AN INVENTORY AND ASSESSMENT OF SIGNIFICANT TOPOGRAPHIC CHANGES IN THE UNITED STATES

BY

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A dissertation submitted in partial fulfillment of the requirements for the

Doctor of Philosophy

Major in Geospatial Science & Engineering

South Dakota State University

2006

AN INVENTORY AND ASSESSMENT OF

SIGNIFICANT TOPOGRAPHIC CHANGES IN THE UNITED STATES

This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this dissertation does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ACKNOWLEDGEMENTS

The USGS Geography Discipline Research Prospectus provided partial funding for this work, and the USGS Geographic Analysis and Monitoring Program provided additional funding for the project. The efforts of EROS colleagues on development of the NED and processing of SRTM data are gratefully recognized. The support of EROS management for employee participation in the AEWR and GSE graduate programs at SDSU is acknowledged. Special thanks go to Darrell Napton for guidance and insight along the way. Finally, and most importantly, all gratitude and appreciation go to Amy, Karl, and Brian for their encouragement, support, and understanding, without which this project could not have been completed.

ABSTRACT

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November 21, 2006

The effects of human actions upon the environment have been well documented, and the topic continues to be a primary one in geography and earth science research. Many studies have focused on human induced changes in land cover. Some 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. In this case, the geomorphic activity is evidenced by significant changes to the topographic surface throughout the conterminous United States. To meet the requirement for locational and quantitative information about significant topographic changes, the study makes use of seamless multi-temporal elevation data and land cover data. The National Elevation Dataset (NED) and the Shuttle Radar Topography Mission (SRTM) data form a unique pair of elevation datasets that can be used to detect and analyze 20th century topographic surface changes in the United States. The National Land Cover Dataset (NLCD) provided land cover information at a 30-meter resolution that matched

the NED and SRTM data. The NED supplied the historical elevation information that was subtracted from the recently collected SRTM data to create a difference grid that provided information about where topographic changes have taken place. The difference grid was processed with a vertical accuracy based threshold to delineate areas of significant elevation change. The delineated areas were subject to a filtering process to eliminate errors of commission, resulting in a dataset of polygon features that outline the areas of significant topographic changes in the conterminous United States. The polygons are attributed with numerous terrain parameters calculated from the NED and SRTM data, the difference grid, and the NLCD. The primary types of topographic changes resulting from human geomorphic activity include surface mining, road construction, urban development, dam construction, and landfills. Notable concentrations of topographic change polygons are found in the mining areas of central Appalachia, northern Minnesota, eastern Wyoming, and southern Arizona, and in the expanding urban areas in coastal southern California. Summary statistics of the distribution of change polygons were accumulated and tabulated for different reporting units, including states, counties, and ecoregions. The environmental effects of topographic changes can be quantified in a number of ways, including hydrologic effects, visual impacts, and comparisons among regions for the effects of mining on topographic relief. Topographic changes are often accompanied by land cover changes, and an example in Appalachia shows the direct correspondence between mining expansion and reduction in forest cover. Although some unique dataset characteristics and data quality issues presented a challenge to development of reliable topographic change maps, the

inventory was successfully completed, and it represents a first ever accounting of topographic change across the United States. The results provide locational and quantitative information for individual change features, and thus complement well the existing summary reports of the total effect of human geomorphic activity. Future work in topographic change analysis over broad areas may benefit by investigating alternatives for extraction of significant features, and by adding additional elevation data over finer time intervals to move from simple change detection to monitoring.

TABLE OF CONTENTS

Page

ABSTRACT iv

LIST OF TABLES xi

LIST OF FIGURES xii

CHAPTER 1. INTRODUCTION AND BACKGROUND 1

Research Issue 2

Literature Review 4

Human Impacts in Geomorphology 4

Direct Anthropogenic Processes 9

Indirect Anthropogenic Processes 12

Quantifying Human Geomorphic Activity 19

Statistical and Summary Approaches 20

Geospatial Data Approaches 24

Change Detection 28

Summary of Relevance 31

CHAPTER 2. DATA SOURCES 37

Elevation Data 37

National Elevation Dataset 37

Shuttle Radar Topography Mission Data 38

Reference Geodetic Control Points 39

Land Cover Data 40

Ancillary Reference Data 41

CHAPTER 3. DATA PROCESSING METHODS AND PROCEDURES 46

SRTM – NED Vertical Differencing 46

Accuracy Assessment of Elevation Data 50

Significant Change Thresholds 54

Filtering of Elevation Difference Mask to Identify True Topographic Changes 58

Tabulation of Statistics Characterizing the Extent of Topographic Change 66

CHAPTER 4. RESULTS, ANALYSIS, AND DISCUSSION 90

Regional Geography of Topographic Surface Changes 92

Types of Topographic Surface Changes from Human Activity 94

Mining 95

Road Construction 98

Urban Development 99

Dam Construction 100

Landfills 101

National Results 101

States 102

Counties 103

Ecoregions 103

Watersheds 105

Managed Areas 106

Quadrangle Base Maps 106

1x1-Degree Tiles.....107

Ranking Features Based on Magnitude of Change 108

Quantification of the Effects of Topographic Changes 111

Hydrologic Effects 111

Visual Impacts 113

Regional Differences in the Effects of Surface Mining.....117

Proximity of Topographic Change Areas to Other Features 120

Comparison with Land Cover Status and Trends Data.....121

Error Sources, Uncertainty, Limitations, and Uses.....124

CHAPTER 5. CONCLUSIONS.....187

Primary Findings 187

Suggestions for Further Research 192

Relevance for Anthropogenic Geomorphology 196

REFERENCES.....199

APPENDICES 212

Appendix 1. States Containing Topographic Change Polygons 212

Appendix 2. Top Ranked Counties (by Area) Containing Topographic Change Polygons 213

Appendix 3. Top Ranked Ecoregions (by Area) Containing Topographic Change Polygons 214

Appendix 4. Top Ranked Watersheds (by Area) Containing Topographic Change Polygons 215

Appendix 5. Ranked Managed Areas (by Area) Containing Topographic Change Polygons 216

Appendix 6. Top Ranked Quadrangles (by Percentage) Containing Topographic Change Polygon 217

LIST OF TABLES

Page

Table 1.1. Comparison of features resulting from movement of materials by geomorphic processes. 33

Table 1.2. Rates of geomorphic activity. 34

Table 3.1. Error statistics (in meters) of NED vs. 13,305 reference geodetic control points. 74

Table 3.2. Error statistics (in meters) of SRTM vs. 13,305 reference geodetic control points. 75

Table 3.3. Significant change thresholds for each land cover class.....81

Table 3.4. Filter steps applied to areas of significant elevation differences to produce the final set of polygons that delineate topographic surface changes across the conterminous United States.....87

Table 4.1. Summary statistics for polygons in the inventory of topographic changes in the conterminous United States. 134

Table 4.2. Change polygons categorized by majority land cover class. 135

Table 4.3. The top ranked states in terms of several categories of topographic change. 146

Table 4.4. Summary statistics for the number and total length of streams contained within topographic change polygons in the conterminous United States. 165

Table 4.5. Area, volume, and viewshed information for a comparison among several topographic change features. 171

Table 5.1. Top ranked counties according to total area of topographic change polygons, with the primary type of mining responsible for the changes identified. 198

LIST OF FIGURES

Page

Figure 1.1. Magnitude and location of (a) human geomorphic activity and (b) natural geomorphic activity by rivers....35

Figure 1.2. Views of the effects of canal and channel construction in coastal Louisiana marshes....36

Figure 2.1. Shaded relief portrayal of the National Elevation Dataset. 42

Figure 2.2. Shaded relief portrayal of the Shuttle Radar Topography Mission dataset....43

Figure 2.3. Distribution of reference geodetic control points. 44

Figure 2.4. The National Land Cover Dataset (1992 version)....45

Figure 3.1. 934 1x1-degree tiles used for organizing and processing input data. 68

Figure 3.2. Apparent vertical change due solely to misregistration of multi-temporal DEMs. 69

Figure 3.3. Coordinate system referencing for native format NED and SRTM....70

Figure 3.4. Diagram of the SRTM – NED coregistration process. 71

Figure 3.5. Example of coregistered NED and SRTM, and the derived difference grid for an area in eastern Kentucky. 72

Figure 3.6. Illustration of the effects of a vegetation canopy on SRTM data and the derived SRTM – NED difference grid for an area in southern Michigan. 73

Figure 3.7. NED error (in meters) plotted against elevation, slope, aspect, and local relief....76

Figure 3.8. SRTM error (in meters) plotted against elevation, slope, aspect, and local relief....77

Figure 3.9. Comparison of the vertical accuracy of the NED and SRTM data for each land cover class. 78

Figure 3.10. Comparison of vertical accuracies for SRTM and NED elevation data for urban/built-up and forest classes. 79

Figure 3.11. Idealized histogram of SRTM – NED difference values with the statistically based thresholds for determining significant changes. 80

Figure 3.12. Example of residual misregistration causing false detection of vertical change. 82

Figure 3.13. Example of dense vegetation causing false detection of vertical change. 83

Figure 3.14. Example of data voids in SRTM data for an area in southeastern Utah. 84

Figure 3.15. Example of source data artifacts causing false detection of vertical change. 85

Figure 3.16. Test group of 30 1x1-degree tiles used for development of decision rules for filtering of change mask. 86

Figure 3.17. Example of the results of the filtering process applied to significant elevation differences. 88

Figure 3.18. Flow diagram of the overall data processing procedure that resulted in a delineation of topographic surface changes across the conterminous United States. 89

Figure 4.1. Map of the 5,263 polygons that delineate areas of significant topographic change in the conterminous United States. 133

Figure 4.2. Counties containing change polygons representing new or expanded water bodies. 136

Figure 4.3. Watersheds (hydrologic cataloging units) containing change polygons representing new or expanded water bodies. 137

Figure 4.4. Example of topographic change caused by mining in Perry County, Kentucky. 138

Figure 4.5. Example of topographic change resulting from road construction in western Maryland.....139

Figure 4.6. Example of distance-to-nearest-road dataset for the Chino Hills area in Orange County, California. 140

Figure 4.7. Orange County, California is the top ranked county for topographic change related to urban development. 141

Figure 4.8. Topographic changes resulting from urban development in the Chino Hills area in Orange County, California. 142

Figure 4.9. Topographic surface changes resulting from urban development in Poway, California (San Diego County). 143

Figure 4.10. Topographic surface change resulting from dam construction (Lake Pleasant near Phoenix, Arizona).....144

Figure 4.11. Topographic surface change resulting from landfill operation (Sunshine Canyon landfill in Sylmar, California). 145

Figure 4.12. Counties containing topographic change polygons. 147

Figure 4.13. Level III ecoregions containing topographic change polygons. 148

Figure 4.14. Watersheds (8-digit hydrologic cataloging units) that contain topographic change polygons. 149

Figure 4.15. Managed areas (federal, state, tribal, and military lands) that contain topographic change polygons.....150

Figure 4.16. USGS 7.5-minute quadrangle maps that contain topographic change polygons.....151

Figure 4.17. 1x1-degree tiles that contain topographic change polygons.....152

Figure 4.18. Qualitative comparison of the magnitude and distribution of human geomorphic activity calculated by Hooke (1999, p. 690) vs. data derived in this study. 153

Figure 4.19. Top ranked topographic change polygon: largest cut area (8.75 km^2), and largest cut volume (1.25×10^9 m^3).....154

Figure 4.20. Top ranked topographic change polygon: largest fill area ($9.79\ km^2$). 155

Figure 4.21. Top ranked topographic change polygons: largest fill volume ($5.16 \times 10^8\ m^3$), largest mean elevation change (-177.3 m) and largest relief change (263.7 m) for a cut.....156

Figure 4.22. Top ranked topographic change polygon: largest mean elevation change for a fill (104.6 m).....157

Figure 4.23. Top ranked topographic change polygon: largest relief change for a fill (73.5 m). 158

Figure 4.24. Top ranked topographic change polygon: largest mean slope change for a cut (33.2°).....159

Figure 4.25. Top ranked cut polygon based on the combined ranks for area, volume, and change in elevation, relief, slope, and aspect. 160

Figure 4.26. Top ranked fill polygon based on the combined ranks for area, volume, and change in elevation, relief, slope, and aspect. 161

Figure 4.27. Alterations to the local drainage pattern resulting from surface mining in Perry County in eastern Kentucky. 162

Figure 4.28. Example of a mountaintop mining area in which the negative topographic changes (cuts) coincide with the divides between first order drainage basins.....163

Figure 4.29. Streams contained within topographic change polygons for an area in Perry County in eastern Kentucky.....164

Figure 4.30. Perspective views of the road cut through Sideling Hill in western Maryland.....166

Figure 4.31. Viewshed for the Sideling Hill road cut in western Maryland.....167

Figure 4.32. Viewshed for a quarry located near San Juan Capistrano, California. 168

Figure 4.33. Viewshed for a mine located near Worthington, Pennsylvania. 169

Figure 4.34. Comparison of the viewsheds for the Sideling Hill road cut in western Maryland and three large mine features. 170

Figure 4.35. Combined viewshed of 24 topographic change features in Webster County, West Virginia. 172

Figure 4.36. Five ecoregions used as a basis for regional comparisons of topographic change. 173

Figure 4.37. Scatterplot of change in mean elevation vs. change in relief for mining polygons in two ecoregions. 174

Figure 4.38. Increased relief resulting from surface coal mining near Gillette, Wyoming. 175

Figure 4.39. Changes in mean elevation for mining polygons in five ecoregions. 176

Figure 4.40. Changes in relief for mining polygons in five ecoregions. 177

Figure 4.41. Changes in mean slope for mining polygons in five ecoregions. 178

Figure 4.42. The total length of streams affected by topographic change polygons for five ecoregions. 179

Figure 4.43. Percentage of streams affected by cuts vs. fills for five ecoregions. 180

Figure 4.44. Data used to calculate the distance from mines to nearest major city for five ecoregions. 181

Figure 4.45. Summary statistics of the distance from mines to the nearest major city for five ecoregions. 182

Figure 4.46. Summary statistics of the distance from mines to the nearest road for five ecoregions. 183

Figure 4.47. Sample blocks from the land cover trends study that contain change polygons. 184

Figure 4.48. Multi-date land cover maps (top row) for one 10x10-km sample block from the land cover status and trends study. 185

Figure 4.49. Perspective views of the sample block data shown in Figure 4.48.....186

CHAPTER 1

INTRODUCTION AND BACKGROUND

The effects of human actions upon the environment have been well documented, and the topic continues to be a primary one in geography and earth science research. Human actions have had impacts on the Earth's lithosphere, biosphere, atmosphere, hydrosphere, and cryosphere. Numerous studies have been conducted, and continue to be done, on the specific changes that have taken place in each of these broad categories. In many studies and reports on human-induced transformation of the Earth's surface, the seminal work by Marsh (1864), *Man and Nature*, is cited as the first detailed documentation of the human influence on the environment. Marsh's work has been credited with establishing the guiding principles of conservation as well as the systematic study of human modification of the environment. Thomas (1956), published nearly 90 years after Marsh's initial work, was the next landmark volume to provide a broad assessment of anthropogenic transformations, with many of the contributed papers focused on the perspective of environmental history. Turner *et al.* (1990) is also often cited as an extensive review of the impact of human activities in causing changes to the Earth's surface. Additionally, Goudie (2000) presented a comprehensive overview of human impacts on vegetation, animals, soil, water, atmosphere, and climate. These volumes, along with many other published works, provide the basis and context for ongoing study of anthropogenic transformation of the environment. In recognition of the pervasiveness of human activity, and the subsequent effects on the environment, Crutzen

and Stoermer (2000) have proposed using the term "anthropocene" for the current geological epoch. Included in their rationale for the proposal is their belief that "mankind will remain a major geological force for many millennia, maybe millions of years, to come" (p. 18).

In a recent discussion on "The Big Questions in Geography," Cutter, Golledge, and Graf (2002) have identified the following as one of the important issues that need to be better addressed by geographers: how has the earth been transformed by human action? They urged geographers to better define and explain how the human-induced transformations vary geographically. They also recognized that such studies may emphasize one of two components: the physical aspects of the transformations, or the underlying causes of the changes. The detection and description of the physical aspects of human-induced land surface change, their first component, is the primary objective of the research reported herein.

Research Issue

In his overview of the human impact on the environment, Goudie (2000) dedicated a chapter to discussion of humans as a geomorphic agent, and he stated that "the human role in creating landforms and modifying the operation of geomorphological processes such as weathering, erosion and deposition is a theme of great importance though one that, particularly in the Western world, has not received the attention it deserves" (p. 261). He went on to say that "there are very few spheres of human activity which do not, even indirectly, create landforms" (p. 261).

Haff (2002) has recognized the significance of including human activities into the study of geomorphology, advocating use of the term "neogeomorphology" to emphasize the importance of a fundamental change to the field by focusing on recent anthropogenic processes and their underlying principles. Because the geomorphic effects of human activities have appeared rapidly (in the context of earth history) and are global in scope, Haff stated they "should represent a compelling topic of study for the science that concerns itself with the evolution and form of the Earth's surface" (p. 310). Haff went on to conclude that neogeomorphology differs from classical geomorphology by coupling human intention to the physical variables that characterize the land surface.

Compared with studies on the human impact on the biosphere, the atmosphere, and the hydrosphere, the number of studies on the human transformation of the physical form of the land surface is much less. Even though many of the processes (such as urbanization, industrialization, agricultural expansion) that have affected the biotic, atmospheric, and hydrologic resources have also affected the morphology of the land surface, understanding the transformation of the physical form of the land surface is not often the primary goal of the research.

General surveys of human geomorphic agency (Nir, 1983; Goudie, 1993; Piacente, 1996) exist, as do descriptive case studies of anthropogenic changes to the topography of specific locations (Whitehall and Kennedy, 2000; Campanella, 2002). There have been several reports that compare the total effects of humans as geomorphic agents to natural agents (Hooke, 1994; Hooke, 1999; Douglas and Lawson, 2001; Wilkinson, 2005), as well as numerous studies of site specific geomorphic consequences

of human activity (reviewed below). However, there is a noticeable lack of quantitative documentation that includes specific locations of individual land surface features resulting from human geomorphic activity across broad areas. Thus, 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. In this case, the geomorphic activity is evidenced by significant changes to the topographic surface throughout the conterminous United States.

Literature Review

The need for examining the impacts of humans on the form and shape of the land surface has been adequately recognized in the scientific literature, and such research complements well the ongoing studies of changes in the land use/land cover. Hooke (1999) summarized nicely the underlying rationale for conducting research on topographic surface changes (p. 687):

> Despite their prowess, humans are not given much press in textbooks on geomorphology. This is, in part, because there is less mystery and beauty surrounding the operation of a bulldozer or excavator than there is in the development of meanders, of beach cusps, or of a multitude of other landforms. However, as geomorphologists and responsible citizens of planet Earth, we must not ignore the impact we are having in shaping our home.

Human Impacts in Geomorphology

There have been some studies that have looked at the total effects of human activity as a geomorphic agent, most notably the works of Roger Hooke, which are cited quite often in the literature on anthropogenic geomorphology. Hooke (1994) compared

humans with other geomorphic agents on a global scale. He used estimates of the following three types of earth moving activity to quantify human impacts on the land surface: excavations for houses, mineral production, and road building. Hooke described how he calculated the total amount of rock and soil moved each year in the United States for these activities and how that is scaled for a global estimate. He also estimated the total amount of material moved annually by natural geomorphic agents (rivers, glaciers, slope processes, wave action, wind, mountain building, and deep ocean sedimentation). In the end, his estimate of material moved by humans of 45 billion tons per year is greater than any other single geomorphic agent. This amount of material is moved by unidirectional unbalanced processes, meaning that the material moved is not replaced with new material. Hooke also pointed out that humans often move material uphill against gravity and follow no natural physical rules, in contrast to most other geomorphic agents that move material in a predictable fashion (downslope due to gravity). Thus, the visual impact of human geomorphic activity is usually much greater than that of natural processes. This fact, in combination with the quantitative estimate of amount of material moved per year led Hooke to conclude "humans are arguably the most important geomorphic agent currently shaping the surface of the Earth" (p. 224).

Hooke (1999) went on to conduct a more in-depth comparison of human geomorphic activity with the geomorphic activity of rivers in the conterminous United States. Again, he used the amount of material moved by each of these processes to make the comparison, and he also added a spatial component by partitioning into 1x1-degree cells the total amount of material moved. He explained his use of volume of material

moved per unit time to evaluate geomorphic processes by reasoning that all processes alter the land surface by moving material. The movement of material involves initiation of motion, motion, and cessation of motion, or erosion, transportation, and deposition, respectively, in traditional geomorphology terms. Table 1.1 shows a simple comparison of features resulting from movement of earth materials. Hooke found that humans moved more material per year than rivers, with the greatest amounts in the east where the population density is highest and coal mining is concentrated in Appalachia. In total, rivers move less material than humans, but the effects of rivers are greatest in the west where steeper, sparsely vegetated slopes yield higher sediment loads. Hooke did point out some limitations of his comparison methodology in which he used figures for material transported by rivers over long distances to oceans, whereas most of the material moved by humans is only transported short distances. He again stated that the visual impacts of human geomorphic activity are great, although they are difficult to quantify.

Hooke (2000) published a third study that built upon his previous work by adding the element of history, looking at estimates of the amount earth moved by humans over the past 5,000 years. His analysis included both intentional earth moving (building and road construction and mining), which are facilitated by technological developments, and unintentional earth moving (agriculture). Over this time period, earth moving by humans has increased exponentially, and, not surprisingly, the curve follows closely the trend of world population growth over the same period Hooke's conclusions again showed the enormous impact human activities have had on the physical shape of the Earth's surface.

The question of how humans as a geomorphological agent compare in terms of spatial and temporal scales to "natural" (non-human) agents has been addressed in several papers. Phillips (1997b) recognized that "human agency is recent and short-lived on geologic time scales, yet its scope can be vast, and its rates and magnitudes considerable" (p. 104), so he used examples of geomorphic changes in the North Carolina coastal plain to investigate whether human activity represents an isolated disturbance that is eventually lost in the noise in long term landform evolution, or if it represents a fundamental change in the geomorphic system. Not surprisingly, Phillips concluded that the answer depends on the specific physical process in question and the time scale of interest. This work was a more detailed look at geological/geomorphological agents in the context of earlier work by Phillips (1991) on the nature of the role humans play in environmental systems. Phillips explained that humans can be considered as an external factor in earth surface systems, or they can be considered an intrinsic system component. He stated that researchers should be aware of this distinction when studying human impacts on the environment because, whether or not the choice is made consciously, the view of the human role as exogenous or endogenous can influence, or perhaps even determine, the results of the analysis. He summarized his discussion by stating that (p. 328):

> If the conceptualization of human agency is not a clear, logical outcome of the research problem or study design, these results suggest that it is most appropriate to treat the human factor as an intrinsic part of earth surface systems. Treating humans as exogenous may result in an overly optimistic assessment of the ability of earth surface systems to adapt or recover from human alteration.

Hooke (1994) agreed with this viewpoint of the endogenous role of humans in environmental systems when he stated that (p. 217):

> Humans, however, are not unnatural. They are just as much a part of the natural environment as any other organism, and so the products of human activities also must be considered to be natural, be they books, buildings, or sanitary landfills.

Hooke's view is further supported by his classification of humans as a biological agent of landform evolution, equal to the more well studied physical and chemical agents.

de Boer (1992) also addressed the issue of spatial and temporal scales in geomorphology. He examined numerous studies that are relevant to the issue of scale in geomorphology to develop, state, and explain a series of propositions. While his work does not explicitly mention human geomorphic processes, the discussion has aspects that are applicable to anthropogenic geomorphology, including questions such as "how do short-term process rates relate to long-term landform evolution" (p. 304). de Boer summarized a key finding when he stated that "dominance of landscape evolution by high-frequency, low-magnitude processes results in a smooth landscape having small-scale irregularities, whereas dominance by low-frequency, high-magnitude processes produces an irregular landscape having large-scale irregularities" (p. 303). It can be argued that this contrast provides a useful way to compare natural geomorphic processes ("high-frequency, low-magnitude"; "smooth landscape"; "small-scale irregularities") versus human geomorphic processes ("low-frequency, high-magnitude"; "irregular landscape"; "large-scale irregularities").

Goudie (2000) cited a classification of anthropogenic landform processes that is useful also for organizing a review of previous work on human-induced surface change:

Direct anthropogenic processes:
- Construction
- Excavation
- Hydrologic interference

Indirect anthropogenic processes:
- Acceleration of erosion and sedimentation
- Subsidence
- Slope failure
- Earthquake generation

Direct Anthropogenic Processes

In the scientific literature, there are many more examples of indirect anthropogenic processes than there are of direct processes. However, there are some useful studies of direct processes, and two of the studies by Hooke (1994, 1999) provide a comprehensive overview of the total effects of direct human geomorphic activities. Hooke (1994) first examined the amount of material moved annually by humans as compared to the amounts moved by natural geomorphic agents. Hooke focused on three types of earth moving activity by humans: excavation for house construction, mineral production, and road construction. He used various sources to estimate the amount of earth material moved annually in each of the three activities, and then he used two different methods to scale the values to global estimates: gross national product (GNP) and energy consumption. He went on to estimate the annual amounts of mass moved by natural geomorphic agents. Hooke's findings, which are summarized in Table 1.2, show

that the total amount moved by human activities (including the effects of agriculture on river sediment loads) is equal to or greater than any other single geomorphic agent.

Hooke's second study (1999) compared in more detail human geomorphic activity with that accomplished by rivers in the United States. For that study, he added a spatial component, comparing the amount of material moved within 1x1-degree blocks in the conterminous United States. For the total human geomorphic activity, Hooke included the activities of house construction, mining (coal, stone, gravel, and sand), and agriculture (sediment load contributed to rivers). He used population density to scale the total activity and to distribute it spatially among the 1x1-degree cells. To estimate the spatial geomorphic activity of rivers, Hooke used published relationships of sediment yield to drainage basin size and relief. Figure 1.1 shows the differences in magnitude and location of human geomorphic activity versus natural geomorphic activity by rivers. The highest amounts of material moved by humans occur in the east where the population density is the greatest and coal mining is concentrated in the Appalachian region. The relatively high amounts in the Midwest are due to agricultural activity contributing significantly to sediment loads. The major population centers in the west and southwest are also seen as peaks, due to the increased housing starts in growing urban centers. Comparatively, rivers account for less material moved than human activities. Rivers move the most material in the west where relief is greater and sparsely vegetated slopes contribute more sediment.

The effects of direct anthropogenic processes can be seen in local conditions. Baroni, Bruschi, and Ribolini (2000) reported the effects of marble quarrying in the

Italian Alps. The first effect of the quarrying is large deposits of waste material known locally as "ravaneti." Because marble has been quarried in the area since the first century B.C., the ravaneti are a common landscape feature throughout the region. As quarrying techniques have evolved, the more recent layers of the ravaneti contain more fine-grained material than the older underlying quarry debris. Because the fine-grained material is less permeable, medium intensity rainstorms have triggered landslides and debris flows, secondary effects of the original anthropogenic land transformation.

The coastal plain and Mississippi River delta in Louisiana is a dynamic coastal environment that is experiencing significant changes, many of which are manifested in loss of coastal wetlands (Boesch *et al.*, 1994). Many of the changes in coastal Louisiana are the result of indirect anthropogenic geomorphic activity, but some of the observable changes result directly from human geomorphic activity, namely construction and dredging of canals and navigation channels. Wetlands are lost in a very direct manner when they are excavated to cut canals and channels through the marsh surface. In many cases, the canals and channels are constructed to facilitate transportation to and from oil and gas production sites. Usually the excavated material is deposited in spoil banks along the canal, which may inhibit or prevent overbank flooding that supplies necessary nutrients and sediment to marsh vegetation, and may also accelerate local subsidence due to the added weight from the spoil (Boesch *et al.*, 1994). Figure 1.2 shows two views of the effects of canal and channel construction in the Terrebonne Basin of coastal Louisiana. In both cases, the only land that remains in the immediate vicinity of some of the canals and channels is the spoil banks excavated and deposited during construction.

Hydrologic interference is one of the types of direct anthropogenic processes cited by Goudie (2000). Construction of dams is the primary type of hydrologic interference that causes geomorphic effects. Earth materials are displaced during dam construction, but the larger geomorphic effect is the inundation of land by the reservoir behind the dam. Graf (1999) has provided a detailed inventory of dams and their hydrologic effects in the continental United States. He concluded that the dams in the United States can store a volume of water that almost equals one year's mean runoff. He also found that the hydrologic and ecologic impacts from dams on rivers have already exceeded the likely impacts of global climate change in the near future.

Indirect Anthropogenic Processes

Goudie (2000) emphasized the importance of indirect human geomorphic processes (p. 263):

> Landforms produced by indirect anthropogenic processes are often less easy to recognize, not least because they tend to involve, not the operation of a new process or processes, but the acceleration of natural processes. They are the result of environmental changes brought about inadvertently by human technology. None the less, it is probably this indirect and inadvertent modification of process and form which is the most crucial aspect of anthropogeomorphology.

Phillips (1997a) agreed with Goudie that geomorphic changes due to anthropogenic activities can be difficult to recognize. Phillips described historic changes in a very low relief environment (North Carolina coastal plain) to illustrate how human actions can result in significant soil erosion even in areas without the well known risk factors of high

slope and climate variability. Geomorphic changes in such flat terrain often do not leave obvious visible evidence.

There are numerous examples in the scientific literature of the results of indirect anthropogenic geomorphic processes. Many of these examples involve modification or interruption of hydrologic processes and the corresponding effects on geomorphic processes.

Modification to sediment fluxes is a common indirect anthropogenic effect, including both increased erosion (and subsequent deposition) from deforestation, agriculture, grazing, mining, and construction, as well as decreased flux from reservoir siltation and reduced river discharge (Vorosmarty *et al.*, 2004). Douglas (1990) presented a thorough overview of artificial sedimentation processes including landfill operations, mining waste, land reclamation from the sea, soil conservation practices (such as terracing), and reservoir siltation. Garcia-Ruiz and Valero-Garces (1998) examined the effects of historical land use changes related to livestock production and cultivation on the geomorphic processes in a high relief environment. The observed results of the human activity were severe soil erosion, increased sediment supply, and debris flows. Airborne sediment fluxes are also affected by human activities. Gill (1996) described the effects of human disturbance of saline lakes and playas in arid and semiarid areas. These disturbances increase the eolian transport of sand and dust. The result is air pollution from “fugitive” dust, defined by Gill as “naturally occurring compounds released into the atmosphere by human actions” (p. 207).

The effects of changes in land use are numerous, including indirect effects on geomorphic processes. Clark and Wilcock (2000) presented a detailed example of the effects of changing land use on stream channel morphology in Puerto Rico. Starting in the early 1800's and continuing for over 100 years, much land in northeastern Puerto Rico was cleared for agriculture. Clark and Wilcock reported that runoff increased by about 50%, and that the clearing of steep slopes resulted in landslides, gullying, and large loads of coarse sediments being delivered to stream channels. Over the last 50 years runoff has stayed relatively high (due to a shift from agricultural land uses to industrial and residential uses) while the sediment supply has decreased. This has allowed the streams to begin removing the coarse sediments deposited earlier in their channels. Clark and Wilcock concluded that such processes within the channel would not normally be expected of these streams, so the current conditions are a reflection of the past land use changes within the basins.

The effects of changes in land use on fluvial geomorphology have been well documented. Knox (1977) discussed the human impacts on stream channels resulting from conversion of natural land cover to agriculture in Wisconsin. The conversion of native forest and prairie to cropland and pasture was accompanied by increased flooding, erosion, and sedimentation. Consequently, these hydrologic responses to land use change were the cause for significant changes in the physical shape of stream channels. Graf (1979) examined the effects of gold and silver mining on the creation and modification of stream channels in Colorado. In this case, the human activity consisted of two stages: the initial deforestation to expose the land surface, and the subsequent movement of soil and

rock as part of the mining action. The results included rapid erosion of slopes and entrenching of stream channels. Trimble (1992) investigated the origin of bottomland swamps along the Alcovy River in the Piedmont province in Georgia. Through the use of both historical and geographic data, he concluded that the swamps resulted from human activities beginning at the time of European settlement in the early 1800's. The clearing of the land by the settlers coupled with their farming practices led to rapid soil erosion along the stream banks, and thus aggradation of the main stream. The bed of the stream was built up to level of the valley floor leading to repeated flooding of the bottomland and subsequent swamp formation.

Ziegler, Sutherland, and Giambelluca (2001) examined very local scale effects of human land use on a basic geomorphic agent, runoff (leading to erosion). Their study demonstrated that until a dense vegetation layer capable of intercepting rainfall formed some 12 to 18 months after an agricultural plot was abandoned, Horton overland flow was greatly accelerated. They also noted that walking paths designed to provide access to agricultural fields decreased the time to Horton overland flow (runoff) generation.

Road construction has a direct geomorphic effect, but the presence of roads has a continuing influence on geomorphology, especially in forested areas. Several studies describe some of the indirect effects of roads on surface features. Jones *et al.* (2000) found that roads can alter the starting and stopping points of debris flows. Because many of the forest roads were constructed by excavating the hillslope and filling the downhill side of the road with the same material, small landslides originate from the downhill portion. When these landslides occur close to streams, they often reach the stream and

become debris flows, which can severely disturb the stream channel morphology. Wemple, Swanson, and Jones (2001) reported similar findings that roads function as both production and deposition sites for mass movement of earth materials. They also reported that the net effect of roads is an increase in sediment production throughout the basin, and that in extreme precipitation events even stream channels far from the initiation sites can be impacted significantly. Wigmosta and Perkins (2001) used a numerical watershed model to study the effects of the road network on streamflow characteristics within an experimental watershed. Their simulations showed that placement of the roads, and whether some water is allowed to pass under roads through culverts, affects the proportions of overland and channel flow.

The cycle of annual flooding is an important component of the geomorphic processes at work in floodplain environments. Several studies have pointed out the effects of human activities on flooding. Yin and Li (2001) cited three types of human activities that have resulted in more frequent and more severe floods on the middle reaches of the Yangtze River: first, removal of vegetation has led to severe runoff and erosion, and thus increased flooding; second, flood storage capacity has been decreased within the basin due to land reclamation and reduced lake sizes from siltation; and third, construction of levees has caused flood levels to rise because of restricted flood discharge capacity. Klimek (2002) looked at overbank sediments as evidence of human land use changes, namely forest clearing for agricultural expansion. Klimek found that the sediments showed evidence of increased soil erosion and corresponding increased flood frequency and amplitude.

Many of the changes in the Louisiana coastal marshes are the result of indirect human geomorphic activity, in this case the interruption or modification of the regular supply of sediments needed to form and maintain wetlands. Organic material from marsh plants contributes to soil creation, but a significant amount of marsh soils come from inorganic sediment (up to 50% by weight of salt marshes and up to 70% of freshwater marshes) (Boesch *et al.*, 1994). Thus, a regular influx of inorganic sediment is required for coastal wetland survival in a deltaic environment. For freshwater marshes, riverine flooding supplies the sediment, while brackish and salt marshes receive river sediments indirectly as a result of storm surges delivering resuspended sediments from marine bays (Boesch *et al.*, 1994). In the case of Louisiana's coastal wetlands, the Mississippi River has been the supplier of the necessary sediments.

Several studies have documented the declining sediment load carried by the Mississippi River. A baseline sediment budget for the Mississippi River basin prior to most human modification of the drainage network has been established (Kesel, Yodis, and McCraw, 1992), and decreases in the sediment load of the Mississippi River have been documented (Kesel, 1988; Kesel, 1989). Kesel (1989) has reported that the suspended sediment load of the Lower Mississippi River decreased nearly 80% since 1850. He further broke down the time period into an historic period (prior to 1900), a pre-dam period (1930-1952), and a post-dam period (1963-1982). The suspended sediment load decreased 43% from the historic to the pre-dam period, presumably as a result of changing agriculture and land management practices. The suspended load further decreased 51% from the pre-dam to the post-dam period, and this decrease

coincides with construction of dams and reservoirs on the Missouri and Arkansas rivers. Kesel concluded that the decline of Louisiana's coastal wetlands is due in large part to the reduced sediment load of the Mississippi River and the elimination of overbank flow because of artificial levees.

As Kesel (1988, 1989) suggested, man-made modifications to the natural Mississippi River system for flood control and to facilitate navigation have exacerbated the problem of reduced sediment supply to the Louisiana coastal marshes. Artificial levees preclude the annual overbank flooding which historically had distributed suspended sediments to the wetlands. The modified river now works as an efficient system for delivery of sediment to the edge of the continental shelf in the Gulf, far from the areas where it is needed for wetland building processes (Bourne, 2000). Although the reduced sediment load of the Mississippi River is a well-documented factor contributing to wetland loss, numerous scientists believe that the inhibited delivery of sediment because of man-made structures in the delta region has been more of a factor in wetland loss in the last 50 years (Boesch *et al.*, 1994).

The human activity of constructing canals and navigation channels also indirectly affects hydrologic and geomorphic processes important for coastal marsh formation and maintenance. Studies by Swenson and Turner (1987) and Turner and Rao (1990) have documented in detail the detrimental effects of canals spoil banks on wetland hydrology. Because regular water flow into and out of the marsh can be interrupted by spoil banks, vegetation can be stressed by prolonged drying or flooding. If the stresses are severe enough the vegetation dies off, thereby reducing the sediment trapping capability of the

marsh. The result is an increase in the formation of shallow ponds behind the spoil banks, and a corresponding decrease in the areal extent of the marsh surface. Turner and Rao (1990) also showed that wetland-to-water conversion occurs as a result of canals and spoil banks up to two kilometers away from those man-made features, so in an area of high density of canals the land losses can be significant. Other indirect effects of canals and channels include saltwater intrusion and increased erosion. As wetlands are removed by canal and channel construction, the effects of tide and wind push salty Gulf of Mexico water further inland into brackish and freshwater marshes and swamps. The marsh and swamp vegetation cannot tolerate the increased salinity, leading to vegetation die-offs. As the vegetation dies, the soil substrate is more susceptible to wave erosion from wind and boat wakes, leading to further removal of the land surface (Boesch *et al.*, 1994; Bourne, 2000; Fischetti, 2001).

Quantifying Human Geomorphic Activity

The recognition of humans as a geomorphic agent has been well established. As a field of study, geomorphology is quantitative by nature, and, as with other geomorphic agents, there have been numerous efforts to quantify the results of anthropogenic processes. Two basic methods have been used: (1) statistical and summary approaches; (2) geospatial data approaches. The former method has generally been used for characterizing the cumulative effects of human activity over broad areas, while the latter method has been employed most often over local study sites.

Statistical and Summary Approaches

The most well known efforts to quantify and summarize the total human geomorphic effects, and to place them in the context of other geomorphic processes, are those reported by Hooke (1994; 1999; 2000), reviewed in detail above. Nir (1983) presented a comprehensive overview of anthropogenic geomorphology, covering in detail many of the processes that Hooke used to estimate the total human impact. Nir, as does Hooke (1994), cited the human defiance of gravity in anthropogenic processes (p. 13):

> Man can act against the natural force of gravity. He has become capable of moving vast quantities of rock, gravel, and soil from one locality to another and is even able to create new reliefs. He can raise water above its natural channels. Such achievements cannot be brought about by natural processes.

Nir also recognized, as did Goudie (2000), that human intervention in the environment indirectly affects natural processes, either by accelerating or decelerating the natural rates.

To evaluate the magnitude of human geomorphic activity, Nir used the approach of estimating the volume of material moved annually by anthropogenic processes, which was later also employed by Hooke. Nir chose three direct human processes (mining, urban construction, road/railway construction) and three indirect processes (grazing, agriculture, forest clearing), whereas Hooke chose three direct human processes (excavation for house construction, road building, mining) and only one indirect process (agricultural contribution of sediment load to rivers). Although their numbers do not match, as different data sources and assumptions were used by each, Nir and Hooke both

identified the sediment moved in agriculture (an indirect process) as the largest anthropogenic geomorphic effect. They also agreed on the ranking of mining (a direct geomorphic process) as the second largest anthropogenic process. It is interesting to note that both of these human activities generally take place in rural areas, so close proximity to a population center is not necessarily a requirement for the occurrence of a significant land transformation.

Wilkinson (2005) also used a statistical and summary approach to come to the conclusion that human activity is the most important geomorphic agent at work on the Earth's surface. He concentrated on rates of human-induced soil erosion from agriculture in comparison with rates of natural sediment production. Wilkinson used a geologic time perspective to characterize the rates, with the calculated rates extrapolated to show that continental surfaces have been lowered by tens of meters per million years by natural agents, whereas anthropogenic processes move materials at a rate that would lower continental surfaces by hundreds of meters per million years. He summarized by stating that "humans are now an order of magnitude more important at moving sediment than the sum of all other natural processes operating on the surface of the planet" (p. 161). Similar to Hooke (2000), Wilkinson also examined the time element of human geomorphic activity throughout history by scaling the calculated human-induced erosion rate by population trends, thereby concluding that humans became the primary agent of erosion about 1,000 years ago. He also provided an interesting comparison to place the amount of material moved by human activities in context by stating that at current annual rates the material would fill the Grand Canyon in approximately 50 years. Finally,

Wilkinson provided a reminder that even though natural and anthropogenic processes have been compared quantitatively, "human earth moving and soil loss do not equal sediment yield" (p. 164) in the same manner as the term is used for large river fluxes. He also reminded readers that the location of the areas of most intense erosion differ for human processes (agriculture in low relief regions) versus natural processes (high relief mountain basins).

Douglas and Lawson (2001) employed the perspective of "industrial ecology" in their statistical and summary quantification of human geomorphic activity in Britain. They explained that industrial ecology is concerned with the flows of energy and materials between industrial and ecological worlds, and the effects of the flows on the environment, and thus is an appropriate context for analyzing extraction and transportation of earth materials. Douglas and Lawson estimated that in Britain the "deliberate materials shift" (human geomorphic activity) is 14 times more than the shift of materials by natural processes. This is compared to their cited global estimate of an annual material shift due to mineral extraction being nearly three times that of sediment delivery by rivers to the oceans. Douglas and Lawson concluded that because of "deliberate shifting of materials by direct human action" the "overall rate of change of the land surface of Britain is now more rapid than at any time since the last glaciation" (p. 29). Their conclusions also addressed the underlying causes of the significant changes to the land surface (p. 29):

> The processes that are most driving changes in the shape of the British landscape today are related to industrial and urban growth activities. Direct excavation, construction, and dumping move much more materials

> than the accelerated erosion of arable fields and the overgrazing of uplands.

Estimates of human geomorphic activity derived from statistical and summary analysis over specific study sites can be extrapolated to produce global scale estimates. Rivas *et al.* (2006) studied landform transformations due to urban and infrastructure development, mining, and quarrying over four sites in Spain and Argentina. They considered both direct and indirect effects and observed that human activity is the primary agent contributing to landform modification and earth material movement. The observed rates of material transport were estimated to be two to four orders of magnitude greater than natural rates. The authors calculated the "geomorphic footprint" (expressed in cubic meters per person per year) for the study areas, and then scaled that result to a global estimate based on mineral production data. Similar to previous studies (Hooke, 1994; Hooke, 1999; Wilkinson, 2005), Rivas *et al.* compared their global estimate to data on erosion rates and sediment transport from natural processes, and they concluded that human activity in mining and urban development, as they observed at their study sites, is the primary contributor to movement of earth materials. They also surmised that the change to human activities being the primary geomorphic agent, instead of natural processes, most likely did not happen until the beginning of the 20th century, which is a view that differs significantly from Wilkinson's (2005) findings.

In an attempt to better quantify observed and potential human geomorphic impacts, a number of indices have been proposed. Savchik (2000) described how ecological indices designed to assess species diversity can be adapted to measure

landform diversity. Repeated measurements with these indices in areas undergoing topographic change could detect decreases in relief and landscape diversity. Savchik also described the "relief resilience" approach, which assesses the capacity of the landscape to absorb human geomorphic changes. The approach uses a cumulative measure of human impacts on relief, which "is equal to the sum of volumes of all man-made landforms per unit area" (p. 365), combined with a measure of relief vulnerability. Savchik has used these indices to map areas of undisturbed relief versus highly transformed relief. In an effort to measure quantitatively the combined influence of human and environmental factors on geomorphic processes, Nir (1983) has developed the "index of potential anthropic geomorphology." The index combines measures of urban population, literacy rate, climate, and relief to provide an indication of the vulnerability of a political subdivision to adverse geomorphological actions. Nir has applied the index to 37 countries to provide a relative ranking of risk of negative geomorphic transformations.

The summary studies that quantify the total global effects of human geomorphic activity reviewed above offer a diversity of values for the amounts of materials moved by natural and anthropogenic processes. This is not surprising given the wide range of data sources used, assumptions made, and scaling methods employed. However, the conclusions in each report are in agreement that human activity is the primary geomorphic agent at work today.

Geospatial Data Approaches

In contrast to the statistical and summary studies reviewed above that generally address broad areas, studies of human geomorphic impacts that use a geospatial data

approach often are limited in scope to a specific site or region. Hooke's (1999) study of human geomorphic activity in the United States spans the summary and geospatial data approaches by adding a spatial component. Hooke created maps of the spatial distribution of the amount of earth materials moved by humans by assigning calculated values to 1x1-degree grid cells on the basis of mineral production and population statistics (Figure 1.1).

In the most general sense of the term, geospatial data have been widely used in geomorphology studies for many years, especially in commonly available forms such as topographic maps and aerial photographs. Other forms of geospatial data, especially those with a strong historical component, including travel and exploration journals, newspaper articles, land and geological surveys, and ground based landscape photography have become important information sources (Trimble and Cooke, 1991), particularly when used with newer geographic information science tools (Napton, 2004). Campanella (2002) presented a detailed topographic history of New Orleans in which several forms of geospatial data are used effectively throughout, including maps, satellite images, digital elevation models (DEMs), and aerial and ground based photography.

The changes to the shape of the land surface resulting from human activity are often described based on site observation. Terrestrial photography and aerial photography are also useful for documenting site-specific changes that have occurred, and the current impacts of the changes. For larger areas, geospatial data must be used to inventory and analyze human-induced geomorphic changes. The value of historical

geospatial data held by the U.S. Geological Survey (USGS) to land change studies was recognized in a recent report (National Research Council, 2002, p. 103):

> The USGS manages a national treasure of historic data ranging from maps and remotely-sensed imagery to long-term data collected from biologic, hydrologic, and geologic systems. These historic data are not artifacts valuable only for their curiosity. Rather, they indicate long-term trends in natural systems and baselines measures to assess human influences. Historic data allow the interpretation of present data.

Remote sensing data, a major subset of geospatial data, have long been recognized as a valuable source of information for land change studies. Satellite remote sensing, in particular, has been a commonly used tool for assessment of the effects of human actions on the environment. Newer remote sensing technologies, including interferometric synthetic aperture radar (InSAR), have proven quite useful in detecting topographic and hydrologic changes due to natural processes (Smith, 2002; Solomon, 2003; Kiel, Alsdorf, and LeFavour, 2006), and they are also proving useful for detecting anthropogenic landforms (Menze, Ur, and Sherratt, 2006).

Regional studies have made use of geospatial data to quantify vertical land surface change and map its distribution. Chirico and Epstein (2000) presented an excellent discussion of using elevation data derived from historical topographic maps to determine the spatial extent of human-induced land surface change over the past 100 years in the Philadelphia, Pennsylvania area. Of particular concern in Philadelphia are former stream valleys that were filled as the urban area expanded. In some of these areas the fill material has remained unconsolidated, and these areas are experiencing compaction, subsidence, and subsequent property loss. A significant challenge in their

approach was to account for the horizontal and vertical errors in their elevation datasets. Chirico and Epstein used a set of control points from a GPS survey of their study area to correct for the offsets between their two elevation datasets prior to differencing to determine areas of change. The study resulted in a map of "possible" fill and "probable" fill areas, and many of these areas coincide with stream valleys and transportation infrastructure.

Butler (1989) also described a study of geomorphic change in which the quality and accuracy of the topographic information derived from maps was an issue. Historical maps of the Harrison Lake area in Glacier National Park in Montana were used to study changes in the shape of the lake, presumably due to its water level increasing because of new glacial deposits acting as a dam. As the methods of mapping and ground observations for the preparation of each map were investigated it was discovered that errors in early source maps for the area were propagated in later topographic maps used for the study. In fact, the changes seen on the series of historical maps were false, as no real change in the shape of Harrison Lake had taken place. Butler's conclusion that the quality of the topographic data used for geomorphic change studies must be verified is sound advice for future studies of land surface change.

Where suitable geospatial data exist, especially multi-temporal DEMs, there are numerous analysis techniques available to quantify geomorphic changes. Etzelmuller (2000) provided a comprehensive review of mathematical techniques that are used to analyze vertical surface changes, ranging from local to global scale analyses. Included in the discussion are methods that operate on the elevation data, on the differences between

elevation datasets, and on parameters derived from the elevation data, including slope, surface roughness, and relief. Etzelmuller also discussed how error in the input elevation datasets propagates to the derived measures of difference, and he illustrated many of the concepts with a comparison of two DEMs over a valley glacier in Norway.

Inventory and analysis of land surface changes in the United States are active science activities. Loveland *et al.* (2002) are studying land cover trends by examining in detail the rates, causes, and consequences of contemporary land use/land cover change. The surface characteristics of land use and land cover that are being inventoried and assessed for changes are contained in two dimensions. While the underlying cause of a mapped change in land use/land cover may be directly related to a geomorphic surface change, the topographic change itself may not be detected, rather just the reflection of it in the land use/land cover. The ability to do a nationwide inventory and assessment of changes in land use/land cover is directly related to the availability of suitable remote sensing and other geospatial data with the required spatial and temporal resolution to map the features of interest.

Change Detection

Change detection using multi-temporal remote sensing data is a well established practice in geographical studies of land transformation (Lunetta and Elvidge, 1998). Most remote sensing based change detection studies are concerned with conversion between land cover types (Yuan, Elvidge, and Lunetta, 1998), thus multispectral images have been widely used as primary source data. With multispectral images, there is a wide choice of available approaches that take advantage of the multiple spectral bands, and

these can be broadly categorized into pre-classification and post-classification approaches (Lunetta, 1998). Most of the pre-classification methods involve a mathematical combination, or transformation, of the individual spectral bands. Post-classification approaches first label features according to specific classes for each of two dates, then differences in the class labels for coincident locations are analyzed to map and describe the changed areas. A post-classification approach may involve manual interpretation of remote sensing images to label classes of interest. Such is the case in the project described by Loveland *et al.* (2002) in which manual interpretations of Landsat images are done to map land cover changes across a 30-year time period. In this case, the interpretations are done for small (10x10-kilometer) sample blocks to statistically estimate regional land cover trends. Such a sampling approach is appropriate, and necessary, for producing regional and national land cover change information cost effectively on a recurring basis. In many change detection projects, the goal is to produce spatially explicit change maps, so an algorithmic pixel based method is performed on the digital remote sensing data.

The simplest form of the pre-classification methods is image differencing in which data from one date is subtracted pixel-by-pixel from data acquired on a different date. The resulting difference image is then usually thresholded, often on the basis of the standard deviation of the difference values, to isolate and distinguish areas of significant changes. The image subtraction method of change detection is the one that is most applicable to detecting geomorphic transformations as expressed in vertical changes in the topographic surface. Elevation data are not multidimensional in the same sense as

multispectral images, which have multiple measurements at the same locations (pixels). DEMs have one only one "band" of information, thus simple image differencing of the elevation data from two dates produces a new dataset that can reveal where surface modifications (elevation changes) have taken place. Etzelmuller (2000) has suggested other methods of detecting topographic changes based on elevation derivatives, but in each case the derivatives are still formed from the single "band" elevation data, not from multiple bands as for multispectral images. A criticism of the image differencing method for change detection is that it is too sensitive to image misregistration (Yuan, Elvidge, and Lunetta, 1998), a warning that is important for use of the method for geomorphic analysis.

Multi-temporal DEMs have been used in various settings to detect geomorphic changes. Betts, Trustrum, and De Rose (2003) used DEMs derived from stereo aerial photography to detect changes in an area subject to severe hillslope erosion. Their analysis included DEM subtraction and adjustment of the resulting difference dataset to correct for systematic errors. They concluded that the use of sequential DEMs provided detailed difference information that was useful for an ongoing study of gully erosion. Mills *et al.* (2005) used multi-temporal DEMs created from kinematic GPS points to detect changes in a coastal setting. In recognition of the difficulties in removing all the random and systematic errors in the DEMs, the difference values were subject to a critical value (threshold) to detect changes. The chance of detecting false changes due to misregistration of the DEMs was reduced by use of a surface matching algorithm to precisely align the multi-temporal datasets.

Summary of Relevance

The need for examining the impacts of human actions on the form and shape of the land surface has been adequately recognized in the scientific literature, and such research complements well the ongoing studies of changes in land use and land cover. The research on characterizing the nature and extent of topographic changes in the United States reported below is based in the context of the body of work on human geomorphic transformations that has been reviewed above. In the context of Goudie (2000), the features of interest for this study are those resulting from direct anthropogenic processes. The physical aspects of human land transformations, as cited by Cutter, Golledge, and Graf (2002), are the emphasis. In the context of Phillips (1991), this study treats human geomorphic activities as both external (exogenous) and intrinsic (endogenous). When looking at topographic impacts at a specific site, they can be viewed as endogenous, meaning that the landscape at that location will not on its own recover to its previously existing state. Over larger areas, such as ecoregions, the detected topographic changes can be viewed as exogenous, that is, they will not disrupt the fundamental functioning of the area's environmental system processes. In terms of concepts expressed by Nir (1983), this study employs a classic approach used for geomorphological case studies, that of looking at conditions before and after man's intervention. Hooke (1994, 1999) advocated evaluating human geomorphic actions on the basis of the resultant visual and environmental effects, and the research reported below addresses that concept. Such an evaluation is best done locally to capture and quantify specific land transformations, and the geospatial datasets used in this study facilitate detailed mapping and assessment. Nir

(1983, p. 14) summarized nicely this idea of the local, but intense, nature of human geomorphic impacts:

> Most activities of Man pertain to discrete areas, be it in densely built areas, open pit mines, highways under construction, or rivers being dammed. These activities, when compared with those of natural processes, are, however, highly intensive. Their impact per unit area is many times greater than that of natural processes.

Although the primary geomorphic impacts of direct anthropogenic processes are local, the accumulation of impacts regionally and nationally is also important to assess. Indeed, the USGS has recognized the importance of the type of research reported here in its science plan for geographic research (McMahon *et al.*, 2005) in the recommended action to "establish a consistent, repeatable methodology that identifies the changes in the topographic form of the Nation at appropriate intervals" (p. 11). The plan offers the following rationale for such an effort (p. 11):

> Understanding the characteristics of a changing surface form and the links between changing land use, land cover, and surface form is an important element of understanding the overall causes and consequences of land change.

Action	Resulting landform		
Initiation of motion (erosion)	Valleys	Cirques	Road cuts
Cessation of motion (deposition)	Floodplains or deltas	Moraines	Landfills
Agent of motion (transportation):	Water	Glaciers	Excavators / trucks

Table 1.1. Comparison of features resulting from movement of materials by geomorphic processes (Hooke, 1999).

Agent		Mass moved (Gt/yr)
Humans	GNP scaling	30
	Energy use scaling	35
	Energy use scaling plus river sediment loads	45
Rivers	Long distance sediment transfer (present)	24
	Long distance sediment transfer (in absence of human disturbance)	14
	River meandering, starting on 4th order streams	39
	River meandering, starting on 5th order streams	23
Glaciers	At present	4.3
	Pleistocene	10
Slope processes		0.6
Wave action	Sediment flux	1
	Erosion	0.24
Wind		1
Mountain building	Continental	14
	Oceanic	30
Deep ocean sedimentation		7

Table 1.2. Rates of geomorphic activity (Hooke, 1994). Values are giga-tons of earth material moved per year.

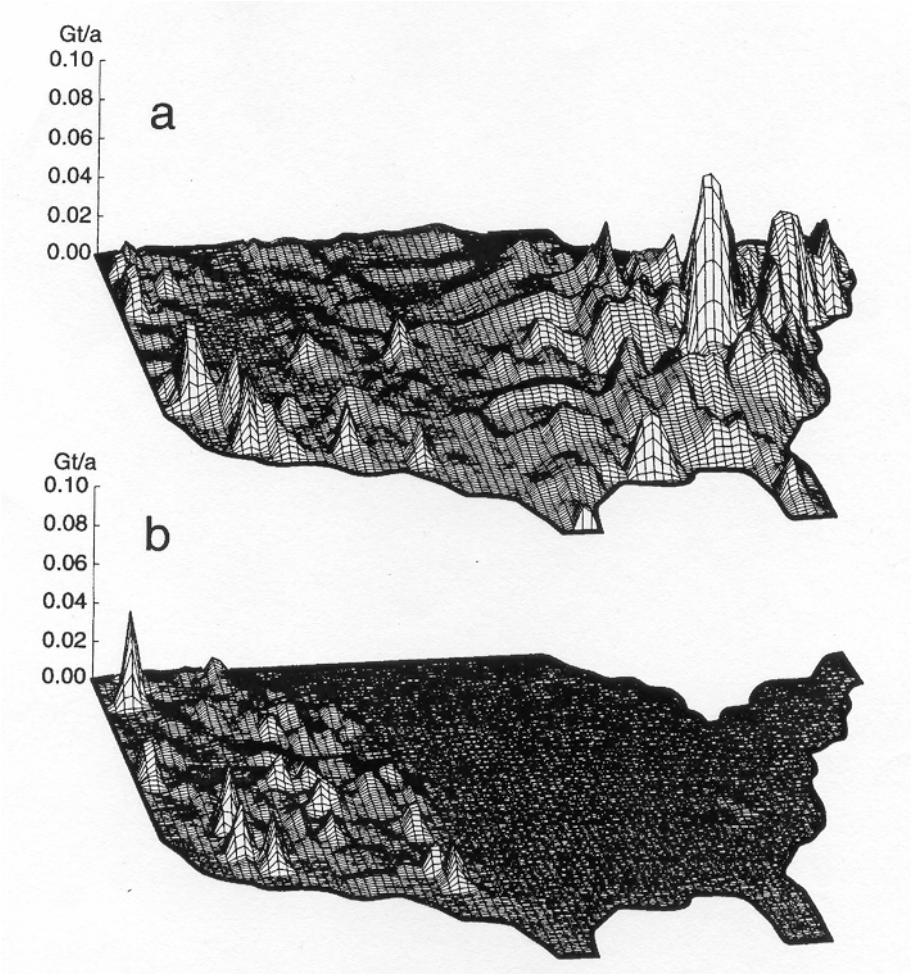


Figure 1.1. Magnitude and location of (a) human geomorphic activity and (b) natural geomorphic activity by rivers. Values are giga-tons of earth material moved annually (Hooke, 1999, p. 690).

Figure 1.2. Views of the effects of canal and channel construction in coastal Louisiana marshes. The spoil banks are the only land remaining in the immediate vicinity of the excavated areas. For locational reference, the red arrows mark corresponding features. The area shown in the top half of the figure is approximately 3.2 kilometers north to south by 4.1 kilometers east to west. (Source: top – USGS Digital Raster Graphic; bottom – www.coast2050.gov)

CHAPTER 2

DATA SOURCES

Geospatial datasets with national coverage and suitable resolution and accuracy are a key requirement to meet the goal of this study, which is a national accounting of topographic surface changes, including the location and characteristics of the changed areas. Fortunately, high quality seamless elevation and land cover datasets exist with full coverage over the conterminous United States, and this availability facilitates detailed mapping over broad areas.

Elevation Data

The detection of human geomorphic activity, as indicated by vertical changes to the land surface, is accomplished by comparison of multi-temporal elevation data. As such, multi-date elevation data with matching characteristics over the large study area of the conterminous United States are required. The National Elevation Dataset (NED) and the Shuttle Radar Topography Mission (SRTM) data form a unique pair of elevation datasets that can be used to detect 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 (approximately 30 meters), and each is managed as a seamless dataset for efficient access and manipulation.

National Elevation Dataset

The NED produced by the USGS provides seamless coverage of the "best available" elevation data of the United States (Gesch *et al.*, 2002). The NED is a multi-

resolution dataset, 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 and regional 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 USGS 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 bimonthly cycle that incorporates recent elevation data collections from both USGS and non-USGS sources so that the dataset 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-change) dataset for multi-temporal analysis. Figure 2.1 shows an overview of the NED used for this study.

Shuttle Radar Topography Mission Data

The Shuttle Radar Topography Mission, a joint project of the National Aeronautics and Space Administration and the National Geospatial-Intelligence Agency, was flown aboard the Space Shuttle Endeavour in February, 2000. The mission resulted in a near-global digital elevation dataset unprecedented in its coverage and resolution (Farr and Kobrick, 2000). The InSAR mission collected 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 dataset 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 detecting and assessing the effects of topographic surface modifications over broad areas. Figure 2.2 shows an overview of the SRTM data used for this study. Note the presence of several data voids in the SRTM coverage where interferometric radar data were not collected. Even though 99.96% of the targeted landmass was mapped by SRTM (Kobrick, 2006), a small shortage in the availability of instrument duty cycle hours during the duration of the mission meant that some areas could not be covered.

Reference Geodetic Control Points

Detailed information about the absolute vertical accuracy of the NED and SRTM data is required for the change detection method (described in Chapter 3). 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 (Figure 2.3) includes the points distributed throughout the conterminous United States that NGS uses for gravity and geoid modeling (National Geodetic Survey, 2003; Roman *et al.*, 2004). As such, they provide an excellent independent reference against which the NED and SRTM data can be assessed.

Land Cover Data

The USGS has produced several national land cover products that are useful for assessing the landscape effects of human geomorphic activities. 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 geomorphic effects because land cover change often corresponds with the physical transformation of the land surface relief. The 1992 version of the NLCD was used for this study (Figure 2.4). Although the NLCD 2001 version has additional data layers (canopy density and impervious surfaces) that may have been useful for interpreting SRTM data, and the source dates are a close match to that of SRTM, the newer NLCD was not used because it does not yet have complete coverage for the conterminous United States.

The information being developed by Loveland *et al.* (2002) on the status and trends of land cover in the United States has also been used to help analyze the detected areas of topographic change (described in Chapter 4). Spatially explicit land cover maps, and corresponding land cover change products, are produced for five dates between 1973 and 2000 for 10x10-kilometer sample blocks to derive regional land cover statistics (Loveland and Acevedo, 2006). Both the sample block data and the regional summary

statistics are useful for characterizing the relationships between land cover and topographic surface change.

Ancillary Reference Data

A number of ancillary datasets proved useful for quantifying, summarizing, and describing the distribution of topographic change areas across the United States. In addition to the basic political subdivisions of states and counties, as portrayed in the USGS National Atlas (U.S. Geological Survey, 2006), the footprints of the USGS 7.5-minute quadrangle map series were also used. Level three ecoregions (Omernik, 1987; U.S. Environmental Protection Agency, 2003) and a delineation of managed areas (federal, state, tribal, and military lands) from the USGS National Atlas were also used to help map topographic change areas nationally. Delineations of streams (Verdin, 2000; Franken, 2004) and watersheds (Seaber, Kapinos, and Knapp, 1987) were also useful for describing the context of topographic change areas in the United States.

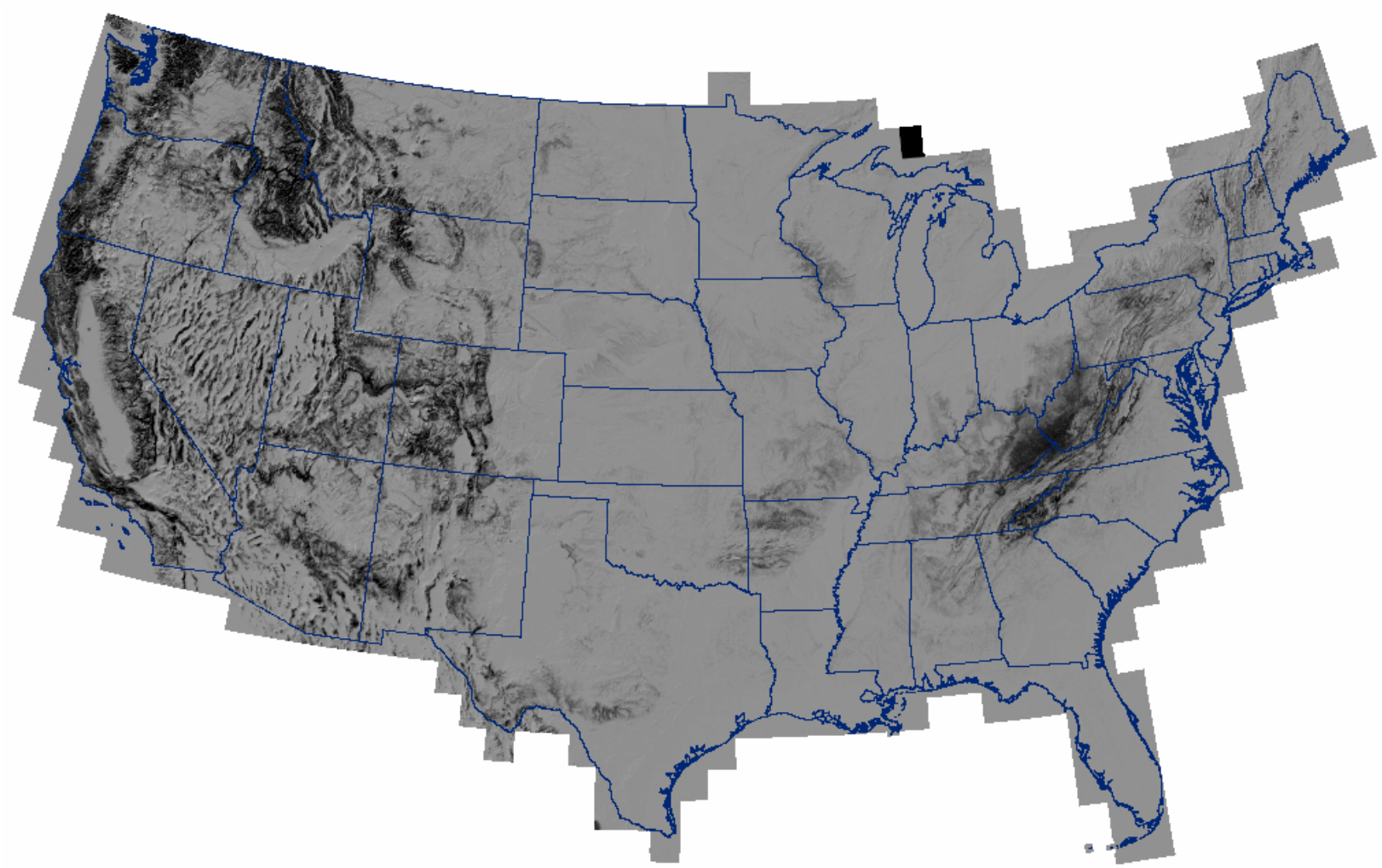


Figure 2.1. Shaded relief portrayal of the National Elevation Dataset.

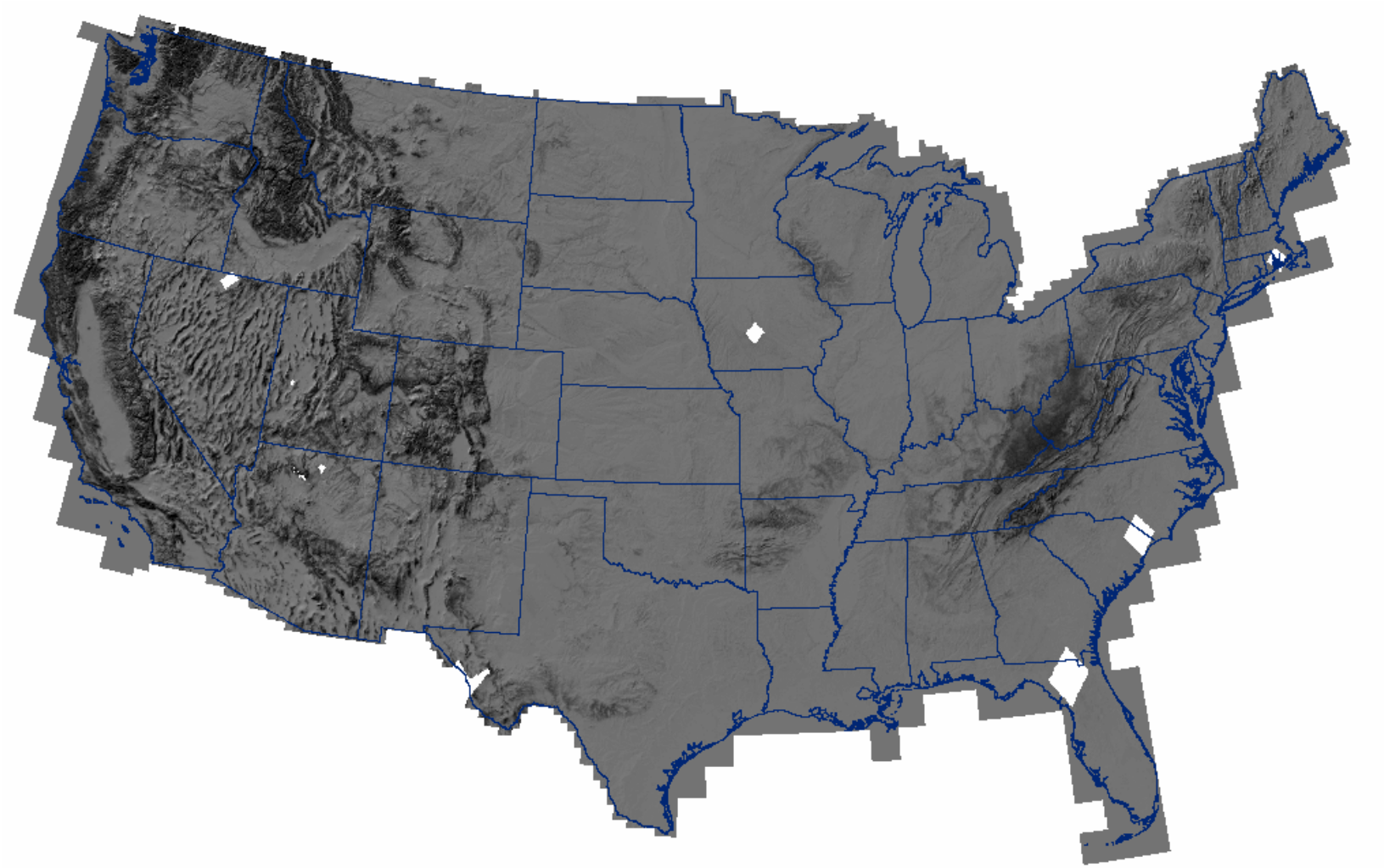


Figure 2.2. Shaded relief portrayal of the Shuttle Radar Topography Mission dataset.

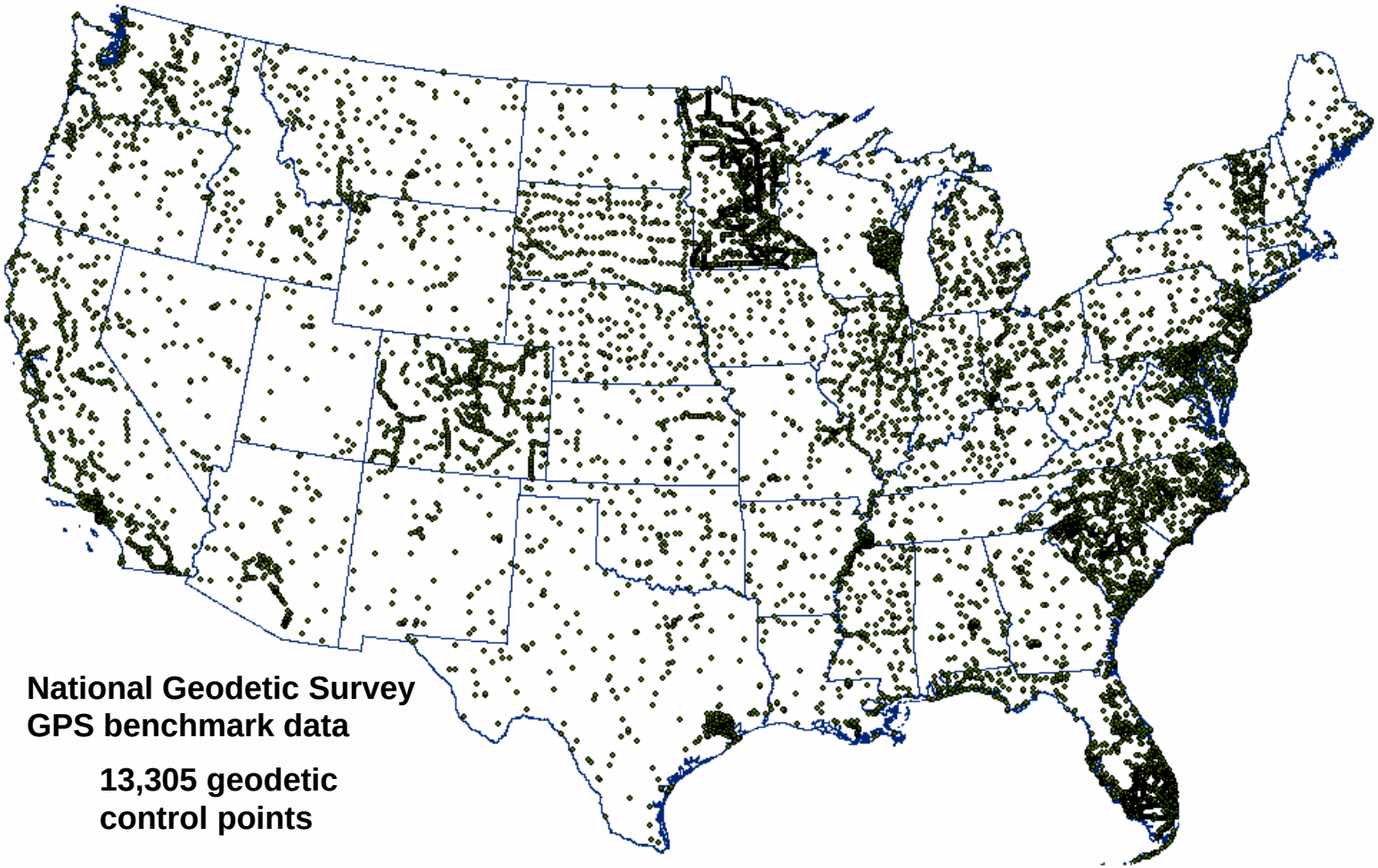


Figure 2.3. Distribution of reference geodetic control points.

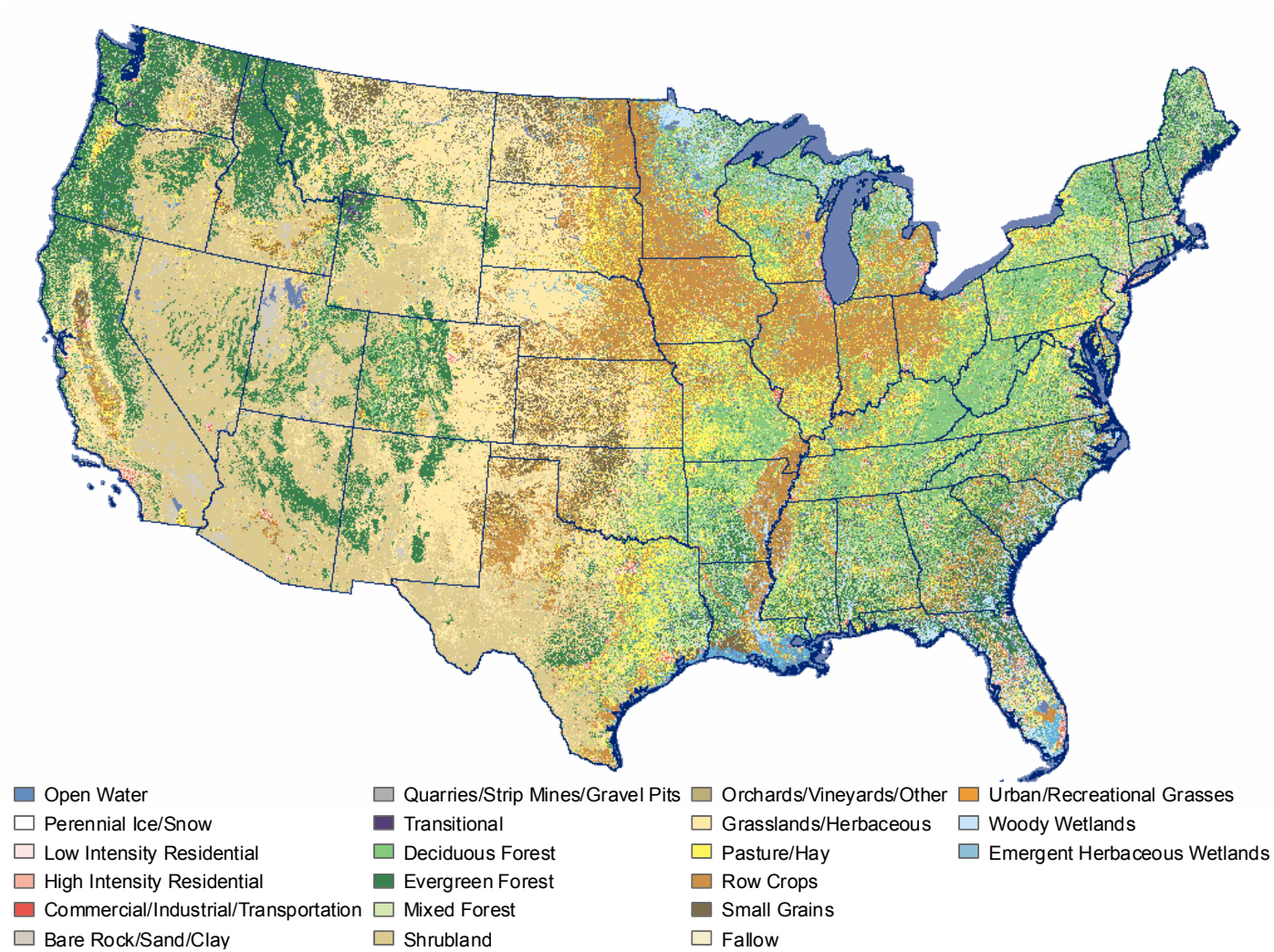


Figure 2.4. The National Land Cover Dataset (1992 version).

CHAPTER 3

DATA PROCESSING METHODS AND PROCEDURES

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 this 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 (Figure 3.1). 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 GIS and statistical software tools, and was automated as much as possible with scripted command files to standardize the procedures.

SRTM – NED Vertical Differencing

As described by Lunetta (1998), image differencing has long been used as an effective change detection technique for coregistered digital remote sensing datasets. One image is simply subtracted from another image on a pixel-by-pixel basis. As applied to gridded DEMs, Etzelmuller (2000) described the result of image differencing as "differential surfaces" and said that they "are a measure of the spatial distribution of mass displacement in a system" (p. 133). He further explained that (p. 133):

> The advantage of local differential surfaces is that the areas of mass change are both localized and quantified. The disadvantage is that the DEMs have to be of very high accuracy.

Both of the advantages cited by Etzelmuller 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. Etzelmuller's mention of DEM quality is another key aspect, and the processing described below measures and accounts for the accuracy of both of the input elevation datasets.

To obtain the best results in an image differencing operation, the input datasets need to be precisely aligned. The effects of registration quality on land cover change detection have been well documented (Townshend *et al.*, 1992; Stow, 1999; Verbyla and Boles, 2000). For vertical change detection with DEMs, the alignment of the input datasets is critical, especially in high relief areas. Even for a single DEM, a registration error (horizontal displacement) can introduce an apparent elevation error (Hodgson and Bresnahan, 2004). In other words, even if an elevation measurement is without vertical error, if that observation is shifted horizontally from its true position the effect of the planimetric error is manifested in the vertical dimension. The only condition where this is not true is on flat ground, and the effect of a given horizontal error increases as the slope of the ground (α) increases (Hodgson *et al.*, 2005):

$$\text{Elevation error} = \tan \alpha \times \text{horizontal displacement}$$

In the case of a pair of DEMs, the horizontal displacement results from an offset in alignment between the two datasets, and in areas of higher relief the apparent change in

elevation due solely to planimetric error can be falsely detected as topographic change. Figure 3.2 presents a diagram of an idealized case where the actual land surfaces have not changed and have been measured identically in each DEM, but a horizontal offset between the two DEMs results in an apparent vertical change in the difference grid, the magnitude of which is a function of the surface slope.

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. In their native formats, each dataset is in a geographic (latitude/longitude) coordinate system with a resolution of 1-arc-second. The SRTM data are referenced horizontally to the WGS84 datum, whereas the NED is referenced horizontally to the NAD83 datum. Thus, a transformation was done on the SRTM data to convert it to NAD83 referencing, although at the resolution of the data the difference between the datums is probably negligible. The primary adjustment in the coregistration process was required to account for a difference in the way the NED and SRTM data are referenced to the geographic coordinate system in their native formats. NED uses "cell corner" referencing in which integer lines of latitude and longitude fall on the edges of a cell (pixel) along a 1x1-degree tile boundary. In contrast, SRTM uses "cell center" referencing in which integer lines of latitude and longitude fall at the center of a cell along a 1x1-degree tile boundary. This effectively results in a one-half pixel shift between the two datasets. Such a shift would not be a concern for some applications. However, as described above, this offset could result in false elevation changes in a difference grid in higher relief areas if left unadjusted. Figure 3.3 shows a diagram of the

NED and SRTM coordinate system referencing in their native formats. Figure 3.4 shows how the one-half pixel shift is removed to bring the NED and SRTM into precise alignment. Prior to the adjustment, each NED pixel is centered on the intersection of four SRTM pixels. These four pixels are averaged and the resulting value is placed into the upper left position of the 2x2-window. The 2x2-window is then moved one column and the operation is repeated, each time averaging four original SRTM elevation values. The procedure is repeated until the entire 1x1-degree tile of SRTM data has been processed. The output grid is then shifted a distance of one-half pixel in both the x and y directions (by modifying the reference latitude and longitude coordinates) to bring the SRTM data into precise alignment with the NED grid. The averaging operation on the SRTM data has the added advantage of slightly reducing the high frequency noise that is inherent in radar-derived elevation data.

The NED is referenced vertically to the NAVD88 datum, while the SRTM are referenced vertically to the EGM96 geoid. NAVD88 is an orthometric (sea level referenced) datum, which is closely approximated by the geoid (Zilkoski, 2001), thus the NED and SRTM elevations are essentially in the same reference system so no vertical transformations were required.

After coregistration, a difference grid was created for each 1x1-degree tile by subtracting the NED from the 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 3.5 shows an example of the NED, SRTM, and the derived difference grid for an area in eastern Kentucky that has experienced topographic change due to surface coal mining. A final step in this initial part of the data processing flow for the 1x1-degree tiles included generation of other coregistered grids needed for subsequent processing, such as shaded relief from the NED and SRTM data and land cover data from the NLCD.

Accuracy Assessment of Elevation Data

The thresholding approach (described below) used to distinguish significant differences from the raw difference grids requires a measure of the absolute vertical accuracy of each input elevation dataset. The NED and SRTM data were compared to an independent reference geodetic control point dataset from NGS, described in Chapter 2. These points have centimeter-level accuracy in their horizontal and vertical coordinates, as they are produced by high precision GPS observations on established survey benchmarks (Roman *et al.*, 2004). Because of their broad distribution across the conterminous United States (Figure 2.3) and their very high accuracy, the points served as an excellent reference dataset for assessing the absolute vertical accuracy of the NED and SRTM.

An important aspect of the accuracy assessment was the calculation of vertical accuracy by land cover class. This was done in recognition of the fact that SRTM is a "first return" system in which 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. In areas where buildings are prevalent, the measured SRTM elevations represent the combined effects of the rooftops and other structures within the resolution cell. This phenomenon of SRTM recording non-bare earth elevations where vertical features are present on the surface has been well documented (Carabajal and Harding, 2006; Hofton *et al.*, 2006), and it is being exploited to produce maps of canopy height and biomass (Kellndorfer *et al.*, 2004; Simard *et al.*, 2006). Figure 3.6 illustrates the effects of the presence of a tree canopy on SRTM data and the derived SRTM – NED difference grid. In this illustration for an area in southern Michigan, the large vertical differences are due solely to the presence of trees. Comparison with the 2001 version of NLCD in this area confirms that the elevated areas that are very apparent in the SRTM shaded relief image are groups of trees, as they are included in the NLCD canopy density dataset.

The first return nature of SRTM data is a critical characteristic to consider when generating SRTM – NED differences grids because in vegetated and built-up areas many of the vertical differences are not indicative of topographic surface changes, but rather reflect the presence of radar scatterers above the ground surface. This leads to uses of the difference grids beyond just detecting geomorphic changes. Indeed, that has already been the case with the difference grids generated from this project, which have been distributed to researchers for use in biomass and carbon modeling (Kellndorfer *et al*., 2006), production of NLCD 2001 data over Kentucky, and riparian vegetation mapping in Texas for air and water quality monitoring.

The reference control points were in the same coordinate system as the input elevation data (decimal degrees of latitude/longitude in NAD83 for horizontal; decimal meters in NAVD88 for vertical), which facilitated comparison with the NED and SRTM data. The control point dataset was intersected with the NED and SRTM data, as well as with the NLCD to label each point with the land cover at each location. The control points were located in 849 of the 934 1x1-degree tiles used as processing units. The elevations from NED and SRTM were derived for each control point location through bilinear interpolation, differences were calculated between the reference point elevation and the corresponding NED and SRTM elevations, and summary statistics were accumulated. The differences were calculated by subtracting the GPS point elevation from the NED and SRTM elevations. This results in statistics that are easy to interpret, with a positive error meaning that the NED or SRTM was too high at that point, and a negative error meaning that the NED or SRTM was too low. The root mean square error (RMSE), as described in Maune, Binder-Maitra, and McKay (2001), was calculated, which is a commonly used method to express vertical accuracy of elevation datasets. The overall absolute vertical accuracy calculated for the NED is 2.44 meters (RMSE), whereas the assessment of the SRTM showed an accuracy of 3.53 meters (RMSE). The assessment included examination of the accuracy as a function of specific terrain conditions. Land surface characteristics, including slope, aspect, and local relief, were derived directly from the NED and were associated with each control point. Local relief was calculated within a 1500x1500-meter square (approximately one square mile) centered on the point location. Figures 3.7 and 3.8 show the error for NED and SRTM,

respectively, at each GPS control point location plotted against elevation, slope, aspect, and local relief. The NED and SRTM errors appear to be truly random, as there is no discernible correlation or relationship with any of the terrain parameters. This is evident in the distribution of data points in the scatterplots; in each case, the values are uniformly distributed around the zero error axis.

Table 3.1 and Table 3.2 list the summary statistics of the errors for NED and SRTM, respectively, segmented by land cover class. Figure 3.9 compares graphically the accuracies for NED and SRTM for each NLCD class. For all classes except one (quarries/strip mines/gravel pits), the uncertainty, as measured by the RMSE, of the SRTM exceeds that of the NED. This is not unexpected given the nature of the SRTM system measuring the height of the first reflective surface. For the quarries/strip mines/gravel pits class, the areas would generally be devoid of vegetation and buildings, so the SRTM measurement more likely represents ground level, and thus is closer to NED elevation. The reported accuracies for SRTM fall well within the mission specifications, which agrees with previous assessments (Rodriguez, Morris, and Belz, 2006; Shortridge, 2006). The effects of land cover on the uncertainty of SRTM elevation measurements and the overall better performance by NED in terms of vertical accuracy have also been documented in previously published results (Shortridge, 2006). Figure 3.10 compares the accuracies for six land cover classes for which the SRTM data are more likely to be affected by the reflective surface above ground level, the urban/built-up and forest classes. Note that the largest uncertainty in SRTM data occurs in the evergreen forest class (5.16 m RMSE), which is most likely due to the SRTM radar

signal penetrating very little into the dense conifer canopy before being reflected. Thus, the derived elevation measurement is for a surface located significantly above the elevation of the ground surface as represented in the reference geodetic points. This effect is supported by the measurement of the overall positive elevation bias for evergreen forest that approaches two meters. In other words, the SRTM elevations for evergreen forests are, on average, nearly two meters above the ground surface elevations. Interestingly, the bias for deciduous forests is much lower at less than one-half meter. A partial explanation for this observation may be that SRTM data were collected in February, which represents leaf-off conditions for deciduous forests in the conterminous United States, and more of the radar signals probably penetrated the relatively open canopy and reflected from the ground surface.

Significant Change Thresholds

The next step in the data processing procedure was to threshold the difference grids to isolate areas of significant change. This 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 RMSE, which is the statistical equivalent of the standard deviation for normal distributions. The accuracy values used are those determined in the accuracy assessment procedure described above. The individual absolute vertical accuracies for the NED and SRTM data, segmented by NLCD class (Tables 3.1 and 3.2), 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:

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

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 (Figure 3.11). 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 1% 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 is a practical approach, which is quite necessary when the objective is change detection over a vast area, as is the case for this study.

The thresholds for each land cover class are listed in Table 3.3. 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. For example, in an area identified as low intensity residential in the NLCD, the vertical difference has to be greater than +14.32 meters or less than -14.32 meters for a pixel to be included in the change mask. Note that in area of evergreen forest, the difference has to be of a greater magnitude (fall outside of ±17.57 meters) to be labeled as significant change, which is indicative of the increased uncertainty of the SRTM data in forested areas. Note also that the overall change threshold is ±12.87 meters, which is lower than the threshold for 12 of the 19 NLCD classes. Thus, if a single change threshold had been applied without regard to land cover type, there is a likelihood that many areas could have been erroneously flagged as changed, especially vegetated areas subject to greater uncertainty in SRTM elevation measurements.

The lowest thresholds occur in agricultural areas (NLCD classes of pasture/hay, row crops, small grains, and fallow) that are generally located in lower relief areas. These areas likely had bare ground or short vegetation conditions during the February collection date for SRTM, so they provide a good measure of the best accuracy of elevation measurement that could be achieved by SRTM in the absence of reflective surfaces above ground level (trees or vegetation canopy). Some of the best accuracies for NED were also observed in these areas of agricultural land use/land cover, so the change thresholds are correspondingly lower for these features. Thus, the minimum detectable difference using the change detection approach applied here to the NED and SRTM data

appears to be on the order of 10 meters. Real changes to the topographic surface may have a magnitude much less than 10 meters, especially in low relief coastal areas, but those changes would not be detected by the implemented approach using the NED and SRTM data. With the type of change detection approach used for this study, multi-temporal elevation data with much better vertical accuracies would have to be used to detect geomorphic changes characterized by a vertical alteration of only one or two meters.

While developing, testing, and implementing the thresholding approach, it was noticed that in some areas, the land cover based thresholds eliminated areas from the change mask that had clearly experienced significant topographic surface modifications. The land cover based thresholds were developed on the basis of overall national accuracy statistics. Even though the reference control point dataset has points located throughout the conterminous United States, it is doubtful that it represents the full variability of terrain and land cover conditions across the study area. Consequently, exclusive use of the thresholds based on the derived accuracy statistics may also not capture the full extent of topographic changes. In recognition of this, and in an attempt to include more local factors into the initial delineation of significant difference areas, the threshold approach was supplemented by including pixels from the difference grids that met certain criteria. The local mean and standard deviation of the difference grid were utilized to calculate an additional threshold for selecting areas for inclusion in the change mask. In this case, the thresholds were adapted for each 1x1-degree tile by setting them equal to three times the standard deviation above and below the mean difference for the tile. In this manner, the

philosophy from the accuracy based threshold approach of selecting only extreme difference values was carried through to the local based threshold step. Pixels from the difference grid that met the local statistics based thresholds were added to those that had previously been selected by having met the land cover based threshold criteria. By examining test results of using just the land cover based thresholds or the local statistics based thresholds, it was determined that neither one by itself was completely satisfactory in flagging candidate topographic change areas. However, in combination as a two step threshold process, they were effective in delineating areas of significant differences. The next major step in the data processing procedure involved extensive filtering and refinement of the change area mask (described below), and it was useful to have as input to that process a comprehensive set of candidate areas of statistically significant elevation differences.

Filtering of Elevation Difference Mask to Identify True Topographic Changes

The output of the differencing and thresholding procedures described above was a set of pixels with 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 rather 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 (as described above), there remained residual offsets in some areas that were large enough to cause vertical differences (Figure 3.2) that exceeded the significance thresholds. This condition was not

consistent across the study area, as 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 due to variations in the internal geometry of the SRTM, and also 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 area of the United States (Figure 3.12). 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, there are still areas of vegetation and built structures that are the sole cause of SRTM – NED differences large enough to exceed the threshold. As stated above, 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. Figure 3.13 presents an example of the presence of a vegetation canopy falsely being detected as topographic change.

Extensive viewing and examination of the results from the thresholding operations made it clear that some filtering and refinement of the change mask was necessary to limit it to areas of true topographic change. The threshold results were overlaid on shaded relief images from the NED and SRTM data, Landsat satellite images,

aerial photography, and various topographic maps to visually check the quality of the results in different terrain settings. This visual examination was critical for developing a set of criteria with which to filter the selected elevation differences. Visual inspection of areas contained in the change mask overlaid on reference data is an effective method of verifying if real topographic changes exist, however such a manual approach is impractical for the large study area used in this investigation. Therefore, a set of empirical decision rules based on observed conditions were developed and applied systematically to the significant elevation differences across the conterminous United States. Previous studies using difference grids derived from multi-temporal elevation data and a thresholding approach to detect topographic changes (Shank, 2003; Shank, 2004) also included a post-threshold filtering step to eliminate false detections.

The filtering criteria are based on specific characteristics of the difference areas, and these characteristics are calculated directly from the input elevation data and land cover datasets. Although performed on a pixel-by-pixel basis, the threshold procedure results in groups of connected pixels that form separate entities. Each of these groups of contiguous pixels was treated separately and attributed as a distinct feature. The following attributes were assigned to each feature:

- area
- change in mean elevation
- change in relief
- change in mean slope
- change in median aspect

- majority land cover class
- volume of material removed (cut) or deposited (fill)
- proximity to known mining locations
- source elevation data characteristics:
    - proximity to SRTM data voids
    - NED source DEM production method

The changes in elevation, relief, slope, and aspect were calculated by differencing those terrain parameters as derived from the NED and SRTM data. The majority land cover class was assigned from the NLCD. The volume was calculated from the difference grid. Proximity to known mining locations was determined from the NLCD.

Proximity to SRTM data voids was calculated from the SRTM data. Voids in SRTM data occur where reliable elevations could not be calculated from the radar data because of layover, shadowing, or low interferometric correlation. They occur infrequently, but where they do exist they often fall on steep slopes (Hall, Falorni, and Bras, 2005). Figure 3.14 shows an example of SRTM data voids. It is important to note their location for filtering criteria because significant elevation differences that occur immediately adjacent to the voids are often false changes that are selected only because of slight misregistration of the NED and SRTM data in steep terrain.

The NED source DEM production method code is assigned from the NED spatially referenced metadata (Gesch, 2006). This is an important consideration for the filtering criteria because some areas in the NED are derived from older USGS 7.5-minute DEMs made with obsolete photogrammetric methods. These methods often left artifacts

in the data, and this noise can create areas of erroneous differences when the NED is subtracted from the SRTM data (Figure 3.15).

A test group of 30 1x1-degree tiles was examined intensively to develop the set of decision rules to filter and refine the change mask. The test group (Figure 3.16) necessarily included a wide range of terrain, land cover, and data quality conditions, and it represents a sample of approximately 3% of the 934 tiles used as data processing units. Interactive analysis was conducted by overlaying the areas selected as significant differences from the thresholding procedure on ancillary reference data. This visual check allowed for determination of which features in the change mask represented actual topographic modifications, and the recording of the characteristic range of attribute values for those features. The range of attribute values for the real change features formed the basis for the filtering decision rules. Whereas the differencing, thresholding, and assignment of terrain and land cover attributes had to be performed on gridded (raster) data, the distinct groups of connected pixels of significant differences were then converted to polygon (vector) feature data, which facilitated the filtering by allowing the polygon attributes to be queried and analyzed in a relational database environment.

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 statistical based thresholding and filtering processes could be avoided altogether. However, when the study area is large, 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 of polygons as areas of true topographic surface change is the preferred method that has been implemented for this study.

The primary criteria for acceptance of a polygon into the set of significant topographic surface changes involve the degree to which major terrain parameters as measured from the NED and SRTM data have changed. The parameters of interest are mean elevation, relief, slope, and aspect. If a combination of these parameters have changed enough, then the polygon under consideration is deemed acceptable as a representation of significant geomorphic change. As a matter of practicality, before the terrain parameters are checked, polygons of very small size are eliminated from further consideration. Polygons comprising areas of less than 50 contiguous pixels, which equates to an area of approximately 0.045 square kilometers, were deleted from the change mask. The designation of this size threshold was based on the experience of visual examination, and in practice was quite effective at removing a lot of background noise from the change mask, which greatly aided interpretability of the remaining polygons.

Based on visual analysis of the test tiles, it was observed that the following conditions were generally true for polygons that delineated areas of actual topographic change:

- the percent change in mean elevation exceeded ±5%
- the percent change in relief exceeded ±5%
- the change in mean slope exceeded ±5 degrees
- the change in median aspect exceeded ±18 degrees

The attributes of each candidate polygon were checked to see how many of these four conditions were met. Those polygons with three or four of the conditions being met were retained in the change mask, while those with only one or two conditions being met were eliminated. This filter greatly reduced the number of false detections of change caused by residual misregistration in higher relief areas or the presence of non-ground level surfaces (forest canopy or built structures). Subsequent visual analysis indicated that the change mask still had some problems with delineations of the areas of actual topographic change, so a series of additional criteria was tested and implemented as sequential filter steps to address specific conditions. Table 3.4 outlines the filter steps applied to obtain the final change mask. As listed in the table, the sequential filter steps make extensive use of the terrain parameters measured from the elevation datasets as well as land cover information from the NLCD.

The input change mask to the filtering and refinement process consisted of all the polygons from the individual 1x1-degree processing units merged into a feature dataset covering the entire study area. The change mask contained 219,156 distinct polygons

outlining areas of significant elevation differences from the thresholding process (and after the minimum size criterion of 50 contiguous cells had been applied). The primary filter that checks for at least 3 of 4 terrain parameter change criteria being met (filter step 2 in Table 3.4) reduced the number of candidate polygons in the change mask by more than 88% to 26,064 polygons. The subsequent filter steps (steps 3 through 10 in Table 3.4) further reduced the number to 5,263 polygons, or 2.4% of the pre-filtering total. These polygons represent the final set of features that delineate significant topographic surface changes across the conterminous United States.

An example of an area in West Virginia helps to illustrate the effects of the filtering and refinement applied to polygons outlining significant elevation differences. For the 1x1-degree tile extending between 80 and 81 degrees west longitude and between 38 and 39 degrees north latitude, there were originally 8,252 polygons that outlined areas that passed the elevation thresholds. Most of these polygons were very small and were eliminated by the first filter step that checks for a minimum size of 0.045 square kilometers. After the size criterion was applied, 293 polygons remained, and after all the filter steps were applied a final total of 41 polygons were included as topographic change polygons. Figure 3.17 displays a small area within the example tile that shows some polygons that were eliminated and some that survived the filtering process. In this case, even the eliminated polygons appear to outline areas that have experienced topographic change. However, these polygons were eliminated because they did not meet the requirement for change in terrain parameters (filter step 2 in Table 3.4).

As part of the filtering and refinement process, polygons delineating areas that were entirely flat in the SRTM data were extracted and treated separately. These areas form a special case of surface change because most of them represent reservoirs or water bodies that have changed in water level. Detection of these features was aided by the fact that the SRTM data, as part of its production process, had water bodies and shorelines edited to reflect conditions present during the February 2000 data collection period. Interferometric radar data generally have little useful information about the elevation of water bodies because of the weak returns of the radar signal from water, so an extensive editing process was performed on the SRTM data to ensure correct representation of water features (Slater, *et al.*, 2006). Flat areas in the SRTM data that coincided with significant elevation increases often indicate a new reservoir (if the underlying NED data are not flat) or a significantly increased water level in an existing reservoir or lake (if the underlying NED data are flat and the NLCD indicates a cover type of water). It was also observed that some of the flat features in the SRTM data with a corresponding significant increase in elevation represent features associated with surface mining operations, such as settling ponds and graded spoil banks. A total of 364 polygons were extracted by segmenting flat areas with significantly increased elevations from the SRTM data, and each of these polygons was labeled as 'new,' 'existing,' or 'mining' depending on the relief (or the lack thereof) in the NED and the NLCD class designation for the area.

Tabulation of Statistics Characterizing the Extent of Topographic Change

The final delineation of topographic change polygons included 5,263 distinct features, representing both cuts (decreased elevations) and fills (increased elevations). In

addition, 364 polygons outline areas of reservoir construction or expansion, or other similar hydrologic land uses. 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. Also important are national and regional scale summaries of the location and extent of topographic changes. To provide such information, summary statistics were tabulated for different subdivisions and accounting units, including states, counties, ecoregions, watersheds, quadrangle base maps, and 1x1-degree tiles. Figure 3.18 summarizes the overall data processing procedure that led to the final delineation of change areas and the accumulation of area based summary statistics.

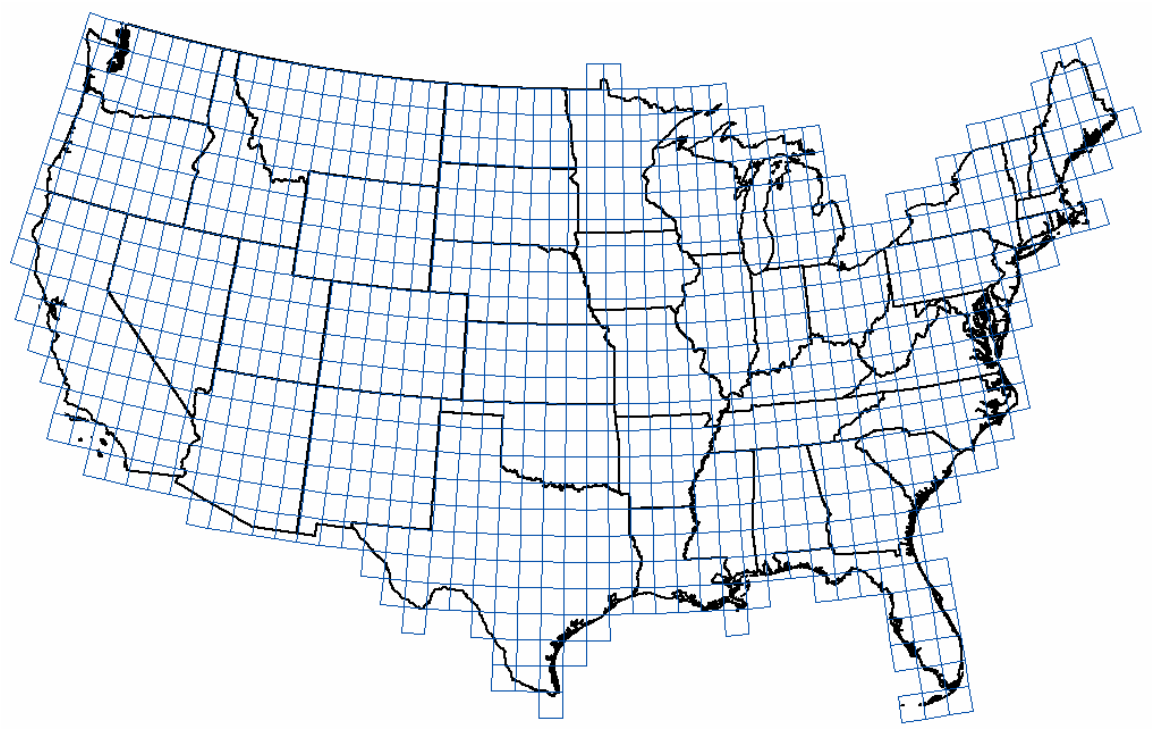
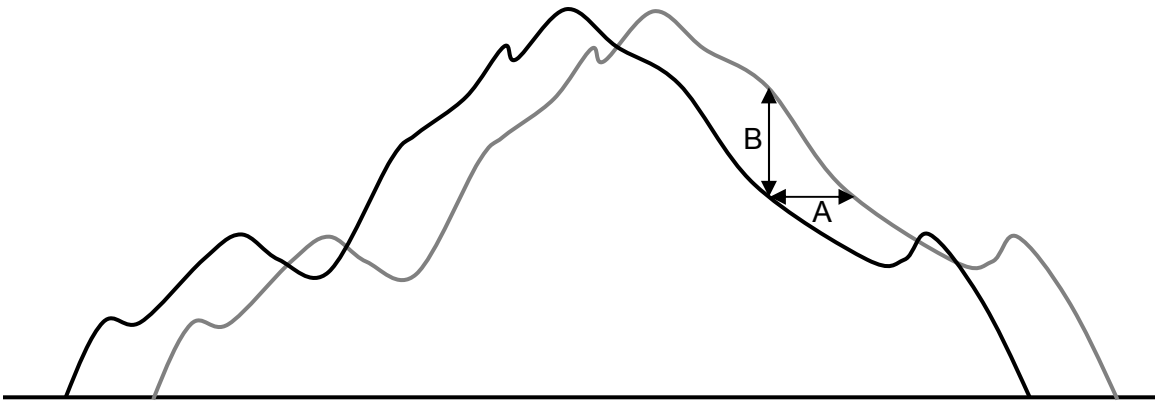


Figure 3.1. 934 1x1-degree tiles used for organizing and processing input data.



A = Δx = horizontal displacement

B = Δz = apparent vertical change

Figure 3.2. Apparent vertical change due solely to misregistration of multi-temporal DEMs.

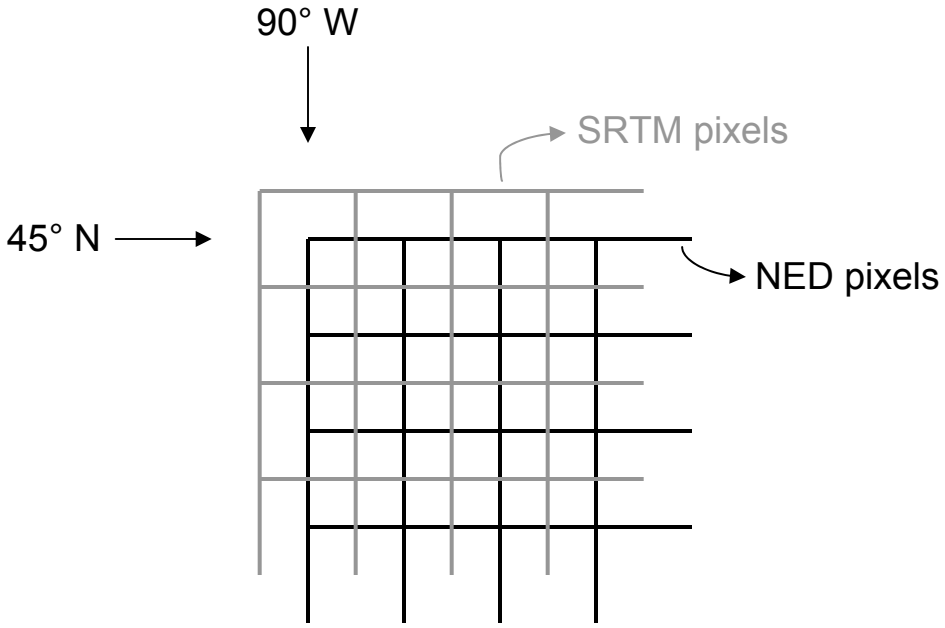


Figure 3.3. Coordinate system referencing for native format NED and SRTM.

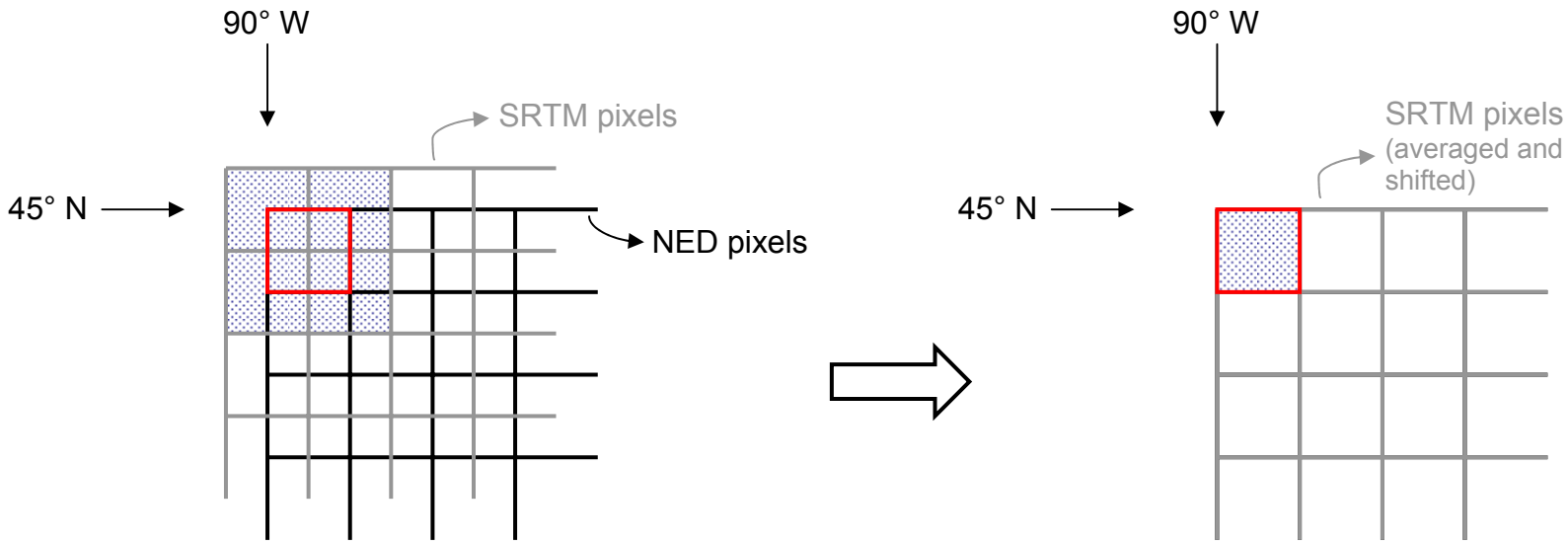


Figure 3.4. Diagram of the SRTM – NED coregistration process. Prior to registration, each NED pixel (red, on left side diagram) is centered on four SRTM pixels (shaded, on left side diagram). These four SRTM pixels are averaged and the resulting value is placed into the upper left position of the 2x2-window. After the averaging is completed for the entire SRTM grid, the output is shifted one-half pixel in both the x and y directions to align the SRTM pixels with the NED pixels (right side diagram).

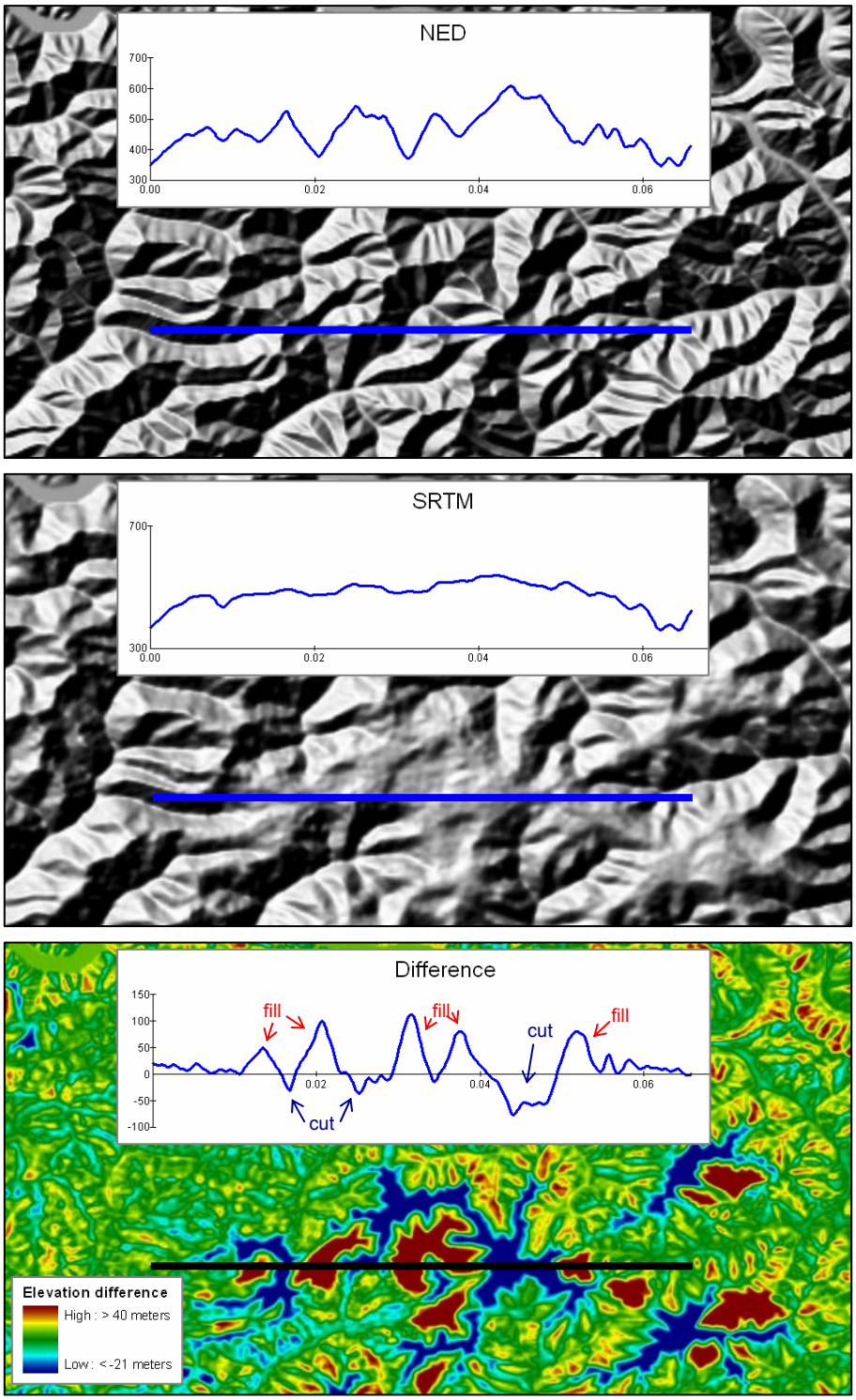


Figure 3.5. Example of coregistered NED and SRTM, and the derived difference grid for an area in eastern Kentucky. The length of the profile is approximately 5.8 kilometers.

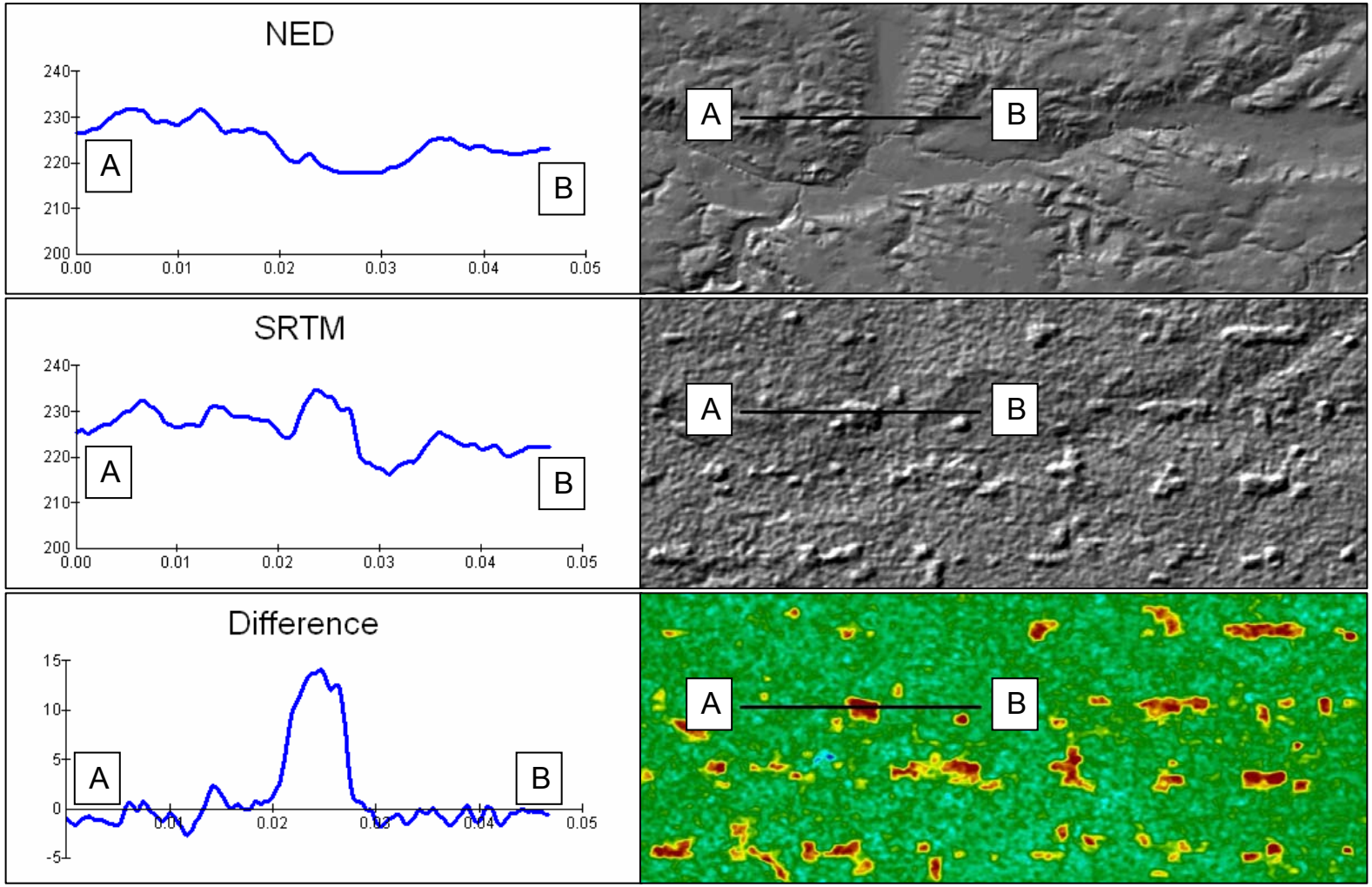


Figure 3.6. Illustration of the effects of a vegetation canopy on SRTM data and the derived SRTM – NED difference grid for an area in southern Michigan. The large difference in the middle of the profile, ranging up to 15 meters, is due solely to the presence of trees. The profile length is approximately 3.8 kilometers.

NLCD class	Number of control points	Minimum	Maximum	Mean	Standard Deviation	RMSE
Low intensity residential	861	-42.64	12.41	-0.34	2.90	2.92
High intensity residential	469	-10.01	9.27	-0.20	2.23	2.24
Commercial/industrial/transportation	2,605	-20.83	12.11	-0.53	2.59	2.64
Bare rock/sand/clay	166	-8.48	6.86	-0.52	2.26	2.32
Quarries/strip mines/gravel pits	25	-2.23	11.81	1.27	3.17	3.35
Transitional	133	-9.17	7.55	-0.50	2.40	2.44
Deciduous forest	789	-19.72	18.74	-0.32	2.95	2.97
Evergreen forest	310	-14.48	7.96	-0.74	2.68	2.78
Mixed forest	237	-13.22	11.75	-0.42	2.69	2.71
Shrubland	687	-21.75	11.16	-0.41	2.91	2.94
Orchards/vineyards/other	68	-6.77	1.07	-0.56	1.56	1.65
Grasslands/herbaceous	1,039	-15.08	9.59	-0.45	2.36	2.40
Pasture/hay	2,046	-11.98	13.90	0.04	1.97	1.97
Row crops	2,498	-15.31	14.50	-0.12	2.11	2.11
Small grains	209	-4.89	14.34	0.15	1.46	1.46
Fallow	40	-5.99	5.83	0.30	1.84	1.84
Urban/recreational grasses	512	-13.34	11.01	-0.20	2.18	2.19
Woody wetlands	236	-16.86	5.60	-1.06	2.61	2.82
Emergent herbaceous wetlands	375	-13.12	5.45	-1.12	2.31	2.57
Low intensity residential	861	-42.64	12.41	-0.34	2.90	2.92
All	13,305	-42.64	18.74	-0.32	2.42	2.44

Table 3.1. Error statistics (in meters) of NED vs. 13,305 reference geodetic control points.

NLCD class	Number of control points	Minimum	Maximum	Mean	Standard Deviation	RMSE
Low intensity residential	861	-15.43	21.22	1.12	3.61	3.78
High intensity residential	469	-12.13	12.39	1.50	3.32	3.64
Commercial/industrial/transportation	2,605	-18.59	28.48	-0.13	3.58	3.59
Bare rock/sand/clay	166	-18.61	13.13	-0.49	4.48	4.50
Quarries/strip mines/gravel pits	25	-6.58	6.74	-1.08	2.84	2.99
Transitional	133	-8.32	16.16	1.61	3.67	4.00
Deciduous forest	789	-15.59	23.24	0.38	3.75	3.77
Evergreen forest	310	-20.82	14.91	1.73	4.86	5.16
Mixed forest	237	-7.40	14.30	1.27	3.46	3.68
Shrubland	687	-31.11	13.35	-0.10	4.17	4.17
Orchards/vineyards/other	68	-6.69	11.04	2.73	3.61	4.51
Grasslands/herbaceous	1,039	-12.93	10.33	0.42	3.38	3.40
Pasture/hay	2,046	-17.65	16.83	-0.55	2.98	3.03
Row crops	2,498	-11.80	12.23	-0.47	2.90	2.94
Small grains	209	-8.94	9.97	-1.14	2.86	3.07
Fallow	40	-8.07	4.45	-1.92	2.33	3.00
Urban/recreational grasses	512	-12.80	30.31	-0.10	3.65	3.65
Woody wetlands	236	-23.17	11.62	1.23	3.95	4.13
Emergent herbaceous wetlands	375	-11.21	15.75	1.08	3.85	3.99
Low intensity residential	861	-15.43	21.22	1.12	3.61	3.78
All	13,305	-31.11	30.31	0.09	3.52	3.53

Table 3.2. Error statistics (in meters) of SRTM vs. 13,305 reference geodetic control points.

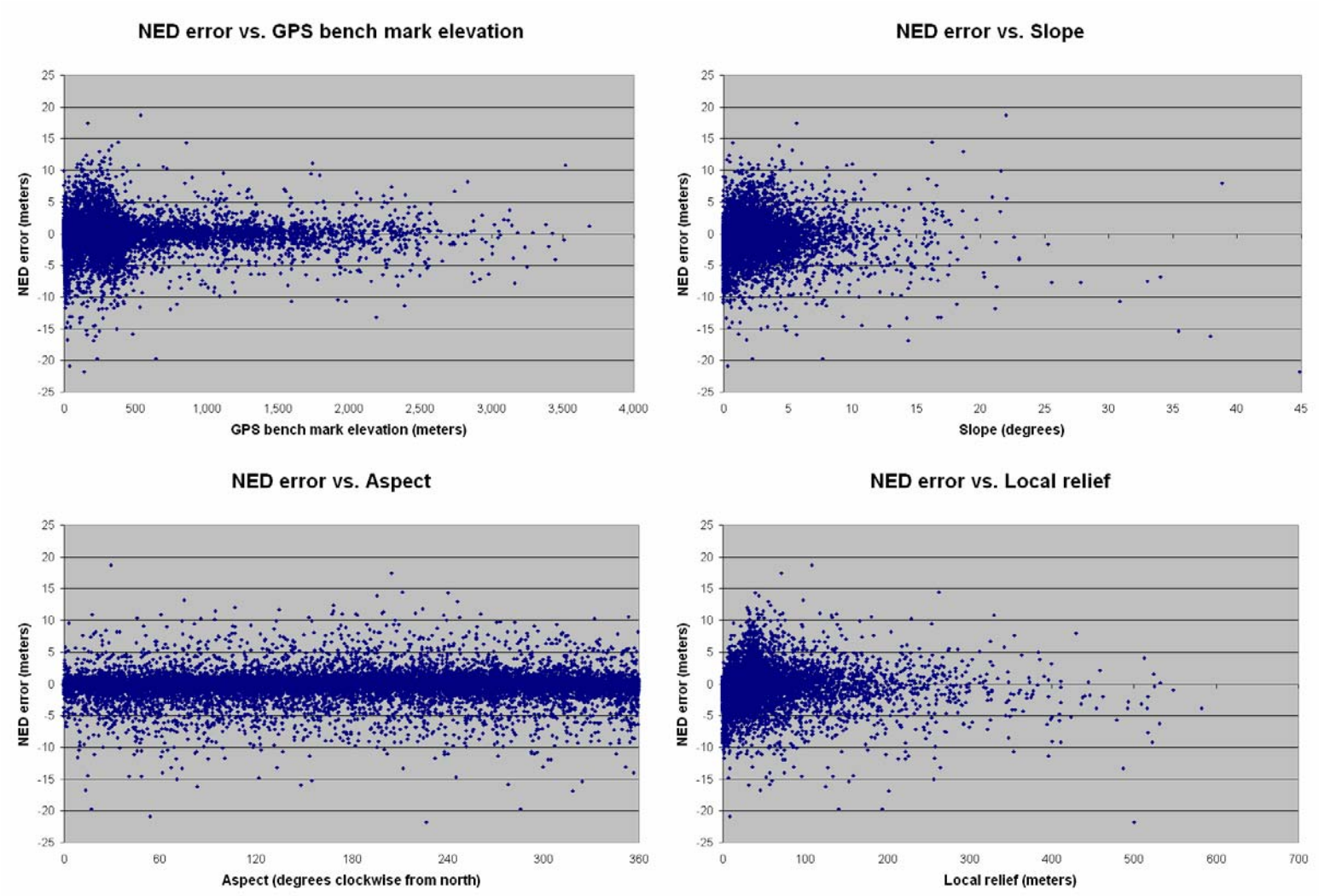


Figure 3.7. NED error (in meters) plotted against elevation (upper left), slope (upper right), aspect (lower left), and local relief (lower right).

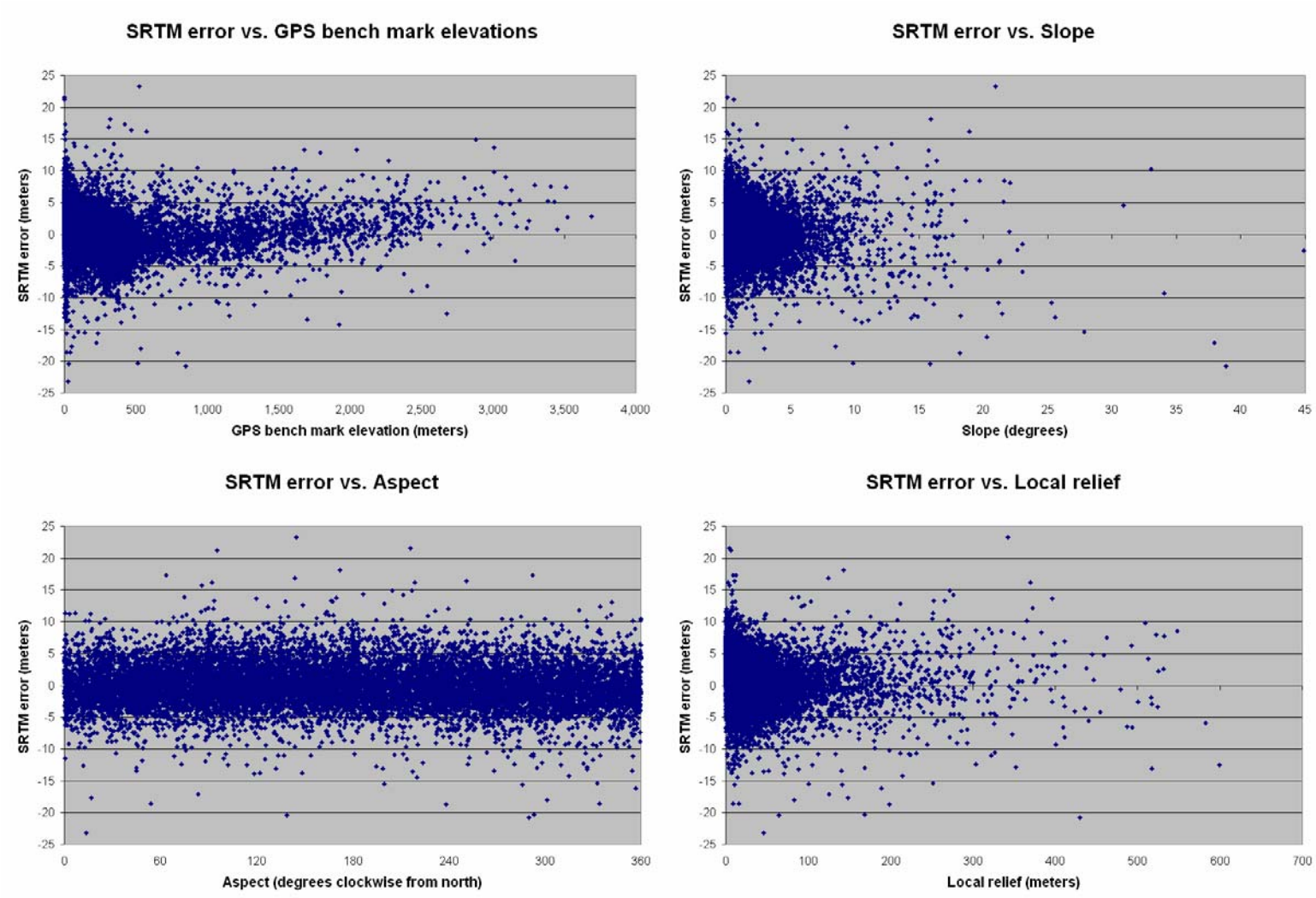


Figure 3.8. SRTM error (in meters) plotted against elevation (upper left), slope (upper right), aspect (lower left), and local relief (lower right).

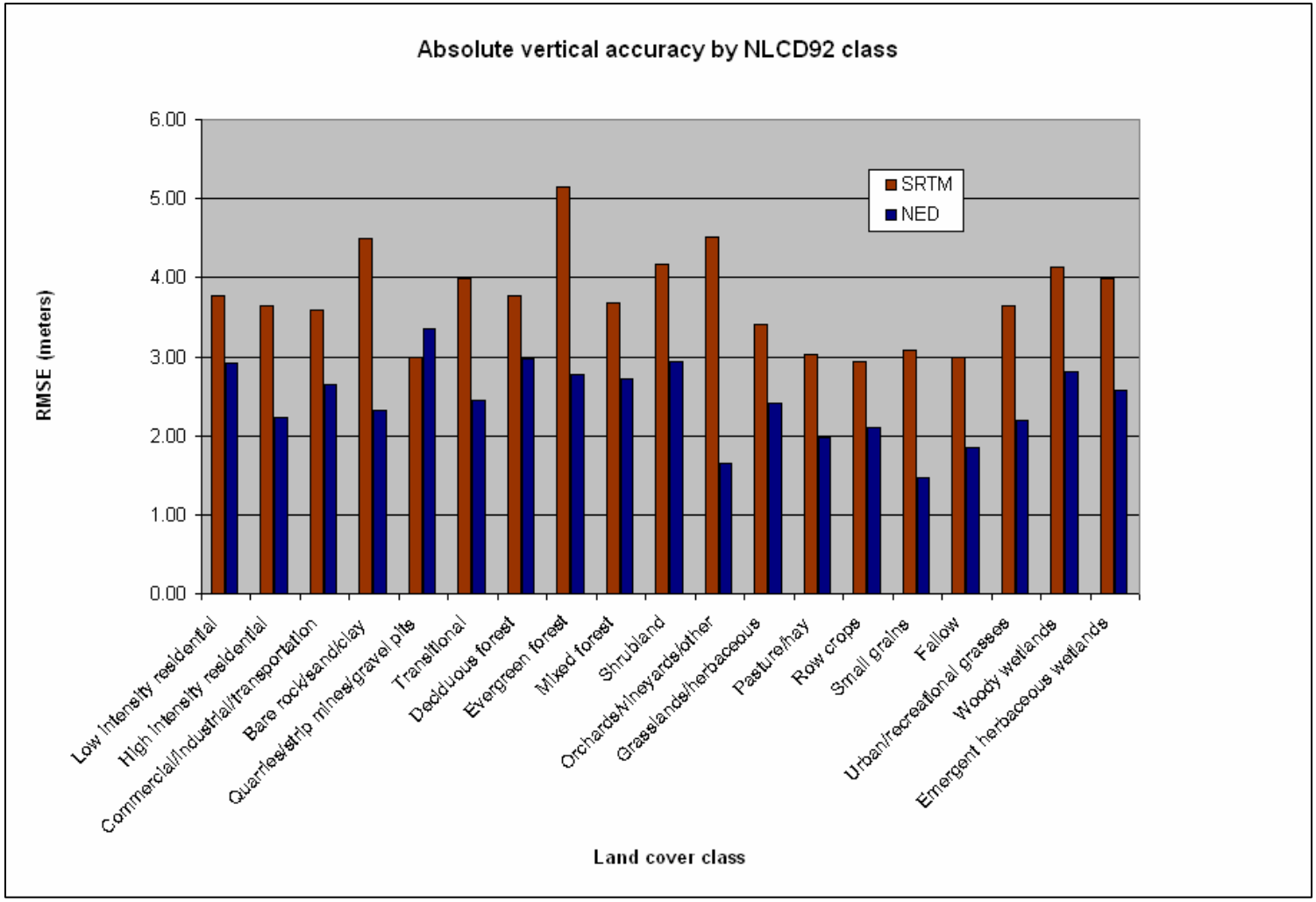


Figure 3.9. Comparison of the vertical accuracy of the NED and SRTM data for each land cover class.

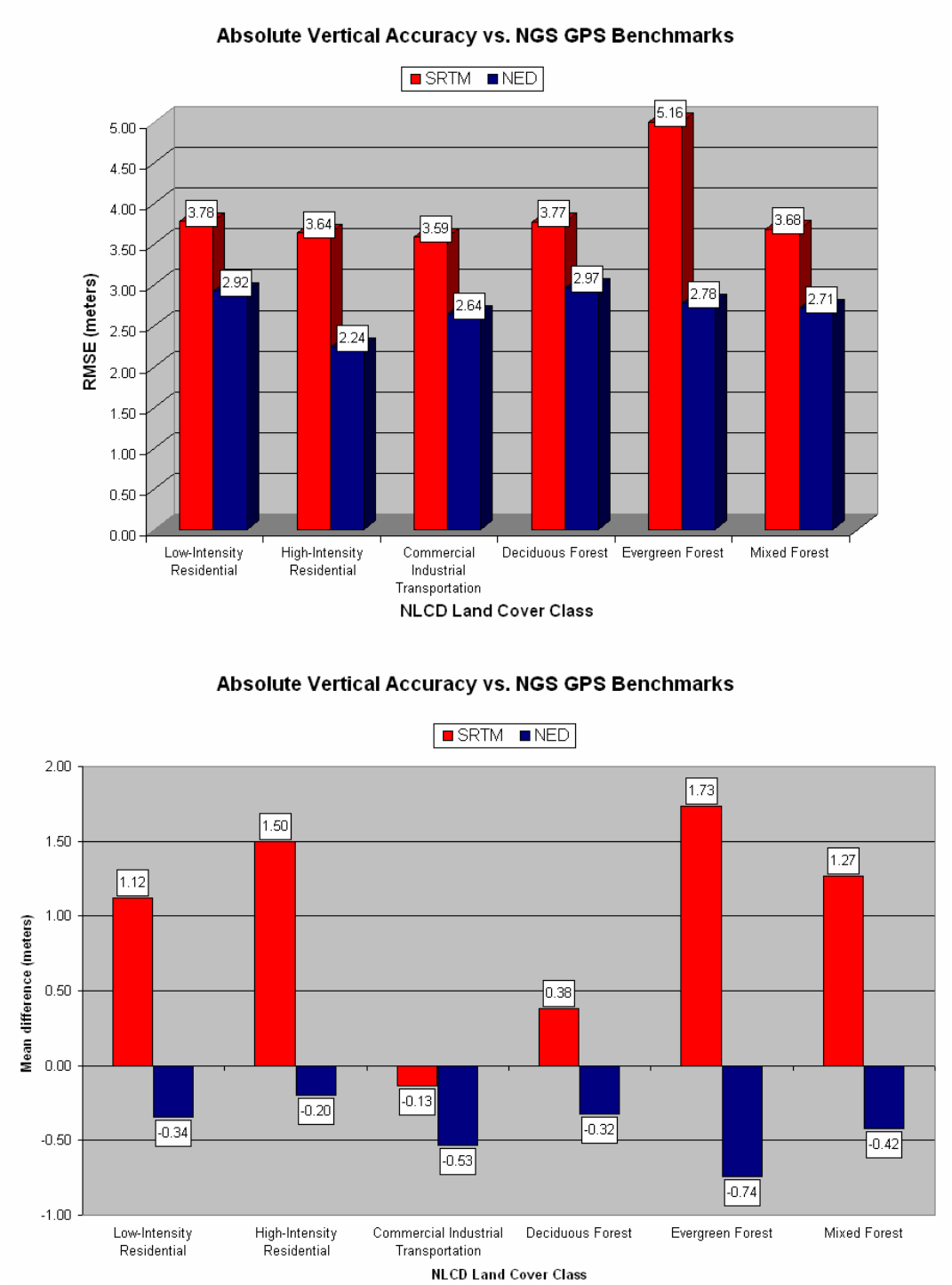


Figure 3.10. Comparison of vertical accuracies for SRTM and NED elevation data for urban/built-up and forest classes (top: RMSE, as a measure of uncertainty; bottom: mean difference, as a measure of elevation bias).

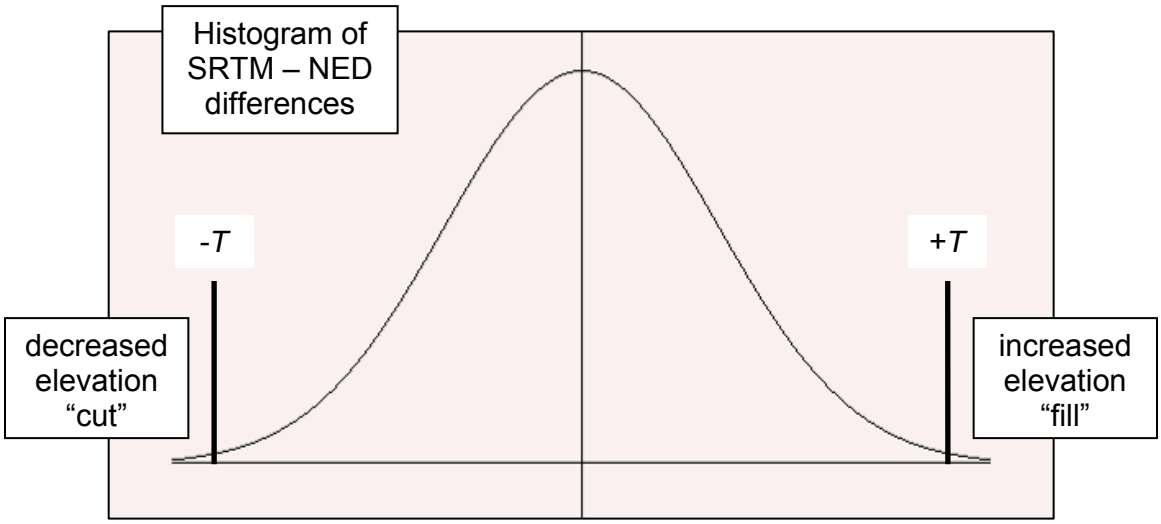


Figure 3.11. Idealized histogram of SRTM – NED difference values with the statistically based thresholds for determining significant changes.

NLCD class	SRTM RMSE (m)	NED RMSE (m)	Threshold (m)
Low intensity residential	3.78	2.92	±14.32
High intensity residential	3.64	2.24	±12.81
Commercial/industrial/transportation	3.59	2.64	±13.36
Bare rock/sand/clay	4.50	2.32	±15.18
Quarries/strip mines/gravel pits	2.99	3.35	±13.46
Transitional	4.00	2.44	±14.05
Deciduous forest	3.77	2.97	±14.39
Evergreen forest	5.16	2.78	±17.57
Mixed forest	3.68	2.71	±13.72
Shrubland	4.17	2.94	±15.30
Orchards/vineyards/other	4.51	1.65	±14.40
Grasslands/herbaceous	3.40	2.40	±12.50
Pasture/hay	3.03	1.97	±10.85
Row crops	2.94	2.11	±10.86
Small grains	3.07	1.46	±10.21
Fallow	3.00	1.84	±10.55
Urban/recreational grasses	3.65	2.19	±12.78
Woody wetlands	4.13	2.82	±14.98
Emergent herbaceous wetlands	3.99	2.57	±14.24
All	3.53	2.44	±12.87

Table 3.3. Significant change thresholds for each land cover class.

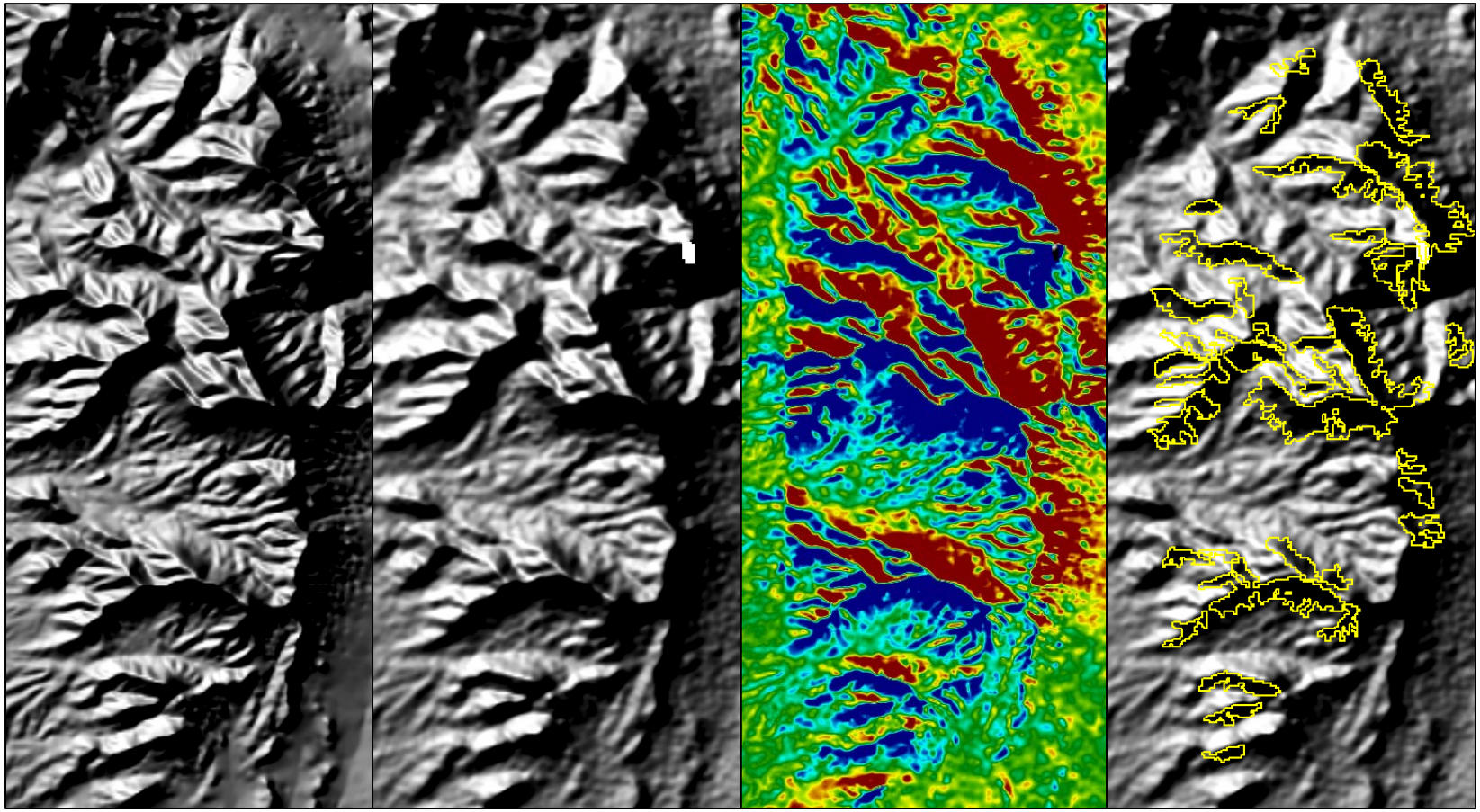


Figure 3.12. Example of residual misregistration causing false detection of vertical change. Images are (from left to right): NED shaded relief, SRTM shaded relief, SRTM – NED difference grid (blue = significant decrease in elevation; red = significant increase in elevation), areas of significant differences (outlined in yellow) overlaid on SRTM shaded relief. There are no actual topographic changes in this area in south central New Mexico. Note that the areas of significant differences are located immediately adjacent to sharp changes in the topography (ridges and cliffs). The area shown is approximately 3.9 km east-west by 10 km north-south.

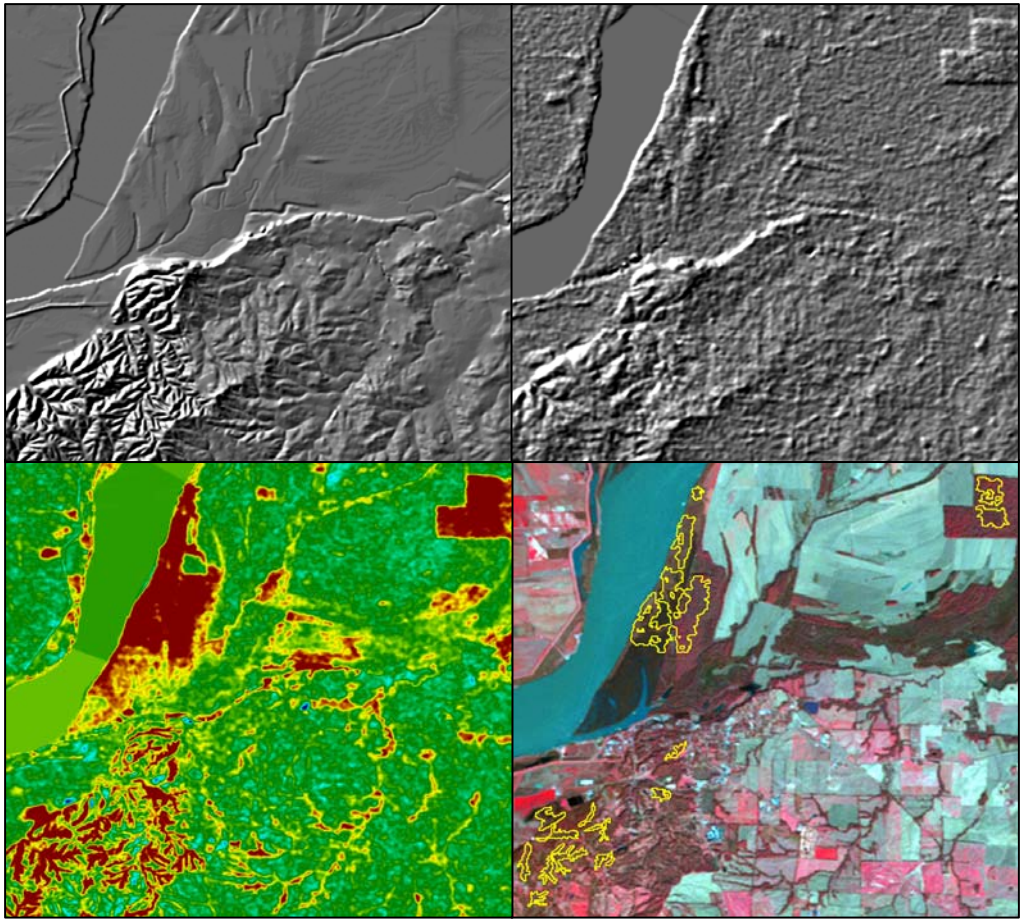


Figure 3.13. Example of dense vegetation causing false detection of vertical change. Images are: NED shaded relief (upper left), SRTM shaded relief (upper right), SRTM – NED difference grid (lower left; red = significant increase in elevation), areas of significant differences (outlined in yellow) overlaid on a color infrared rendition of a Landsat image (lower right). There are no actual topographic changes in this area in western Kentucky. Note that the areas of significant differences coincide with areas of dense bottomland and upland forest. The area shown is approximately 10.3 km east-west by 11.2 km north-south.

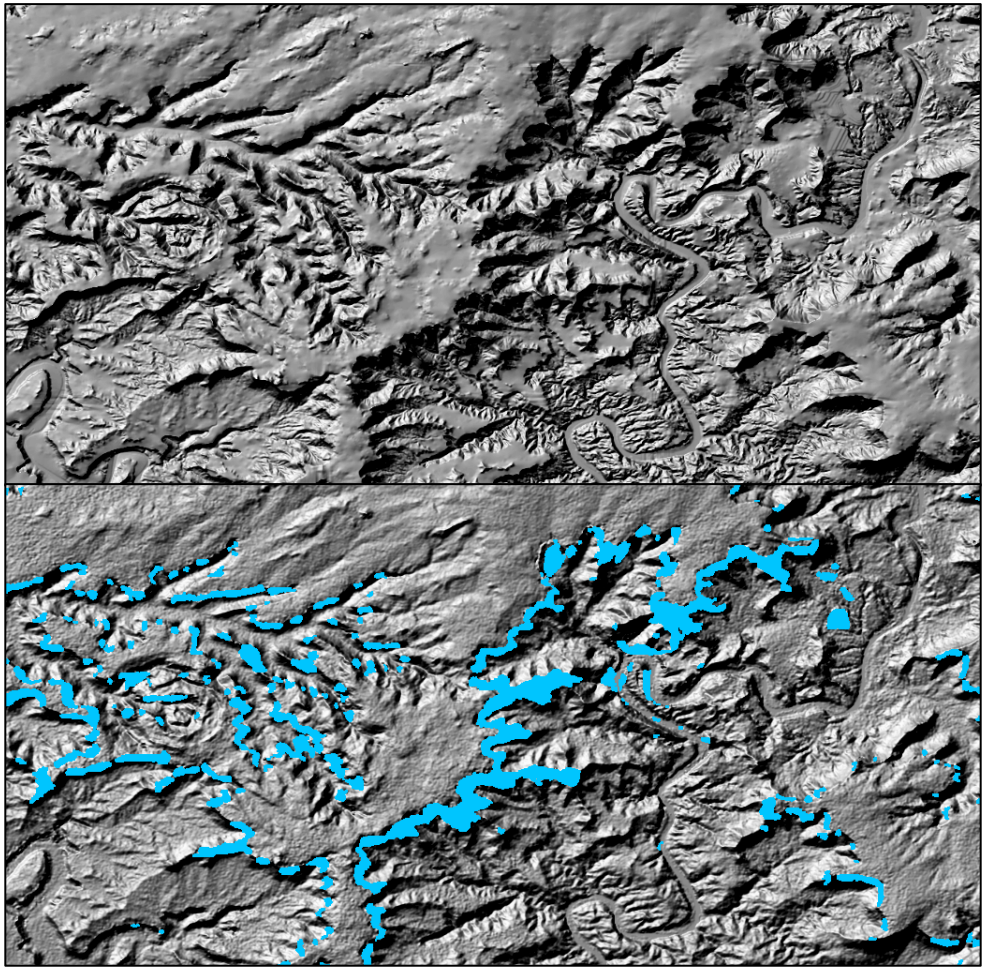


Figure 3.14. Example of data voids in SRTM data for an area in southeastern Utah. Comparison of NED shaded relief (top image) and SRTM shaded relief (bottom image), with SRTM voids shown in light blue. Note how the voids occur at sharp changes in the topography. The area shown is approximately 32 km east-west by 19.7 km north-south.

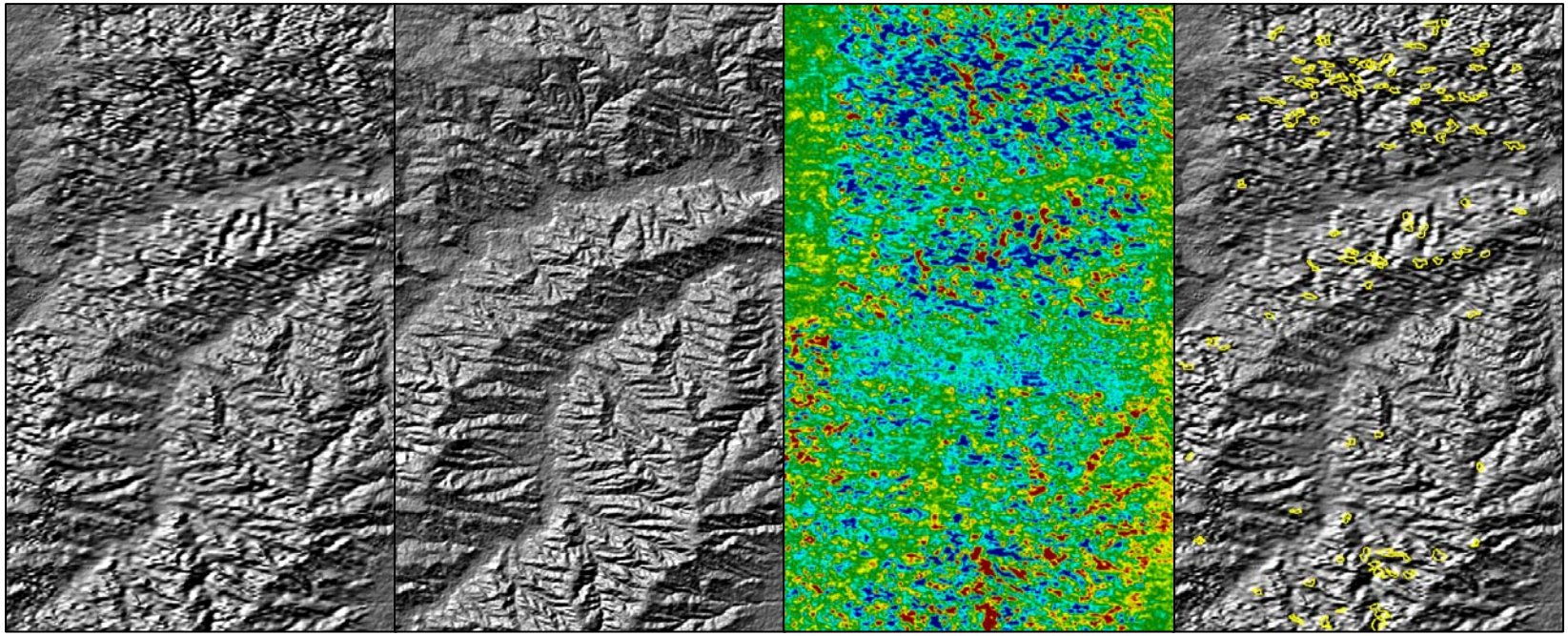


Figure 3.15. Example of source data artifacts causing false detection of vertical change. Images are (from left to right): NED shaded relief, SRTM shaded relief, SRTM – NED difference grid (blue = significant decrease in elevation; red = significant increase in elevation), areas of significant differences (outlined in yellow) overlaid on NED shaded relief. There are no actual topographic changes in this area in eastern Wyoming. Note that the areas of significant differences are located over artificial highs and lows in the NED due to production artifacts in the original USGS DEM source data. The area shown is approximately 12.8 km east-west by 27.7 km north-south.

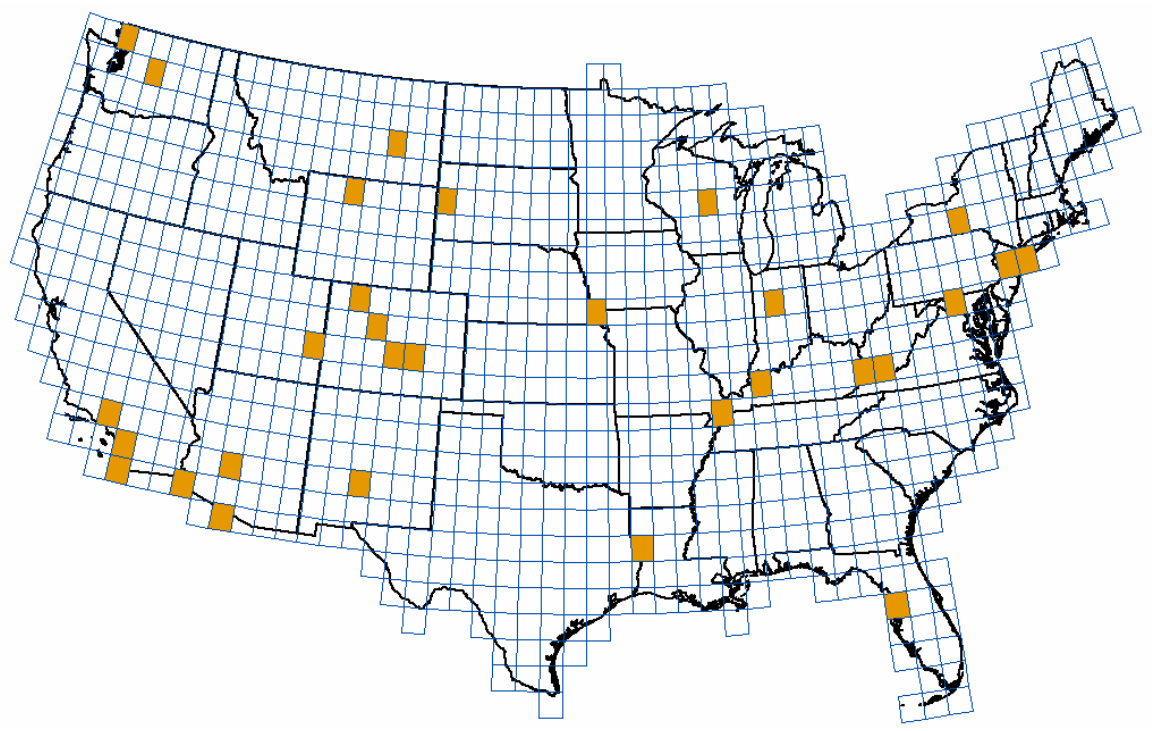


Figure 3.16. Test group of 30 1x1-degree tiles used for development of decision rules for filtering of change mask.

Filter step	Action	Note
1	Delete polygons encompassing areas less than 50 contiguous pixels (0.045 km^2)	
2	Delete polygons that do not meet at least 3 of 4 terrain parameter change criteria: ±5% change in mean elevation; ±5% change in relief; ±5° change in mean slope; ±18° change in median aspect	Eliminates many false change detections due to misregistration and presence of vegetation in higher relief areas
3	Delete polygons with a positive change in mean elevation ("fill") in low relief areas (≤5 m) with a majority land cover type of urban/built-up, forest, agriculture, or wetland	Eliminates false change detections ("fills") in flat areas, especially urban cores, wooded swamps, and shelterbelts/woodlots
4	Delete polygons over areas in which the NED was derived from obsolete, artifact prone photogrammetric production methods	
5	Delete polygons that are entirely flat in either the NED or SRTM data	Many of these polygons represent a special case of reservoirs/water bodies and are treated separately in a later process
6	Delete polygons that share a border with areas of SRTM data voids	Eliminates false detections due to misregistration in steep terrain areas, and eliminates false detections ("fills") in urban cores
7	Delete polygons that do not exceed a ±5% change in mean elevation and have a majority land cover type of bare rock, shrubland, grassland, or pasture	Eliminates false detections due to misregistration in higher relief arid/semi-arid areas
8	Add polygons that have a majority land cover type of quarries/strip mines/gravel pits (and pass the size criterion of filter step 1)	Takes advantage of ancillary source of labeling (NLCD) to include known areas of topographic alteration due to surface mining
9	Add polygons that pass the size criterion of filter step 1 and are located within a 500 m buffer of polygons that have a majority land cover type of quarries/strip mines/gravel pits	Adds polygons that are in close proximity to known surface mines and have probably experienced topographic change after the date of NLCD source data
10	Delete polygons that are within the 500 m mine buffer (applied in filter step 9) but do not meet any of the terrain parameter change criteria of filter step 2	Eliminates false change detections due to misregistration in higher relief areas or presence of dense vegetation adjacent to surface mines

Table 3.4. Filter steps applied to areas of significant elevation differences to produce the final set of polygons that delineate topographic surface changes across the conterminous United States.

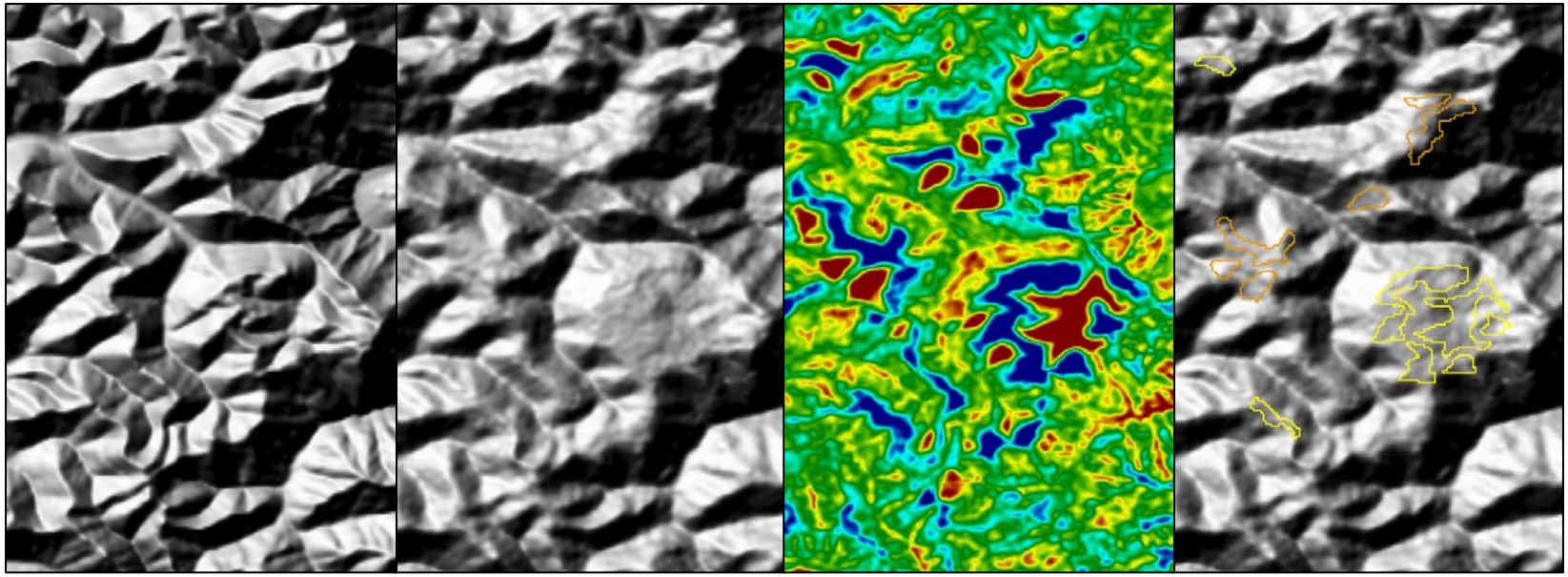


Figure 3.17. Example of the results of the filtering process applied to significant elevation differences. Images are (left to right): NED shaded relief, SRTM shaded relief, SRTM – NED difference grid (blue = significant decrease in elevation; red = significant increase in elevation), polygons outlining areas of significant topographic change overlaid on SRTM shaded relief (yellow = polygons remaining after filter process; orange = polygons eliminated by filter process). The area shown is located in West Virginia, and is approximately 3.7 km east-west by 6.9 km north-south.

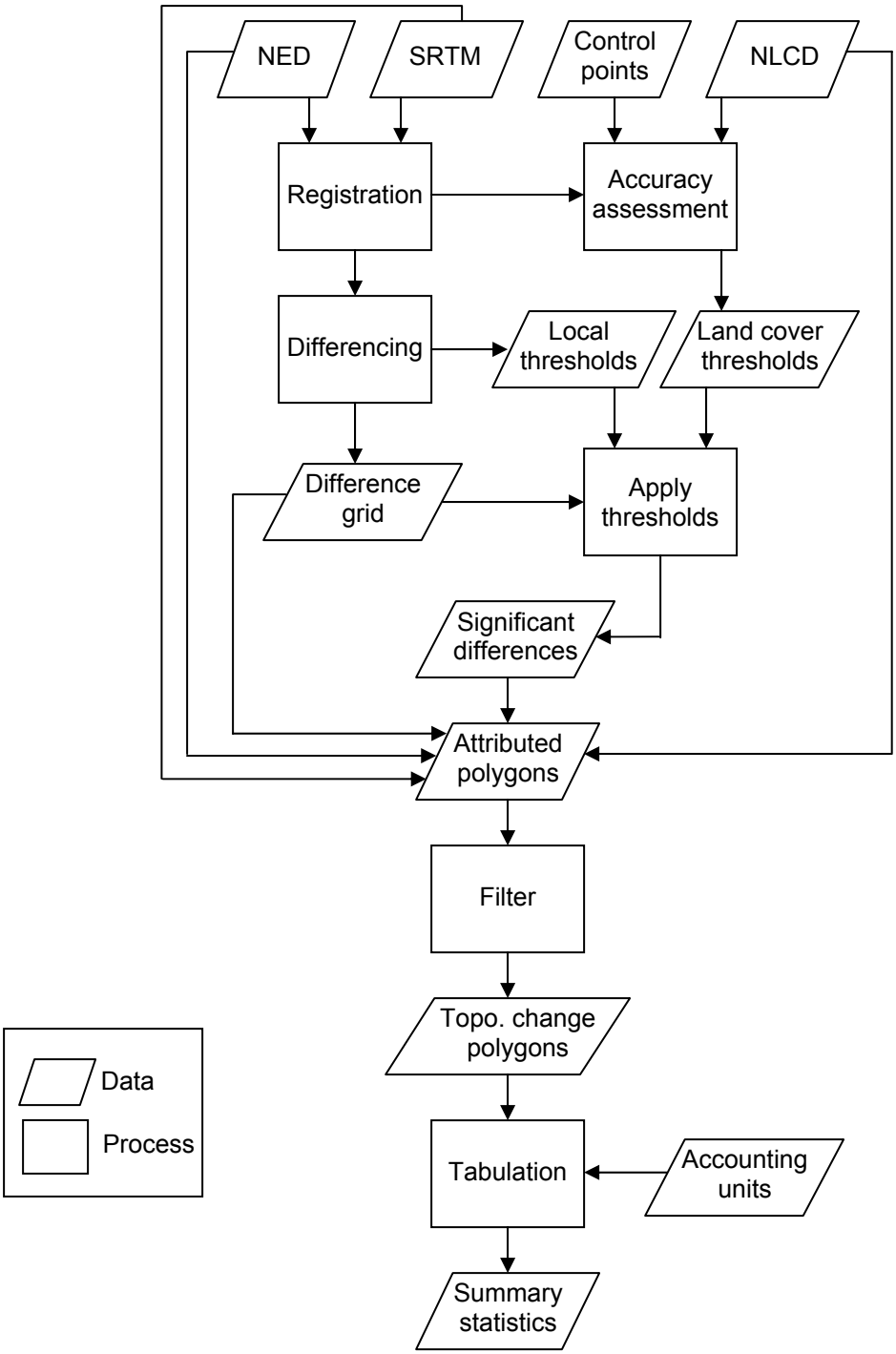


Figure 3.18. Flow diagram of the overall data processing procedure that resulted in a delineation of topographic surface changes across the conterminous United States.

CHAPTER 4

RESULTS, ANALYSIS, AND DISCUSSION

The primary result of the data processing explained in Chapter 3 is a polygon feature dataset that locates and describes the areas in the conterminous United States that have experienced significant topographic change during the 20th century. The spatial distribution of the 5,263 polygons is shown in Figure 4.1. The individual change polygons range in area from 0.03 to 9.79 square kilometers, with the average size at 0.24 square kilometers. Table 4.1 lists the overall summary statistics for the full collection of change polygons. Table 4.2 shows the proportion of the change polygons that fall into major land cover categories. Over two-thirds (67.5%) of the polygons represent cut areas (significantly decreased elevation), and the remainder (32.5%) represent fill areas (significantly increased elevation).

Table 4.1 indicates that the total amount of material that has been displaced is 4.33×10^{10} cubic meters. This total was derived by summing the volume attribute for all the polygons, regardless of the type of change (cut or fill). When the volume of a cut is considered to be negative and the volume of a fill is considered to be positive, the total volume for the entire dataset sums to -1.25×10^{10} cubic meters, which is considerably different from the previously calculated total. The discrepancy between these two numbers provides some insight into the nature of the collective surface changes represented by the polygon dataset. As noted above, the majority of the polygons are cut areas, where elevation is decreased (and the volume moved is recorded as a negative

value). If the number of cut areas was equal to the number of fill areas, it could be expected that the negative and positive volumes would balance each other and the overall total volume would equal zero. In other words, the volume of earth material excavated (cut) would be equalized by the volume deposited (fill). As observed, this is not the case as there is a net loss of material in the system. The cuts account for 2.79×10^{10} cubic meters of material removed, whereas the fills account for 1.54×10^{10} cubic meters of material deposited. The difference between these figures is the observed loss to the system of 1.25×10^{10} cubic meters. In direct anthropogenic processes, material must first be excavated before it can be deposited. In this context, nearly 45% of the volume of material removed was either not deposited, or it was not deposited in manner that resulted in features that are detectable through elevation differencing. Considering that the primary land use represented by the change polygons is mining (Table 4.2), it can be assumed that a large portion of the "lost" material is the mineral content that was extracted from the mining sites. In reality, this volume of material was not completely lost from the system, but rather it was removed from the mining site, distributed, and consumed elsewhere so there is no detectable deposition of fill material to balance with the cut volume. This is an example of the unbalanced flow of materials described by Hooke (1994) in which he points out that much of the material moved in anthropogenic processes is not replaced. Hooke (1999) also points out that much of the material moved by human action is only transported over short distances. While this is certainly true for overburden in surface mining operations, it is not the case for the extracted mineral. As a

valuable commodity, it is worthwhile to move the mineral material over longer distances, and its transportation is not hindered by cost constraints.

As described in Chapter 3, features were extracted that are characterized by significantly increased elevations coinciding with flat areas in the SRTM data. In many cases these are reservoirs, lakes, or other water bodies that have experienced a water level rise or inundated area expansion. Figure 4.2 shows the locations of the 364 polygons, which fall into 239 counties across the conterminous United States (nearly 8% of the total). Of the change polygons in this special class, 15% are labeled as 'new' where NLCD did not indicate a land cover of water; 78% are labeled as 'existing' where the polygons shares a border with an existing water body; and 7% are labeled as 'mining' where NLCD indicated the mining land cover class as the majority within the polygon. Additionally, the 364 special case polygons are contained within 213 hydrologic cataloging units (Figure 4.3), which represents approximately 10% of the total of these watershed delineations in the conterminous United States that are commonly used for water resources management (Seaber, Kapinos, and Knapp, 1987). The presence of hydrologic alterations as indicated by the change polygons may be important for water resources management within the affected units.

Regional Geography of Topographic Surface Changes

Examination of the spatial distribution of the topographic change polygons across the conterminous United States as displayed in Figure 4.1 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 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 characteristics of the regional geography of topographic change that are recognized from the conterminous United States map in Figure 4.1 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

Other more subtle, but still recognizable, features include:

- change polygons in central Florida that represent landscape modifications from phosphate mining
- a concentration of change polygons representing limestone quarries located along the escarpment at the southeast edge of the Edwards Plateau in south central Texas
- a cluster of change polygons in eastern Wisconsin that represent limestone quarries in the Niagara formation; other polygons in this concentration, as well as in Minnesota, Iowa, Illinois, and Michigan, represent the numerous gravel and sand pits located in glacial deposits
- a roughly aligned group of quarries along the fall line in Georgia and South Carolina at the boundary between the Piedmont and the coastal plain
- a string of change polygons that is roughly aligned along the route of the Erie Canal in central and western New York

Recognition of these differing regional patterns and features of topographic change from a small scale map of the conterminous United States underscores the value of conducting the inventory across the full expanse of the 48 contiguous states.

Types of Topographic Surface Changes from Human Activity

Direct anthropogenic processes create several types of landform modifications that remain as a distinct imprint on the topographic landscape. Provided below are

examples that have been detected in this project of the types of topographic surface changes resulting from the major human geomorphic activities.

Mining

According to the label assigned from the NLCD to each change polygon, mining is the predominant land use/land cover represented in the topographic change inventory (Table 4.2). This is not surprising, as surface mining operations have been previously identified by Hooke (1994; 1999) and Nir (1983) as the largest direct anthropogenic process in terms of the amount of material moved. Further evidence of the dominance of mining as the primary human geomorphic activity is seen in its contribution to the total volume of material moved as calculated from the entire topographic change dataset. The polygons labeled with mining as the majority land cover account for 57.5% of the total number of change polygons, but they contribute 74.9% of the total volume of material moved. It is likely that this contribution from mining is even higher, as many of the polygons included in the change mask because of their close proximity to mine locations (filter step 9 in Table 3.4) also are probably mines that were not yet in operation at the time of NLCD source data collection.

Some of the most notable examples of the topographic surface changes resulting from mining are seen in the Appalachian coalfields where mountaintop mining is a commonly used approach for coal extraction. Although the practice of mountaintop mining has been used since the 1970s, it continues to be controversial issue, with ample documentation both supporting and criticizing it (Gardner and Sainato, 2005; Fox, 1999). Regardless of the arguments for and against mountaintop mining, it is without dispute

that a significantly altered landscape is the result of the practice. Remote sensing and other geospatial data, including multi-temporal elevation data, have been used to successfully map and describe landform features associated with mountaintop mining (Shank, 2003; Shank, 2004). In mountaintop mining operations the ridges are removed to expose the coal seam, and the overburden from the excavation is deposited into the heads of adjacent valleys, graded, and stabilized. In terms of topographic change detection through DEM differencing, the area of ridge removal is indicated by a significant decrease in elevation, while the adjacent valley fills appear as areas of significantly increased elevation. In the context of movement of materials by geomorphic processes described by Hooke (1994) (Table 1.1), the mountaintop removal is the initiation of motion (erosion), the agent of motion (transportation) is the dragline excavator and truck, and the cessation of motion (deposition) is the valley fill.

Figure 4.4 shows a mountaintop mining area in Perry County in eastern Kentucky. In the middle panel, the blue areas represent significant elevation decreases (mountaintop removal), and the red areas represent significant elevation increases (valley fills). The spatial arrangement of the adjacent blue and red polygons (cuts and fills, respectively) separated by a thin area is the characteristic signature of mountaintop mining in the highly dissected topography of the central Appalachians. Clearly, the areas between the leveled ridges and filled valleys have also been disturbed, although the observed vertical differences in those areas were not large enough to exceed the significant change threshold bounds. This illustrates one of the limitations of using just elevation change to detect human geomorphic activity: the individual change polygons may not delineate the

entire disturbed area. Although the elevations between adjacent cut and fill polygons have not changed enough to be detected, mining has generally flattened the entire area, so the distribution of local slope and aspect values has been significantly altered.

The Landsat image (bottom panel) in Figure 4.4 illustrates an important aspect of topographic change due to mining in Appalachia. There is a corresponding change in land cover as the forest is removed prior to mining operations. Monitoring of the land cover trends in this region indicates that coal mining is the dominant driver of land cover change, especially forest conversion, in the years from 1973 to 2000 (Sayler, 2006). Analysis of the polygons included in the topographic change mask due to their close proximity to mine locations (filter step 9 in Table 3.4) shows that the majority (more than 54%) are labeled as forest according to the NLCD. Many of these polygons are likely located in the eastern United States coalfields because of the high density of mines in central Appalachia. In contrast, shrubland, agriculture, or grassland was identified as the majority land cover category for 16%, 14%, and 10%, respectively, of the polygons located within 500 meters of known mines. It is likely that many of these polygons are located near expanding mines in the western United States.

The Landsat image in the bottom panel of Figure 4.4 also includes a feature that illustrates an interesting issue associated with mountaintop mining, that of post-mining land use. Active mining operations coincide with many of the change polygons, although the image indicates that some of the disturbed area has already been reclaimed and revegetated. In the right central portion of the image an airport runway has been built on newly available flat ground that resulted from mining operations. Such post-mining

development has been touted as one of the advantages of mountaintop mining (National Research Council, 1981; Gardner and Sainato, 2005).

Road Construction

Road construction is one of the primary activities in which humans move large quantities of earth materials. The importance of road construction as a major anthropogenic process is evidenced by both Hooke (1994, 1999) and Nir (1983) using it as one of only a few factors to calculate the total human geomorphic impact on the environment. Brooks, Lachenbruch, and Wentworth (2002) demonstrate with a case study that the cuts and fills required to create flat ground for road and building construction have a geomorphic footprint that is twice the size of the flat area, assuming a 20% natural slope. At a 30% slope, the area that needs to be graded is three times the size of the desired flat area. Thus, even though a roadway may use only a relatively small area, in hilly terrain the geomorphic imprint can be several times larger.

Figure 4.5 shows a major road cut through a prominent ridge in western Maryland, Sideling Hill. The cut was made to accommodate the route for Interstate Highway 68. As measured from the SRTM – NED difference grid, the depth of the cut is 98 meters, and the volume of material removed is 3.52×10^6 cubic meters, which agrees to within 2.4% of the published volume of 3.44×10^6 cubic meters (Reger and Conkright, 2005).

Although it was not used systematically in this study, a distance-to-nearest-road dataset exists (Watts, 2005) that could be helpful to characterize topographic change polygons. The 30-meter resolution raster dataset indicates the straight line distance to the

nearest road for every location in the conterminous United States. Initially, it was thought that this dataset could be used to help label topographic change polygons as road cut or fill features by looking at the minimum distance-to-nearest-road value within a polygon. A minimum value of zero would indicate that a road crossed the polygon, and thus the feature may be due to new road construction. After viewing test areas of known road construction changes, it became clear that the roads dataset used as a basis for the distance calculations did not include many of the obvious new roads. Watts (2005) does point out the limitations of the inconsistent and older source data. Figure 4.6 shows an example of the distance-to-nearest-road dataset for the Chino Hills area in Orange County, California. Even though the national distance-to-nearest-road dataset was not used in this study to automatically label change polygons, it could be useful for interpretation of topographic changes over local areas.

Urban Development

The importance of urban development (including building construction and associated road construction) as a human geomorphic process has been recognized by Hooke (1994, 1999) and Nir (1983) in that each of them included it as a primary input for calculations of the total amount of material moved. The topographic change polygon dataset includes many features that are the result of earth moving operations for urban development.

The southern California counties of Orange, San Diego, and Los Angeles are the top ranked counties in terms of area of topographic change polygons labeled as urban/built-up according to the NLCD. Orange County, the top ranked county, contains

72 change polygons (Figure 4.7), most of which appear to be associated with new development. The detected change areas are located in the higher relief portions of the county where cuts or fills, or both, are required to reduce the terrain slope enough to allow for housing and commercial building construction. Figures 4.8 and 4.9 provide examples of where the cut and fill polygons associated with urban development are located on the landscape.

Dam Construction

Hydrologic interference is a primary direct anthropogenic process identified by Goudie (2000), and dam construction is one type of interference that usually has very obvious effects. Certainly, earth materials are moved during dam construction, but the larger impact is likely due to the inundation by the reservoir behind the dam. As described in Chapter 3, a special case of topographic change coinciding with flat areas in the SRTM data was extracted, and these areas can indicate a hydrologic alteration on the surface. Figure 4.10 shows an example of a large reservoir expansion that was detected by the elevation differencing and thresholding approach. This reservoir is Lake Pleasant, located northwest of Phoenix, Arizona, and is part of the Central Arizona Project, a large water supply system. A smaller reservoir existed as a result of a dam constructed on the Agua Fria River in the 1920s. In the early 1990s the U.S. Bureau of Reclamation constructed a much larger dam and the size of Lake Pleasant nearly tripled (U.S. Bureau of Reclamation, 2006). The volume calculated from the difference grid associated with the change polygon can be used to characterize the additional water supply resulting from the new dam construction and reservoir expansion. Given the calculated volume of 7.57

x 10^8 cubic meters, a current population of the Phoenix-Mesa-Scottsdale metropolitan area of 3.86 million people (U.S. Census Bureau, 2006), and a per capita daily water use of 218 gallons (City of Phoenix, 2005), the additional capacity stored in Lake Pleasant equates approximately to an eight month supply of water for the entire Phoenix metropolitan area.

Landfills

Topographic change due to landfill operations has been observed based on some of the features delineated by the elevation differencing and thresholding process. The resulting altered landforms from landfills differ from other anthropogenic activities in that much of the deposited material is not rock and soil that had been previously excavated, but rather it consists of man made material that has been transported to the deposition site. Figure 4.11 shows an example of topographic change due to landfill operations, in this case the Sunshine Canyon landfill in Sylmar, California. The operation and expansion of this landfill continues to be a controversial topic in the local area (Milloy, 2003; Environmental News Network, 2005; Greene, 2005). The close proximity of the landfill site to a major transportation artery is a reminder that visual impacts of human geomorphic activities can be significant, as Hooke (1994, 1999) pointed out.

National Results

A primary objective of this study is to map (locate and describe) the extent of recent human geomorphic activity, as indicated by significant changes to the land surface topography. Hooke (1999) was the first to quantify spatially the effects of human

geomorphic activity over the United States, although it was done at a very coarse spatial resolution of 1x1-degree cells (Figure 1.1). The inventory of topographic changes completed for this study includes features mapped to the nominal 30-meter resolution of the input multi-temporal elevation datasets. Consequently, spatially explicit change maps have been produced, and statistics have been accumulated for a number of different accounting and reporting units, some broad (states and ecoregions) and some small (quadrangle base maps).

Maps of the location of the individual change polygons are useful for presenting and describing the overall nature of 20th century human geomorphic activity across the conterminous United States. In addition, accumulating summary statistics within various accounting and reporting units helps describe the density of topographic change areas within subdivisions of the landscape with which researchers and resource managers are familiar.

States

The spatial distribution of the topographic change polygons across the states is shown in Figure 4.1. Some noteworthy patterns seen on the map are: a dense concentration of polygons in eastern Kentucky and southern West Virginia; a distinct cluster of polygons in northern Minnesota; several larger groups of polygons in Wyoming and southern Arizona; a concentration of polygons in the highly urbanized areas of coastal southern California; and an overall higher density of polygons in the eastern United States. Change polygons are located in all states except Rhode Island and the District of Columbia. Appendix 1 includes a complete listing of the states containing

change polygons, with the number and total area of the polygons and the total volume of displaced material given for each state. Table 4.3 lists the top ranked 15 states in a number of categories. Considering the numerical positions in all six categories in Table 4.3 collectively, the top ranked states affected by topographic change are, in order:

1. Minnesota
2. Arizona
3. Nevada
4. Wyoming
5. Kentucky
6. Pennsylvania
7. California
8. Michigan
9. New Mexico
10. West Virginia

Counties

Because so many other statistics and phenomena are reported and mapped on a county basis, they are a useful accounting unit with which to view the occurrences of topographic change. The counties that contain topographic change polygons are shown in Figure 4.12. A total of 1,170 counties contain change polygons, which represents 37.6% of the counties in the conterminous United States. It is interesting to note that there are some states in which nearly all the counties are included. This is especially true in the west, where the counties tend to be much larger. Appendix 2 lists the top ranked counties according to the total area of topographic change within the county.

Ecoregions

Ecoregions have been developed and are being used to study the place dependency of environmental processes, including anthropogenic transformations of the land surface (Marston, 2006). Ecoregions are also the basis for reporting on the status

and trends of land cover and land cover change (Loveland *et al.*, 2002; Loveland and Acevedo, 2006). As a geographic framework that is useful for studying the response of the environment to human activities, ecoregions form a useful basis on which to view the distribution of topographic changes across the United States. Figure 4.13 shows the level three ecoregions (Omernik, 1987; U.S. Environmental Protection Agency, 2003) that contain topographic change polygons. Appendix 3 lists the top ranked ecoregions according to the total area of topographic change within the ecoregion.

Consideration of the top two ecoregions in terms of the number of change polygons, the Central Appalachians and the Northern Lakes and Forests, provides an interesting view into the differences between regions in the character of topographic changes. The number of topographic change polygons and their total area for the Central Appalachians ecoregion is 1,195 polygons and 84.36 square kilometers, respectively. For the Northern Lakes and Forests ecoregion, the numbers are 427 polygons and 159.48 square kilometers. Note that the Central Appalachians ecoregion has almost three times the number of change polygons as the Northern Lakes and Forests ecoregion, but those polygons cover only about half as much area. Conversely, the Northern Lakes and Forests ecoregion only has about a third of the change polygons that the Central Appalachians ecoregion has, but those polygons cover twice as much area. Consequently, even though the topographic change polygons cover less area in the Central Appalachians ecoregion, their greater number and spatial arrangement likely result in more landscape fragmentation than in the Northern Lakes and Forests ecoregion. This relationship between the number of change polygons and their total area likely has

important implications for habitat fragmentation, a key indicator of ecological condition (Jones *et al.*, 1997). The sum of many smaller landscape changes can have a large cumulative effect, perhaps even more than the effect of a small number of very large change areas. Thus, when comparing the cumulative effects of topographic changes among different regions, it can be useful to consider the number of polygons to total area relationship. However other regional conditions must also be considered to determine if that relationship is a reliable indicator of landscape impacts.

Watersheds

Because they are a natural partitioning of the land surface, watersheds have been used extensively to study and report on environmental conditions. As such, they provide another useful way to view and present the extent of topographic changes. The connectivity of watersheds may be an important condition when assessing the impacts of land surface transformations. For instance, an important consideration might involve determining which watersheds are immediately downstream of the watersheds that contain topographic change polygons. Figure 4.14 shows the watersheds in the conterminous United States that contain topographic change polygons. In this case, the watersheds are the hydrologic cataloging units defined by Seaber, Kapinos, and Knapp (1987), which are widely used in water resources studies. These watersheds are commonly referred to as 8-digit cataloging units because of the unique code assigned to each unit. The 8-digit cataloging units have the detail, accuracy, and information content equivalent to a 1:250,000-scale topographic map. The average size of the 8-digit units is slightly less than 4,000 square kilometers. Note that not all the cataloging units are

watersheds according to the strict definition, as some units have an administrative or political boundary rather than a drainage divide. Appendix 4 lists the top ranked watersheds according to the total area of topographic change within the watershed.

Managed Areas

A delineation of managed areas (federal, state, tribal, and military lands) from the USGS National Atlas (U.S. Geological Survey, 2006) was overlaid on the topographic change inventory. Approximately 11% of the change polygons fall within the general boundaries of the managed areas (Figure 4.15). Presumably, some of these change polygons are on the private land holdings that are encompassed by the general extent of the managed areas. Appendix 5 lists the managed areas that are either intersected by or are in very close proximity to topographic change polygons. The list includes the top ranked managed areas according to the total area of topographic change contained within them.

Quadrangle Base Maps

Many resource managers and geospatial data users are familiar with the USGS 7.5-minute quadrangle map series. Also, much of the geospatial data managed by the USGS was originally produced in tiles corresponding to the 7.5-minute maps. The topographic map quadrangles are still commonly used as base maps for outlining data collection strategies and defining project boundaries. Thus, it is useful to characterize the extent of the topographic change inventory in term of the footprints of the 7.5-minute map series. Figure 4.16 shows the 7.5-minute quadrangles within the conterminous

United States that contain topographic change polygons. Appendix 6 lists the top ranked quadrangles according to the percentage of the map that is covered by change polygons.

1x1-Degree Tiles

Summary statistics were also accumulated on the basis of the 1x1-degree tiles used for data management and processing. A total of 500 tiles contain topographic change polygons (Figure 4.17), which represents over 53% of the conterminous United States tiles. Summarizing on a 1x1-degree tile basis facilitated a qualitative comparison with Hooke's (1999) initial spatial characterization of human geomorphic activity in the conterminous United States (Figure 4.18). The source data, assumptions, and methods used for Hooke's results versus those used for this study are quite different; however, some similarities in the graphics in Figure 4.18 do exist. The peak representing Appalachian coal mining is apparent in each map. Perhaps more interesting than any similarities, are the differences between the maps, which directly reflect the disparate source data and processing approaches. Hooke's data for mining included only coal, stone, sand, and gravel, whereas the topographic changes detected in this study include all types of mining, especially iron in the Upper Midwest, Powder River Basin coal, and copper and gold in the west. Thus, the prominent peaks are located in the north and the west on the map from this study, and they don't appear to have a direct counterpart in Hooke's map. Some of the differences are also likely related to temporal factors such as the relatively recent growth in western coal mining that may not be reflected in Hooke's source data. Also, one of Hooke's primary inputs was the amount of material moved through the indirect anthropogenic process of agriculture, which was not a consideration

for this study. Thus, relatively high peaks are seen in the Midwest on Hooke's map, which is contrasted with the mostly featureless middle portion of the map from this study. Also, it is important to note that the fundamental unit, and consequently the vertical scale, plotted for each map are different, with Hooke using the amount of material moved annually and this study using the total volume of material moved. Hence, the comparison is only qualitative. Nevertheless, this type of generalized map is helpful for visualizing the magnitude and distribution of human geomorphic activities.

Ranking Features Based on Magnitude of Change

Each of the polygons in the topographic change inventory has numerous attributes associated with it (as described in Chapter 3). These attributes allow a ranking of features based on the magnitude of change, as measured by polygon descriptors (area and volume) and changes in terrain parameters (elevation, relief, slope, aspect). The ability to do such a ranking points out one of the advantages of producing spatially explicit change maps from geospatial data over broad areas: the effects of changes at specific locations can be quantified. The examples given below are the largest changes as defined by several attributes. The existence of these topographic change features is well documented (Richason, 1972; Francaviglia, 1991; Francaviglia, 1992) and they are likely well known to communities in their vicinity, so their delineation is not new information. What is new information, perhaps, is their ranking compared to other similar features across the United States. Viewing of these examples is also useful for learning about the performance and results of the topographic change detection process developed and applied in this study.

Figures 4.19 through 4.26 present the individual topographic change polygons that are top ranked in terms of one or more parameters. Not surprisingly, each of these features is associated with large surface mining operations. It is clear that some of the features in these figures represent an expansion of the mining activity that was already evident when the source data for the NED were collected (Figures 4.19, 4.20, 4.22, 4.24, and 4.25). In these cases, the changes in elevation resulting from continued earth moving were enough to be detected as significant surface transformations, even when the area was already in a disturbed condition. Three of the example areas appear to have no evidence of surface modification in the NED data (Figures 4.21, 4.23, and 4.26), thus the mining was initiated some time after the date of the NED source material. The date of the NED source material refers to the date of the information (quadrangle map or aerial photography) from which the USGS 7.5-minute DEM was derived.

By assigning quantitative attributes to individual change features based on the elevation and difference datasets, comparisons can be made with other well known features. The alteration to Mount St. Helens as a result of its 1980 eruption is often cited as an example of topographic change, in this case, a catastrophic natural transformation. After the eruption, the USGS constructed a new DEM, and thus when paired with the DEM representing pre-eruption conditions, the value of multi-temporal elevation data was recognized. The individual feature mapped in this study with the greatest volume change is the Bingham Canyon copper mine in Utah, with a volume of 1.25×10^9 cubic meters (Figure 4.19). Although this amount is more than twice the volume of the second ranked feature (the cut at the Rodeo Creek, Nevada gold mine, Figure 4.21), the volume

of material removed from Mount St. Helens (2.83 x 10^9 cubic meters) (Brantley and Myers, 2000) is nearly 2.3 times greater than the volume removed at Bingham Canyon. Geomorphic events with a magnitude like that of Mount St. Helens are rare, at least within a human lifetime, thus they attain much notoriety. As such, they are often used to give context to other similar phenomena. The total volume of 4.33 x 10^{10} cubic meters calculated in this study equates to more than 15 times the volume moved in the Mount St. Helens eruption. As a side note, even though the largest man made geomorphic feature (Bingham Canyon mine) detected in this study equates to less than half of the amount of material moved in the 1980 Mount St. Helens eruption, it is interesting to note that it contributes nearly 3% of the total volume of materials moved as calculated in this study. This is quite significant, given the fact that the Bingham Canyon mine is just one of 5,263 features in the topographic change inventory. In his analysis of anthropogenic processes, Wilkinson (2005) also recognized the usefulness of relative comparisons with natural geomorphic features and events when he stated that (p. 163):

> current annual amounts of rock and soil moved over Earth's surface in response to construction and agricultural practices are ~18,000 times that of the 1883 Krakatoa eruption in Indonesia, ~500 times the volume of the Bishop Tuff in California, and about 2 times the volume of Mount Fuji in Japan. At these rates, this amount of material would fill the Grand Canyon in ~50 yr.

Such comparisons are helpful for giving context to the magnitude of human geomorphic activity, and they may be most effective for capturing interest in the subject from the non-scientific readership.

Quantification of the Effects of Topographic Changes

The terrain parameters measured for each feature in the topographic change inventory are useful for describing the surface modifications at the specific locations of the polygons. However, in many cases the individual change polygons are members of a larger set that collectively represent a surface disturbance distributed over an area greater than that of any of the individual polygons. These groups of change polygons produce cumulative effects on the environment, and quantification of the effects of the changes must consider the numerous polygons together. The effects of changes over areas more broad than the scale of individual polygons are quantified below.

Hydrologic Effects

Because the shape of the land exerts strong control over the collection and flow of surface water, changes to the topography can have a significant effect on local drainage conditions. Figure 4.27 demonstrates how the local surface drainage features have been altered as a result of mining operations. Standard hydrologic analysis tools were used to delineate watersheds and flow paths (stream channels) from the NED and SRTM data for four adjacent watersheds covering a mountaintop mine area in Perry County in eastern Kentucky. Note how the removal of the local drainage divides and the filling of local stream valleys have significantly altered the surface hydrology of the four watersheds draining the disturbed area. Some upslope areas have changed watersheds and now drain through a different stream network than in the original condition. In mountaintop mining, the valley fills are placed in the heads of hollows, which are the first order drainage basins (Phillips, 2004). When the ridge tops that form the drainage divides

between these headwater basins are removed, the result is altered drainage patterns as seen in Figure 4.27. Figure 4.28 shows another example area where the topographic changes classified as cuts coincide with the local drainage divides. The basins and stream lines are from the USGS Elevation Derivatives for National Applications (EDNA) dataset (Verdin, 2000; Franken, 2004), which was derived from the NED. The basins outlined in yellow are the EDNA reach catchments, with a nominal drainage area of 4.5 square kilometers. The effects of surface coal mining on local hydrologic conditions have been widely studied, including the impacts on base flow (Bonta *et al.*, 1997), peak and storm flows (Bryan and Hewlett, 1981; Phillips, 2004), and stream bed geomorphology (Wiley *et al.*, 2001). Thus, the topographic change inventory can be useful for indicating locations where these hydrologic processes may be affected.

Of particular concern in mountaintop mining areas is the length of streams affected by the valley fills. Starting in 1999, the U.S. Environmental Protection Agency conducted an extensive series of studies of mountaintop mining in preparation for an environmental impact statement (EIS) (U.S. Environmental Protection Agency, 2005). The draft EIS was released in 2003, followed by a public comment period, and the final EIS was released in late 2005. The EIS reports that approximately 1,930 kilometers of headwater streams (2% of the streams in the study area) were directly impacted by mining between 1992 and 2002. Also, an estimated 1,165 kilometers of streams (1.2% of the streams in the study area) were buried by valley fills from 1985 to 2001. A comparison of the topographic change polygons with a hydrography dataset can be useful for describing the impacts of land surface alterations. Such a comparison was done by

overlaying the change polygons derived in this study with the EDNA streams layer. The first order EDNA streams are delineated based on a drainage area of at least 4.5 square kilometers. A total of over two million unique stream reaches are contained in the EDNA stream network over the conterminous United States. Figure 4.29 shows an example of the streams contained within the topographic change polygons for an area in Perry County in eastern Kentucky. As expected for this region, the streams fall within the areas depicted as valley fills. Table 4.4 presents the summary statistics for the number and total length of streams contained within topographic change polygons in the conterminous United States. Note that nearly three quarters of the polygons of positive topographic change (fills) contain stream segments, whereas less than a third of the negative topographic change polygons (cuts) contain streams.

Visual Impacts

When contrasting the general nature of anthropogenic processes versus other geomorphic agents, Hooke (1994) concluded that the visual impact of human activity generally is greater than that of natural processes. He summarized by saying that (p. 225):

> Most geomorphic processes move sediment in a predictable direction, and the ultimate driving force is gravity. Humans, however, move soil or rock hither and yon, often in defiance of gravity, and governed by no apparent physical rules. Consequently, the visual impact of human geomorphic activity is vastly greater than that of most traditional geomorphic agents such as, for example, a river redistributing a similar amount of sediment in a floodplain or depositing it below sea level in a delta.

Hooke (1999) chose to quantitatively compare human activity with other geomorphic agents on the basis of the mass of material moved per unit time, but he also suggested that (p. 688):

> An alternative might be to consider the visual impact of a geomorphic process. Here, humans excel. We immediately notice when earth is moved for a new building or a highway cut, but it normally takes detailed measurements to detect an equivalent amount of mass transfer by a traditional geomorphic agent. Visual impacts, however are difficult to quantify.

Goudie (2002) also recognized the importance of the visual aspect of the environment when he states that (p. 245) "the main stimulus to an interest in geomorphology is an interest in visually appealing landscapes." While Goudie was referring to the beauty of natural landforms, the appearance of an anthropogenic landscape can also draw much attention, if for no other reason than to view or study the stark contrast to nearby unaltered natural features.

With the ability to detect specific areas of topographic surface change from multi-temporal elevation datasets, 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. Perspective views derived from pre- and post-event elevation data are a simple qualitative method of presenting the visual effects of a vertical land transformation (Figure 4.30). 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 a specific location, or stated conversely, the areas on the landscape from which a specific location can be seen. For assessing the effects of a topographic

surface change, 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 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. The examples presented below demonstrate how the visual impacts of human geomorphic activities detected with multi-temporal geospatial data can be quantitatively assessed.

Figure 4.31 shows the viewshed for the Sideling Hill road cut in western Maryland (see also Figure 4.5 and Figure 4.30). For computational efficiency, the viewshed was limited to a radius of 12.5 kilometers from a point at the centroid of the topographic change polygon, with the point having been assigned the maximum SRTM elevation within the polygon. It has been shown that using representative terrain points for viewshed calculation greatly reduces computation time without any significant reduction in visibility information (Rana, 2003). The planimetric area of the cut itself is relatively small at 0.08 square kilometers, but because of its location on a very prominent topographic feature in the area the cut can be seen from many locations over long distances. One way to characterize the magnitude of an individual topographic change feature (cut or fill) is to compare its planimetric area to the volume of displaced material. Such a comparison will indicate the relative shallowness or steepness of the vertical land

transformation. The volume-to-area ratio for the Sideling Hill road cut is 43.22, which is slightly higher than the average ratio of 29.73 for all features in the topographic change inventory. A more useful metric may be the viewshed-area-to-change-area ratio, especially for quantifying and comparing the visual impacts of specific topographic change features. The viewshed-area-to-change-area ratio for the Sideling Hill road cut is 1242.0, which indicates that the viewshed is very large relative to the area of the topographic change polygon. Figures 4.32 and 4.33 show the viewsheds for two features that have approximately the same planimetric area and volume as the Sideling Hill road cut. Note that in each case the viewshed-area-to-change-area ratio is much less than the ratio for the Maryland road cut.

Figure 4.34 compares the Maryland road cut to three other features in terms of their viewsheds. These three features are the largest mines by area in each of the following ecoregions: Northern Lakes and Forests (upper right on Figure 4.33), Wyoming Basin (lower left), and Northwestern Great Plains (lower right). In each case, the area and volume of the mine greatly exceed that of the road cut, but the viewshed is smaller for the mine. Also, the viewshed-area-to-change-area ratios for the three mines are roughly the same, but each is significantly less than the ratio value for the road cut. This illustrates the usefulness of the ratio to quantify and compare the visual impacts of individual topographic change features. Table 4.5 lists further information for the topographic change features shown in Figures 4.31 through 4.34. Note that the volume-to-area ratio provides little, if any, discrimination among the features, whereas the

viewshed-area-to-change-area ratio clearly distinguishes the variable visual impact of the change features.

Figure 4.35 illustrates how the combined viewsheds of a group of topographic change features can be used to assess the visual impacts over a larger area. Webster County, West Virginia contains 24 topographic change polygons for total of 1.95 square kilometers (0.14% of the county). The combined viewsheds for these 24 features cover 118.71 square kilometers, which is more than 60 times the area of the change polygons. Most, but not all, of the combined viewshed area falls within the county, with 98.93 square kilometers covered (6.84% of the county) that represent an area more than 50 times the area of the change polygons. The remainder of the combined viewshed area falls into an adjacent county, which is an example of the concept of externality that is important in land use planning (Platt, 1996). A viewshed of any topographic change feature could be considered to be an expression of externality, but in this case the effects actually fall into a neighboring jurisdiction.

Regional Differences in the Effects of Surface Mining

Because the topographic change inventory has near national coverage, comparisons can be made among broad regions. Figure 4.36 shows a set of five level three ecoregions that were used as a basis for regional comparisons of topographic change. Specifically, the cumulative effects of surface mining were compared across the following ecoregions: Central Basin and Range, Wyoming Basin, Northwestern Great Plains, Northern Lakes and Forests, and Central Appalachians. These five ecoregions were selected because they contain significant numbers of mining sites, and collectively

they represent a wide variety of the types of surface mining in the United States. Examples of mining for precious metals are found in the Central Basin and Range; mining typical of the western U.S. coalfields is found in the Wyoming Basin and Northwestern Great Plains; open pit iron ore mining is prevalent in the Northern Lakes and Forests; and mountaintop and contour mining for coal is concentrated in the Central Appalachians. The subset of topographic change polygons labeled according to the NLCD as quarries/strip mines/gravel pits was extracted for each of the five ecoregions and treated as a separate dataset. As documented earlier, surface mining is the primary direct anthropogenic process responsible for significant topographic changes, so it is useful to further examine its overall effects on the landscape.

As a result of viewing the topographic change polygon dataset overlaid on the NED and SRTM data, it was recognized that the expressions of landscape transformations due to surface mining differed across the study area. In particular, the physical shape of mined lands differed markedly between the western U.S. and Appalachian coalfields. Of course, some of the contrast is due to the difference in the type of natural landforms present before mining began, but the basic terrain parameters of elevation and relief changed in different ways for the two regions. Figure 4.37 shows a scatterplot of change in mean elevation versus change in relief for the mining polygons in the Northwestern Great Plains, which contain the major coal producing Powder River basin, and the Central Appalachians, which contain the mountaintop coal mining areas in eastern Kentucky and southern West Virginia. The scatterplot shows fairly distinct clusters of points indicating that the changes in elevation and relief conditions due to

mining are different for the two regions. In general, relief is decreased by mountaintop mining in Appalachia as the there is an overall flattening of the landscape. Ridges are leveled and adjacent valleys are filled to approximately the same level. In contrast, in the western coalfields where the natural relief is lower, the surface mining generally increases relief as pits are excavated and overburden is deposited on adjacent land. The differing character of relief changes as noted in the plot supports the observed conditions (Figure 3.5 and Figure 4.38). Another contrast between these two ecoregions in terms of the effects of surface coal mining is the potential for further surface modifications. In the mountaintop mining areas the land cannot be returned to its original shape as part of the reclamation process, whereas in the western U.S. coalfields there is a much greater potential for the land to be returned to its pre-mining form.

Figures 4.39, 4.40, and 4.41 compare changes in mean elevation, relief, and mean slope, respectively, for mining polygons in the five focus ecoregions. Changes in mean elevation follow a similar pattern for all five ecoregions. However, for changes in relief and mean slope, the Central Appalachians ecoregion stands alone compared to the other four ecoregions. Changes in relief and mean slope are negative, which is the opposite of the other four ecoregions. This is especially true for changes in mean slope (Figure 4.41) where the mining polygons in the Central Appalachians show an overall decrease in slope at least twice the magnitude of the increase seen for the other ecoregions. These significant decreases in relief and slope for the Central Appalachians reflect the general leveling of the land surface in mountaintop mining areas. Such leveling stands in contrast to increased relief and slope for surface mining areas in other regions.

As described above in the section on hydrologic effects, surface mining operations can have significant effects on streams. To compare the coincidence of streams and topographic change areas across ecoregions, the change polygons were intersected with the EDNA national stream network. A specific interest here was to determine if there was a difference between cuts and fills in terms of their locations relative to streams. Figure 4.42 shows the total length of streams covered by change polygons for each of the five focus ecoregions. The fill polygons in the Central Basin and Range and Northern Lakes and Forest ecoregions impact the most total stream length, with each exceeding 120 kilometers of affected streams. Figure 4.43 compares the proportions of affected total stream length covered by cuts and fills for each ecoregion. Note that once again the Central Appalachians ecoregion stands in contrast to the other four ecoregions. Nearly 100% of the streams affected by topographic changes fall within fill polygons, as illustrated in Figure 4.29. It is likely than many of the occurrences are at locations of valley fills, one of the primary environmental issues associated with mountaintop mining.

Proximity of Topographic Change Areas to Other Features

The near national extent of the topographic change dataset also allows for spatial comparisons, such as proximity of change polygons to roads and urban areas. Such comparisons have been done for the proximity of mines to roads and major cities for the five focus ecoregions. Figure 4.44 shows the locations of the centroids of mining polygons within the five ecoregions and the locations of cities with a population of greater than 100,000 from the 2000 census. Figure 4.45 compares the summary statistics

of the distance from mines to the nearest major city (by ecoregion). Note that the mines within the Northwestern Great Plains ecoregions are the farthest removed from major urban centers. The minimum distance from mines to the nearest road was calculated by intersecting the mining polygons with the national distance-to-nearest-road dataset (Watts, 2005). Figure 4.46 shows the summary statistics for the distance calculations (by ecoregion). Note that on average the mining polygons are farthest from the road network in the Northern Lakes and Forests ecoregion. This may imply a less dense road network in the vicinity of the mines. Distance from mines to roads may also become important as mining areas are expanded. More road construction may be required as mining is expanded in regions that currently have a greater overall distance from mines to roads.

Comparison with Land Cover Status and Trends Data

The topographic changes detected in this study usually have a corresponding land cover change. To examine this relationship more closely, features in the topographic change inventory were compared with data from an ongoing study of the status and trends of land cover in the United States (Loveland *et al.*, 2002; Loveland and Acevedo, 2006). The status and trends project uses a sampling based approach in which land cover maps and change products are produced for five dates for 10x10-kilometer sample blocks to derive regional land cover statistics. A total of 2,693 sample blocks are distributed throughout the level three ecoregions, which provide the spatial framework for the project. The Central Appalachians ecoregion, which contains the most topographic change polygons of any ecoregion (see Appendix 3), was selected for detailed comparison with the land cover trends data. Figure 4.47 shows the 13 sample blocks that

contain 61 individual topographic change polygons, which sum to an area just less than 6 square kilometers. These change polygons were intersected with the land cover maps and change maps for each of the sample blocks. Figures 4.48 and 4.49 show an example of the multi-date land cover maps for one of the sample blocks.

The most recent land cover map for each sample block is from either 1999 or 2000. As recorded on those land cover maps, 86% of the area covered by topographic change polygons is mapped as the mining land cover class, 13% of the area as the grassland/shrubland class, and 1% as the forest land cover class. In looking at land cover change from 1990 to 2000 over the topographic change polygons within the sample blocks, the following is noted: the land cover changed from forest to mining for 58% of the area, 12% of the area changed from mining to grassland, and 26% remained as mining. An example of the forest to mining conversion is seen in the Landsat image in Figure 4.4. The mining to grassland conversion likely represents post-mining revegetation associated with reclamation, an example of which can be seen in the foreground of the perspective view in Figure 4.49. Another metric reported in the land cover trends data is the number of land cover changes that have occurred over a given location between the years 1973 to 2000. For the area covered by topographic change features, 74% of the total experienced one land cover change (most likely forest to mining or mining to grassland), 16% had two land cover changes (most likely forest to mining to grassland), and 4% had three changes. While the coincident area of topographic change polygons and land cover trends maps is limited, the observed land cover characteristics within the polygons support the observation that in this ecoregion

specific land cover changes appear to be highly correlated with topographic changes. Specifically, mining is the predominant land cover class associated with the change polygons according to the latest land cover maps, and the majority of the area experiencing topographic change had a shift in land cover from forest to mining between 1990 and 2000. These observations are supported by the land cover trends project report for this ecoregion, which concludes that most of the land cover changes in this region are related to coal mining (Sayler, 2006).

It could be useful to extend the comparison of topographic change features with the land cover trends data. However, outside of the Central Appalachian ecoregion there is little overlap among the change polygons and the sample blocks. A total of 138 sample blocks contain topographic change polygons, which is approximately 5% of all the sample blocks. These 138 blocks contain 275 topographic change polygons, which represents slightly more than 5% of the total number of polygons in the inventory. It should not be surprising that few change polygons intersect the sample blocks. Even though there are more than 5,000 polygons distributed throughout the study area, topographic changes are scarce on the landscape as their total area is less than 0.02% of the area of the conterminous United States. Also, the trends sampling scheme was designed to capture land cover variability across broad areas, so there is no direct reason why many topographic change areas would be included. For these reasons, the lack of coincidence between the mapped topographic change features from this study and the land cover trends data probably precludes derivation of reliable national statistics on the correspondence of topographic and land cover change. However, the analysis

summarized above for the Central Appalachians ecoregion shows that there is useful information in comparing topographic change and land cover change. Perhaps the best use of topographic change information is to aid in interpreting land cover changes in local settings. In this case, the SRTM – NED difference grids could be thresholded with care to ensure that all topographic change features of interest are included before the subsequent comparison with land cover maps.

Error Sources, Uncertainty, Limitations, and Uses

In a study such as this one, with diverse input datasets that cover a broad area, data characteristics and quality can have spatially varying effects on derived information. As discussed in Chapter 3 in the context of data processing methods, unique characteristics of both the NED and SRTM data had to be accounted for in the processing approach in order to reduce errors of commission. While it is desirable to have a final topographic change inventory that is inclusive of all significant surface alterations, to do so while also having no false changes included would require an extraordinary manual clean up process. Thus, the decision in the data processing approach was to err on the side of omission, resulting in a conservative accounting of topographic change across the conterminous United States. Even so, the final change inventory dataset is undoubtedly not without errors, and these errors contribute uncertainty to the information. This uncertainty, in combination with innate characteristics of the input datasets, leads to limitations of the information about topographic change in the United States. The sources of error and uncertainty, and the known limitations of the change inventory, are

cited below so that users of the topographic change dataset and any derived information are aware of the associated caveats.

As with any thematic dataset, it would be advantageous to have detailed information about the accuracy of the delineation of topographic change features across the United States. Unfortunately, there is no readily available reference dataset with which to compare the inventory to generate accuracy statistics. Reference data would have to be specifically generated through manual interpretation of remote sensing data for a sample of locations, as has been done for accuracy assessment of land cover maps. In lieu of such an approach, which is outside the scope of this study, the best that can be done currently to describe the uncertainty of the inventory data is to identify the known conditions that contribute to it.

As discussed earlier in Chapter 3, there are inherent properties of the primary input elevation datasets that lead to less than perfect results when they are processed to detect significant topographic changes. The first return nature of SRTM elevation measurements and the production artifacts in the NED and SRTM data can lead to false detections of topographic change. Artifact, in this sense, is any characteristic of the elevation data that does not reflect an actual topographic feature on the ground. The residual errors in coregistration of the NED and SRTM data can also lead to apparent vertical changes, but in reality are only due to misalignment of the elevation datasets. The filtering steps (Table 3.4) that are applied after the differencing/thresholding operation effectively remove many problem areas, but the process is not perfect.

A primary contributor of uncertainty is the reliability of the land cover data, the NLCD, that are used extensively in this study. Land cover information is used as a fundamental input for the accuracy assessment and the subsequent calculation and application of the significant elevation difference thresholds. Land cover data are also used to assign a label to each elevation change polygon, and this label is used not only in the filtering process, but also in the accumulation of summary statistics. The NLCD certainly is not 100% accurate, so any misclassification errors can be transferred to the change inventory. This thematic error propagation can be manifest in several forms: first, in mislabeling of reference control points, which affects the calculation of land cover based vertical accuracy thresholds for the difference grids; and second, in mislabeling locations on the difference grid during thresholding, which results in the wrong threshold being applied and features being either included or excluded incorrectly from the change mask.

The thematic accuracy of NLCD has been assessed (Stehman *et al.*, 2003; Wickham *et al.*, 2004), and the results vary across the ten regions in the conterminous United States used for NLCD production. Generally, the classification is less accurate for the more detailed Anderson level two classes (Anderson *et al.*, 1976) employed by the NLCD (Figure 2.4), but improves markedly when classes are combined into Anderson level one designations. The overall accuracy for the ten regions at Anderson level two ranges from 38% to 70%, and the range improves to 70% to 85% at Anderson level one. Such an improvement in overall accuracy by going to more general land cover classes is common with land cover maps derived from remote sensing data. The improved overall

accuracy at Anderson level one is important because one of the first filter steps (step 3 in Table 3.4) applied to candidate elevation change polygons considers the general land cover of the polygon. Some of the filter steps (steps 7-9 in Table 3.4) use the NLCD Anderson level two classes that have a lesser accuracy. For instance, the NLCD mining class is important for labeling and filtering topographic change polygons, but the user's accuracy (Story and Congalton, 1986) ranges from only 22% to 67%. Some potential errors in the change inventory due to the use of this mining class that has a lower accuracy are probably avoided by the final filter step (step 10 in Table 3.4), which removes polygons in close proximity to mines if they do not meet the criteria for significant changes in basic terrain parameters. While viewing the results of the elevation differencing and thresholding operations, the match of significant elevation differences and the NLCD mining class appeared to be quite reliable. This general relationship suggests a use of vertical differences from multi-temporal elevation data as ancillary data for improving the delineation of surface mining areas in future land cover mapping efforts.

Another source of uncertainty lies in the land cover based accuracy thresholds used to extract areas of significant elevation change. As described above, the NLCD thematic accuracy is variable, so it is reasonable to accept that some of the reference control points had incorrect land cover labels because of the inherent error in the NLCD. Also, although the reference control points are located throughout the conterminous United States, they likely are not completely representative of the full range of terrain conditions (elevation, relief, slope, aspect). High elevations, high relief, and steep slopes

are probably underrepresented in the control point dataset. This would not be surprising, as the origin of the dataset is surveyed points collected for mapping and geodetic projects. Points in high elevation, high relief, and steep slope areas are not often included in ground surveys because of the difficulty in accessing such sites. Thus, the combination of the spatially variable thematic error in NLCD and the incomplete representation of the full variety in terrain conditions in the reference control points leads to less than perfect land cover based accuracy thresholds. Consequently, application of the thresholds may allow some areas of elevation differences to incorrectly pass the criteria test, for example areas of dense coniferous forest in the mountains of the Pacific Northwest. Many such areas would subsequently have been eliminated by the filtering process, although that process was not perfect either so a few errors of commission likely remain the topographic change dataset.

The dates of the source data for the primary input datasets contribute uncertainty to the overall results of the topographic change inventory and analysis. Specifically, the dates among the NED, SRTM data, and NLCD are inconsistent. The NED source dates (from the quadrangle based DEMs) are highly variable and range from 1931 to 1999, with the average source date being 1966. The NLCD is derived from Landsat data with a nominal source date of 1992, although dates from the early to mid-1990s were used. The SRTM dataset has the most consistent source date, with all the radar data having been collected within 11 days in early 2000. The variability in source dates leads to inconsistent matches of land cover labels and topographic changes. For instance, most topographic changes due to mountaintop mining in eastern Kentucky have an associated

land cover transformation (deforestation). Because of the nominal 10-year difference in source dates for the NLCD and SRTM data, locations that had mining initiated after the date of the NLCD source Landsat data do not show the corresponding change in land cover. The finer time intervals used in the land cover status and trends project do capture more of the mining related land cover transformations, although such changes are only mapped over sample block areas. As mentioned in Chapter 2, the use of the new version of NLCD based nominally on 2001 Landsat data would have provided a useful match between the SRTM data and land cover information, but the incomplete status of the NLCD precluded use of it for this study.

The presence of several large data voids in the SRTM coverage of the conterminous United States (Figure 2.2) potentially contribute a slight bias to national summary statistics of topographic changes. These voids occur where interferometric radar data were not collected. Even though 99.96% of the targeted landmass was mapped by SRTM (Kobrick, 2006), a small shortage in the availability of instrument duty cycle hours during the duration of the mission meant that some areas could not be covered. As a primary objective of the mission was collection of data for a near-global DEM, the decision was made to deliberately have these areas that could not be mapped fall over United States territory where equivalent high quality data were already available (M. Kobrick, personal communication). Note the following void areas on Figure 2.2: northern Florida/southern Georgia, North Carolina-South Carolina border, Rhode Island-Massachusetts border, central Iowa, northern Nevada, northern Arizona, and far western Texas. Collectively, these areas sum to 40,600 square kilometers, which represents

0.52% of the conterminous United States land area. The ecoregions that these void areas are contained within are: Southern Coastal Plain, Middle Atlantic Coastal Plain, Southeastern Plains, Northeastern Coastal Zone, Western Corn Belt Plains, Northern Basin and Range, Arizona/New Mexico Plateau, and Chihuahuan Deserts. These SRTM void areas affect the topographic change inventory in two ways: due to the non-existence of SRTM data, no SRTM – NED differencing, thresholding, and filtering operations were done for these areas, thus there is no delineation of topographic change areas; and, the summary totals for any accounting and reporting units that include these areas are potentially slightly biased towards lower totals because the change detection could not be done for the complete units.

The use of only two dates of elevation data, and the lack of consistent source dates in the NED, means that the topographic change inventory is limited to binary change detection (change/no change). A significant elevation difference indicates that a topographic change has taken place sometime between the date of the NED source data and 2000. From the data available, there is no way of determining when the change was initiated or completed, so it is not possible to determine annual rates of change. There are far fewer choices for the dates of available multi-temporal elevation data than there are for multi-temporal remote sensing images for change detection studies. Multiple time slices of elevation data at a fine interval would be required to accurately determine topographic change rates, similar to the methods used by the land cover trends project to present land cover change rates for the eastern United States (Loveland and Acevedo, 2006).

As is often the case for an analysis done with geospatial data over a broad area, the topographic change inventory completed in this study can be used to target areas where more detailed analysis is warranted. Concentrations of change polygons point out regions where human geomorphic processes are active. For example, a concentration of topographic changes related to expanding urban development appears in coastal southern California. Also, a dense concentration of change polygons occurs in the central Appalachians that are subject to surface coal mining operations. Locations like these could be studied in more detail by using recent high resolution elevation data. Also, even the existing SRTM – NED difference grids could be reprocessed with thresholds and filters tailored to local or regional conditions so that a more complete delineation of disturbed areas can made (compared to the delineation from the more restrictive thresholds used for the national study). Given the extensive set of attributes for each polygon in the change inventory, the features could be categorized into subsets for further analysis. For instance, the features could be grouped into categories based on levels of relative confidence in the correctness of topographic change detection. In this example, polygons that are labeled as mining from the NLCD and have all four critical terrain parameters (elevation, slope, relief, aspect) that exceed significant change limits could be listed as “highly probable” changes, whereas polygons with land cover subject to uncertainty from the first return nature of SRTM data (forest and urban/built-up classes) could be listed as “possible” changes. Such a categorization of changes has been previously used for effective presentation of topographic changes (Chirico and Epstein, 2000).

An immediate, practical use of the topographic change inventory is to inform the USGS mapping program where updates are needed for basic topographic information of the United States. The National Map (Kelmelis *et al.*, 2003) provides the basic topographic map information layers for the nation, and the NED serves as the elevation foundation. As this study has shown, there have been some significant topographic changes within the United States, and these areas should be targeted for map updates so that the USGS National Map meets its goal of having the most up-to-date geospatial information for the nation. Figure 4.16 shows the USGS 7.5-minute quadrangle maps that contain topographic change polygons. These quadrangles are the ones that are candidates for updated topographic mapping. In fact, a number of these areas have already been updated with the high resolution, high accuracy data that have recently been integrated into the NED (Gesch, 2006). One of the most active regions in terms of topographic changes is the mountaintop mining area in central Appalachia where many of the anthropogenic transformations are due to mining expansion in the 1990s (Sayler, 2006). Fortunately for National Map users, the NED covering the West Virginia portion of central Appalachia has recently been updated with high quality elevation data derived from photogrammetric data collected in 2003.

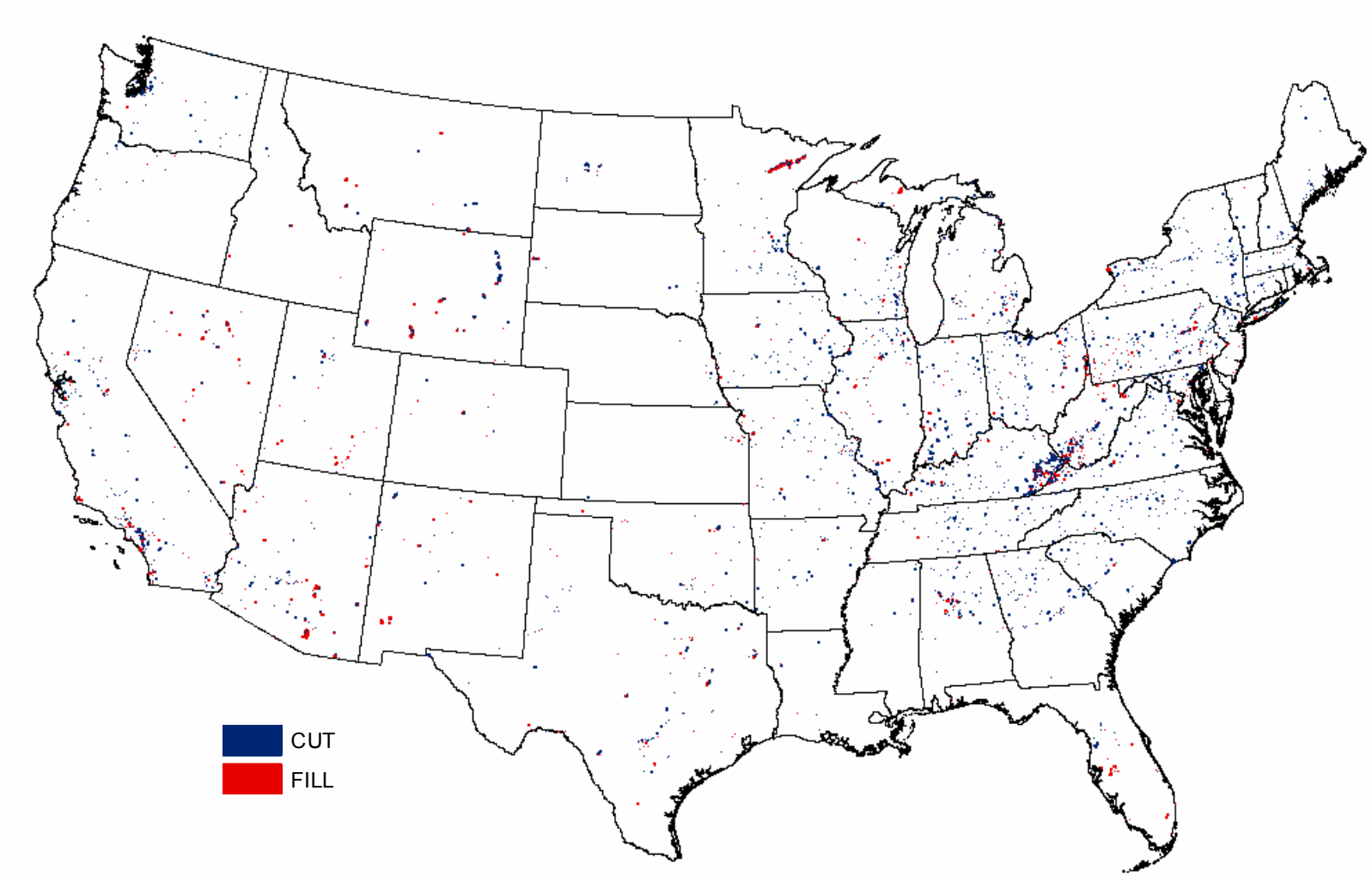


Figure 4.1. Map of the 5,263 polygons that delineate areas of significant topographic change in the conterminous United States. Cut areas are those polygons that have a decrease in elevation, while fill areas are those with an increase in elevation.

Statistic	Area (km^2)	Volume of material moved (m^3)	Change in mean elevation (m)	Change in relief (m)	Change in mean slope (degrees)	Change in median aspect (degrees)
All polygons (5,263):						
Minimum	0.03	222,373	-177.28	-157.44	-31.11	0.00
Maximum	9.79	1,253,487,744	105.94	263.74	33.24	180.00
Mean	0.20	8,209,268	-8.52	4.22	-0.30	41.72
Standard Deviation	0.51	33,238,306	31.77	21.26	7.47	38.50
Total	1,078.70	43,344,935,639				
Cut polygons (3,553):						
Minimum	0.03	222,373	-177.28	-157.44	-22.13	0.00
Maximum	8.75	1,253,487,744	-1.62	263.74	33.24	180.00
Mean	0.19	7,852,257	-28.36	4.68	0.27	42.26
Standard Deviation	0.50	36,069,226	13.51	24.53	7.77	38.35
Total	690.49	27,961,888,735				
Fill polygons (1,710):						
Minimum	0.03	510,646	5.53	-111.27	-31.11	0.00
Maximum	9.79	515,593,088	105.94	73.52	27.77	179.00
Mean	0.23	8,948,835	32.57	3.25	-1.47	40.60
Standard Deviation	0.52	26,420,579	14.80	11.84	6.67	38.81
Total	388.20	15,383,046,905				

Table 4.1. Summary statistics for polygons in the inventory of topographic changes in the conterminous United States.

Land cover category	NLCD class(es)	Number of polygons	Percent of total
Mining	Quarries/strip mines/gravel pits	3012	57.2
Forest	Deciduous forest	760	14.4
	Evergreen forest		
	Mixed forest		
Agriculture	Pasture/hay	656	12.5
	Row crops		
	Small grains		
	Fallow		
Shrubland	Shrubland	272	5.2
Urban	Low intensity residential	260	4.9
	High intensity residential		
	Commercial/industrial/transportation		
Grassland	Grasslands/herbaceous	132	2.5
Wetland	Woody wetlands	16	0.3
	Emergent herbaceous wetlands		
Other	Remaining NLCD classes	155	2.9

Table 4.2. Change polygons categorized by majority land cover class.

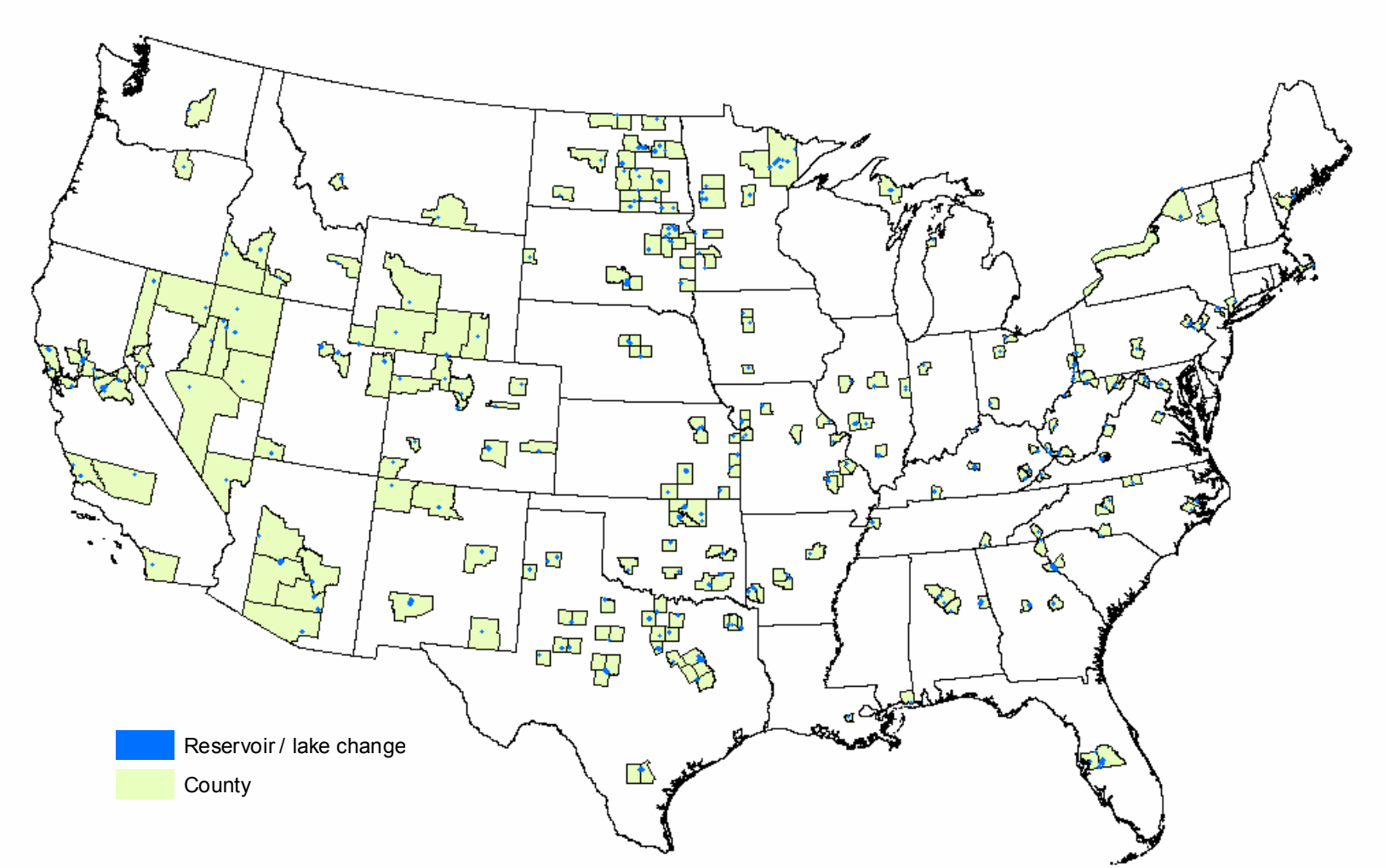


Figure 4.2. Counties containing change polygons representing new or expanded water bodies. In some cases, the features are associated with mining operations.

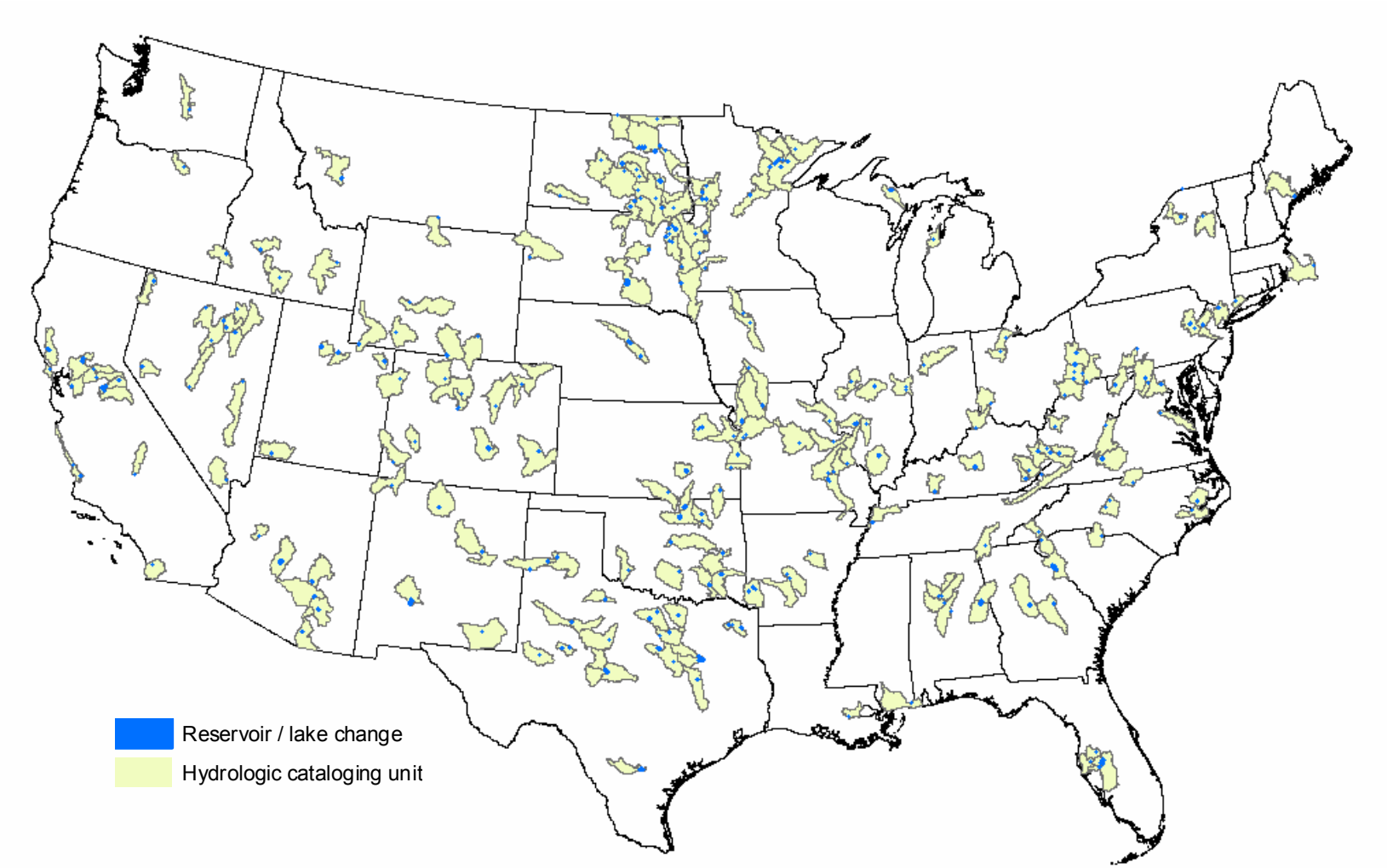


Figure 4.3. Watersheds (hydrologic cataloging units) containing change polygons representing new or expanded water bodies.

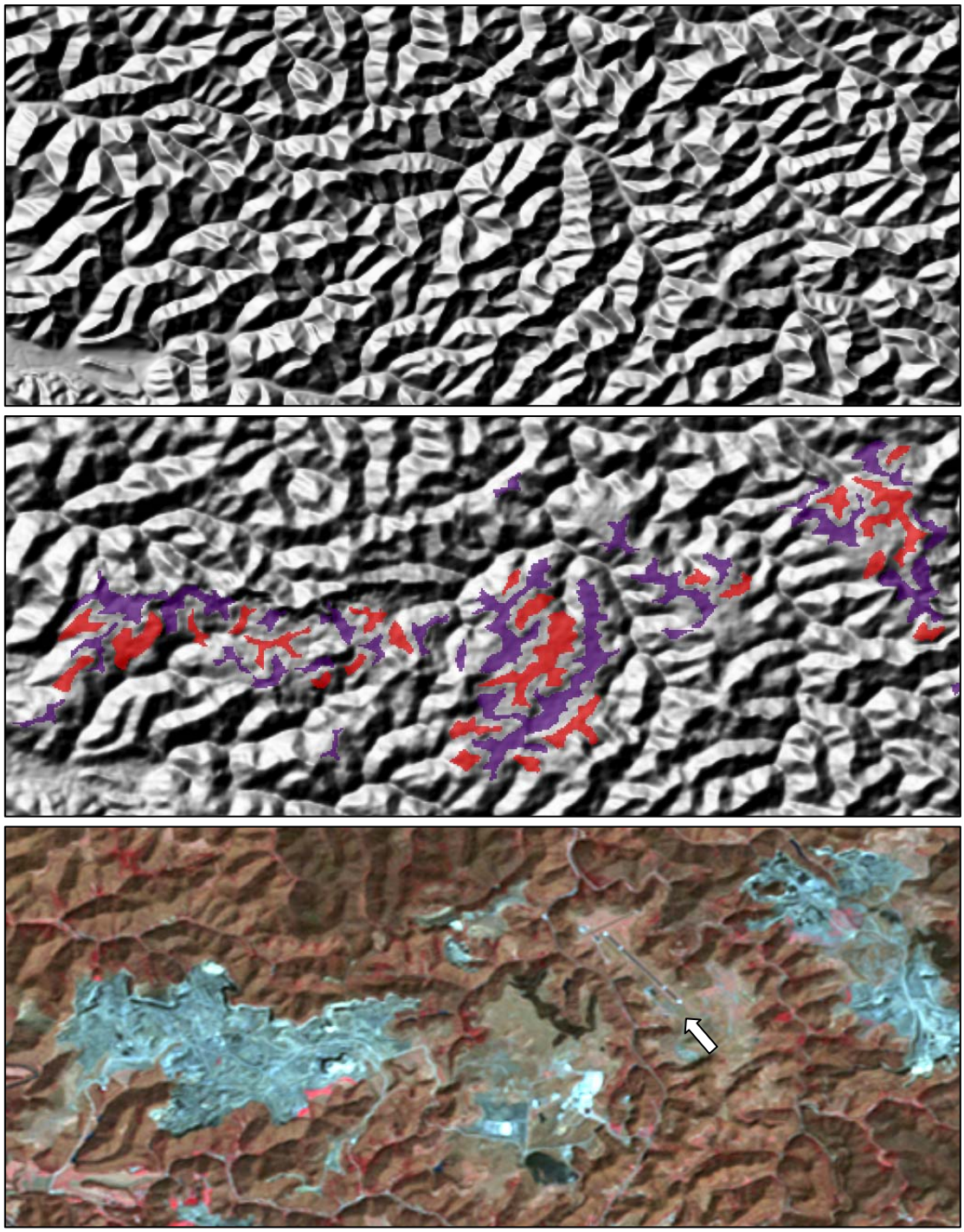


Figure 4.4. Example of topographic change caused by mining in Perry County, Kentucky. Images are: NED shaded relief (top), cuts (blue) and fills (red) overlaid on SRTM shaded relief (middle), Landsat image (color infrared rendition). The arrow points to an airport built on new flat land created by the mining process. The area shown is approximately 12.5 km east-west by 6.5 km north-south.

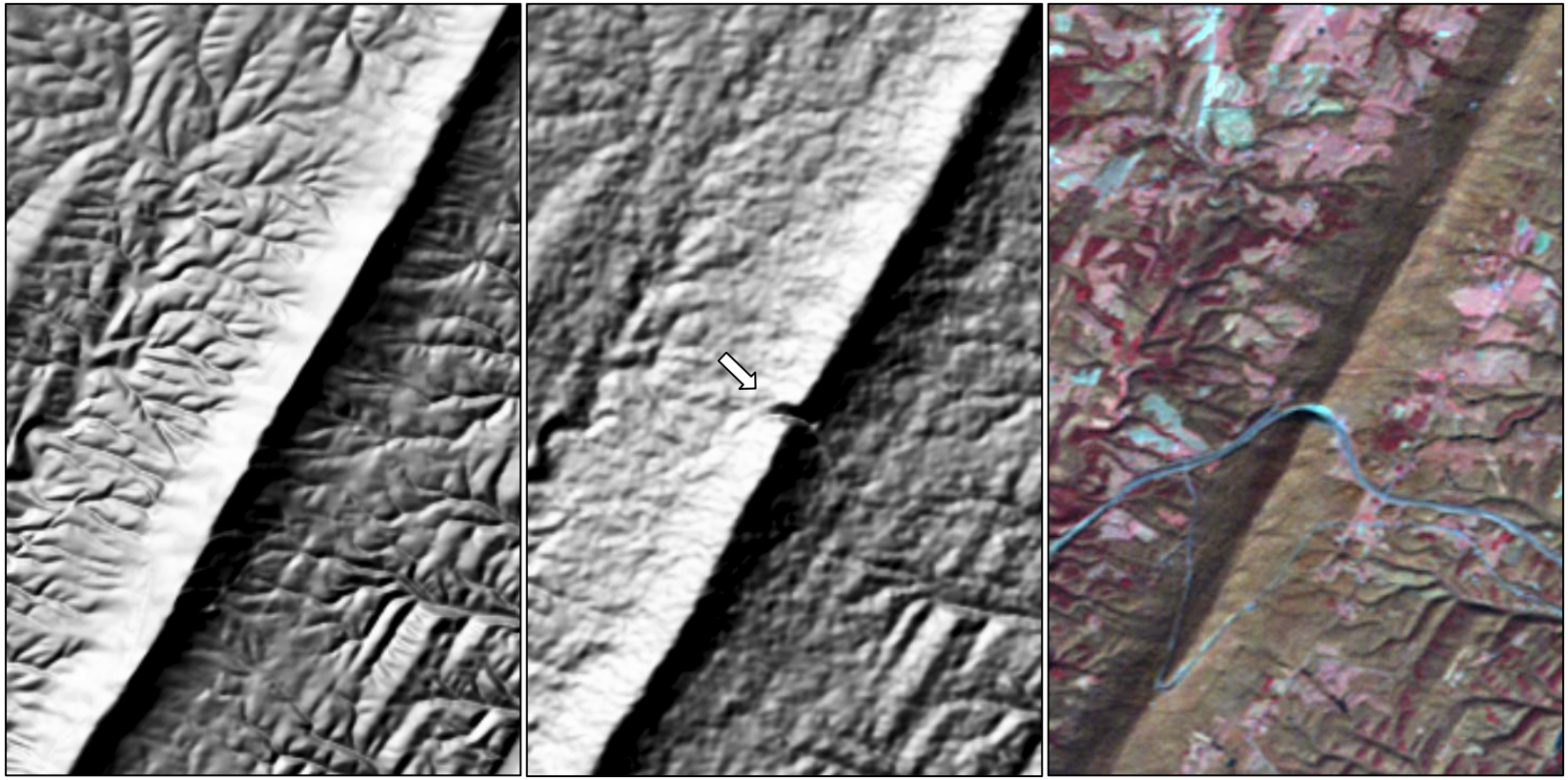


Figure 4.5. Example of topographic change resulting from road construction in western Maryland. Images are (from left to right): NED shaded relief, SRTM shaded relief, Landsat image (color infrared rendition). This road cut through a prominent ridge, Sideling Hill, was made to accommodate Interstate Highway 68. The area shown is approximately 5.0 km east-west by 9.5 km north-south.

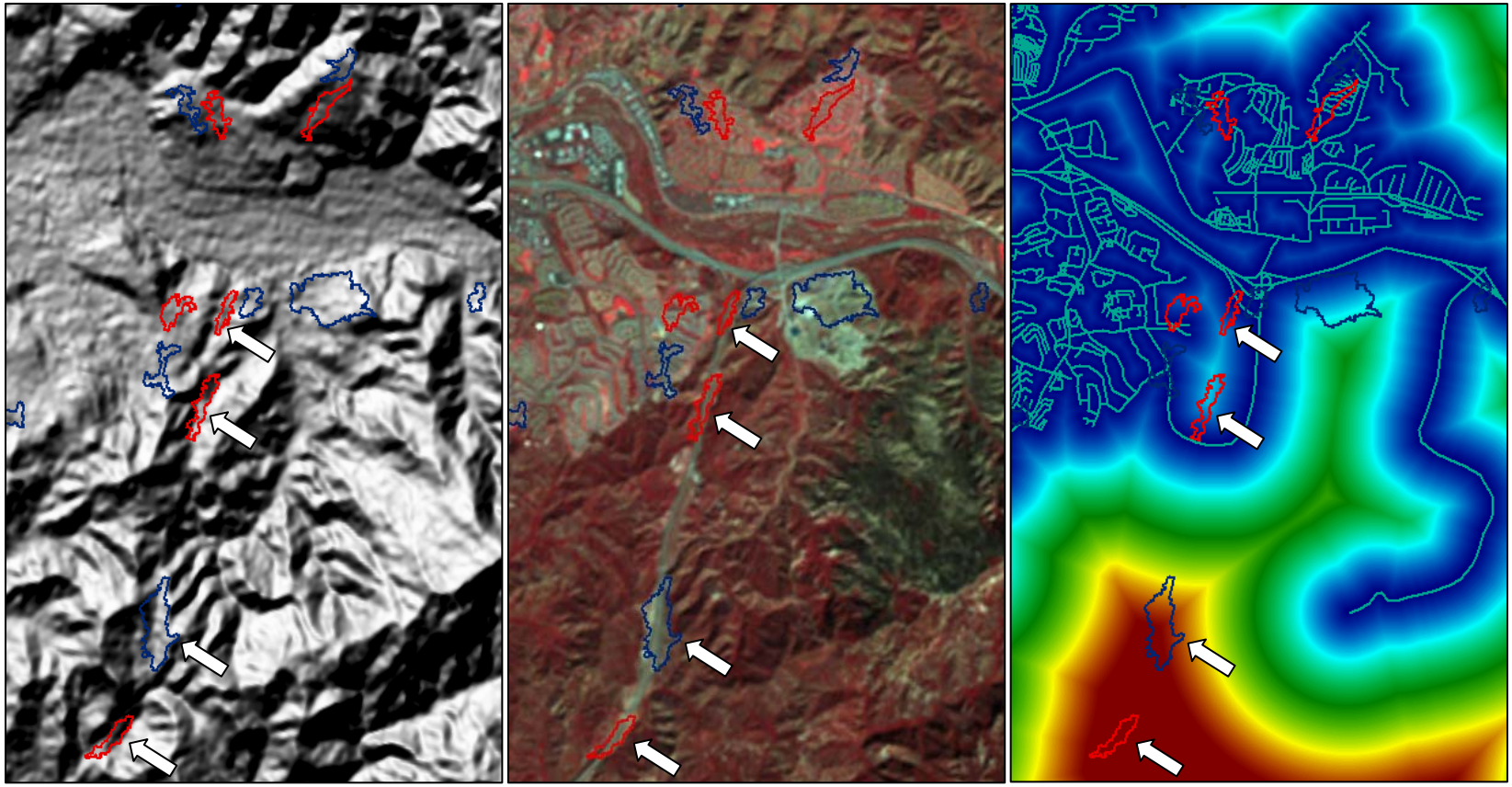


Figure 4.6. Example of distance-to-nearest-road dataset for the Chino Hills area in Orange County, California. Images are (from left to right): SRTM shaded relief, Landsat image (color infrared rendition), distance-to-nearest-road dataset and road network (dark blue = zero meters to nearest road; red = ≥ 2130 meters to nearest road). Topographic change polygons (blue = cut; red = fill) are overlaid on each image. The arrows indicate cut and fill associated with construction of a new major highway. Note that the new highway is not included in the source data used to calculate distance-to-nearest-road.

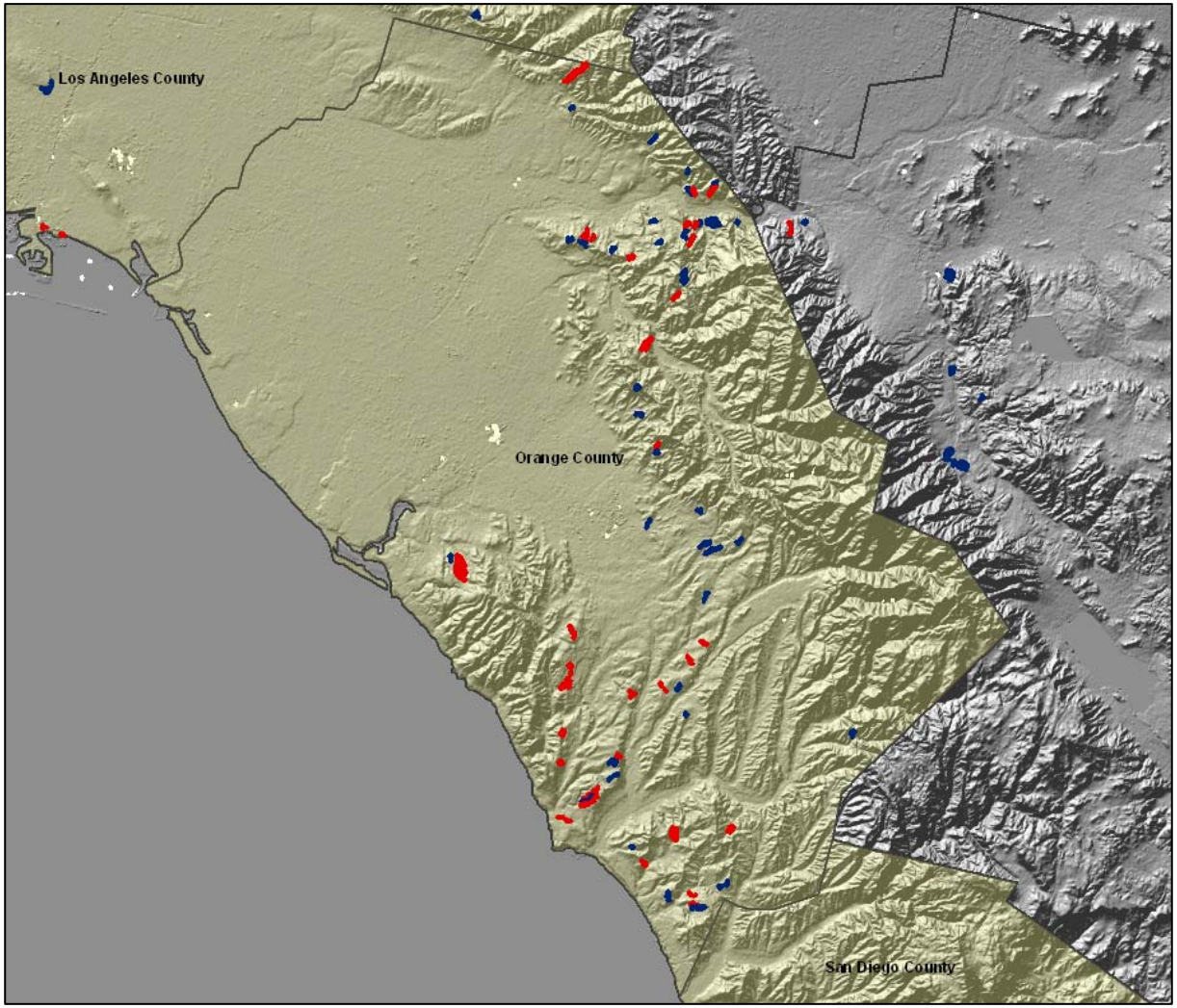


Figure 4.7. Orange County, California is the top ranked county for topographic change related to urban development. Change polygons (blue = cut; red = fill) are overlaid on SRTM shaded relief.

Figure 4.8. Topographic changes resulting from urban development in the Chino Hills area in Orange County, California (blue = cut; red = fill). The inset image (SRTM shaded relief overlaid with change polygons) provides locational reference. The arrow indicates the view direction (towards the east) for the larger perspective view. The area shown in the inset is approximately 11.6 km east-west by 10.7 km north-south.

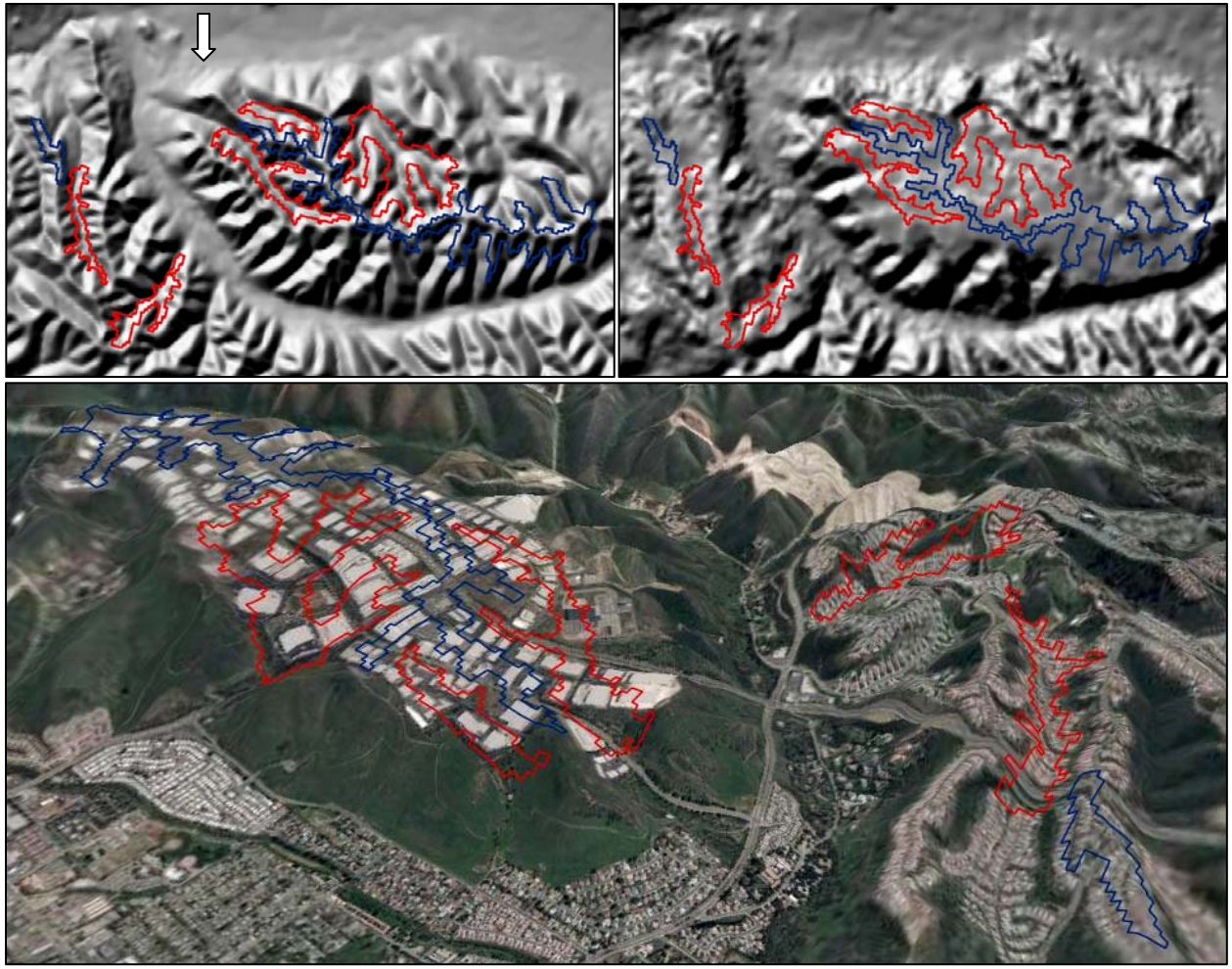


Figure 4.9. Topographic surface changes resulting from urban development in Poway, California (San Diego County) (blue = cut; red = fill). Upper left image is NED shaded relief and upper right image is SRTM shaded relief (both overlaid with change polygons). The arrow indicates the view direction (towards the south) for the larger perspective view. The area shown is approximately 5.9 km east-west by 3.5 km north-south.

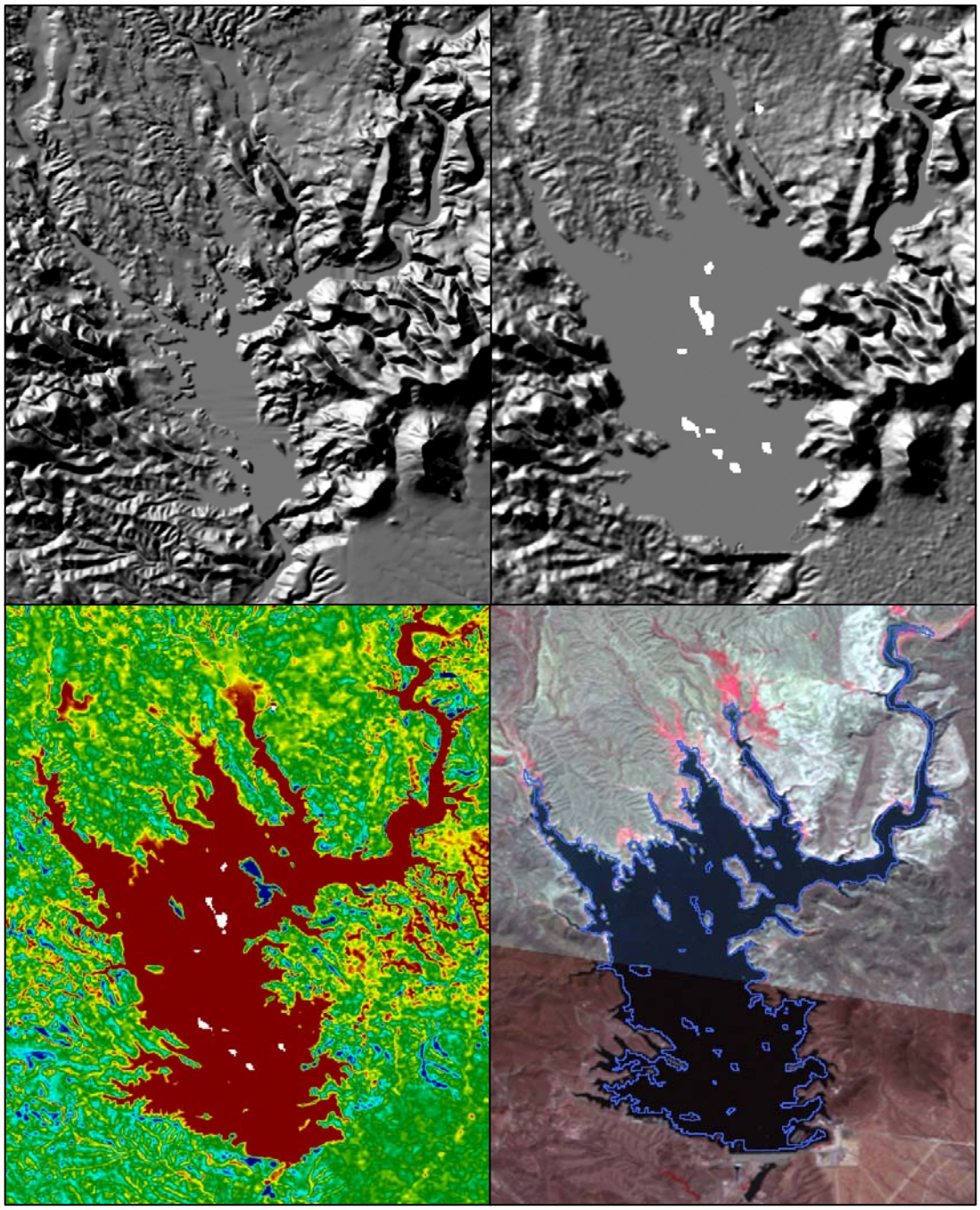


Figure 4.10. Topographic surface change resulting from dam construction (Lake Pleasant near Phoenix, Arizona). Images are: NED shaded relief (upper left), SRTM shaded relief (upper right), SRTM – NED difference grid (lower left) (blue = significant elevation decrease; red = significant elevation increase), Landsat image (lower right) overlaid with change polygon extracted from SRTM – NED difference grid. Note that the polygon aligns closely with the water as depicted on the Landsat image. The area shown is approximately 9.3 km east-west by 13.9 km north-south.

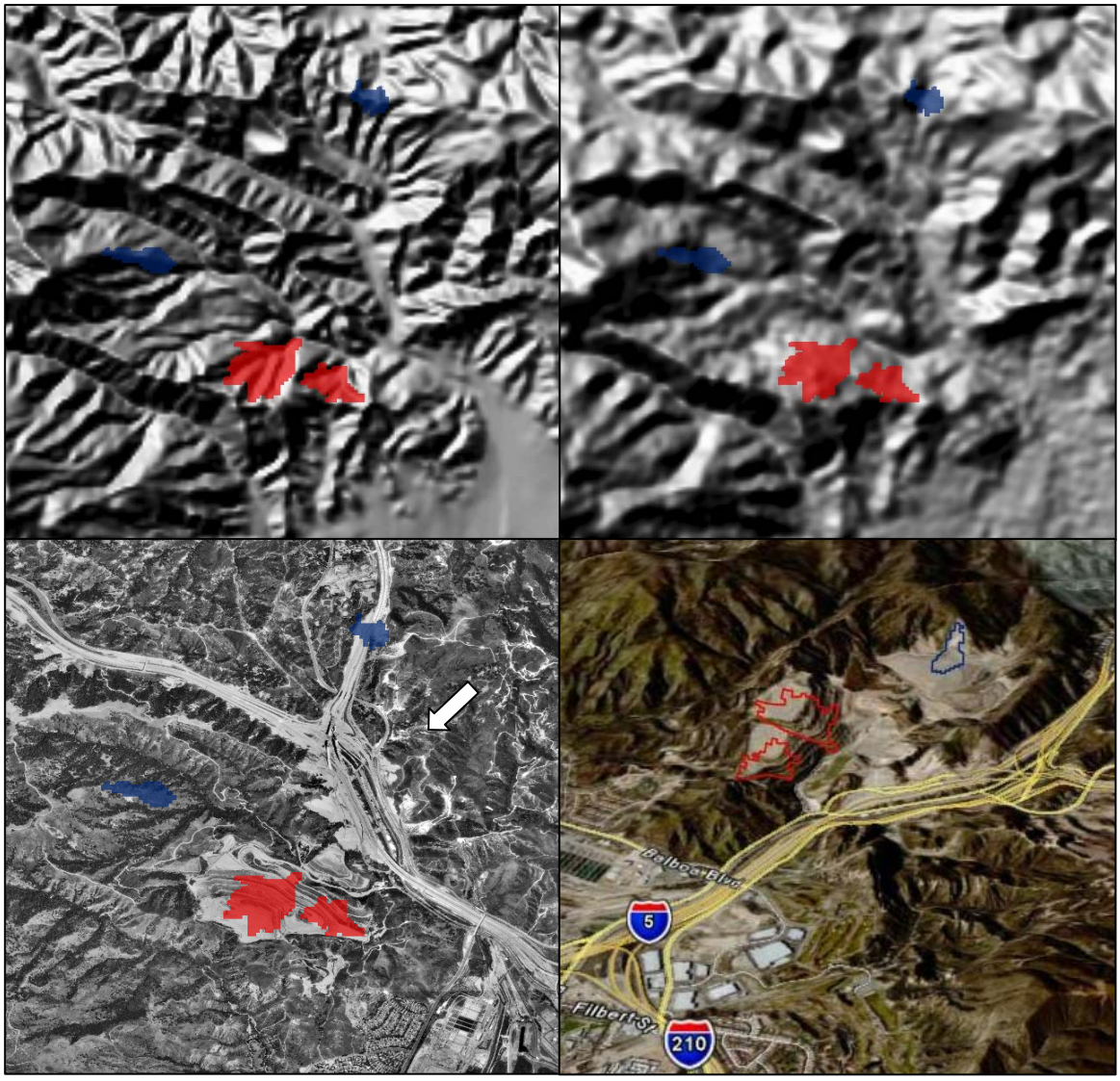


Figure 4.11. Topographic surface change resulting from landfill operation (Sunshine Canyon landfill in Sylmar, California). Images are: NED shaded relief (upper left), SRTM shaded relief (upper right), aerial photograph (lower left), perspective view (lower right). Change polygons (blue = cut; red = fill) have been overlaid on each image. The arrow indicates the view direction (towards the southwest) for the perspective view.

Rank	Number of topographic change polygons	Total area of change polygons	Total volume of change polygons	Total area of mining polygons	Total volume of mining polygons	Total area of urban polygons
1	KY	MN	AZ	MN	AZ	CA
2	MN	AZ	NV	AZ	MN	NY
3	WV	WY	MN	NV	NV	PA
4	WY	NV	WY	WY	UT	TX
5	PA	KY	KY	NM	MI	NV
6	AZ	MI	UT	MI	NM	OK
7	CA	NM	MI	KY	KY	IL
8	OH	CA	CA	PA	WY	WA
9	NY	WV	NM	UT	MT	OH
10	VA	PA	WV	MT	PA	VA
11	IL	TX	MT	OH	WV	MA
12	AL	OH	PA	WV	CA	TN
13	MI	UT	VA	TX	VA	MN
14	NM	MT	OH	FL	ID	IA
15	NV	IL	TX	NY	OH	WI

Table 4.3. The top ranked states in terms of several categories of topographic change.

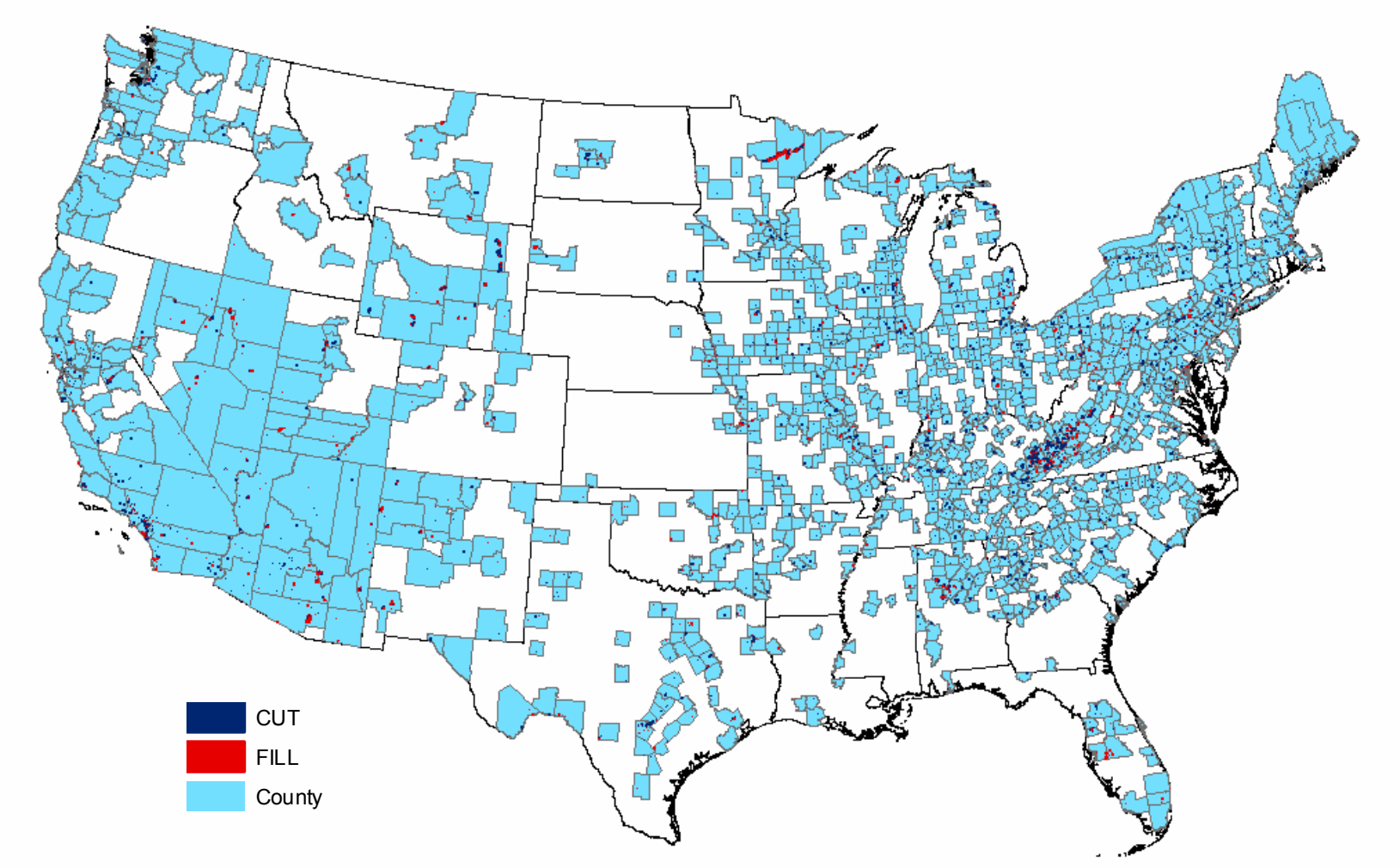


Figure 4.12. Counties containing topographic change polygons. A total of 1,170 counties are represented, which is 37.6% of the counties in the conterminous United States.

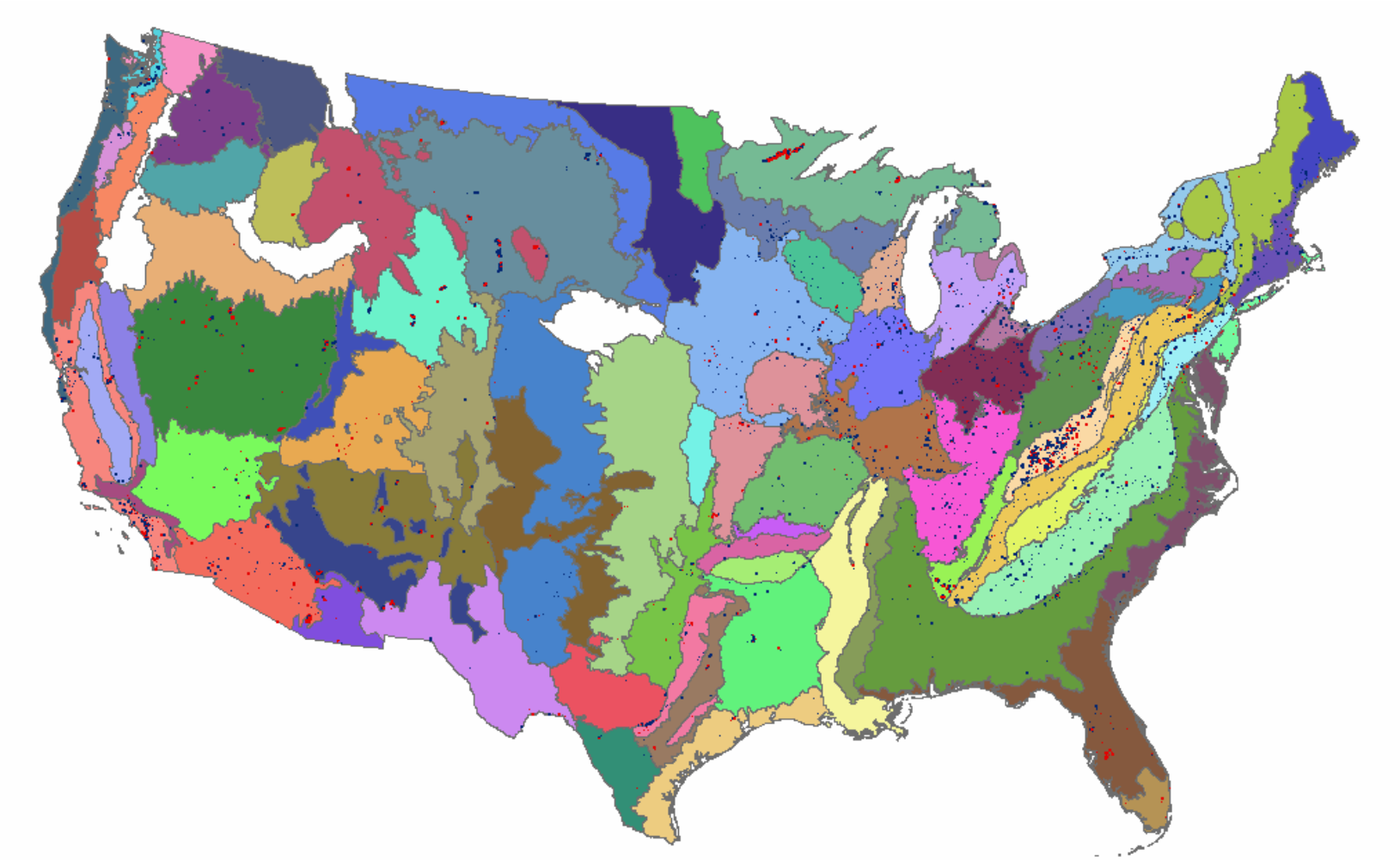


Figure 4.13. Level III ecoregions containing topographic change polygons. Change polygons are contained in 79 out of 84 ecoregions in the conterminous United States. See Appendix 3 for a list of the ecoregion names.

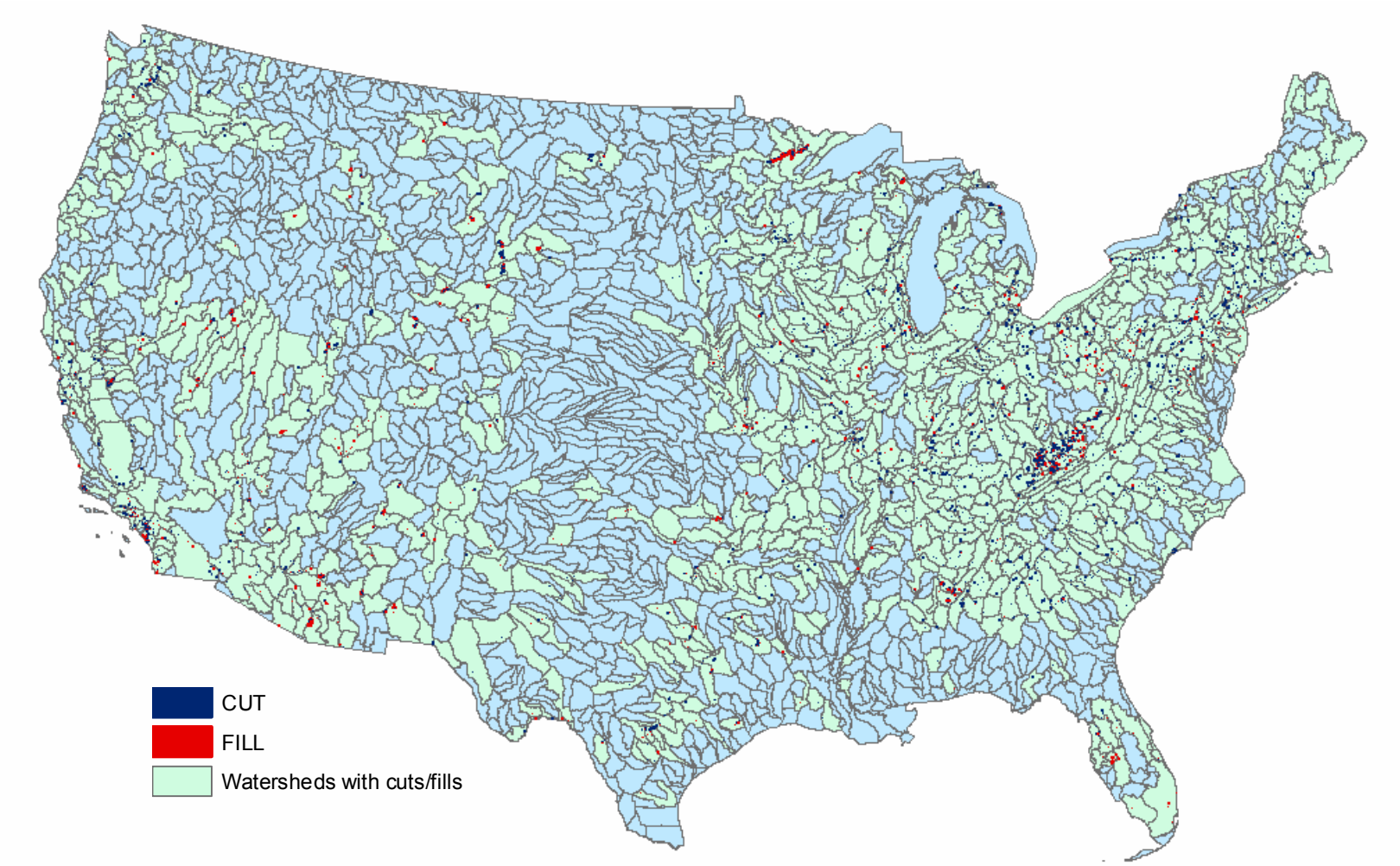


Figure 4.14. Watersheds (8-digit hydrologic cataloging units) that contain topographic change polygons. A total of 888 watersheds are represented, which is 42.1% of the cataloging units in the conterminous United States.

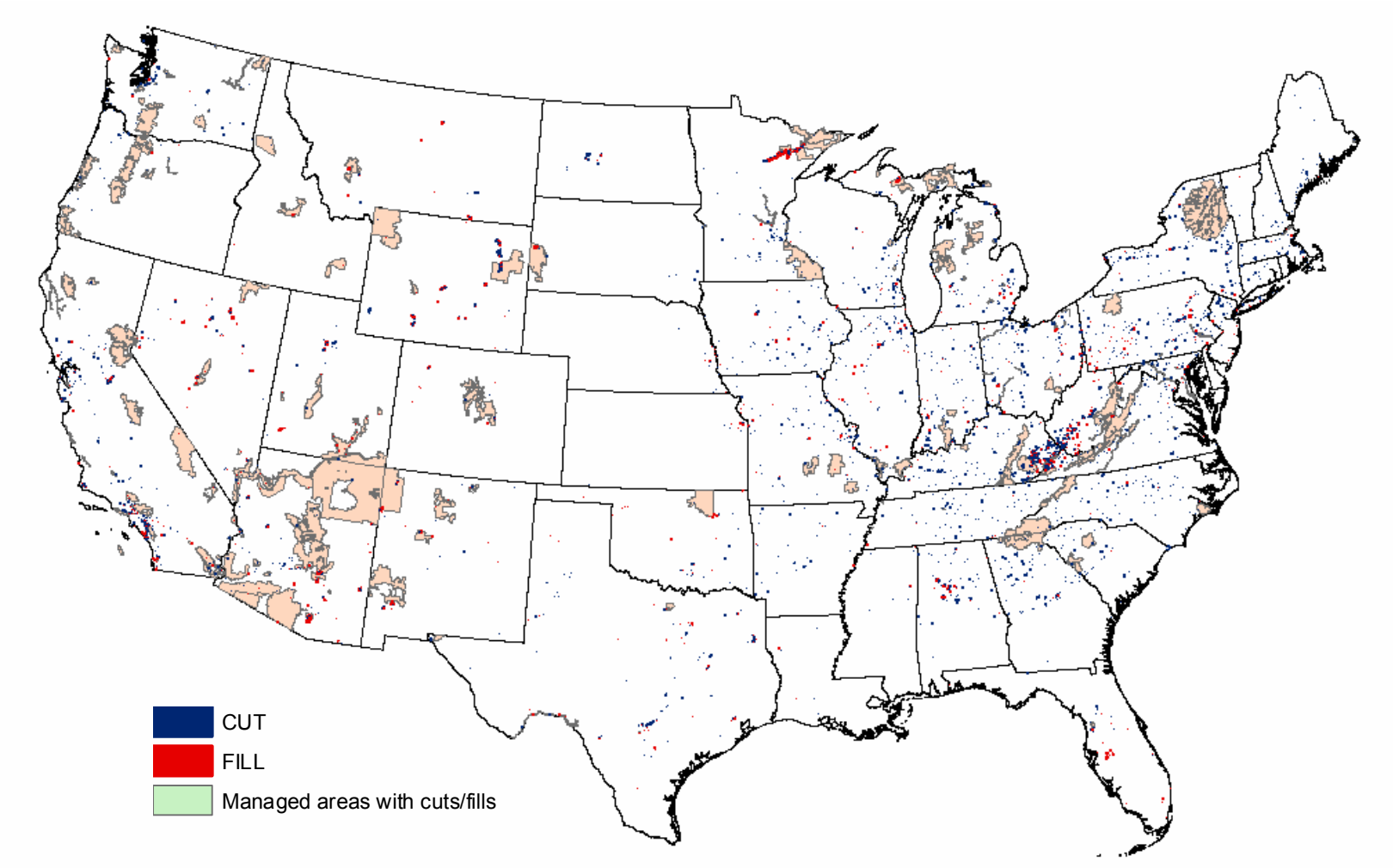


Figure 4.15. Managed areas (federal, state, tribal, and military lands) that contain topographic change polygons. Approximately 11% of the change inventory polygons fall within the general extent of these managed areas.

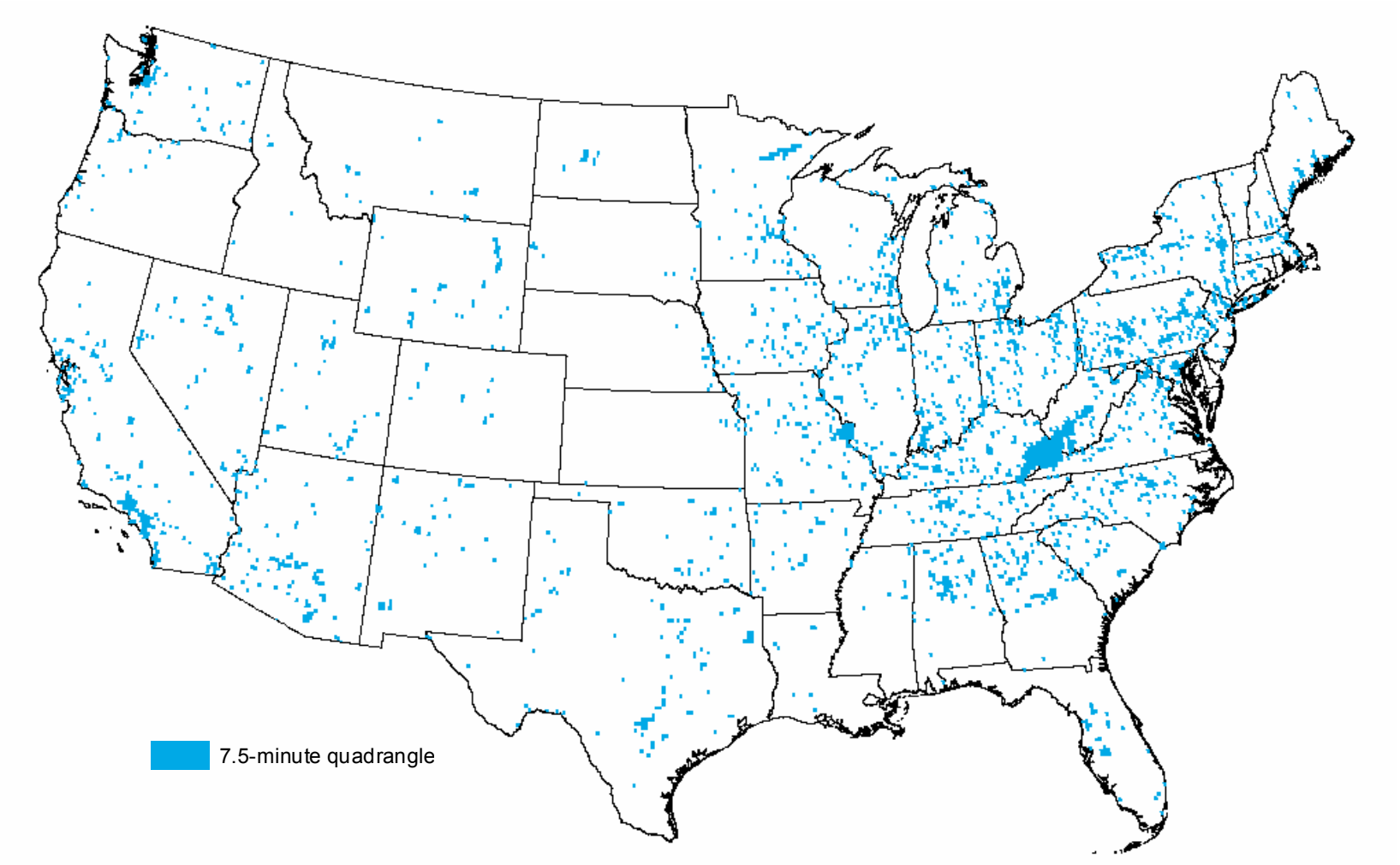


Figure 4.16. USGS 7.5-minute quadrangle maps that contain topographic change polygons. A total of 2,454 quadrangles contain change polygons, which represents over 4.5% of the quadrangles in the conterminous United States.

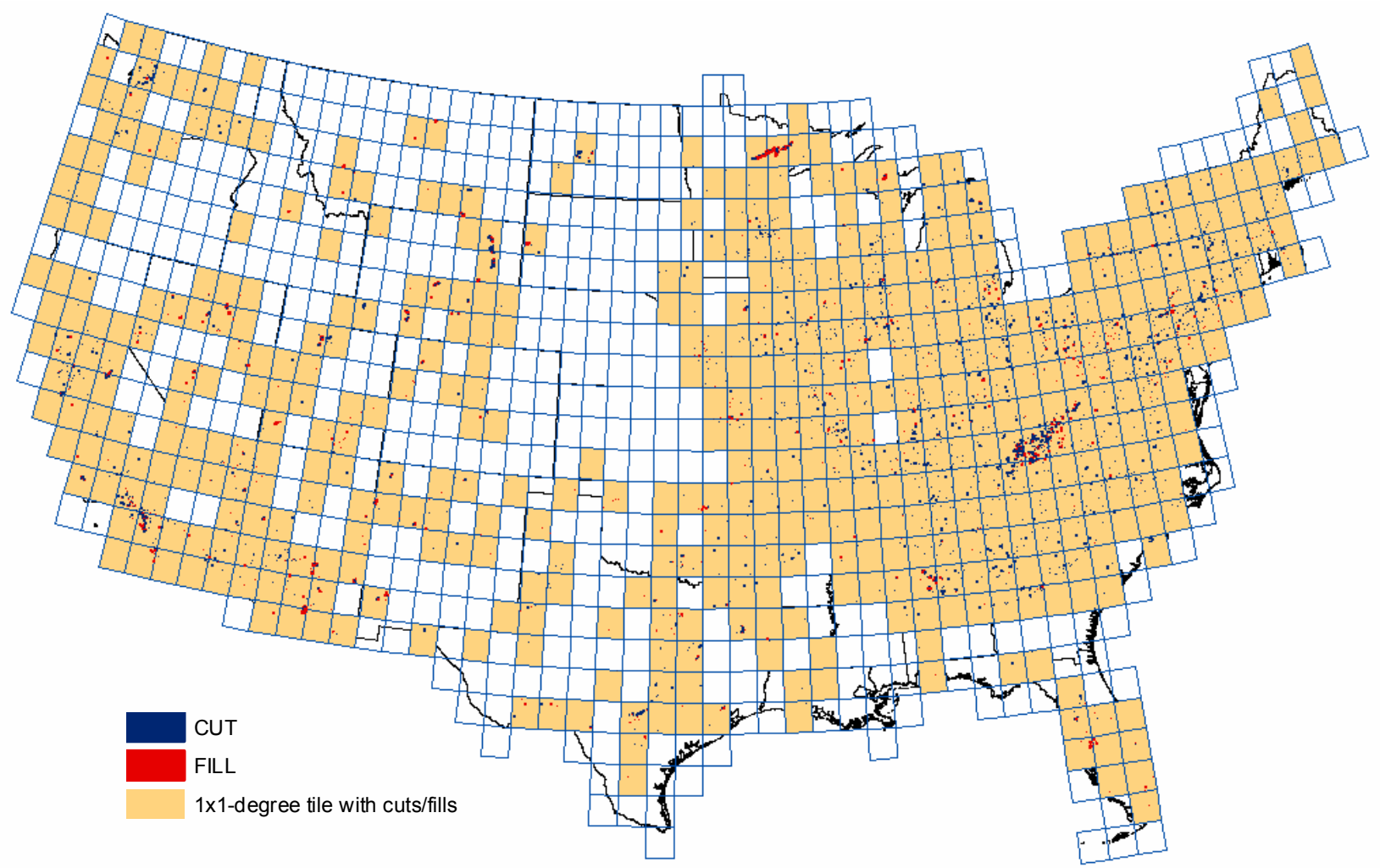


Figure 4.17. 1x1-degree tiles that contain topographic change polygons. A total of 500 tiles contain change polygons, which represents over 53% of the conterminous United States tiles.

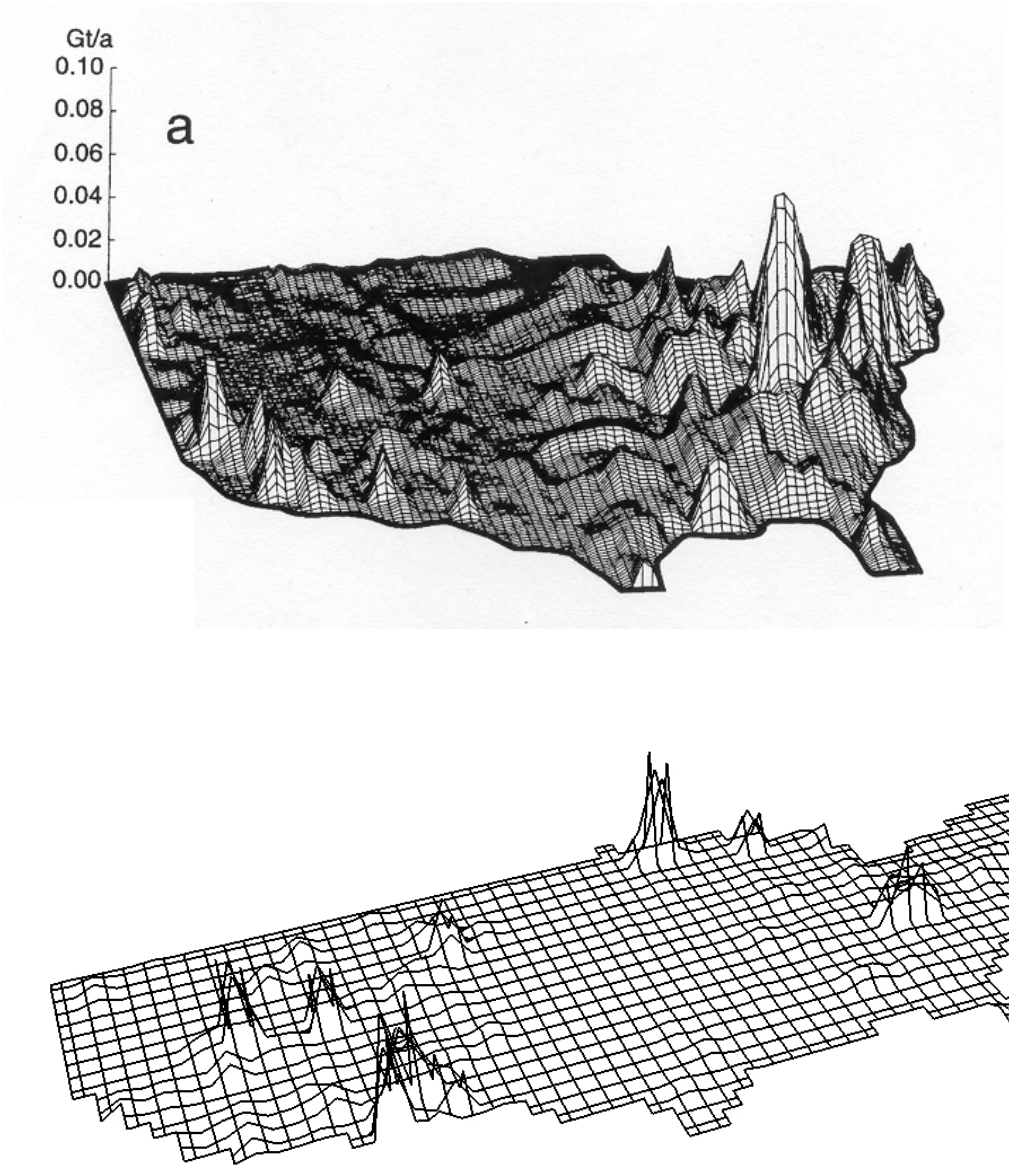


Figure 4.18. Qualitative comparison of the magnitude and distribution of human geomorphic activity calculated by Hooke (1999, p. 690) (top graphic) vs. data derived in this study (bottom graphic). In each case, the data are summarized and presented on a 1x1-degree grid for the conterminous United States.

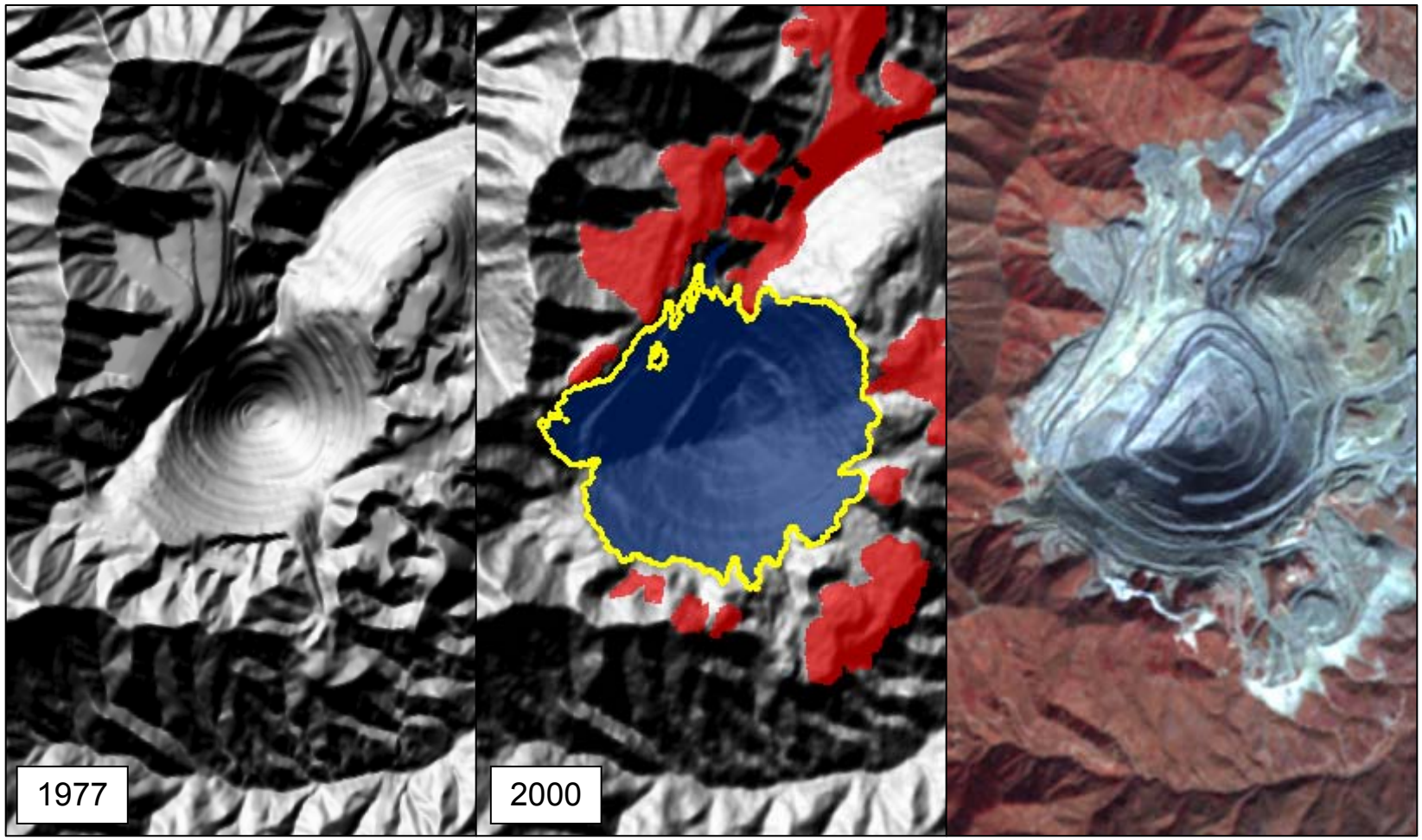


Figure 4.19. Top ranked topographic change polygon (outlined in yellow): largest cut area (8.75 km^2), and largest cut volume (1.25×10^9 m^3). This feature is the Bingham Canyon copper mine in north central Utah. Images are (from left to right): NED shaded relief, SRTM shaded relief with change polygons overlaid (blue = cut; red = fill), Landsat image. The dates of the source data for the NED and SRTM are shown. This area is approximately 5.5 km east-west by 9.7 km north-south.

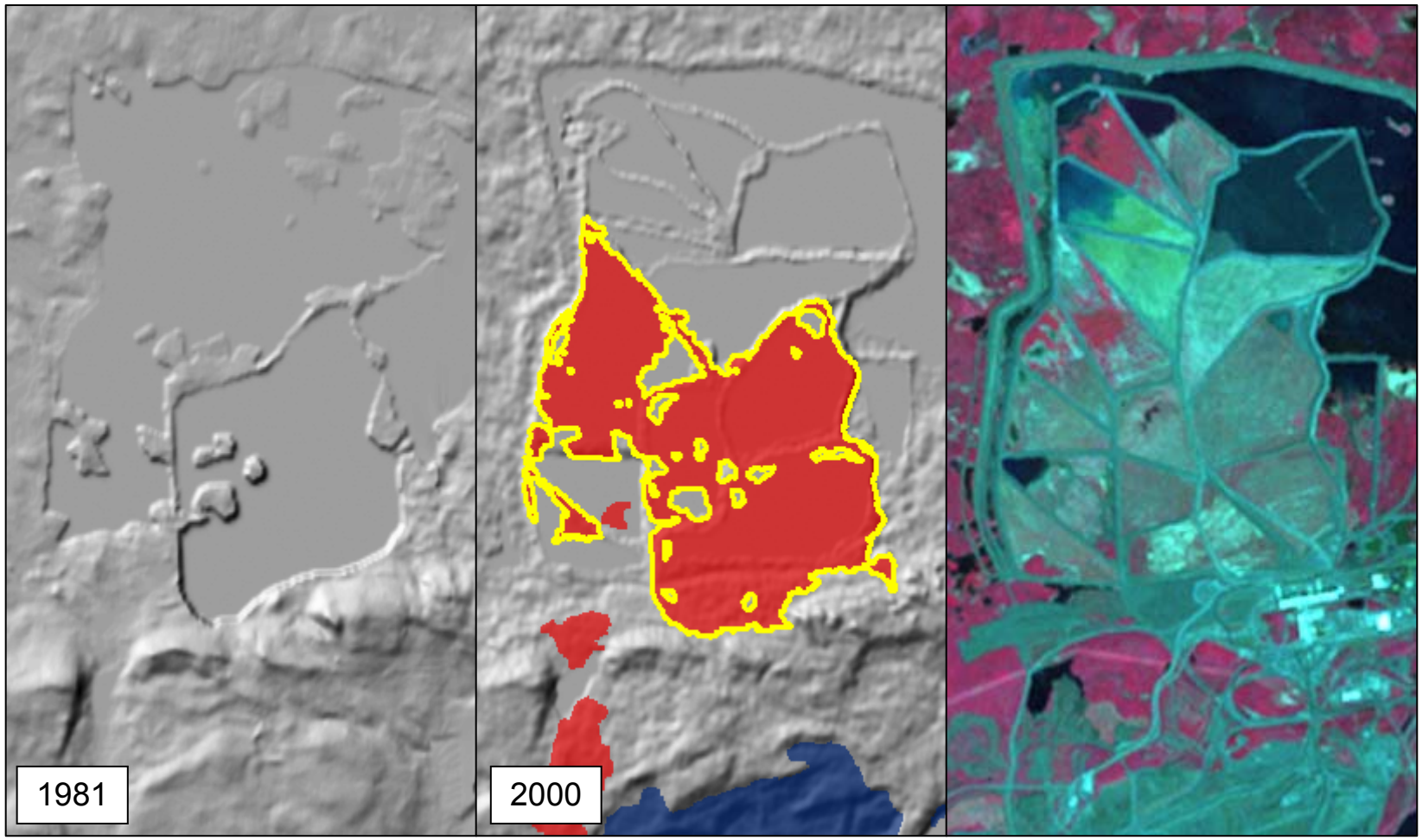


Figure 4.20. Top ranked topographic change polygon (outlined in yellow): largest fill area (9.79 km^2). This mining feature is located in the Iron Range in northern Minnesota near the town of Mountain Iron. Images are (from left to right): NED shaded relief, SRTM shaded relief with change polygons overlaid (blue = cut; red = fill), Landsat image. The dates of the source data for the NED and SRTM are shown. This area is approximately 5.5 km east-west by 9.7 km north-south.

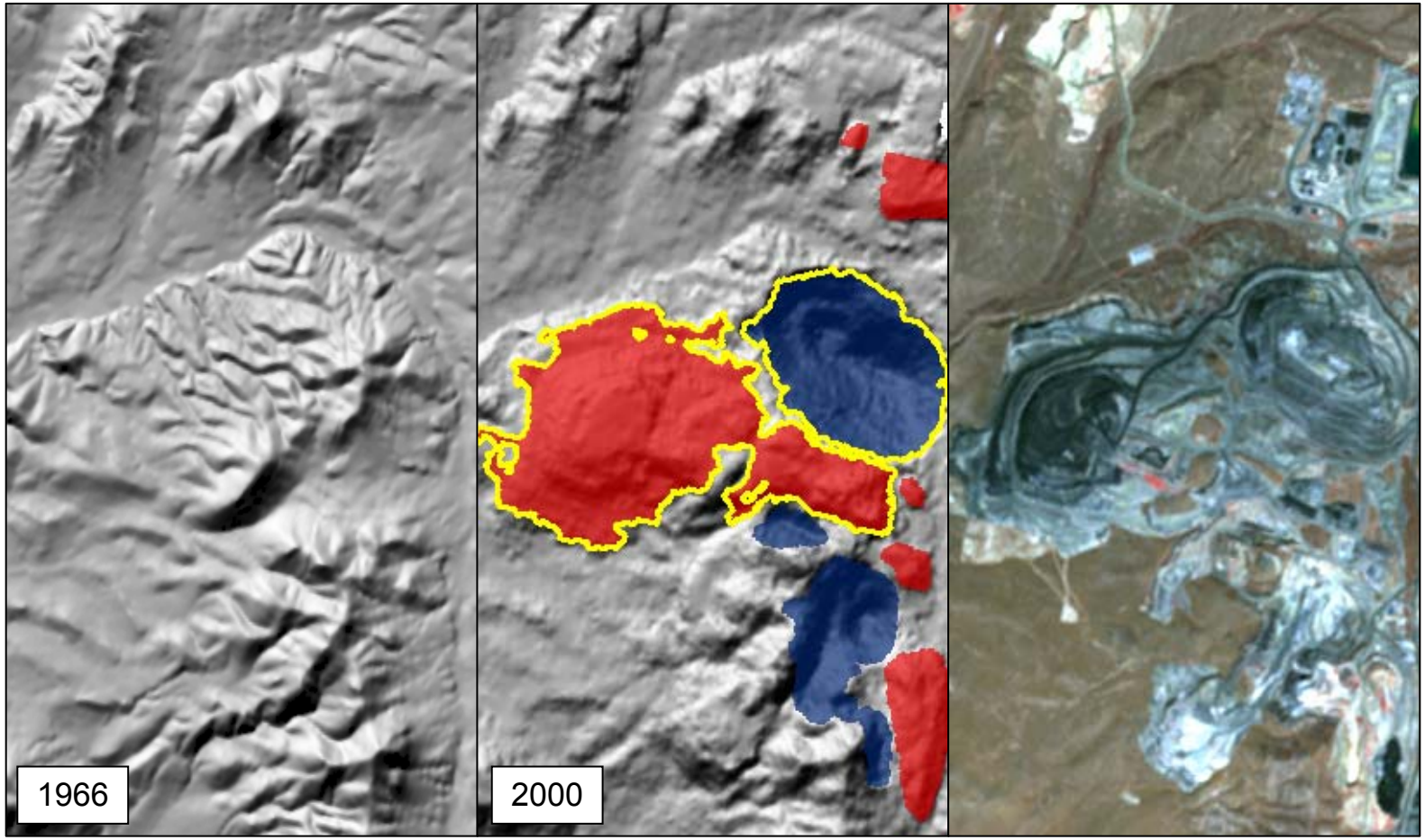


Figure 4.21. Top ranked topographic change polygons (outlined in yellow): largest fill volume (5.16 x 10^8 m^3), largest mean elevation change (-177.3 m) and largest relief change (263.7 m) for a cut. This feature is a gold mining operation near Rodeo Creek in north central Nevada. Images are (from left to right): NED shaded relief, SRTM shaded relief with change polygons overlaid (blue = cut; red = fill), Landsat image. The dates of the source data for the NED and SRTM are shown. This area is approximately 5.5 km east-west by 9.7 km north-south.

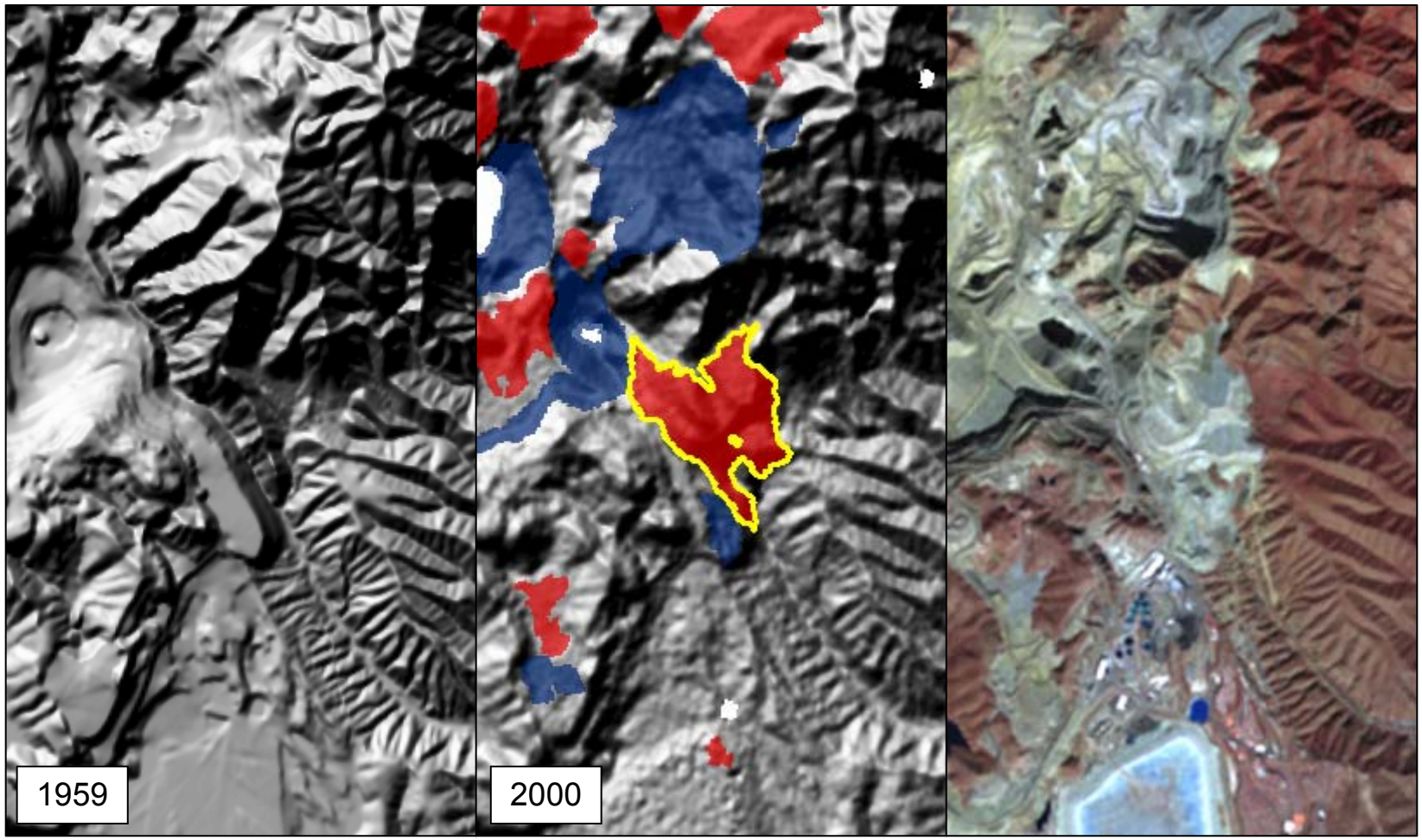


Figure 4.22. Top ranked topographic change polygon (outlined in yellow): largest mean elevation change for a fill (104.6 m). This feature is located at the Morenci copper mine near Clifton in southeastern Arizona. Images are (from left to right): NED shaded relief, SRTM shaded relief with change polygons overlaid (blue = cut; red = fill), Landsat image. The dates of the source data for the NED and SRTM are shown. This area is approximately 5.5 km east-west by 9.7 km north-south.

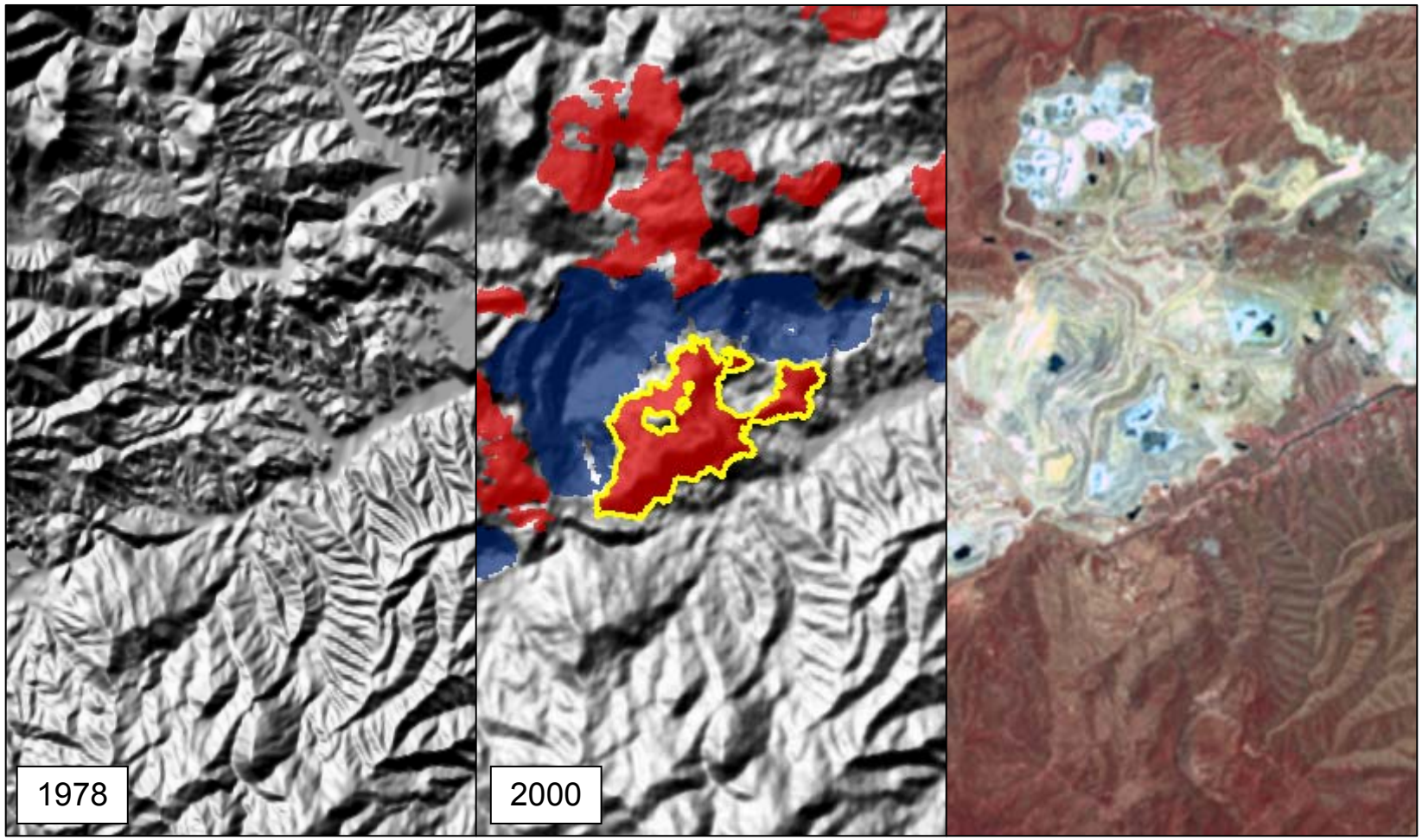


Figure 4.23. Top ranked topographic change polygon (outlined in yellow): largest relief change for a fill (73.5 m). This feature is located at the Inspiration copper mine near Miami in southeastern Arizona. Images are (from left to right): NED shaded relief, SRTM shaded relief with change polygons overlaid (blue = cut; red = fill), Landsat image. The dates of the source data for the NED and SRTM are shown. This area is approximately 5.5 km east-west by 9.7 km north-south.

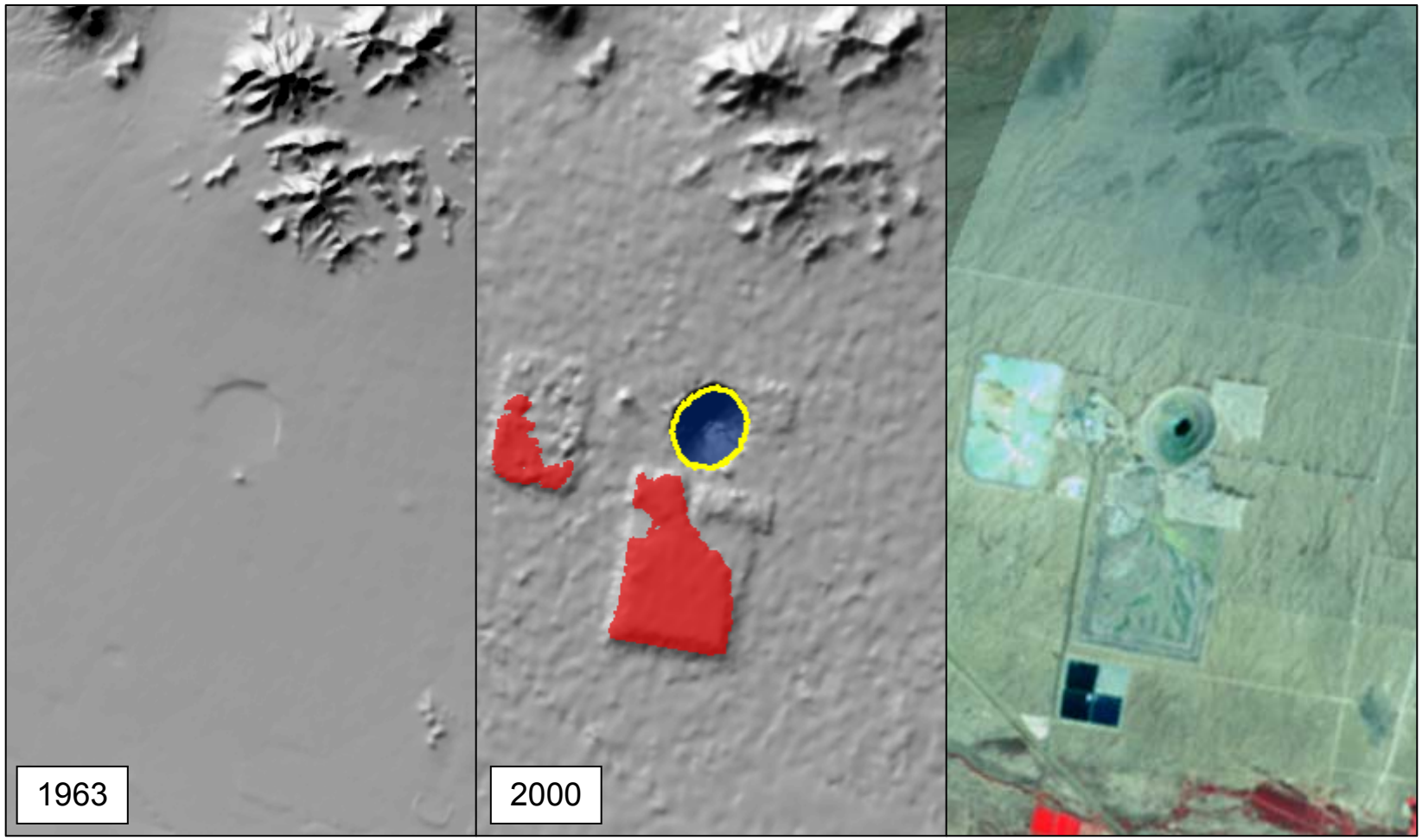


Figure 4.24. Top ranked topographic change polygon (outlined in yellow): largest mean slope change for a cut (33.2°). This feature is the Sacaton copper mine located in south central Arizona. Images are (from left to right): NED shaded relief, SRTM shaded relief with change polygons overlaid (blue = cut; red = fill), Landsat image. The dates of the source data for the NED and SRTM are shown. This area is approximately 5.5 km east-west by 9.7 km north-south.

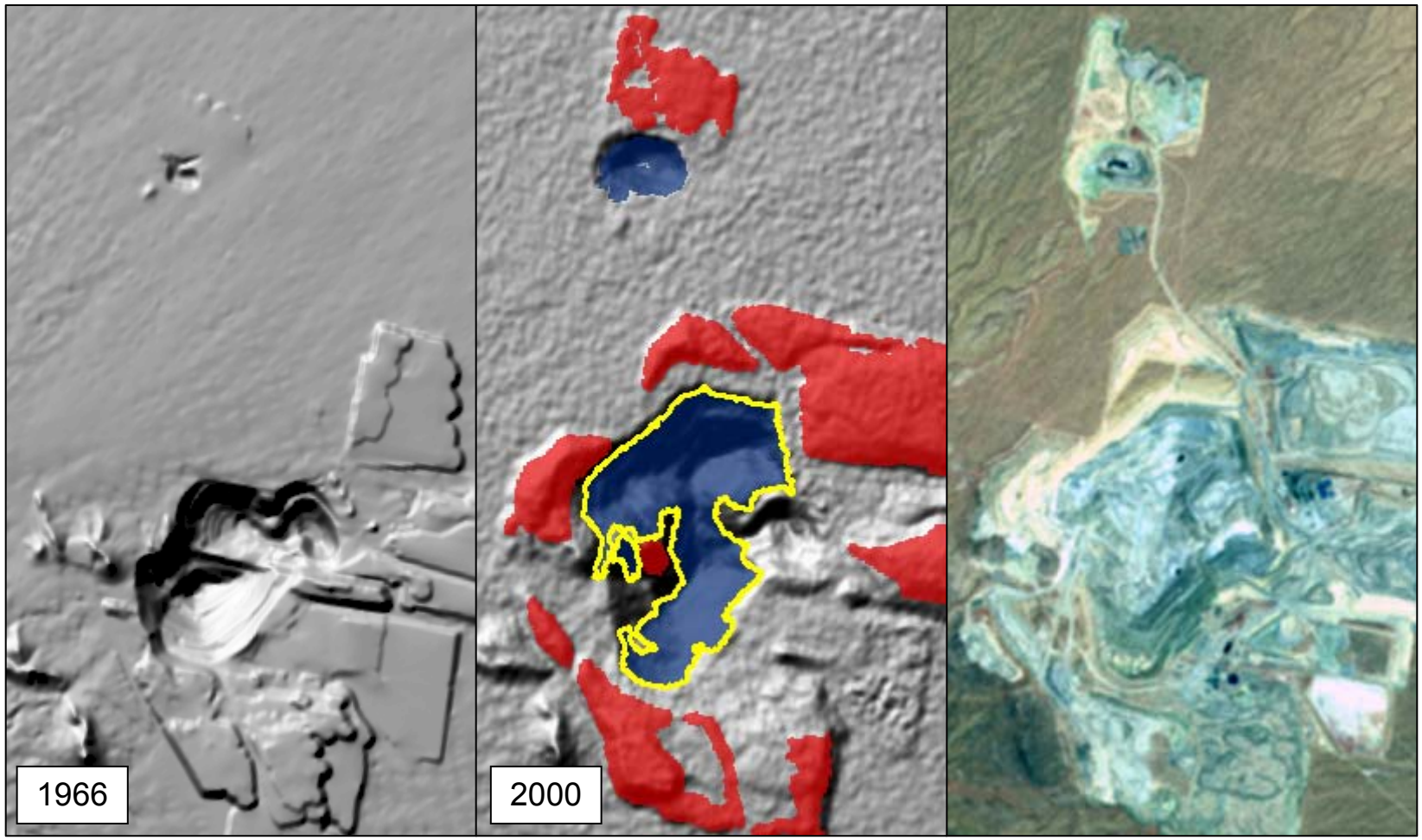


Figure 4.25. Top ranked cut polygon based on the combined ranks for area, volume, and change in elevation, relief, slope, and aspect (outlined in yellow). This feature is located at the Mission copper mine near San Xavier, Arizona. Images are (from left to right): NED shaded relief, SRTM shaded relief with change polygons overlaid (blue = cut; red = fill), Landsat image. The dates for the NED and SRTM source data are shown. This area is approximately 5.5 km east-west by 9.7 km north-south.

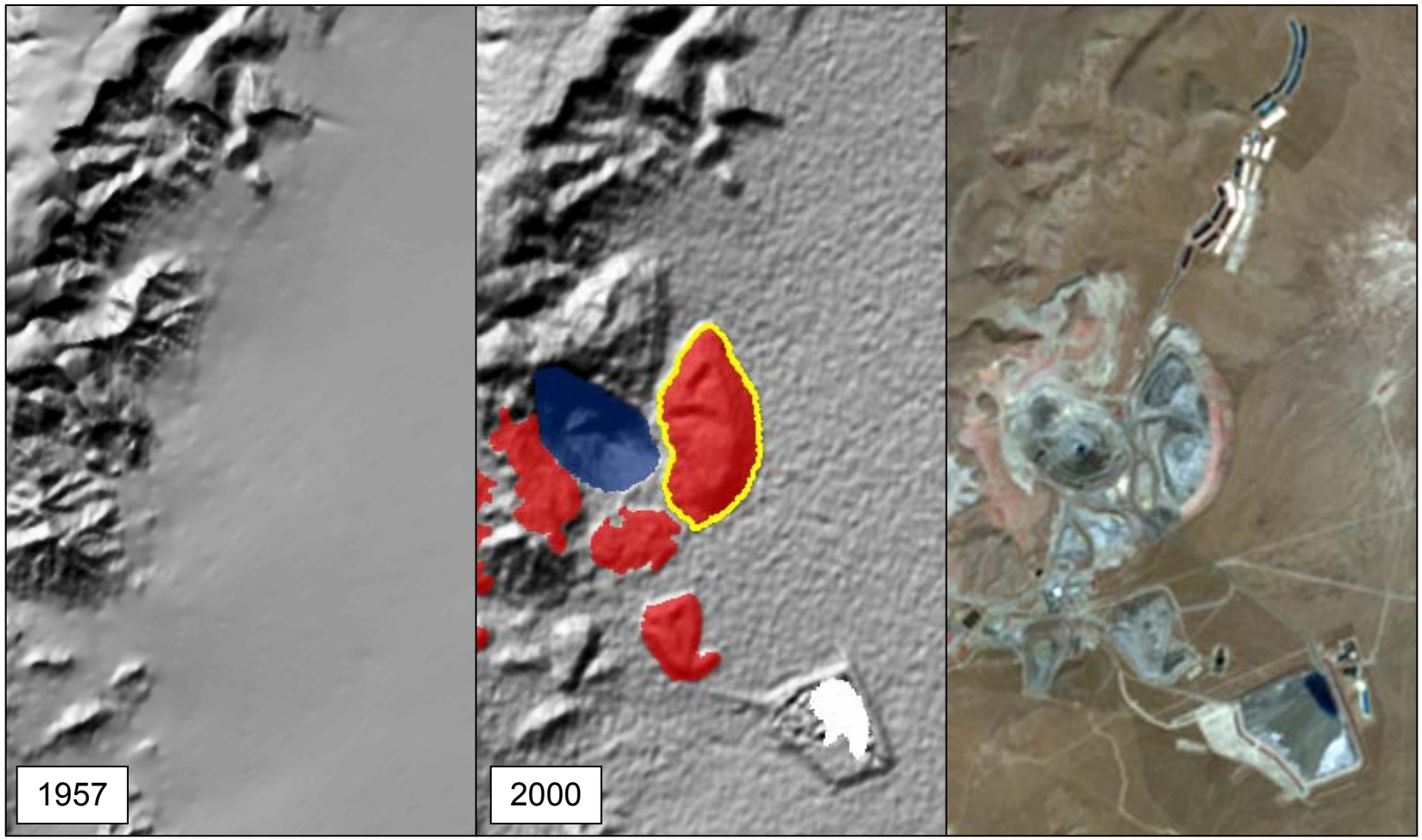


Figure 4.26. Top ranked fill polygon based on the combined ranks for area, volume, and change in elevation, relief, slope, and aspect (outlined in yellow). This feature is located at the McCoy, Nevada open pit gold mine. Images are (from left to right): NED shaded relief, SRTM shaded relief with change polygons overlaid (blue = cut; red = fill), Landsat image. The dates of the source data for the NED and SRTM are shown. This area is approximately 5.5 km east-west by 9.7 km north-south.

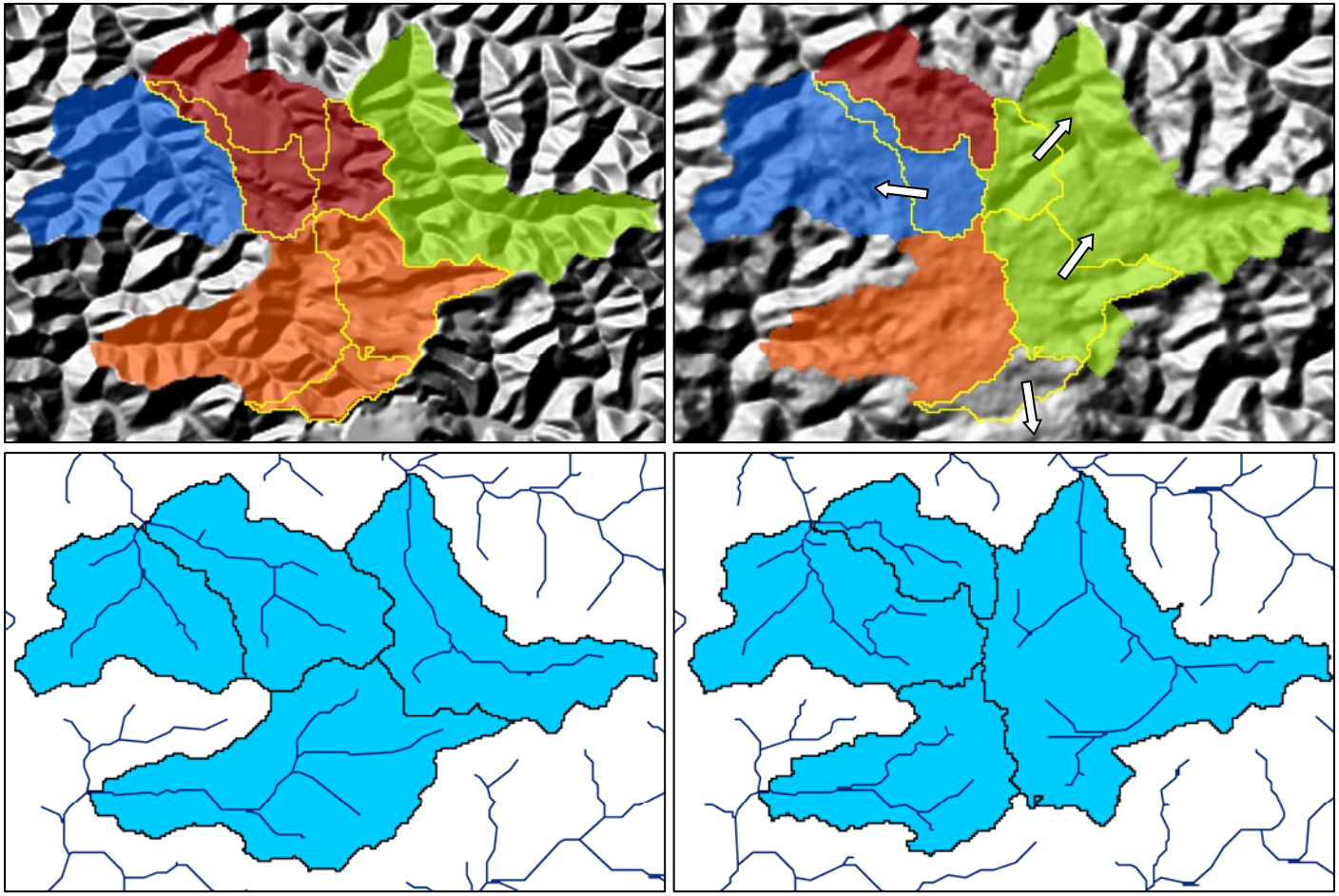


Figure 4.27. Alterations to the local drainage pattern resulting from surface mining in Perry County in eastern Kentucky. Watersheds and stream channels derived from pre-mining elevation data (NED) are on the left. Watersheds and stream channels derived from the post-mining elevation data (SRTM) are on the right. The areas outlined in yellow indicate the portions of the original watersheds that contribute runoff to different streams as a result of the surface disturbance. The arrows indicate the new general direction of runoff. The area shown is approximately 6.6 km east-west by 5.4 km north-south.

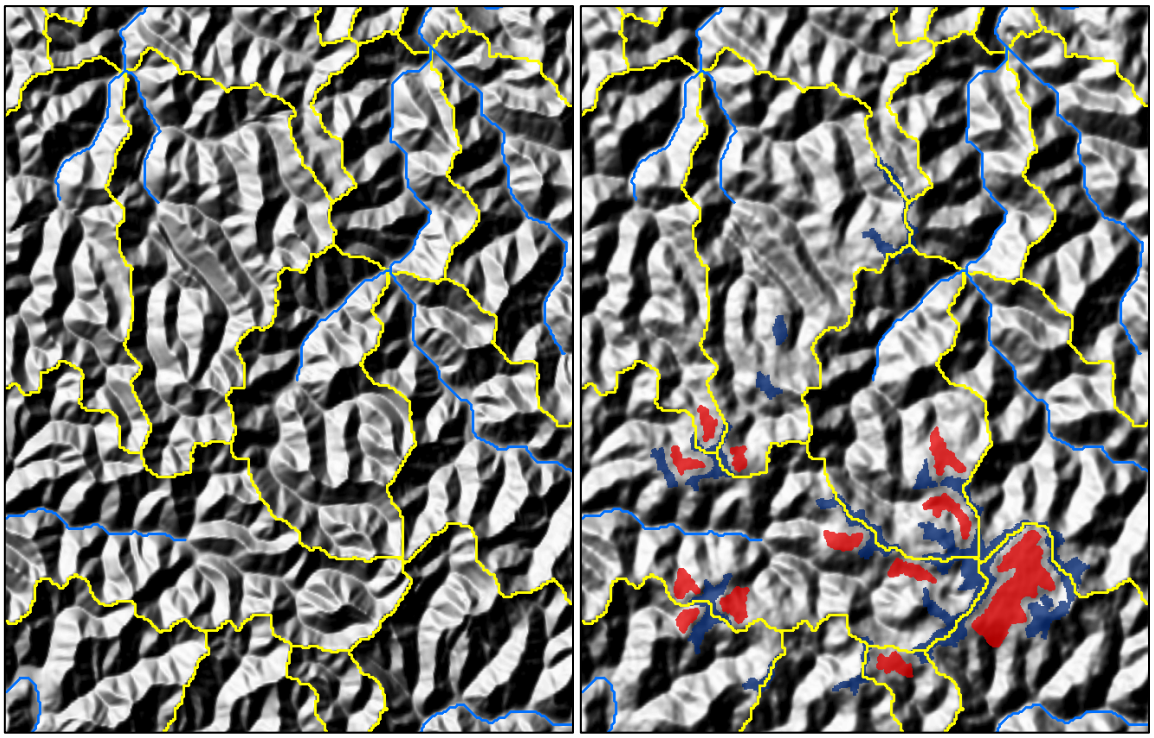


Figure 4.28. Example of a mountaintop mining area in which the negative topographic changes (cuts) coincide with the divides between first order drainage basins. This area is located in eastern Kentucky along the Leslie County-Perry County border. NED shaded relief is on the left, overlaid with DEM derived catchments (yellow) and stream lines (light blue). SRTM shaded relief is on the right, overlaid with topographic change polygons (blue = cut; red = fill). The area shown is approximately 7.7 kilometers east-west by 9.8 kilometers north-south.

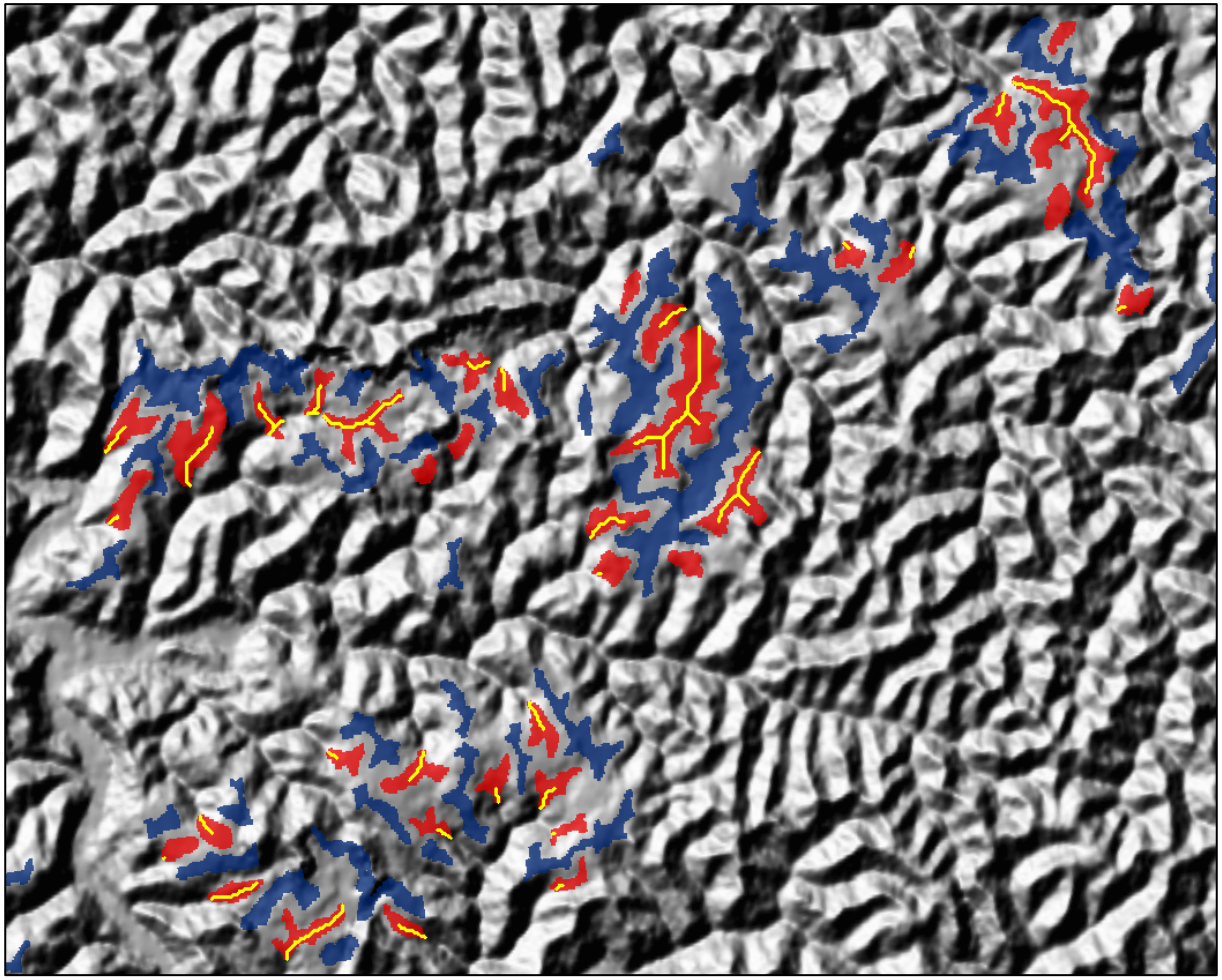


Figure 4.29. Streams (yellow lines) contained within topographic change polygons for an area in Perry County in eastern Kentucky. Change polygons are overlaid on SRTM shaded relief (blue = cut; red = fill). Note that the streams are located in the valley fills resulting from mountaintop mining. The area shown is approximately 13.1 kilometers east-west by 10.6 kilometers north-south.

Topographic change type	Number of polygons containing streams	Percent of total polygons	Number of stream segments	Total length of streams (km)
All	2,553	43.6% (of all polygons)	7,346	1,502
Cut	1,166	39.6% (of cut polygons)	3,211	562
Fill	1,387	72.5% (of fill polygons)	4,135	940

Table 4.4. Summary statistics for the number and total length of streams contained within topographic change polygons in the conterminous United States.

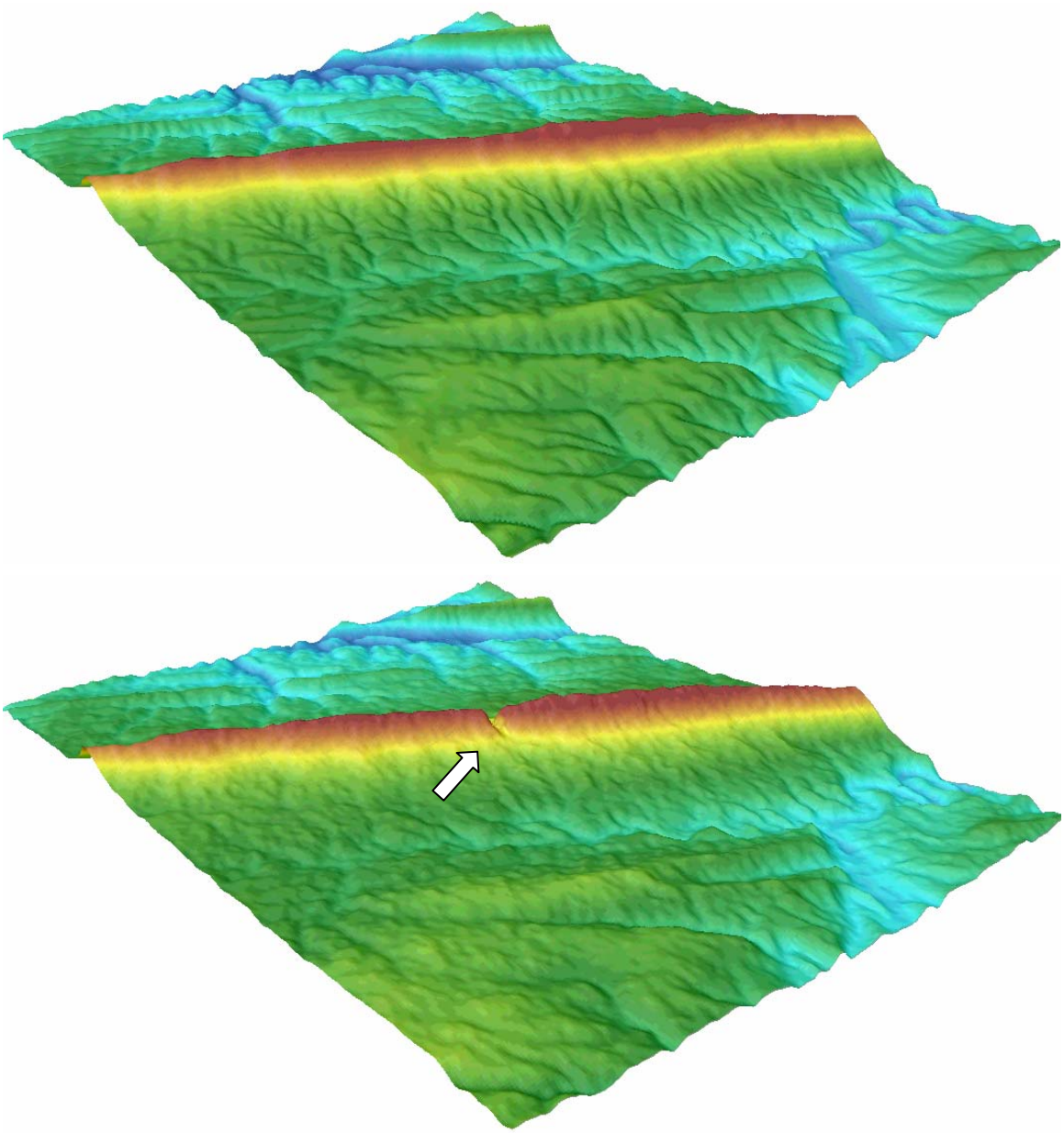


Figure 4.30. Perspective views of the road cut through Sideling Hill in western Maryland (see Figure 4.5). The top image is derived from the NED and the bottom image is derived from the SRTM data (colors range from blue for the lowest elevations to red for the highest elevations within the scene). The viewing direction is towards the southeast. The arrow indicates the location of the cut through the prominent ridge. Without any adjacent terrain features to block the view, the road cut can be seen from many locations over long distances. Perspective views are useful to qualitatively portray the visual impacts of topographic surface changes.

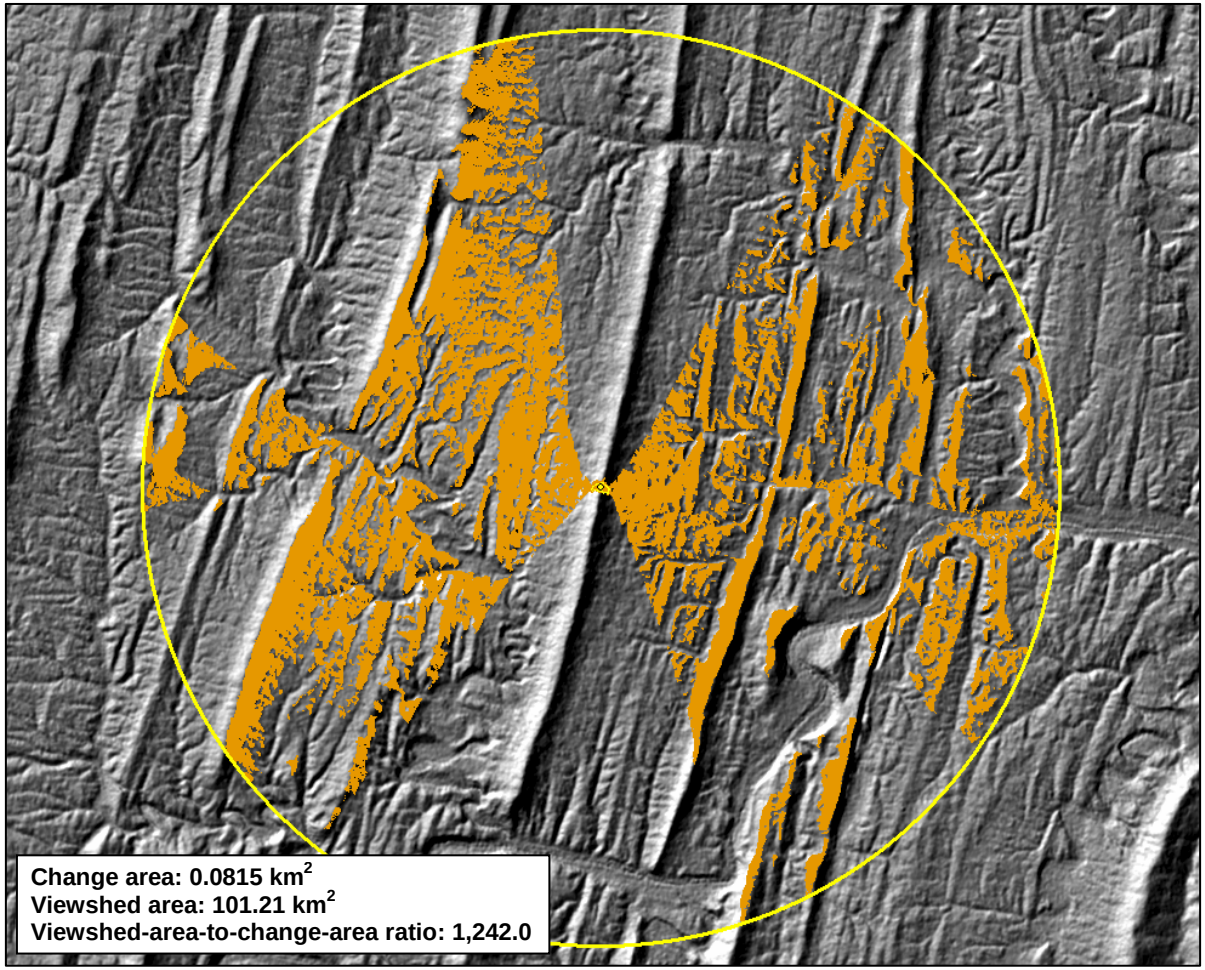


Figure 4.31. Viewshed for the Sideling Hill road cut in western Maryland (see Figure 4.5 and Figure 4.30). The viewshed (orange) and the topographic change polygon and its centroid (yellow) are overlaid on SRTM shaded relief. The circle, with a radius of 12.5 km, shows the extent of the viewshed calculations. The area shown is approximately 32.7 kilometers east-west by 26.4 kilometers north-south.

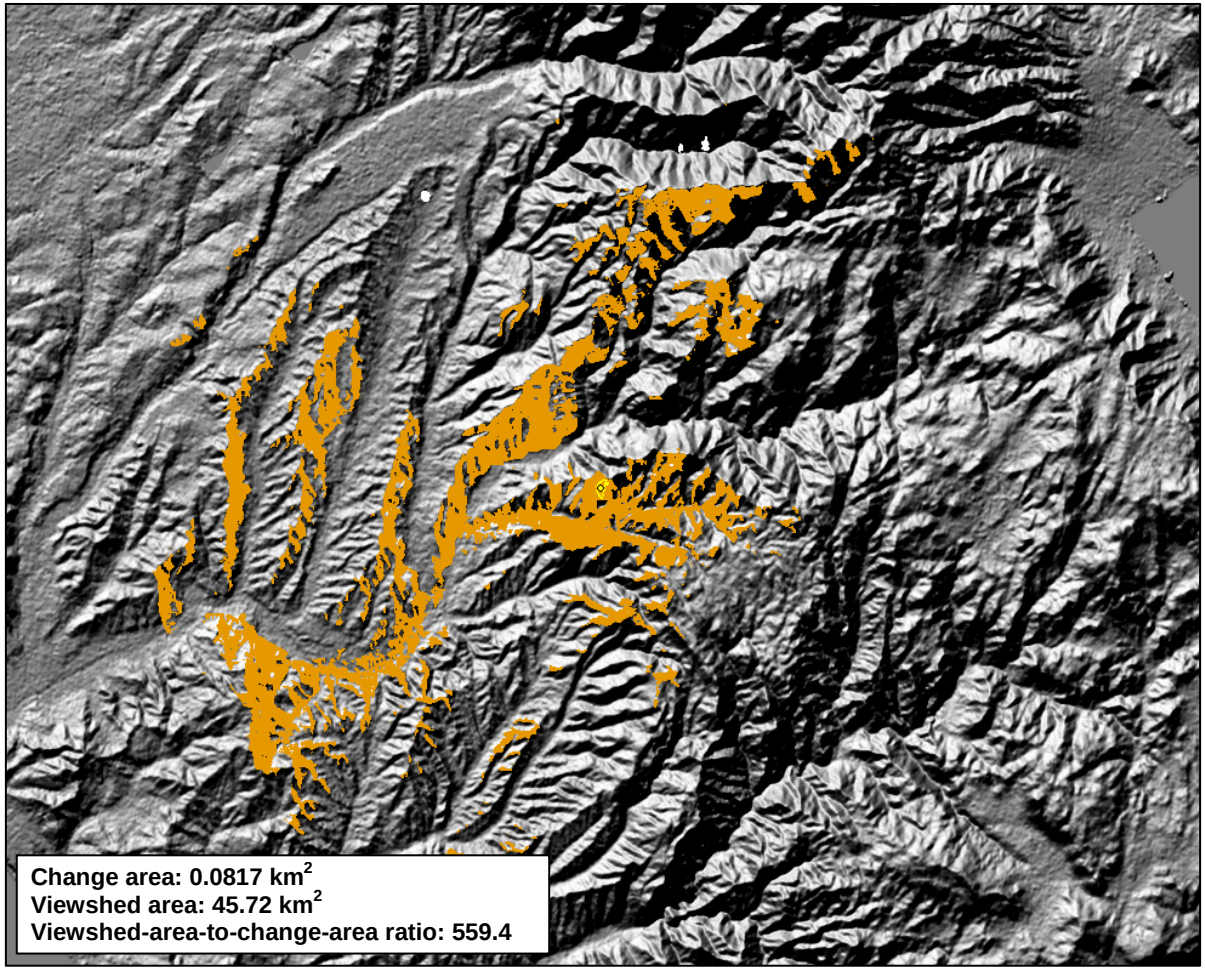


Figure 4.32. Viewshed for a quarry located near San Juan Capistrano, California. The viewshed (orange) and the topographic change polygon and its centroid (yellow) are overlaid on SRTM shaded relief. The area shown is approximately 32.7 kilometers east-west by 26.4 kilometers north-south.

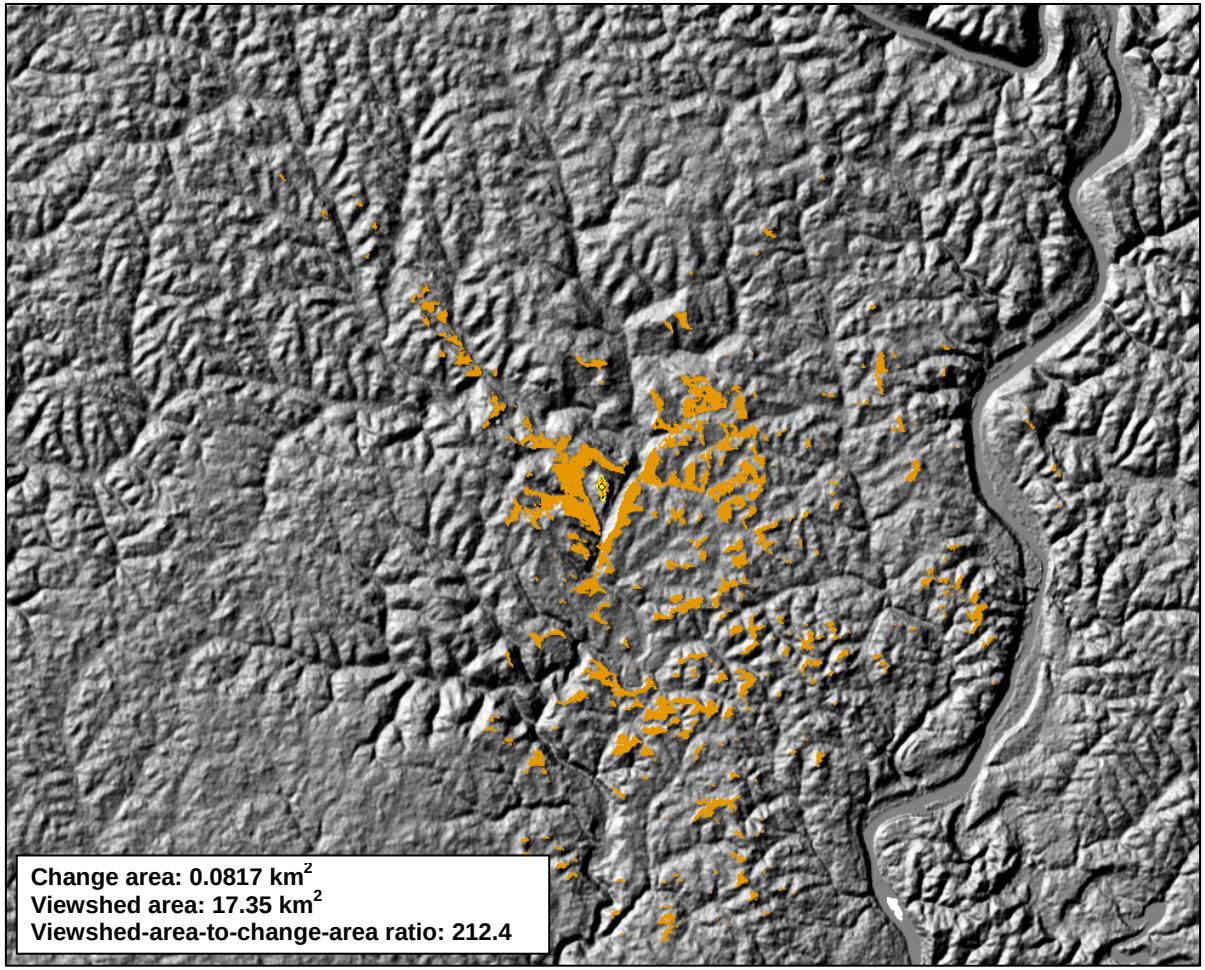


Figure 4.33. Viewshed for a mine located near Worthington, Pennsylvania. The viewshed (orange) and the topographic change polygon and its centroid (yellow) are overlaid on SRTM shaded relief. The area shown is approximately 32.7 kilometers east-west by 26.4 kilometers north-south.

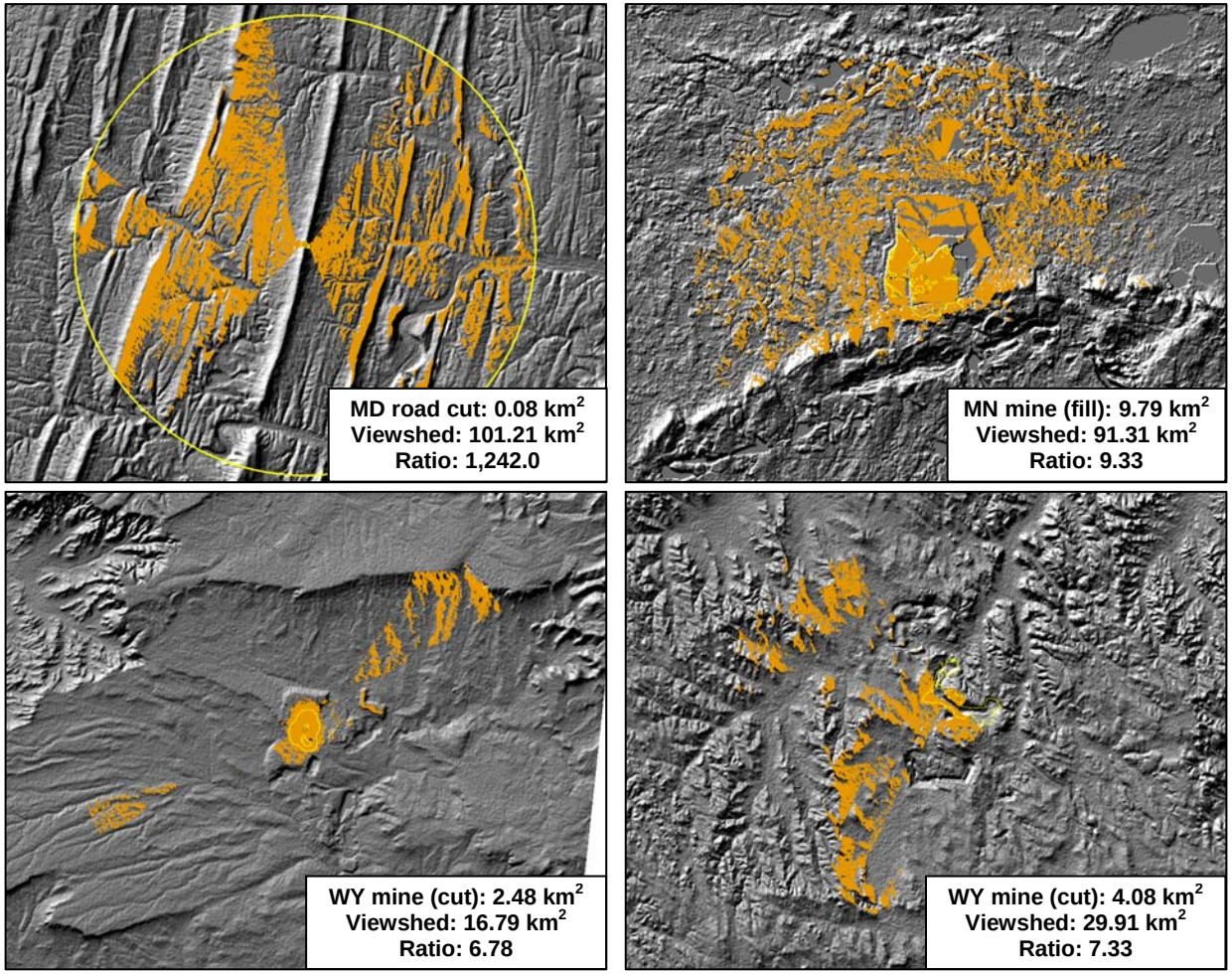


Figure 4.34. Comparison of the viewsheds for the Sideling Hill road cut in western Maryland and three large mine features. The planimetric area of the road cut is very small compared to the mines, but its topographic setting results in a very large viewshed area. Consequently, the viewshed-area-to-change-area ratio for the road cut is much higher than the mine ratios. The size of each area shown is approximately 32.7 kilometers east-west by 26.4 kilometers north-south.

Topographic change feature	Figure	Change type	Area (km^2)	Volume (m^3)	Volume-to-area ratio	Viewshed area (km^2)	Viewshed-area-to-change-area ratio
Sideling Hill road cut (western MD)	4.31	Cut	0.08	3,522,020	43.22	101.21	1,242.00
Quarry (near San Juan Capistrano, CA)	4.32	Cut	0.08	3,049,160	37.31	45.72	559.36
Mine (near Worthington in western PA)	4.33	Fill	0.08	3,043,200	37.25	17.35	212.40
MN mine (Northern Lakes and Forest ecoregion)	4.34	Fill	9.79	327,769,000	33.48	91.31	9.33
WY mine (Wyoming Basin ecoregion)	4.34	Cut	2.48	110,039,000	44.45	16.79	6.78
WY mine (Northwestern Great Plains ecoregion)	4.34	Cut	4.08	144,823,000	35.48	29.91	7.33

Table 4.5. Area, volume, and viewshed information for a comparison among several topographic change features.

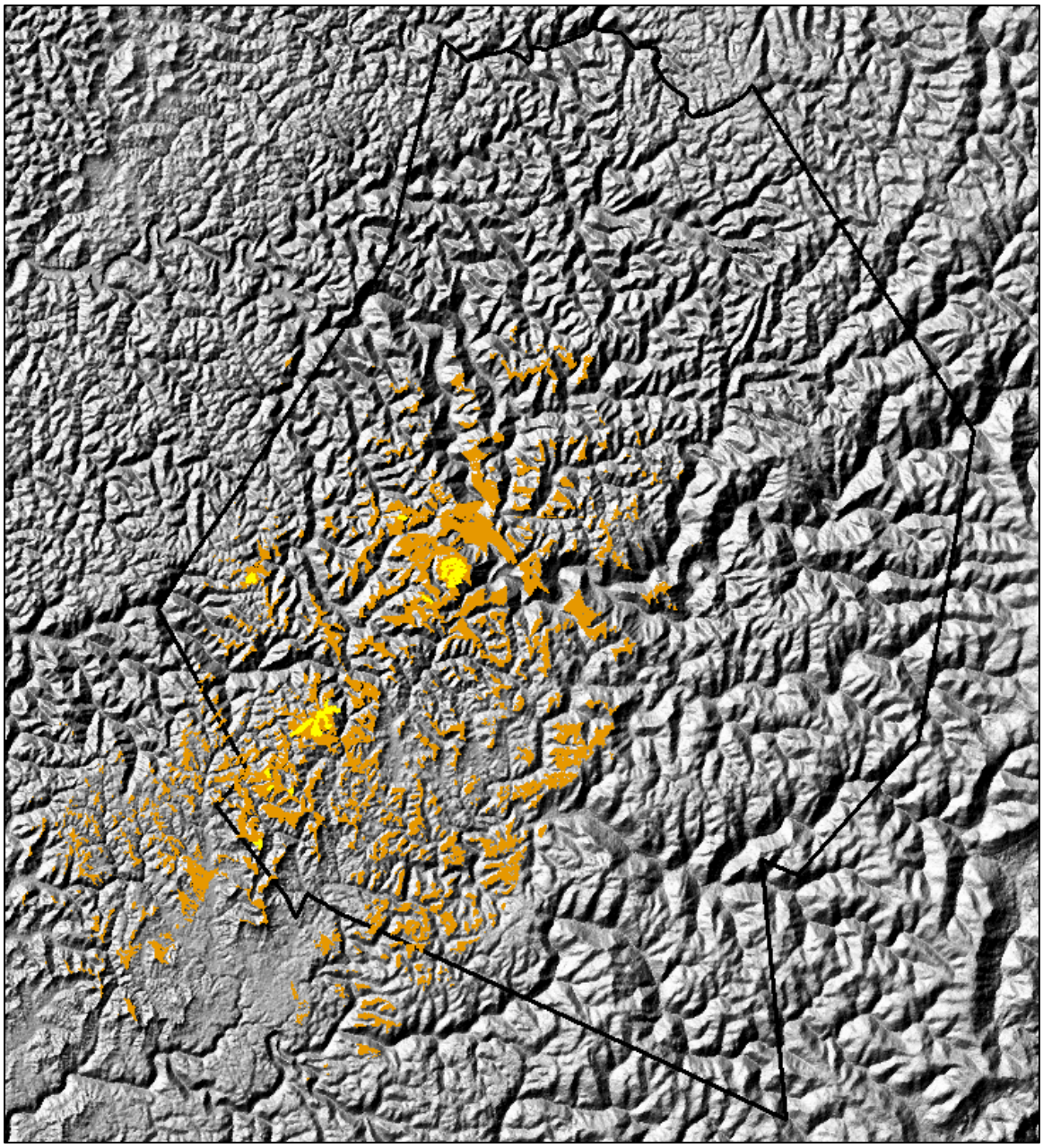


Figure 4.35. Combined viewshed of 24 topographic change features in Webster County, West Virginia. The viewshed (orange), county boundary (black outline), and the topographic change polygons (yellow) are overlaid on SRTM shaded relief. The combined viewshed is more than 60 times the area of the change polygons. The area shown is approximately 52.7 kilometers east-west by 58.1 kilometers north-south.

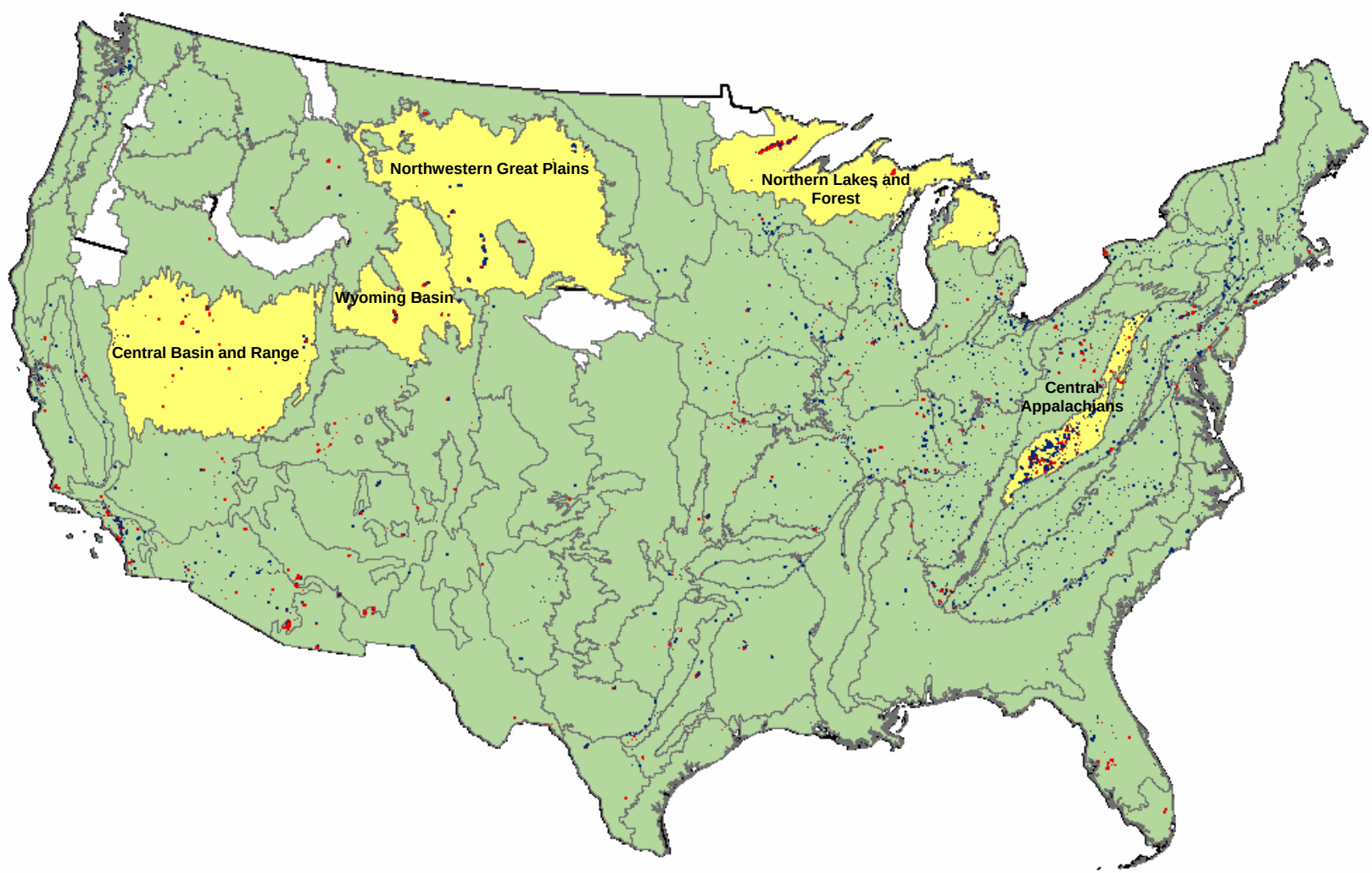


Figure 4.36. Five ecoregions used as a basis for regional comparisons of topographic change.

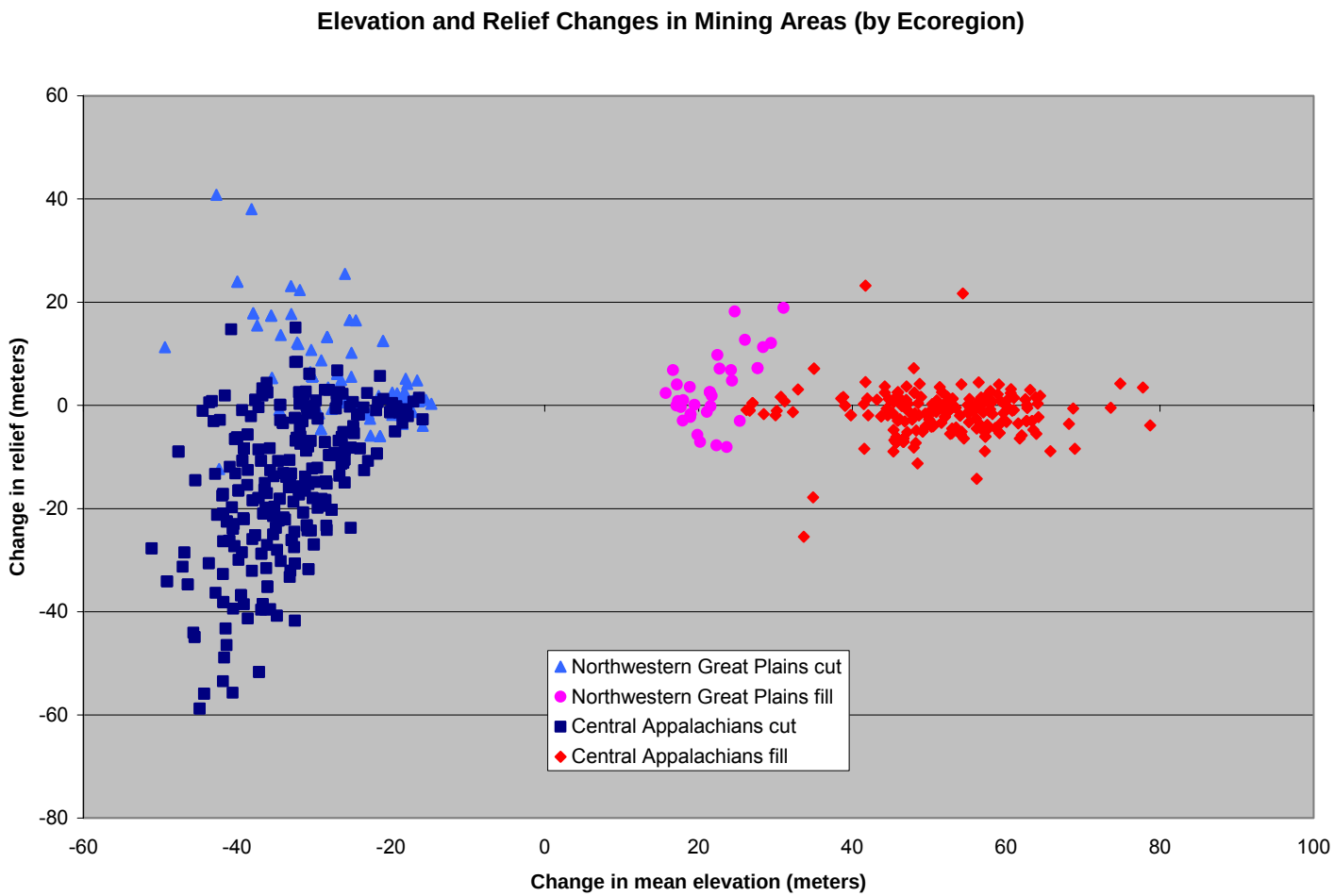


Figure 4.37. Scatterplot of change in mean elevation vs. change in relief for mining polygons in two ecoregions.

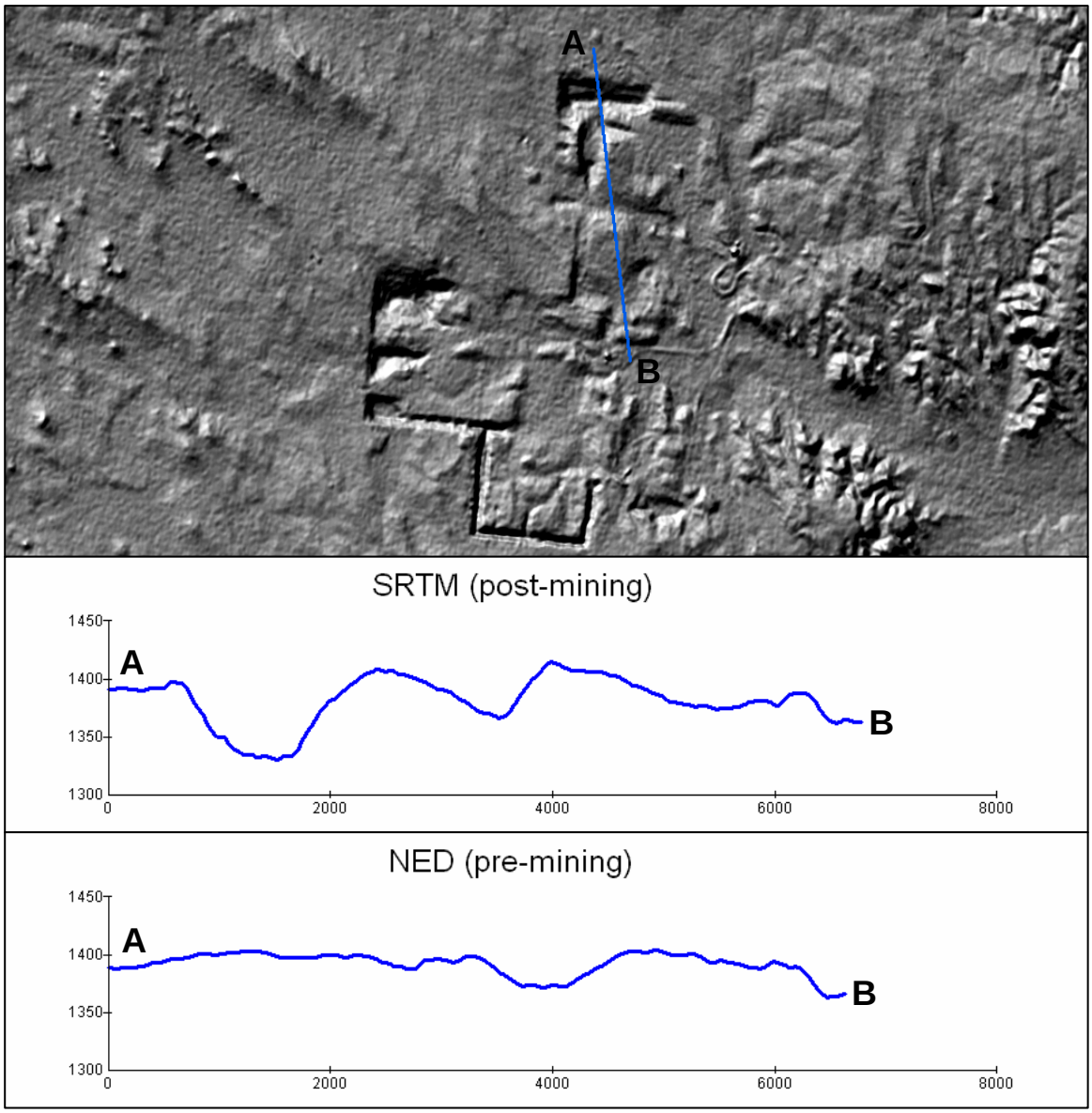


Figure 4.38. Increased relief resulting from surface coal mining near Gillette, Wyoming. The length of the profile is approximately 6.8 km.

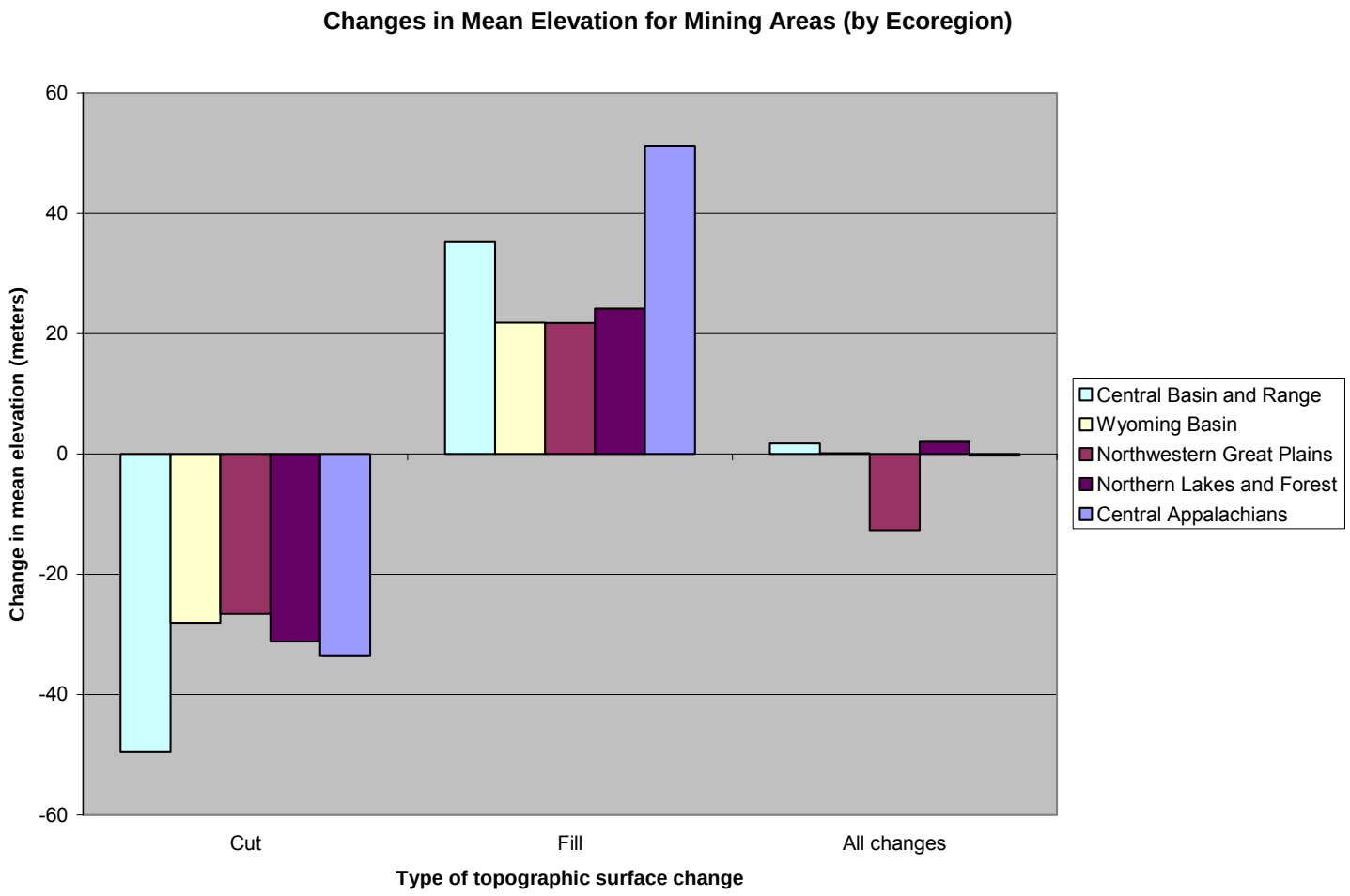


Figure 4.39. Changes in mean elevation for mining polygons in five ecoregions.

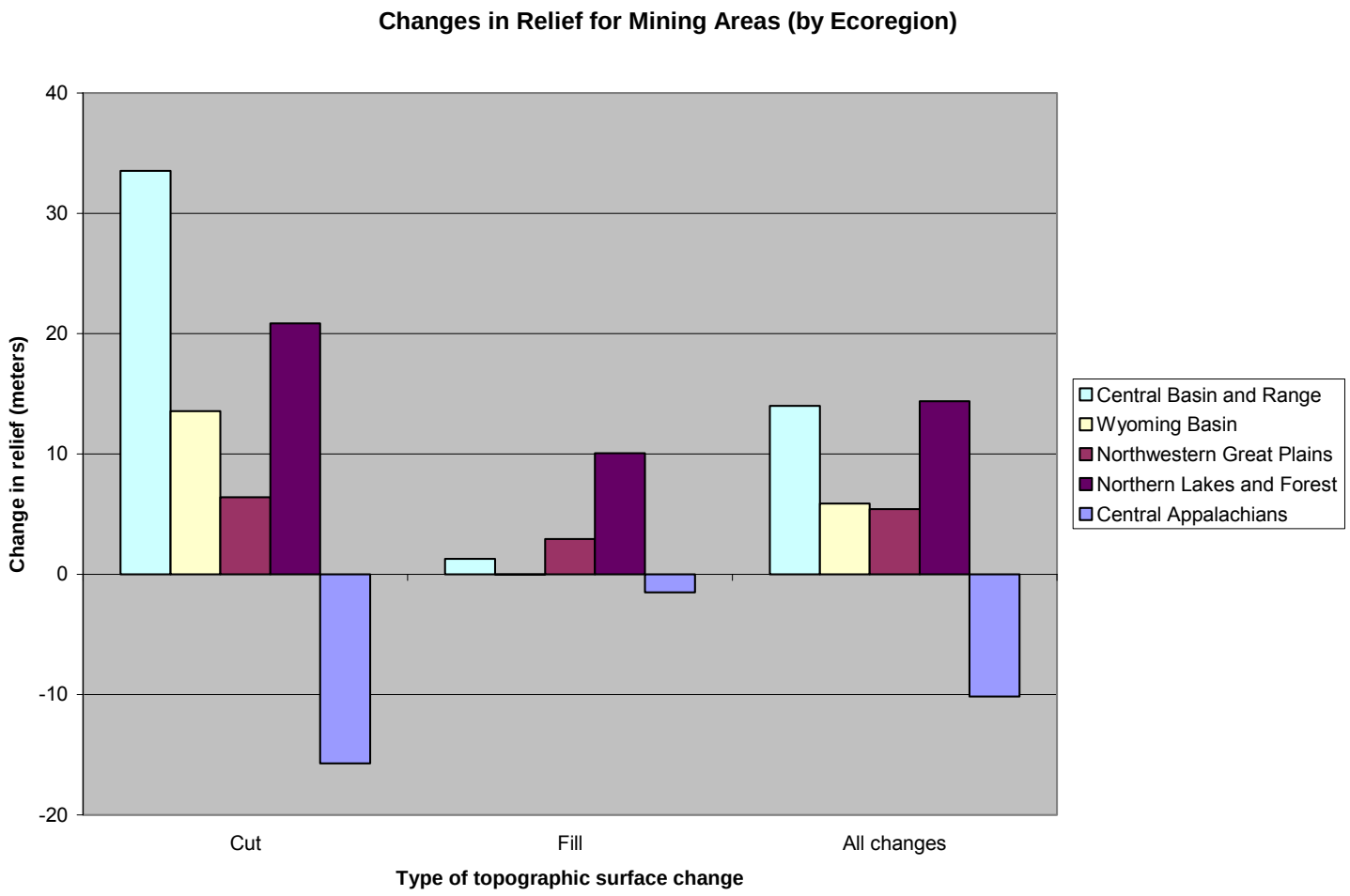


Figure 4.40. Changes in relief for mining polygons in five ecoregions.

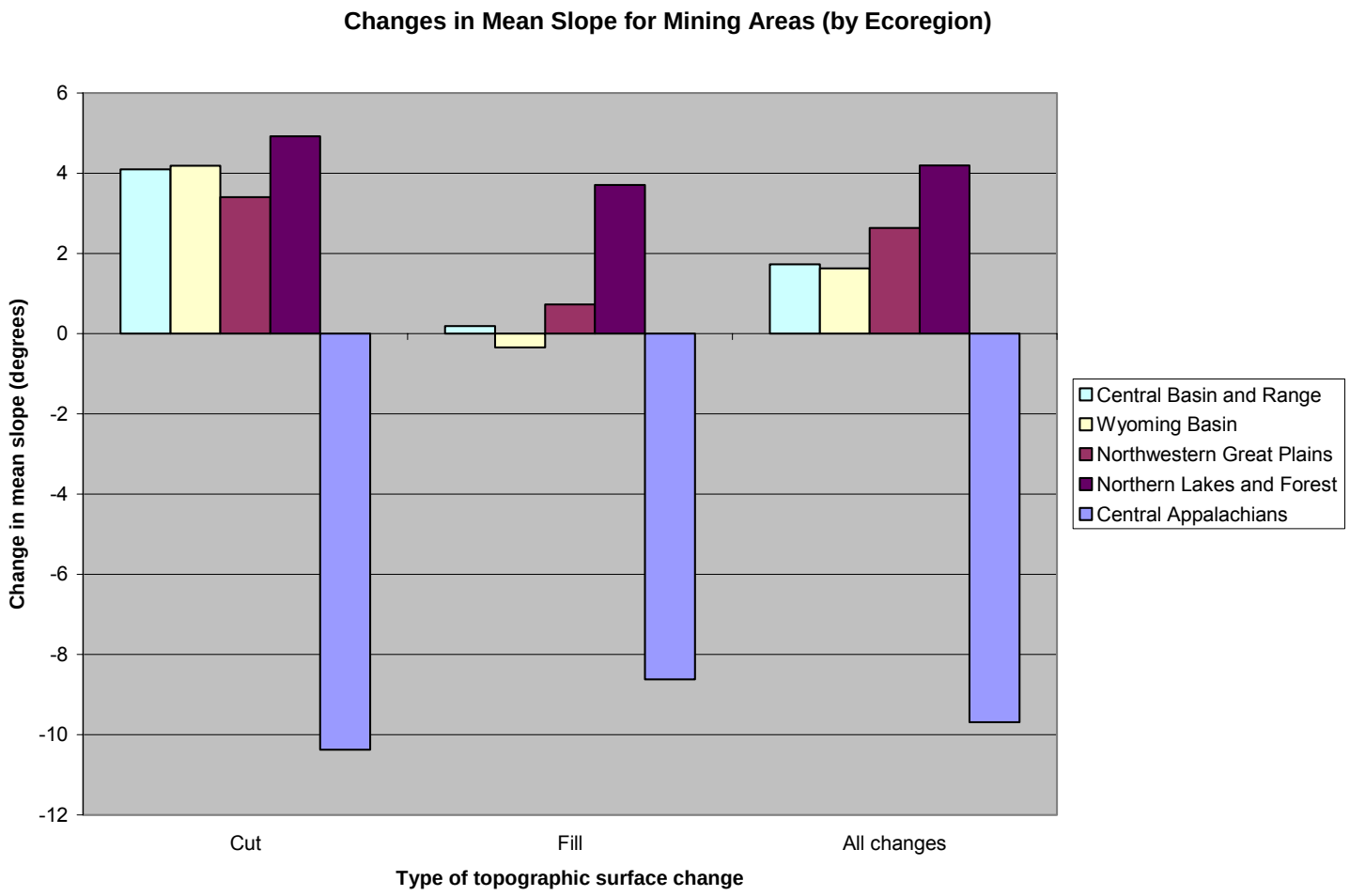


Figure 4.41. Changes in mean slope for mining polygons in five ecoregions.

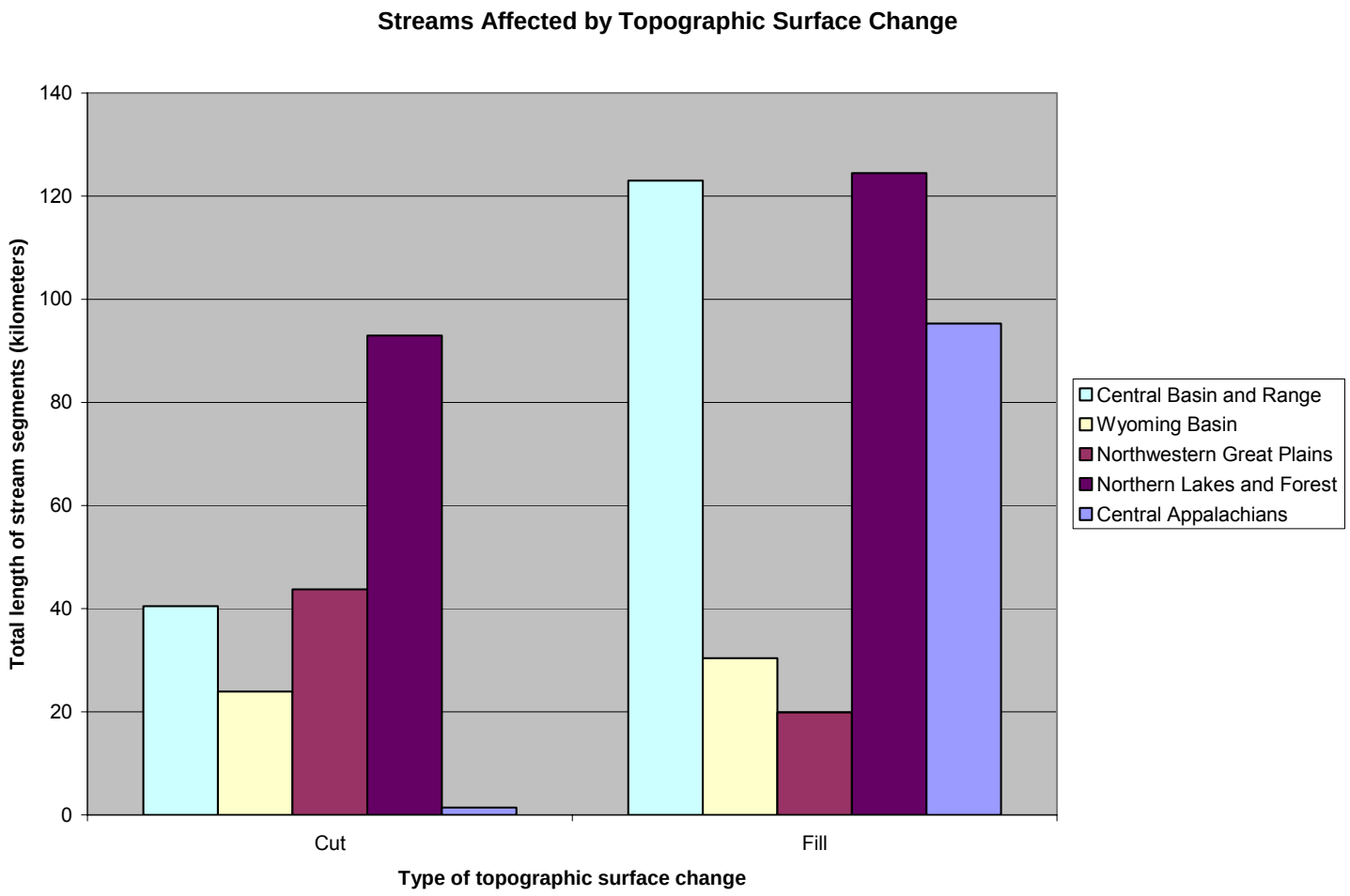


Figure 4.42. The total length of streams affected by topographic change polygons for five ecoregions.

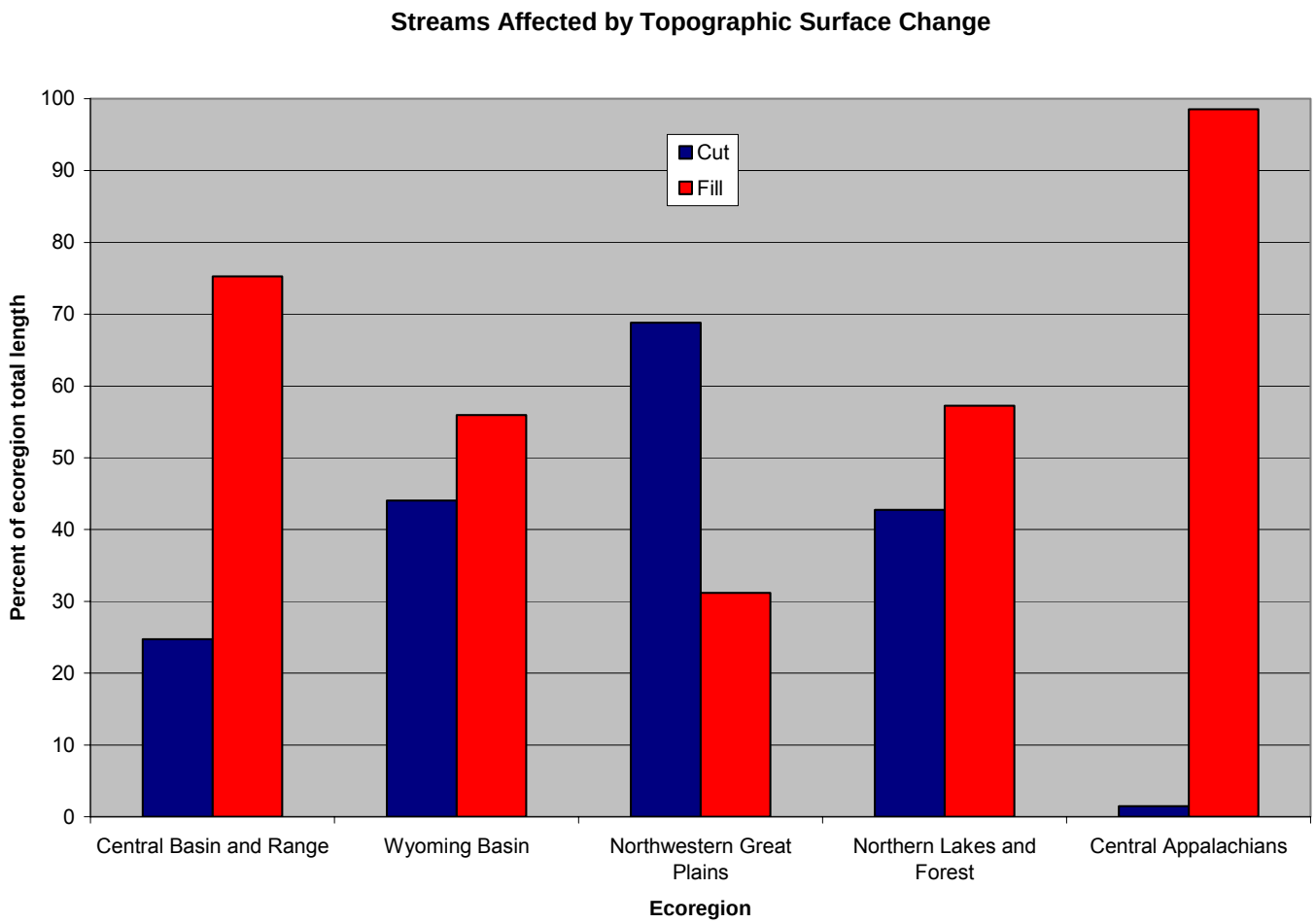


Figure 4.43. Percentage of streams affected by cuts vs. fills for five ecoregions. Note that nearly all the streams affected by topographic changes in the Central Appalachians fall within fill polygons, most of which are likely in valley fills from mountaintop mining operations.

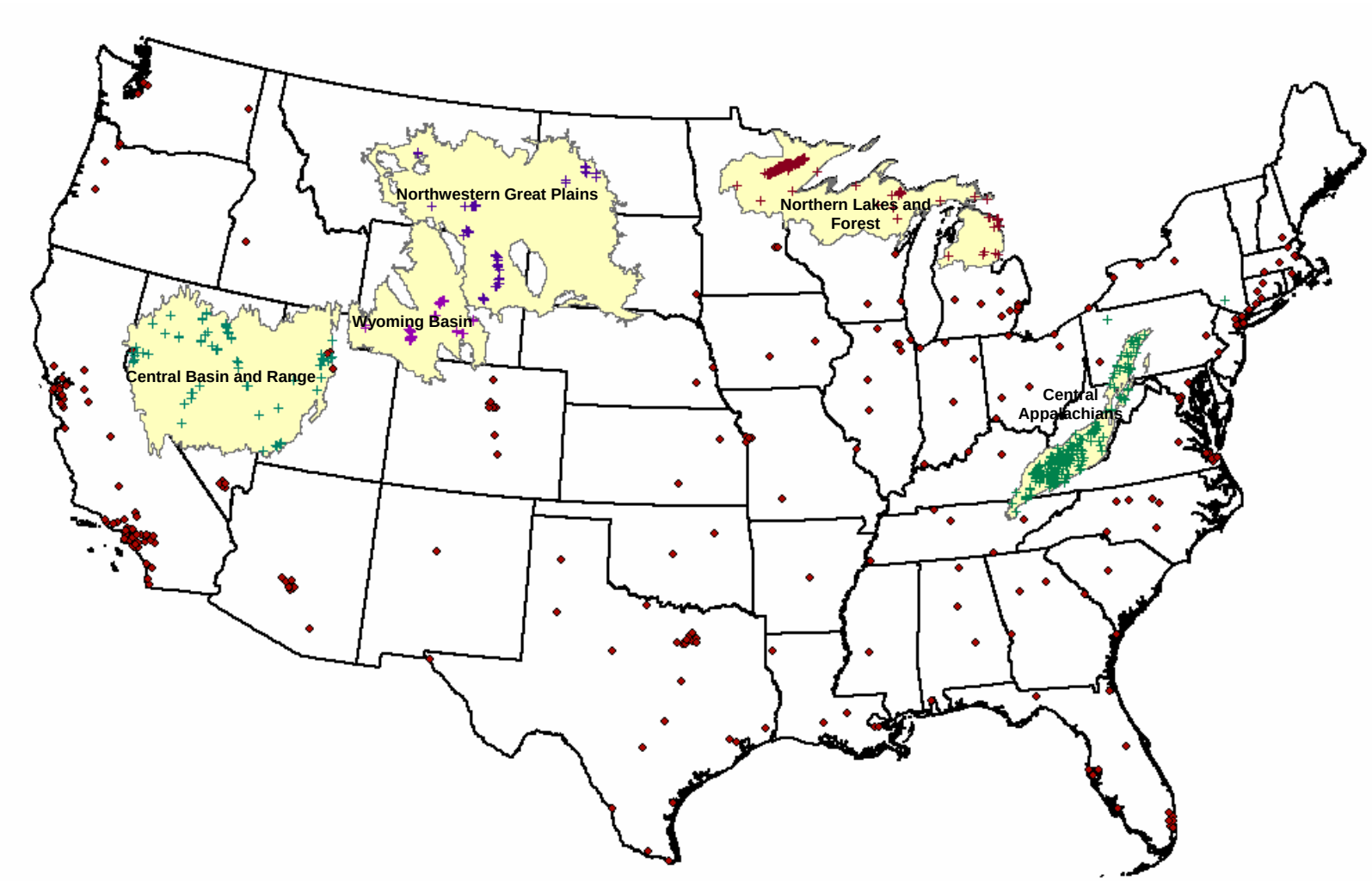


Figure 4.44. Data used to calculate the distance from mines to nearest major city for five ecoregions. Plus signs mark the centroids of mining polygons, and red dots mark the locations of cities with a population of greater than 100,000.

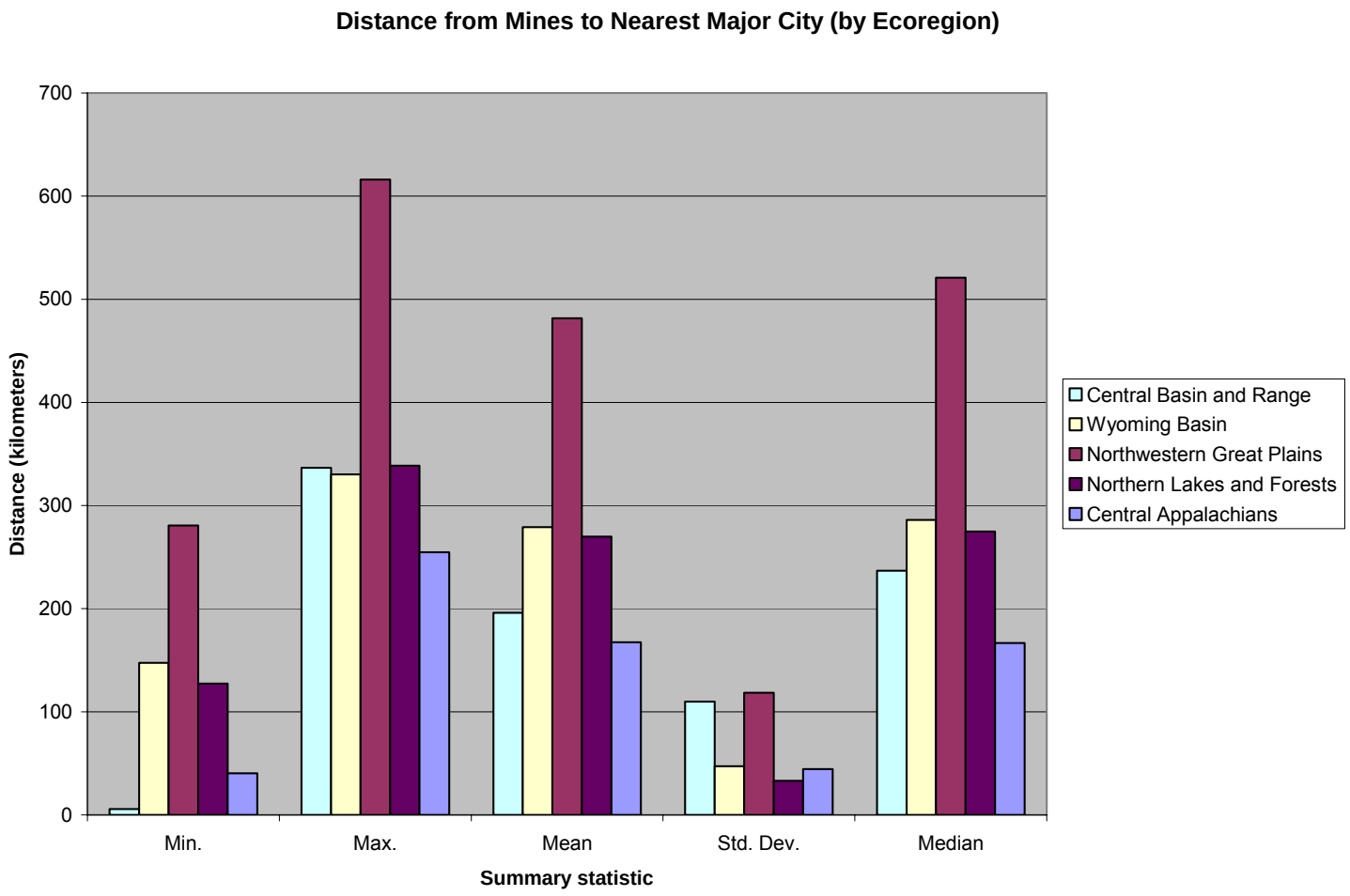


Figure 4.45. Summary statistics of the distance from mines to the nearest major city for five ecoregions.

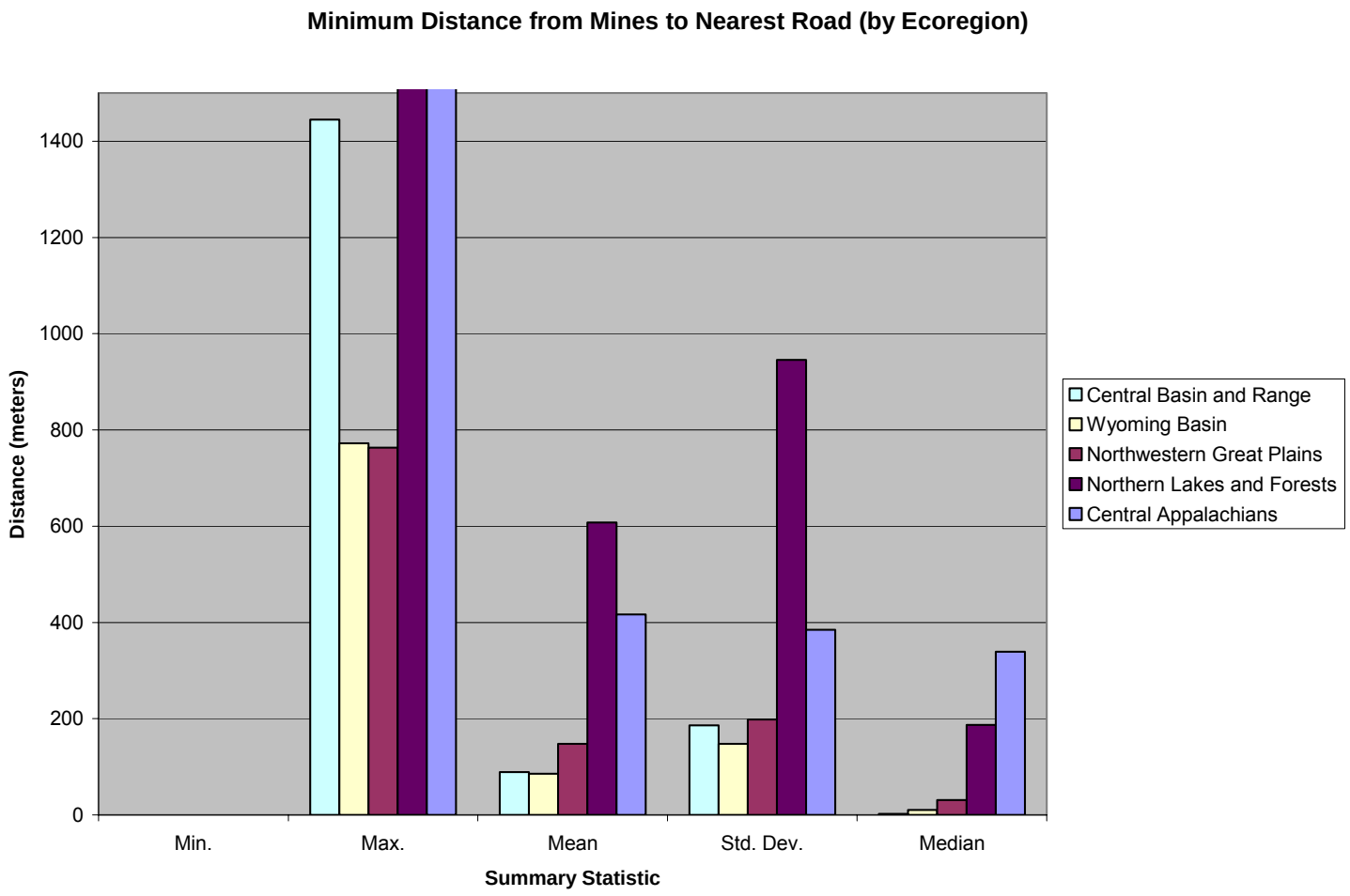


Figure 4.46. Summary statistics of the distance from mines to the nearest road for five ecoregions.

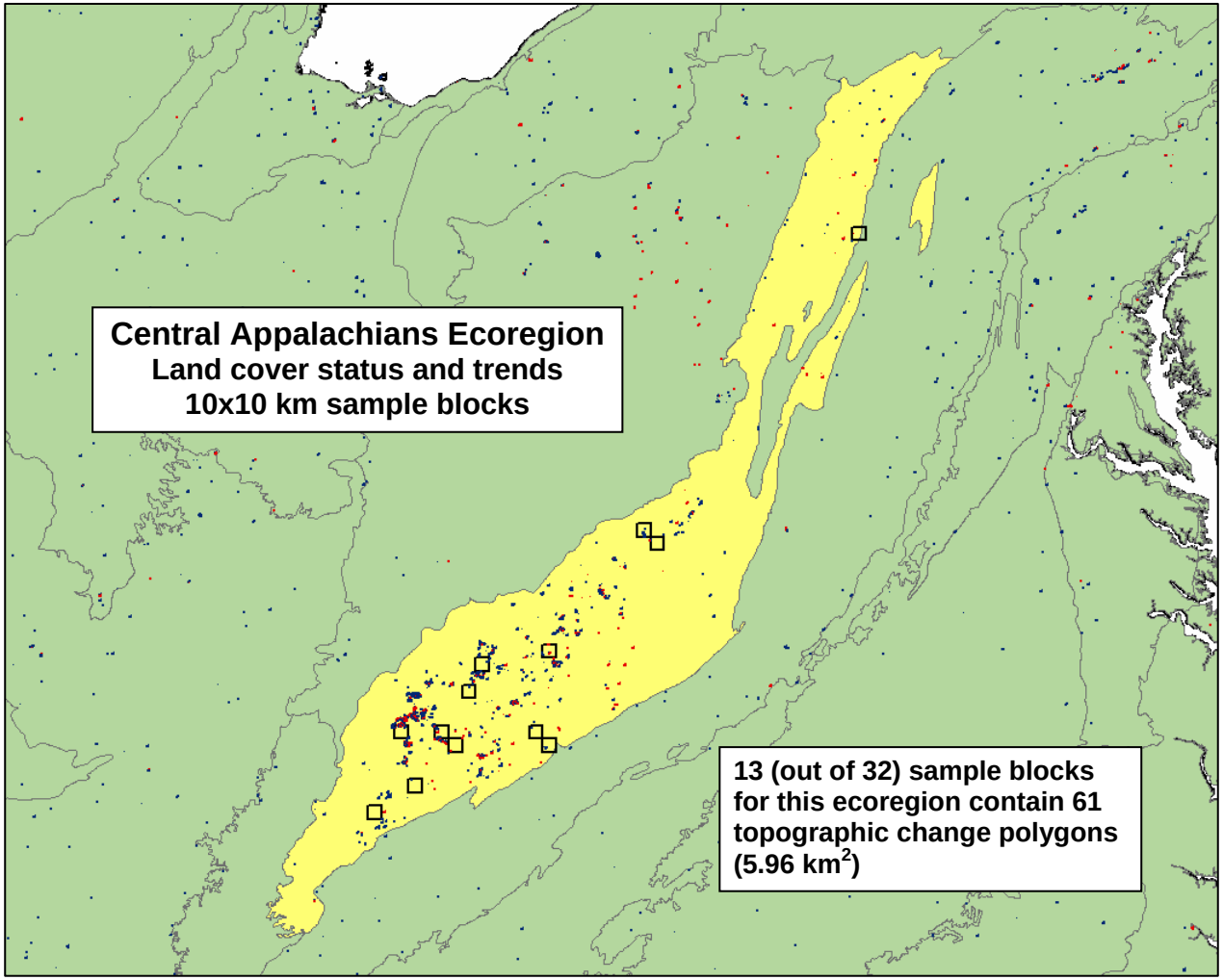


Figure 4.47. Sample blocks from the land cover trends study that contain change polygons. These blocks were used to compare land cover change with topographic change in the Central Appalachians ecoregion.

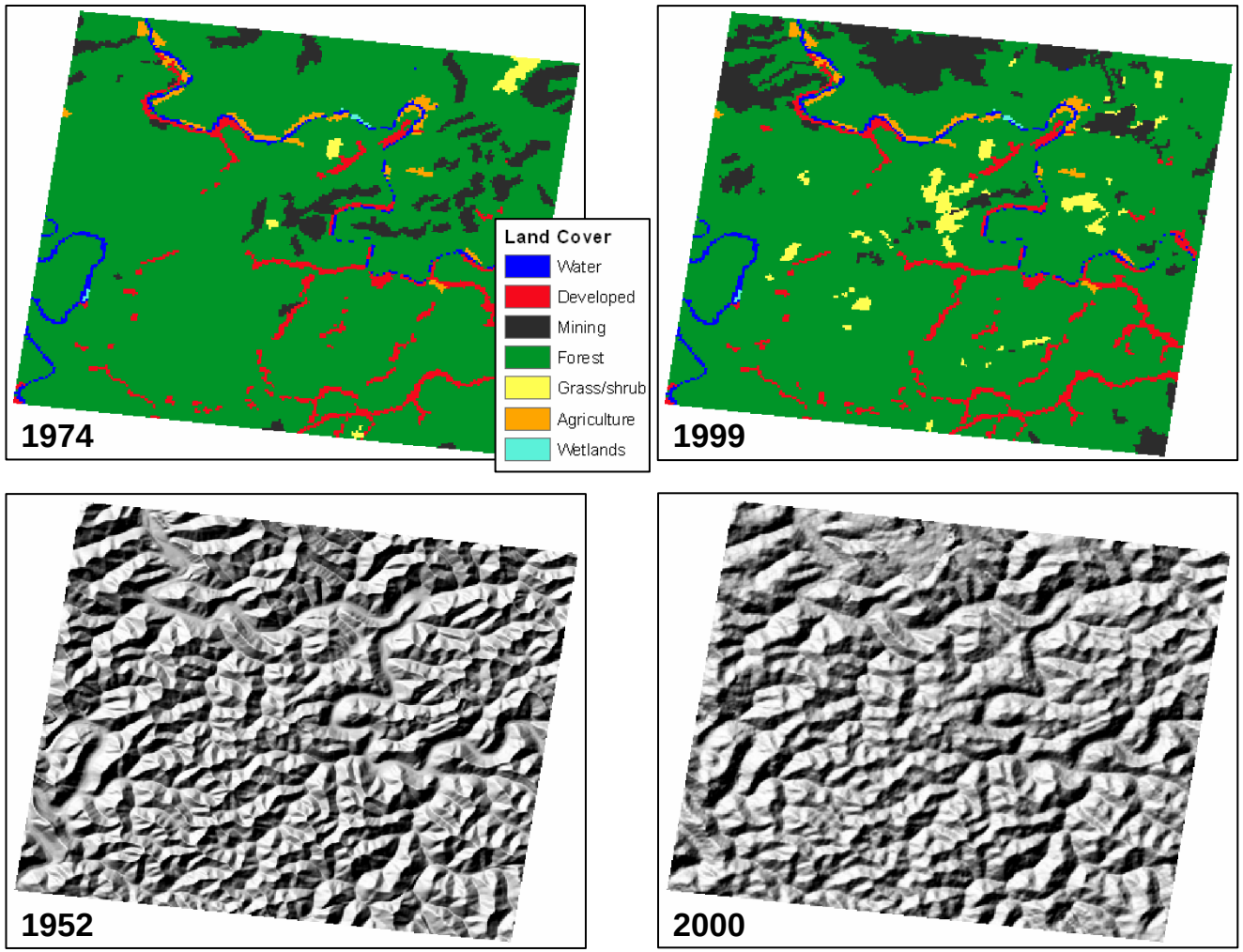


Figure 4.48. Multi-date land cover maps (top row) for one 10x10-km sample block from the land cover status and trends study. This block is located in the Central Appalachians ecoregion. Also shown are NED shaded relief (lower left) and SRTM shaded relief (lower right).

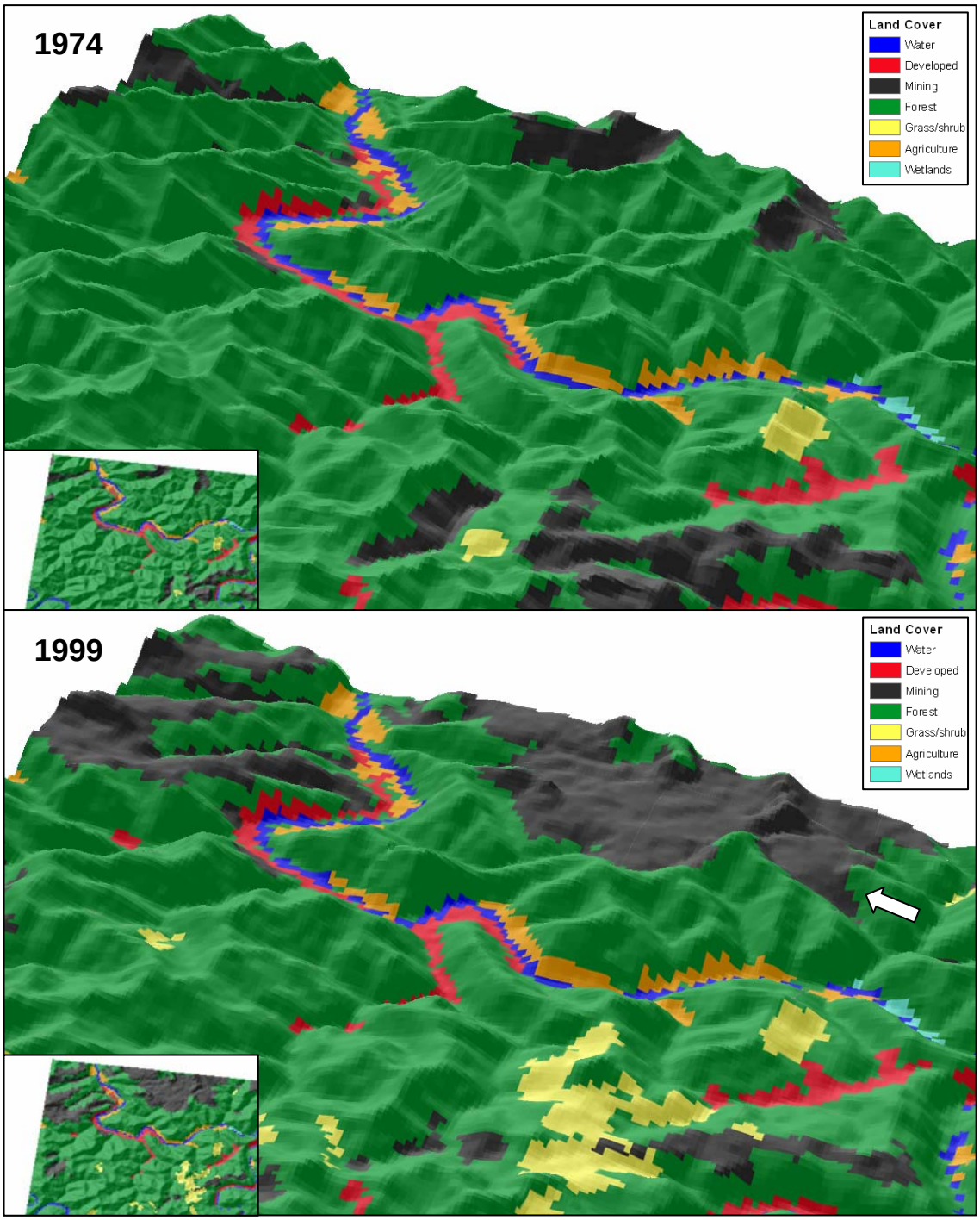


Figure 4.49. Perspective views (looking towards the north) of the sample block data shown in Figure 4.48. The 1974 land cover map has been draped over the NED (top). The 1999 land cover map has been draped over the SRTM data. Note the overall flattening of the landscape in the large mountaintop mining area on the right. The arrow marks a typical valley fill as found in this region.

CHAPTER 5

CONCLUSIONS

The research conducted for this study has resulted in new geospatial datasets that locate and describe significant topographic surface changes in the conterminous United States. In addition, summary statistics and tabulations of changed areas have been produced for several different accounting and reporting units. These results should be useful for researchers working on land change at various scales within the United States. As expected when conducting a study of this extent, several clear paths have emerged for further research related to topographic change monitoring.

Primary Findings

In reference to the primary research issue stated in Chapter 1, 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 non-changed areas.

Although nearly every state and ecoregion contains some features in the topographic change inventory, they are unevenly distributed throughout the conterminous United States (Figure 4.1). The highest concentration of topographic change polygons is found in the mountaintop mining region in eastern Kentucky and southern West Virginia (the Central Appalachians ecoregion). A distinct cluster of polygons is found in the Iron Range in northern Minnesota, resulting from open pit iron ore mining. Several larger groups of change polygons related to surface mining operations are located in Wyoming, northern Nevada, and southern Arizona. Higher densities of change polygons are found near the California cities of San Francisco, Los Angeles, and San Diego, a result of the urban development expanding into higher relief areas adjacent to the cities. Overall, the total area covered by all the change polygons (slightly less than 1,100 square kilometers) is very small (less than 0.02%) compared to the land area of the conterminous United States. However, the topographic change polygons are located throughout the study area,

so the corresponding areas subject to environmental effects of the changes are also scattered throughout the nation. Hence, the dual use of the topographic change inventory is recognized: the national/regional use to present broad patterns of changed areas and summary statistics within larger units (such as ecoregions); the local use to accurately map and quantify the individual topographic change features and associated environmental effects.

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 statements previously made by Hooke (1994; 1999) and Nir (1983) that surface mining is the largest direct anthropogenic 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 within different accounting units, including counties, ecoregions, watersheds, and managed areas (see Appendices). Quantification of the specific changes allows accounting units to be ranked in terms of area or volume of material moved. Geomorphic changes at individual mines likely have been quantified previously, but accumulating and ranking within accounting units provides context with which to compare mining impacts among regions. Table 5.1 lists the top ranked counties in terms of area of topographic changes. In each case, surface mining is the dominant anthropogenic process responsible for the changes, and the primary type of mining has been identified for each county. As with counties, the top ranked ecoregions (Appendix 3), watersheds (Appendix 4), and managed areas

(Appendix 5) in terms of total area of topographic changes are the units that contain numerous large surface mining sites. The topographic change inventory provides spatially explicit evidence of the importance of surface mining as the primary cause of vertical landscape change across the United States. Because of their significant local magnitude and their distribution throughout the nation, these topographic landscape changes should be included in any general discussion of anthropogenic land transformation in the United States.

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. Perhaps this is true for any change detection study over a broad area. 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 (Table 3.4) 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.

The topographic change inventory would be more complete if each change feature was labeled with its origin, such as mining, quarry, road construction, urban development, or landfill. Initially, it was thought that such an attribute could be filled for each feature. However, there is a lack of suitable ancillary data with nationwide coverage to perform such a labeling automatically. Thus, the "where" (mapping) and "how much" (quantifying) questions about United States topographic change have been answered reasonably well, but the "what" (labeling) question is much more difficult to address, especially over such a broad study area. However, the labeling of topographic change features could be accomplished for local or regional areas by interested parties given suitable reference material or local knowledge of landscape processes and conditions.

Topographic change assessment complements traditional land cover change analysis. As the comparison with the land cover status and trends data showed, there is often a close correspondence between topographic change and land cover change. As more high quality, multi-temporal elevation data become available, this study will

provide a foundation for the addition of analyzing the vertical component, or third dimension, of landscape change as a routine part of land transformation studies.

Suggestions for Further Research

As follow-on work to this study is considered, there are some obvious avenues for further research and development that may improve the methods and results for topographic change analysis. As described in Chapters 3 and 4, the thresholding and filtering procedures were developed and implemented for use across the entire study area. Some of the challenges in selecting significant elevation difference thresholds and filtering the results may be lessened if those processing steps are limited to regional or local area application. Ecoregions, or perhaps landform (physiographic) regions, may be a suitable basis for such an approach. The guiding principle in this study for delineating significant change areas was to take a conservative approach by reducing the errors of commission as much as possible. By tailoring the threshold and filter parameters for regional and local areas, the final selection of topographic change polygons may be able to have minimal errors of omission in addition to the minimal errors of commission that were the focus of the current work.

There may be some promise in adjusting the difference grids prior to thresholding if a vertical bias between the SRTM data and the NED can be modeled effectively. The national accuracy assessment completed for this study (Table 3.2 and Figure 3.10) and another comparison of SRTM and NED (Kellndorfer *et al.*, 2004) indicate that an elevation bias does exist for the SRTM data for some land cover classes. Careful measurement of such a bias followed by subsequent adjustment of the difference grids

and thresholds within limited regions may greatly reduce the need for post-threshold filtering to reduce the errors of commission.

As implemented for this study, the post-threshold filtering process primarily relied upon changes in measured terrain parameters (elevation, relief, slope, aspect). There are numerous other higher order terrain descriptors that may have applicability for use in discriminating areas of actual topographic change versus simple elevation difference anomalies. Etzelmuller (2000), Shary (2002), and Guth (2006) describe quantitative measures of surface morphology that can be calculated from gridded elevation data. These descriptors could be calculated from the NED and SRTM data and then compared to see if they are more effective than the basic terrain parameters in distinguishing true topographic changes.

Improved elevation differencing, thresholding, and filtering methods implemented over smaller, more homogenous regions may be useful for more in depth examination of topographic change and its effects at specific sites. The concentrations of topographic change polygons identified from the overall conterminous United States inventory, namely, central Appalachia, northern Minnesota, eastern Wyoming, and urban southern California, should be studied in more detail to fully document the impacts of human geomorphic activity. These studies should include examination of the driving forces behind the topographic changes, and in the context of associated land cover changes, the consequence chain for environmental impacts. An assessment of the accuracy achieved in the topographic change detection process would be a necessary and useful component of the studies. To achieve highly accurate, spatially explicit change maps for specific

study sites, the automated change detection process may have to be augmented with manual interpretation of elevation difference grids, which has been shown to be an effective technique for delineating regional land cover changes (Sohl, Gallant, and Loveland, 2004).

As an alternative to difference grids, Etzelmuller (2000) suggests multi-dimensional classification as a technique to describe topographic surface changes (p. 135):

> A comparable qualitative measure is to classify the surface into homogenous regions, using identical classification parameters for the two data sets which are to be compared. The change of the class sizes and their location can then be investigated.

Such an approach is analogous to post-classification comparisons that have been used to detect land cover changes (Lunetta, 1998; Yuan, Elvidge, and Lunetta, 1998). Classification of the land surface into terrain units based on raster elevation data has been implemented in numerous ways (Blaszczynski, 1997; Irvin, Ventura, and Slater, 1997; MacMillan *et al.*, 2000; MacMillan *et al.*, 2003). Etzelmuller (2000) cites one of the advantages of the classification comparison approach when he describes it as (p. 135) "an especially useful but rough estimate of surface change in areas where it is difficult to distinguish surface changes from differences in DEM quality." It has been shown in this study that the data quality of both the NED and SRTM data is an issue that complicates topographic change detection, so it would be useful to test a landform classification approach with these datasets. The classification approach may also be helpful in delineating an entire disturbed area instead of just the portions of the area that experienced enough elevation change to pass the difference thresholds (Figure 4.4).

Another alternative for change detection that may have some applicability to topographic change is object oriented image analysis. Land cover classification has traditionally been accomplished by grouping individual pixels that have similar spectral characteristics. Recent developments in commercially available software tools provide an object oriented feature extraction approach as an alternative to pixel based techniques for land cover classification and change detection (Gamanya, DeMaeyer, and DeDapper, 2006). Object oriented methods can use diverse input datasets, so they may provide a way to consider elevation differences and land cover maps together to better delineate areas of topographic change.

A logical extension to the type of topographic change analysis reported in this study 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. It is unlikely that a dataset comparable to SRTM, with near global coverage, a consistent data collection method, and a short collection window, will be collected again in the foreseeable future; therefore, the additional time slices of elevation data for topographic monitoring must come from diverse sources. Ideally, these new data will also have much improved horizontal resolution and vertical accuracy over SRTM and NED so that subtle vertical changes in low relief areas can be detected. Such changes are important because in low relief coastal settings even slight changes in surface morphology can have

significant environmental and ecological impacts. Elevation data derived from light detection and ranging (lidar) remote sensing are proving to be quite valuable in environments where high resolution, high accuracy measurements are required to discriminate features with small surface expressions. Multi-temporal lidar data have been successfully used to detect vertical changes in coastal settings with standard elevation differencing (Rosso, Ustin, and Hastings, 2006) and techniques that take advantage of the unique data content of full return waveform lidar (Hofton and Blair, 2002). Future work in topographic change detection and monitoring can take advantage of the lidar and other high resolution, high accuracy data that are continually being integrated into the NED (Gesch, 2006).

Relevance for Anthropogenic Geomorphology

The product of this study is a broad based inventory of specific topographic surface changes resulting from 20th century human geomorphic activity in the United States. Most other studies in anthropogenic geomorphology have concentrated on description and analysis of site-specific geomorphic changes caused by human activities or on comparison of the total effects of humans as geomorphic agents compared to natural agents. The site-specific studies are useful for providing examples of the specific modifications of landforms that result from human activities, while the comparison studies are useful for placing the magnitude of human processes within the context of other ongoing natural geomorphic processes (usually expressed as annual rates of material moved). This study fits into the gap between the site-specific examples of actual anthropogenic changes and the general surveys of human geomorphic agency. The

inventory produced in this study includes quantified land surface change features from human activity at specific locations, but over a broad study area (the conterminous United States). As such, the distribution and patterns of human geomorphic features can be characterized for a large area. Given suitable future collections of multi-temporal elevation data, the inventory sets the stage for ongoing topographic change monitoring in which rates of material moved per unit time can be calculated, as was done in the existing studies of the overall contribution of human geomorphic processes. This investigation contributes to the broad category of geographic studies that document the effects of human action upon the environment. The results from this project should be relevant for any research efforts that consider the general influence of physical geography on natural or cultural phenomena, such as habitat fragmentation, water quality, land use change, and resource extraction.

Rank	County	Area (km^2) of topographic change polygons	Primary type of mining
1	Saint Louis County MN	100.30	iron
2	Campbell County WY	54.75	coal
3	Pima County AZ	43.08	copper
4	Eureka County NV	28.82	gold
5	Pinal County AZ	25.56	copper
6	Gila County AZ	25.43	copper
7	Itasca County MN	24.91	iron
8	Grant County NM	24.53	copper
9	Marquette County MI	19.69	iron
10	Salt Lake County UT	17.15	copper
11	Perry County KY	17.00	coal
12	Greenlee County AZ	13.63	copper
13	Sweetwater County WY	12.68	coal
14	Fremont County WY	9.36	uranium
15	Presque Isle County MI	9.04	limestone
16	Nye County NV	8.62	gold
17	Lander County NV	8.58	gold
18	Pike County KY	8.51	coal
19	Carbon County WY	8.50	coal
20	Lincoln County WY	8.28	coal

Table 5.1. Top ranked counties according to total area of topographic change polygons, with the primary type of mining responsible for the changes identified.

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APPENDICES

Appendix 1. States Containing Topographic Change Polygons

State	Number of topographic change polygons	Area (km^2)	Volume of material moved (m^3)
AL	200	17.26	552,366,107
AR	54	5.69	130,702,949
AZ	319	129.32	8,183,458,220
CA	316	41.22	1,773,279,546
CO	24	8.66	429,114,554
CT	14	1.55	42,591,445
DE	1	0.08	1,394,836
FL	96	15.98	379,374,201
GA	110	12.60	433,366,048
IA	114	9.39	201,069,517
ID	14	4.86	493,058,932
IL	208	21.75	563,219,176
IN	163	16.01	396,549,776
KS	15	1.06	23,032,494
KY	902	61.70	2,442,960,836
LA	8	0.30	5,914,414
MA	51	3.53	83,790,481
MD	50	6.39	236,044,059
ME	35	2.37	53,837,923
MI	191	48.86	1,825,968,430
MN	493	132.03	4,299,523,273
MO	158	12.11	334,460,200
MS	22	1.18	26,521,149
MT	120	22.36	1,043,829,228
NC	105	11.23	374,721,821
ND	34	3.06	57,382,416
NE	33	3.61	87,310,756
NH	20	1.37	27,157,007
NJ	44	3.78	116,578,089
NM	190	45.49	1,755,584,161
NV	182	65.45	4,414,076,802
NY	213	20.53	514,085,814
OH	228	27.38	651,824,036
OK	58	5.25	126,139,087
OR	28	2.25	82,657,834
PA	324	28.75	922,657,052
SC	71	8.72	267,067,009
SD	27	5.12	229,263,093
TN	97	7.51	252,268,593
TX	174	27.48	639,897,329
UT	108	23.45	2,014,169,449
VA	213	17.28	723,726,370
VT	11	0.60	15,336,727
WA	87	9.58	414,914,365
WI	102	9.74	231,756,426
WV	366	33.51	1,420,208,513
WY	335	99.86	2,923,373,070

Appendix 2. Top Ranked Counties (by Area) Containing Topographic Change Polygons

Rank	County	Number of topographic change polygons	Area (km^2)	Volume of material moved (m^3)
1	Saint Louis County MN	265	100.30	3,477,155,632
2	Campbell County WY	92	54.75	1,651,531,417
3	Pima County AZ	61	43.08	2,630,492,815
4	Eureka County NV	40	28.82	2,345,591,454
5	Pinal County AZ	38	25.56	1,621,628,432
6	Gila County AZ	41	25.43	1,488,979,530
7	Itasca County MN	93	24.91	686,020,565
8	Grant County NM	56	24.53	1,063,972,524
9	Marquette County MI	27	19.69	1,158,752,107
10	Salt Lake County UT	25	17.15	1,741,928,391
11	Perry County KY	183	17.00	692,434,013
12	Greenlee County AZ	23	13.63	1,368,226,537
13	Sweetwater County WY	62	12.68	363,607,385
14	Fremont County WY	44	9.36	277,823,422
15	Presque Isle County MI	12	9.04	216,517,261
16	Nye County NV	17	8.62	557,398,827
17	Lander County NV	21	8.58	538,814,347
18	Pike County KY	98	8.51	402,184,458
19	Carbon County WY	27	8.50	291,439,287
20	Lincoln County WY	9	8.28	148,961,344
21	Yavapai County AZ	16	7.55	489,486,287
22	White Pine County NV	22	7.38	404,056,000
23	Breathitt County KY	101	7.34	245,365,734
24	Orange County CA	72	7.11	225,773,295
25	Knott County KY	61	7.04	278,525,361
26	Big Horn County MT	21	6.83	218,793,147
27	Polk County FL	23	6.54	163,430,225
28	Freestone County TX	17	6.50	142,683,660
29	Boone County WV	47	6.36	286,391,646
30	Cibola County NM	21	6.30	189,013,120
31	Silver Bow County MT	14	6.23	319,774,071
32	Logan County WV	42	6.01	281,886,219
33	McKinley County NM	35	5.69	126,768,028
34	Mingo County WV	54	5.52	263,170,544
35	Kern County CA	13	5.48	303,444,892
36	Los Angeles County CA	58	5.45	204,890,267
37	Jefferson County AL	38	5.34	176,068,574
38	Humboldt County NV	25	5.25	218,834,100
39	Santa Barbara County CA	30	5.22	226,257,634
40	Hernando County FL	14	5.19	123,387,712
41	Mohave County AZ	24	4.60	195,324,305
42	Wise County VA	51	4.55	213,584,763
43	Cochise County AZ	15	4.44	245,891,419
44	Moffat County CO	5	4.35	199,557,562
45	Taos County NM	15	4.35	245,782,015
46	Custer County ID	6	4.31	471,108,862
47	Leslie County KY	49	4.24	182,040,701
48	Imperial County CA	22	4.22	151,454,657
49	Lawrence County SD	15	4.06	201,533,260
50	Rosebud County MT	30	3.92	112,277,838

Appendix 3. Top Ranked Ecoregions (by Area) Containing Topographic Change Polygons

Rank	Ecoregion	Number of topographic change polygons	Area (km^2)	Volume of material moved (m^3)
1	Northern Lakes and Forests	427	159.48	5,660,632,828
2	Central Basin and Range	241	87.23	6,348,996,354
3	Central Appalachians	1195	84.36	3,571,256,357
4	Northwestern Great Plains	234	74.05	2,316,077,633
5	Arizona/New Mexico Mountains	146	61.03	3,782,280,752
6	Sonoran Basin and Range	168	52.01	2,829,100,654
7	Wyoming Basin	183	38.44	1,065,094,545
8	Madrean Archipelago	64	37.29	2,456,400,177
9	Piedmont	252	31.91	1,218,793,276
10	Southern and Central California Chaparral and Oak Woodlands	302	30.96	1,277,573,759
11	Ridge and Valley	238	21.93	767,609,243
12	Interior River Valleys and Hills	241	19.41	491,509,815
13	Arizona/New Mexico Plateau	117	19.28	583,941,008
14	Central Corn Belt Plains	181	18.64	471,266,613
15	Middle Rockies	84	18.57	995,901,997
16	Interior Plateau	175	17.21	578,747,123
17	Eastern Corn Belt Plains	105	15.84	394,536,203
18	Eastern Great Lakes and Hudson Lowlands	161	15.42	388,246,407
19	Southern Coastal Plain	76	14.70	352,426,360
20	Northern Piedmont	99	13.70	531,492,456
21	Western Corn Belt Plains	144	13.10	289,042,102
22	Huron/Erie Lake Plains	68	13.00	307,118,124
23	Southwestern Appalachians	142	11.43	349,128,420
24	Southeastern Plains	104	11.09	347,634,317
25	East Central Texas Plains	47	10.68	233,217,245
26	Western Allegheny Plateau	163	9.98	298,686,630
27	Mojave Basin and Range	52	9.55	475,284,948
28	Chihuahuan Deserts	47	8.48	307,073,481
29	North Central Hardwood Forests	68	8.00	166,129,204
30	Southern Michigan/Northern Indiana Drift Plains	100	7.77	161,652,750
31	Southeastern Wisconsin Till Plains	71	6.99	162,762,220
32	Puget Lowland	48	6.91	306,248,319
33	Edwards Plateau	46	6.37	145,298,280
34	Southern Rockies	23	6.23	339,282,679
35	South Central Plains	45	5.74	129,486,331
36	Cross Timbers	44	5.68	145,562,191
37	Colorado Plateaus	36	5.55	275,085,467
38	Northeastern Coastal Zone	68	5.26	126,964,942
39	Middle Atlantic Coastal Plain	46	5.25	122,730,504
40	Central Irregular Plains	66	4.77	108,530,606

Appendix 4. Top Ranked Watersheds (by Area) Containing Topographic Change Polygons

Rank	Hydrologic unit	Number of topographic change polygons	Area (km^2)	Volume of material moved (m^3)
1	04010201 St. Louis	173	72.62	2,576,884,063
2	15050301 Upper Santa Cruz	48	41.49	2,577,331,534
3	05100201 North Fork Kentucky	338	33.02	1,296,534,749
4	07010103 Prairie-Willow	122	31.62	886,274,390
5	15060103 Upper Salt	32	24.36	1,435,744,208
6	16040105 Middle Humboldt	41	21.08	1,771,580,504
7	10120201 Upper Belle Fourche	42	21.02	636,728,241
8	10120103 Upper Cheyenne	22	18.03	503,056,161
9	04030110 Escanaba	24	17.67	1,046,626,136
10	13030202 Mimbres	41	17.50	887,928,418
11	16020204 Jordan	25	17.15	1,741,928,391
12	15050100 Middle Gila	29	14.80	1,072,932,553
13	15040004 San Francisco	25	13.39	1,358,641,454
14	14040105 Bitter	62	12.69	363,688,135
15	16040101 Upper Humboldt	17	11.19	786,037,900
16	05070201 Tug	116	10.98	502,599,340
17	04070003 Lone Lake-Ocqueoc	17	10.89	265,093,327
18	09030005 Little Fork	4	10.16	335,325,534
19	10090208 Little Powder	16	8.32	288,751,029
20	05050009 Coal	57	8.24	371,148,208
21	15050203 Lower San Pedro	10	8.17	439,276,609
22	05070202 Upper Levisa	92	8.04	393,373,473
23	10120101 Antelope	16	7.59	227,088,164
24	16060004 Northern Big Smoky Valley	8	7.58	526,093,591
25	10090101 Upper Tongue	21	7.27	259,818,409
26	10080004 Muskrat	30	7.14	216,373,926
27	15040002 Upper Gila-Mangas	25	7.04	176,090,813
28	10180005 Little Medicine Bow	10	6.92	257,926,180
29	14040108 Muddy	9	6.49	145,827,521
30	13020207 Rio San Jose	22	6.31	189,077,123
31	17010201 Upper Clark Fork	13	6.23	319,759,820
32	05070203 Lower Levisa	67	6.10	283,520,246
33	16040107 Reese	12	6.04	410,614,780
34	05070101 Upper Guyandotte	57	5.93	277,769,490
35	15030202 Burro	12	5.75	416,199,126
36	15020006 Upper Puerco	36	5.68	126,242,129
37	12030201 Lower Trinity-Tehuacana	12	5.67	124,152,398
38	09030001 Rainy Headwaters	15	5.59	145,617,170
39	09030002 Vermilion	20	5.44	223,108,160
40	04100011 Sandusky	22	5.42	125,108,529
41	18060010 Santa Ynez	29	5.15	222,432,027
42	03100207 Crystal-Pithlachascotee	16	4.98	119,242,309
43	03100204 Alafia	20	4.88	121,320,808
44	07120004 Des Plaines	20	4.85	150,494,377
45	18070203 Santa Ana	49	4.70	169,209,675
46	16060008 Spring-Steptoe Valleys	16	4.50	254,784,357
47	10100001 Lower Yellowstone-Sunday	30	4.38	120,285,487
48	14050002 Lower Yampa	5	4.35	199,597,813
49	13020101 Upper Rio Grande	15	4.34	245,685,626
50	17060201 Upper Salmon	6	4.31	471,108,862

Appendix 5. Ranked Managed Areas (by Area) Containing Topographic Change Polygons

Rank	Managed area	Number of topographic change polygons	Area (km^2)	Volume of material moved (m^3)
1	Thunder Basin NG	39	25.61	730,055,018
2	Superior NF	36	13.51	422,287,573
3	Tonto NF	26	12.09	557,524,562
4	San Xavier IndRv	5	8.42	318,740,483
5	Navajo IndRv	43	7.66	189,348,837
6	Laguna IndRv	21	5.93	182,007,602
7	Daniel Boone NF	56	4.98	197,159,348
8	Escanaba River SF	3	4.67	102,530,464
9	Black Hills NF	15	4.06	201,533,260
10	Carson NF	9	3.59	222,815,905
11	Challis NF	4	3.33	367,569,999
12	Jefferson NF	44	2.92	136,440,444
13	Arapaho NF	8	2.32	127,344,879
14	Shoshone NF	7	1.47	41,918,993
15	Lake Superior SF	2	1.05	23,044,600
16	Bear Island SF	4	1.02	28,820,214
17	San Isabel NF	3	0.99	62,470,431
18	Papago IndRv	5	0.91	40,159,022
19	Imperial Sand Dunes RL	8	0.87	21,646,103
20	Toiyabe NF	12	0.75	22,481,901
21	Gila NF	4	0.73	25,570,289
22	Glen Canyon (Utah) NRA	15	0.73	51,035,426
23	Eastern Mojave RL	3	0.68	21,141,939
24	Starved Rock SP	7	0.61	12,246,118
25	Cleveland NF	3	0.47	17,538,008
26	Au Sable SF	3	0.45	8,517,577
27	South Algodones Dunes WSA	3	0.45	10,051,704
28	George Washington NF	3	0.44	32,863,789
29	Chopaka Mountain WSA	2	0.44	26,103,304
30	Patapsco SP	3	0.40	10,651,304
31	Chattahoochee NF	4	0.40	14,720,711
32	Puyallup IndRv	8	0.39	11,285,519
33	Picacho RL	3	0.37	17,763,735
34	Holly SP	4	0.35	7,082,615
35	Deerlodge NF	6	0.35	10,952,547
36	Sierra NF	4	0.35	7,813,199
37	Wilder Ranch SP	6	0.35	8,817,400
38	Coconino NF	4	0.35	11,175,330
39	Hoosier NF	4	0.35	10,264,615
40	Miramar Naval Air Station MilRes	1	0.33	8,421,960
41	Shawnee NF	4	0.32	8,351,676
42	Palisades-Kepler SP	4	0.31	5,638,156
43	Croatan NF	2	0.31	5,513,369
44	Angeles NF	4	0.30	14,329,941
45	Little Miami WScRv	2	0.30	4,796,705
46	Withlacoochee SF	3	0.30	5,447,652
47	Pike NF	3	0.27	7,261,188
48	Richard J. Dorer Memorial Hardwood SF	5	0.27	6,131,947
49	Santa Fe NF	3	0.26	8,536,641
50	Arches NP	1	0.26	8,531,527

Appendix 6. Top Ranked Quadrangles (by Percentage) Containing Topographic Change Polygons

Rank	Quadrangle	Number of topographic change polygons	Area (km^2)	Percentage of map covered by change polygons	Volume of material moved (m^3)
1	kinney_MN	11	20.81	15.92	771,568,895
2	hibbing_MN	50	17.77	13.56	652,463,895
3	inspiration_AZ	21	20.51	12.73	1,265,461,554
4	bingham_canyon_UT	14	15.73	10.66	1,678,558,128
5	aurora_MN	26	11.76	8.99	433,811,630
6	virginia_MN	22	11.75	8.98	457,237,919
7	keewatin_MN	27	10.79	8.24	376,379,676
8	twin_buttes_AZ	26	13.45	8.21	929,592,245
9	reno_reservoir_WY	8	11.15	7.96	308,988,880
10	babbitt_MN	16	9.88	7.57	250,034,129
11	santa_rita_mine_NM	15	12.08	7.44	741,251,592
12	rodeo_creek_ne_NV	16	10.79	7.38	950,479,835
13	san_xavier_mission_AZ	6	11.67	7.13	524,077,771
14	ishpeming_MI	11	9.36	7.02	420,728,335
15	bovey_MN	28	8.56	6.52	205,887,563
16	schroeder_mountain_NV	14	9.38	6.41	694,074,987
17	clifton_AZ	16	10.29	6.36	1,089,674,727
18	palmer_MI	13	8.49	6.36	630,989,026
19	saddle_horse_butte_WY	16	8.82	6.34	236,032,148
20	esperanza_mill_AZ	6	10.30	6.28	522,878,757
21	hot_tamale_peak_AZ	12	10.11	6.25	792,347,051
22	rodeo_creek_nw_NV	4	7.41	5.07	654,454,527
23	round_mountain_NV	6	7.50	4.97	523,561,298
24	eveleth_MN	11	6.46	4.93	249,806,225
25	piney_canyon_nw_WY	12	6.81	4.87	191,791,467
26	the_gap_sw_WY	9	6.60	4.75	222,824,442
27	bagdad_AZ	12	7.19	4.52	479,000,744
28	krypton_KY	66	6.44	4.19	273,265,286
29	rawhide_school_WY	11	5.78	4.18	203,395,672
30	rogers_city_MI	6	5.64	4.15	135,408,269
31	mccoy_NV	11	5.99	4.06	409,246,955
32	moss_agate_reservoir_WY	9	5.75	4.02	212,485,606
33	kemmerer_WY	4	5.78	4.01	17,931,347
34	decker_MT	15	5.09	3.72	172,448,374
35	teckla_WY	7	4.84	3.45	151,551,565
36	calumet_MN	16	4.35	3.31	129,608,462
37	noble_KY	56	5.00	3.26	195,208,335
38	moquino_NM	14	5.12	3.24	159,258,719
39	tyrone_NM	16	5.20	3.20	106,241,577
40	gas_hills_WY	11	4.54	3.20	149,402,865
41	tse_bonita_school_NM	25	4.94	3.15	111,629,830
42	thompson_creek_ID	6	4.31	3.11	471,108,862
43	buhl_MN	17	3.96	3.02	100,759,668
44	lompoc_hills_CA	22	4.62	2.90	206,426,434
45	donie_TX	13	4.74	2.88	97,883,484
46	wind_mountain_NM	13	4.67	2.87	147,251,135
47	eskdale_WV	24	4.32	2.85	202,831,622
48	black_buttes_WY	27	4.10	2.83	107,297,694
49	vest_KY	20	4.33	2.82	169,100,244
50	pengilly_MN	16	3.45	2.63	79,897,945