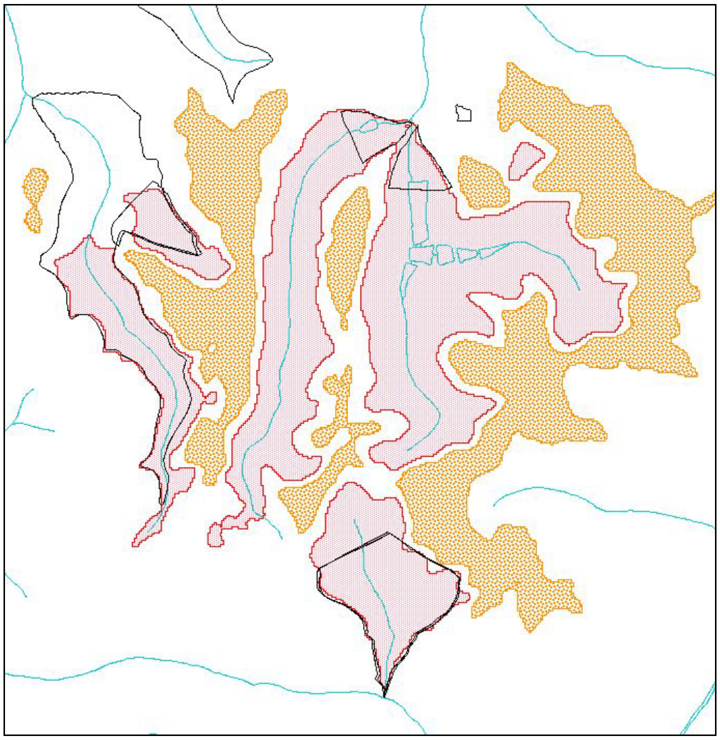

Figure 6. This figure depicts how the analysis could detect the actual shape and extent of fills, improving on the permitted fill inventory. Permitted fills (black outlines) were not always completely delineated on permit maps.

Conclusions

Historical elevation data, in the form of 7.5' hypsography, can be used to detect landscape modifications provided the magnitude of the change is greater than the magnitude of error present in the source data. In the analysis presented here, additional testing was required to effectively separate real changes from error artifacts, even after differences less than one contour interval were eliminated from the difference grid. A high variance in the difference values for a particular region were found to be an effective metric for separating real changes from errors. Other metrics used in the analysis were more specific to the features of interest in the study—mining valley fills—and served to improve the results. The analysis was not able to detect some small, shallow fills due to limitations in the hypsography data source. An additional limitation relates to features constructed prior to compilation of the 'before' data, which, of course, would not be detected.

The fills detected by the analysis significantly improved upon an existing database of valley fills that were digitized from permit application maps. Analysis results confirmed which fills were constructed, which had not been constructed, and which were partially completed. The analysis also found many fills that were not in the inventory, and was able to more accurately determine the shape and extent of many fills that were only partially delineated on the permit maps.