AN INVENTORY OF TOPOGRAPHIC SURFACE CHANGES: THE VALUE OF MULTI-TEMPORAL ELEVATION DATA FOR CHANGE ANALYSIS AND MONITORING

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ABSTRACT:

Landscape change resulting from human activities continues to be a primary topic in geographic research. Many studies have focused upon human-induced changes in two dimensions, namely in land cover. However, those changes may include a corresponding transformation of the third dimension, or vertical component, of the landscape as expressed in the local surface topography. Some previous studies have estimated the total effects of human activity on the landforms and shape of the Earth's surface, but these studies have not emphasized the spatial component of the changes. The primary issue addressed by the research reported here is the need for more comprehensive information on the nature and extent of recent human geomorphic activity. The elevation information from the Shuttle Radar Topography Mission (SRTM) paired with the historical topographic data in the U.S. Geological Survey's National Elevation Dataset (NED) allow for mapping and assessment of significant changes to the shape of the land surface across the conterminous United States. The NED supplied the historical elevation information that was subtracted from the more recently collected SRTM data to create an elevation difference grid that provided information about where topographic changes have taken place. The elevation difference information was filtered and refined to complete a national inventory of vertical landscape changes, and it represents a first ever accounting of topographic change across the United States. The inventory serves as a useful foundation for ongoing monitoring of topographic changes using recently collected high-resolution elevation data, including current work with airborne interferometric synthetic aperture radar data.

1. INTRODUCTION

Landscape change resulting from human activities continues to be a primary topic in geographic research. Many studies have focused upon human-induced changes in two dimensions, namely in land cover. However, those changes may include a corresponding transformation of the third dimension, or vertical component, of the landscape as expressed in the local surface topography. Examples of such transformations include dam construction and reservoir filling, excavation associated with building construction, earth moving from surface mining operations, cut and fill linked to road construction, and sanitary landfills. Some previous studies have estimated the total effects of human activity on the landforms and shape of the Earth's surface (Hooke, 1994, 2000; Nir, 1983), but these studies have not emphasized the spatial component of the changes. The primary issue addressed by the research reported here is the need for more comprehensive information on the nature and extent of recent human geomorphic activity.

2. DATA AND METHODS

The topographic change approach applied in this study makes use of seamless multi-temporal elevation data and land cover data to meet the requirement for locational and quantitative information about significant topographic changes.

2.1 Elevation Data

The detection of human geomorphic activity, as indicated by vertical changes to the land surface, is accomplished by comparing multi-temporal elevation data. As such, multi-date elevation data with similar characteristics over the large study area of the conterminous United States are required. The National Elevation Dataset (NED) (Gesch, 2007) and the Shuttle Radar Topography Mission (SRTM) data (Farr et al., 2007) form a unique pair of elevation datasets that can be used to detect, measure, and analyze 20th century topographic surface changes in the United States. Both the NED and the SRTM data have a nominal spatial resolution of 1 arc-second (about 30 meters), and each resource is managed as a seamless dataset for efficient access and manipulation.

2.2 Land Cover Data and Reference Geodetic Data

The Landsat-derived National Land Cover Database (NLCD) (Vogelmann et al., 2001) is used to help guide detection, mapping, and analysis of topographic surface changes by providing land cover information at a 30-meter scale that matches the NED and SRTM data. The use of land cover data derived from remote sensing along with multi-temporal elevation data allows for a more complete assessment of the geomorphic effects because land cover change often corresponds with the physical transformation of land surface relief.

Detailed information about the absolute vertical accuracy of the NED and SRTM data is required for the change detection method. To calculate the requisite vertical accuracy measurements, the NED and SRTM were compared to an independent reference set of high-accuracy geodetic control points from the National Geodetic Survey (NGS). The "GPS on bench marks" dataset (National Geodetic Survey, 2003)

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includes the points distributed throughout the conterminous United States that NGS uses for gravity and geoid modeling (Roman et al., 2004). The points provide an excellent independent reference against which the NED and SRTM data can be assessed.

2.3 Change Detection Approach

Given that the primary input datasets, NED, SRTM, and NLCD, each have a spatial resolution of 30 meters and the fact that the study area covers the conterminous United States, a considerable amount of data processing was required to detect and quantify areas of significant topographic change. The NED and SRTM data are each supplied as 1x1-degree tiles defined by lines of latitude and longitude, and these tiles provided a convenient and useful scheme for organizing and processing the input data. A total of 934 1x1-degree tiles cover the conterminous United States. Even though the NED, SRTM, and NLCD were partitioned into 1x1-degree tiles for processing efficiency, each dataset is truly seamless, as there are no artificial discontinuities across the tile boundaries. Data processing was accomplished with standard geographic information system (GIS) and statistical software tools and was automated as much as possible with scripted command files to standardize the procedures.

2.4 Elevation Differencing

Image differencing has long been used as an effective change detection technique for coregistered digital remote sensing datasets (Lunetta, 1998). One image is simply subtracted from another image on a pixel-by-pixel basis. As applied to gridded digital elevation models (DEMs), the result of image differencing is a differential surface, which is a measure of the spatial distribution of mass displacement (Etzelmuller, 2000). In a differential surface, the areas of mass displacement are both located and quantified, and both are important for this study in which locating and describing (quantifying) topographic changes are primary goals. Thus, DEM differencing is the most appropriate change detection method.

To minimize the chances of falsely detecting vertical changes because of misregistration, the NED and SRTM data were coregistered as precisely as possible prior to differencing. After coregistration, a difference grid was created for each 1x1-degree tile by subtracting the NED historical elevation from the more recently collected SRTM on a per pixel basis. In this manner, positive values in the difference grid 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, or cuts. Figure 1 is an example of the NED, SRTM, and the derived difference grid for an area in the state of Kentucky in the eastern U.S. that has experienced topographic change due to surface mining for coal.

2.5 Significant Change Thresholds

Thresholds were applied to the difference grids to isolate areas of significant change. This procedure is commonly done in the image differencing method of change detection, and the threshold is often based on the standard deviation value of the differences (Lunetta, 1998). As implemented for this study, the thresholding approach incorporated the inherent absolute vertical accuracy of each of the input elevation datasets, expressed as the root mean square error (RMSE), an accuracy assessment metric commonly used for elevation data (Maune et al., 2007). The RMSE is the statistical equivalent of the standard deviation for normal distributions.

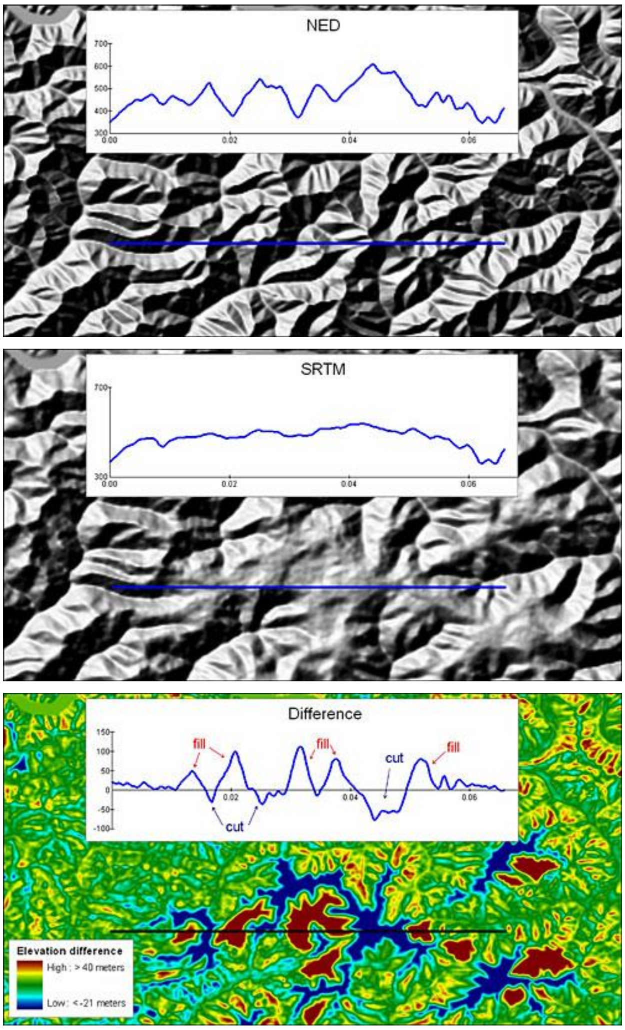

Figure 1. Example of the NED, SRTM, and the derived difference grid for an area in Kentucky in the eastern U.S. The length of the profile is about 5.8 kilometers.

The accuracy values used are those determined in an accuracy assessment of the NED and SRTM data as compared to the independent reference geodetic control point dataset from NGS. These points have centimeter-level accuracy in their horizontal and vertical coordinates, as they are produced by survey quality GPS observations on established bench marks (Roman et al., 2004). An important aspect of the accuracy assessment was the calculation of vertical accuracy by land cover class, recognizing that SRTM is a "first return" system; the elevation measured is that of the first reflective surface that the radar signal encounters. Because of the relatively short wavelength (5.6 cm) of the C-band radar used by SRTM, the reflective surface in most vegetated areas is located within the canopy (Carabajal and Harding, 2006). In areas where buildings are prevalent, the measured SRTM elevations represent the combined effects of the rooftops and other structures within the resolution cell. The first return nature of SRTM data is a critical characteristic to consider when generating SRTM–NED difference grids. In vegetated and built-up areas, many of the vertical differences are not indicative of topographic surface changes but reflect the presence of radar scatterers above the ground surface. The overall absolute vertical accuracy calculated for the NED is 2.44 meters (RMSE), whereas the assessment of the SRTM showed an accuracy of 3.91 meters (RMSE).

The individual absolute vertical accuracies for the NED and SRTM data, segmented by NLCD class, are used to determine the threshold for each land cover class with a formula based on the change detection method suggested by Jaw (2001). The threshold, *T*, is defined by:

$$T = \pm 3 \times \sqrt{\left(RMSE_{SRTM}\right)^2 + \left(RMSE_{NED}\right)^2} \quad (1)$$

In recognition of the fact that the values in the tails of the distribution of difference values represent the likely changes, the root sum of squares is multiplied by a factor of three. The assumption here is that the differences approximate a Gaussian distribution. By using the RMSE for each elevation dataset, the multiplier of three effectively states that differences within the threshold bounds may be due solely to the combined inherent vertical errors (uncertainty) of the NED and SRTM data. Real surface changes are indicated by the most extreme difference values that are beyond three standard deviations above or below the mean difference value.

Stated alternatively, difference values not exceeding the threshold may represent areas that have experienced topographic change, but there is no way to be certain in a statistical sense because the NED and SRTM data may each be in error by an amount that, when combined, result in a difference. Based on probabilities associated with a Gaussian distribution, there is less than a one percent chance that the error of SRTM and/or NED exceeds three times + or – the measured RMSE. In these rare cases, extreme errors in the elevation datasets could cause an area to be erroneously flagged as an area of topographic change. The range of difference values is a continuum, and the selection of thresholds sets an artificial point to segment change versus no change areas. This practical approach is necessary when the objective is change detection over a vast area, as is the case for this study. When applied to the SRTM–NED difference grids on a per pixel basis, the difference values have to exceed the threshold to be identified as significant change.

2.6 Filtering of Elevation Difference Mask

The output of the differencing and thresholding procedures was a set of pixels with elevation differences large enough to be judged significant. Ideally, these differences would represent the set of true topographic changes that could then be used for further analysis. In reality, this was not the case, as the selected differences included areas that clearly did not reflect topographic changes but were related to characteristics of the input elevation datasets. Even though the NED and SRTM data were processed to register them as precisely as possible, there remained residual offsets in some areas that were large enough to cause vertical differences that exceeded the significance thresholds.

This condition was not consistent across the study area. In some areas the registration of the NED and SRTM data was excellent, whereas in other areas the residual offset was very noticeable. The cause of the misregistration is not known; however, it may be caused by variations in the internal geometry of the SRTM and possibly the NED data. The false vertical differences due to the residual horizontal offsets were most prevalent in the higher relief areas in the desert southwest of the United States. In these higher relief areas, the misregistration may be slight but can still lead to significant vertical differences.

Another primary cause for differences being falsely included in the change mask is the first return nature of SRTM elevation data. Even though the accuracy-based threshold accounts for variable accuracy by land cover type, some areas of vegetation and built structures are the sole cause of SRTM–NED differences large enough to exceed the threshold. Even though the geographic distribution of the reference control point dataset used for accuracy assessment was extensive, it may not have been truly representative of the full range of land cover conditions. Thus, the accuracy-based thresholds do not capture all the variability in vertical accuracy due to land cover.

Based on visual and quantitative assessment of the false change areas, a set of filtering criteria was developed and applied to remove as many of the anomalous areas as possible. The primary objective of the filtering process was to reduce the errors of commission as much as possible, even at the expense of omitting areas that appeared visually to have undergone topographic change but their attributes did not meet the filtering criteria. This goal is consistent with the thresholding procedure in which areas had to pass strict statistical criteria to be considered as candidate topographic change areas, tests that undoubtedly eliminated some areas of actual change. If the area of interest for a topographic change study is small, then the set of elevation differences that represent actual topographic changes could be selected manually with a very high degree of accuracy, and the statistically based thresholding and filtering processes could be avoided altogether. However, when the study area is large and data quality is variable, as is the case for this study, automated procedures must be used that result in a manageable set of features. Thus, a conservative approach to labeling areas as true topographic surface change is the method that has been implemented for this study.

The input change mask to the filtering and refinement process consisted of all the candidate areas that passed the statistical threshold test. These areas of contiguous pixels from the raster difference grids were converted to vector polygons and attributed with information from the input elevation datasets and the vertical difference data. The polygons from the individual 1x1-degree processing units were merged into a feature dataset covering the entire study area. After completion of the filtering, 5,263 polygons remained, which represent the final set of features that delineate areas of significant topographic surface change across the conterminous United States.

3. RESULTS AND DISCUSSION

The final delineation of topographic change polygons includes features representing cuts (decreased elevations) and fills (increased elevations). Over two-thirds (67.5 percent) of the polygons represent cut areas (significantly decreased elevation), and the remainder (32.5 percent) represent fill areas (significantly increased elevation). Each of these polygons has numerous attributes that describe the specific surface modification, such as area and volume, and these characteristics are important for analyzing the local impacts of the change on the landscape.

The spatial distribution of the topographic change polygons across the conterminous United States reveals some notable regional differences and patterns of change. Overall, there is a decided concentration of change polygons in the eastern United States, which can be partially explained by the greater population density as compared to the west. The greater density of population centers in the east, as well as the greater length of time of settlement, has created significant requirements for road and other infrastructure construction. The aggregate materials needed for such construction came from the numerous quarries represented by the topographic change polygons.

Other noteworthy observations of the regional geography of topographic change include:

- A dense concentration of change polygons in the mountaintop coal mining region in central Appalachia (eastern Kentucky, southern West Virginia, and southwestern Virginia)
- A distinct cluster of change polygons is found in the Iron Range in northern Minnesota
- Large groups of change polygons representing surface coal mining operations in the Powder River Basin in eastern Wyoming
- Large open pit gold mines are found as a collection of change polygons in northern Nevada
- A concentration of very large open pit copper mining operations is represented by the cluster of change polygons found in southern Arizona
- Higher densities of change polygons are located near the coastal California cities of San Francisco, Los Angeles, and San Diego; these polygons are primarily related to road construction and urban development in higher relief areas.

Direct anthropogenic processes create several types of landform modifications that remain as a distinct imprint on the topographic landscape. The primary human geomorphic activities that are responsible for the land surface modifications represented in the national topographic change inventory are mining, road construction, urban development, dam/reservoir construction, and sanitary landfills. Further results of the topographic change inventory, including a ranking of significant change features, examples of analysis of environmental effects and visual impacts of topographic changes, and a discussion of error sources, uncertainty, and data limitations, are available on the project web site at: http://topochange.cr.usgs.gov/index.php. The topographic change polygon dataset may be downloaded from the web site, and an interactive web map viewer is available to examine the polygons in the context of the NED and SRTM elevation data, the raw vertical difference grid, land cover, and other locational reference data.

4. CONCLUSIONS AND FUTURE WORK

4.1 Primary Findings

In reference to the primary research issue, this study has produced an inventory and assessment of individual land surface features resulting from human geomorphic activity across the conterminous United States. This inventory is quantitative, as the features have been mapped and the changes in terrain parameters have been measured for each feature. The human geomorphic features in the inventory were detected and described based on the changes to their topographic expression. The topographic change inventory is a first ever spatially explicit accounting of anthropogenic geomorphic features throughout the conterminous United States. This summary and description of the extent and nature of the vertical component of landscape change complements well ongoing studies in land use/land cover change, as the two transformations are often closely related. The results of this study demonstrate the validity of using multi-temporal elevation data in an accuracy-based threshold approach to detect significant topographic changes over broad areas, thus emphasizing the value of preserving historical elevation data holdings. Because this study was based on geospatial data, the results include specific locational information for features that has not been present in previous estimates of human geomorphic activity across the United States. This spatial component has the added advantage of facilitating assessment of environmental impacts specific to the individual changed areas, including hydrologic effects and visual impacts that can extend the influence of the disturbed area into adjacent unchanged areas.

It is clear from this inventory of topographic surface changes that mining is the predominant human activity responsible for geomorphic changes during the 20th century in the conterminous United States. This finding supports the conclusion from previous studies (Hooke, 1994, 2000; Nir, 1983) that surface mining is the largest direct anthropogenic geomorphic process in terms of the amount of material moved per unit time. The results of the study reported here add to the previous findings by quantifying and locating specific topographic changes caused by mining.

It became clear while conducting this study that the data characteristics and quality of the input geospatial datasets are a primary challenge to developing reliable topographic change maps over very large areas. In this case, the unique characteristics of the elevation datasets caused a requirement for additional data processing steps. For the NED, the unique characteristics include source data from many small tiles, production artifacts, and variable source data dates. For the SRTM data, the unique characteristics include the first return nature of elevation measurements in urban and forest land cover, residual misregistration, and data voids. The mismatch among source dates for the elevation and land cover datasets also contributed to the uncertainty in characterizing change areas. Because the primary elevation and land cover datasets were used together, the data factors were combined and special processing steps had to be developed and applied to filter out falsely detected changes. If the input elevation, land cover, and reference datasets had consistent source dates, were devoid of production artifacts, and represented the same measurement (ground level for elevation data), then the somewhat subjective filtering steps could be eliminated. The NED, SRTM data, and NLCD did not have the optimal characteristics for change detection datasets; however, their existence is a unique combination of multi-temporal representations of the land surface, so it was worthwhile to develop the necessary processing steps to extract meaningful land change information from them. It is unlikely that there would ever be perfect input datasets for topographic change analysis, especially over large areas, so the type of data processing methods implemented for this study provide a useful model for future topographic change studies.

4.2 Ongoing and Future Work

A logical extension to the topographic change analysis reported here is to increase both the spatial and temporal resolution of the input datasets, and thereby, the information content of the results. Because only two dates of elevation data were used for any given location in this study, only unidirectional changes could be detected. By adding datasets from additional dates, the results can be extended from a simple binary change/no change designation to a monitoring report with rates of change. The addition of more recent elevation data is the focus of current work.

Elevation information derived from U.S. national coverage of airborne interferometric synthetic aperture radar (IFSAR) data (supplied by Intermap in their NEXTMap® product) is currently being used to map and quantify topographic changes that have occurred since the time period covered by the SRTM–NED baseline inventory, thus facilitating detection of change hotspots that can be targeted for repeat elevation surveys. The addition of this third time slice of elevation data allows the progression from simple topographic change detection to topographic surface monitoring, including calculation of change rates.

In the future, the enhanced elevation data (primarily lidar data) from the planned 3D Elevation Program (3DEP) (Snyder, 2013) will allow for fine scale topographic changes to be mapped and detailed analysis of the subsequent environmental effects to be conducted. Topographic change detection and monitoring take advantage of recent progress in the availability and quality of multi-temporal elevation models. Future advances in global digital elevation models, namely TanDEM-X data, will facilitate further development and extension of the topographic change analysis approach with application to areas across the globe.

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