Landscape Volumetrics and Visualizations of the Butte Mining District, Montana

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ABSTRACT

The topography of the Butte Mining District, Montana, has been extensively altered by placer, underground, and open-pit mining since 1864. The earliest known large-scale topographic mapping showing the Butte area was conducted by the U.S. Geological Survey (USGS) in 1895 and published in 1897. In 1903, the map coverage was extended several miles east and west, cultural features were revised where necessary, and the map was published in 1904. The most detailed elevation mapping was produced with photogrammetric techniques in 1989 and 1991 by Horizon, Inc. This study uses these two sets of topographic data to measure and visualize volumetric changes of the landscape. Patterns of change associated with the relatively small volume of material filling Butte's Missoula Gulch and earthworks for highway construction unrelated to mining closely match expected locations, patterns, and thicknesses. The model also estimates the area and allows for visualization of large areas of altered landscape, such as the Berkeley open-pit copper mine and the Yankee Doodle tailings dam. This model provides a visual overview and first-pass assessment tool for an area with multiple environmental concerns, including groundwater and soil contamination, leaching of metals from mine tailings and waste rock, and associated impacts on surface water from runoff.

INTRODUCTION

Calculating and mapping changes in volumes of earth materials have long been of interest to engineers and geoscientists. In some cases, such analyses are referred to as cut-and-fill. Although this terminology is commonplace, it is worthwhile to clarify different usages among disciplines. In mining engineering, for example, cut-and-fill can refer to various underground mining techniques, such as cut-and-fill stoping and undercut-and-fill mining (Hustrulid, 1982; Hustrulid et al., 1989), while in sedimentology, scour-and-fill structures associated with erosion and deposition on channel bottoms have been referred to as cut-and-fill structures (Reineck and Singh, 1986).

In this study, volumetric analysis is most closely aligned with cut-and-fill analyses related to earthworks (Coduto, 1998), especially in the field of transportation engineering (Banks, 2001; Papacostas and Prevedouros, 2000). Such analyses are generally done from a planning perspective, and they are designed to minimize waste (Ferguson et al., 1995). Some studies assume an existing route and consider factors of additional importance such as soil properties (Goktepe and Lav, 2004), simulated activity sets (Askew et al., 2002), and refined geometric designs (Goktepe and Lav, 2003; Easa, 1998; and Hassan et al., 1998). Other methods select and optimize various metrics with computationally intensive applications such as genetic algorithms (Jha and Schonfeld, 2004), simulated annealing (Henderson et al., 2003), and linear programming (Moreb, 1996; Son et al., 2007). Methods that seek to optimize (i.e., minimize) construction costs have received an understandably large amount of attention (Alkass and Harris, 1991; Liu and Sessions, 1993; Akay, 2003; Yabuki and Shitani, 2005; and Stückelberger et al., 2006).

Geoscientists, however, most frequently use volumetric analysis to accurately measure changes in volumes of earth material resulting from geologic processes. Examples include volumetric studies of coastal sediment yield and flux (Brown and Arbogast, 1999; Newsham et al., 2002), flood-tide delta bathymetry (Wheeler, 2005; Wheeler and Peterson, 2006), alluvial deposits (Brasington et al., 2000; Fryirs and Brierley, 2001), erosion from extreme rainfall events and deposition from landslides (Martinez-Casasnovas et al., 2002; Korup et al., 2004), glacial variations with time (Mennis and Fountain, 2001), and lava flows (Stevens et al., 1999).

Both geoscientists and engineers use geographic information systems (GIS) in performing such anal-

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yses. Numerous studies use GIS in computational methods to optimize transportation planning and earthwork (e.g., Chan and Fan, 2003; Gumus et al., 2003; and Jha and Schonfeld, 2004). Mennis and Fountain (2001) explicitly underscore the importance of GIS database development for such temporal change studies. Additionally, the ability of GIS to provide visualizations of such volumetric changes is also important (Burton and Shell, 2000; Jha et al., 2001). Much research focuses on the best use of such visualizations, including using such displays to address complexity/interrelationship/interaction issues (Buttenfield and Mackaness, 1991; Ervin, 2001; and Lo and Young, 2002).

In this study, volumetric analysis is accomplished using GIS software to quantify and visualize changes in the landscape of the Butte Mining District, Montana, associated with surface, subsurface, and open-pit copper (and less extensive silver) mining since 1895–1903. Previous studies have estimated mining volumes associated with mine stockpiles (Jordan, 2002) and pit excavations (Easa, 1998) by comparing two modern-day data sets. Other studies have looked at properly positioning historical maps in a GIS environment to quantify change (Balletti, 2000) and visualize past landscapes (Fuse et al., 1998; Shimizu et al., 1999; and Shimizu and Fuse, 2003). This study does both, using mapped data from 1989–1991 and data from 1895–1903 to obtain detailed volumetric measurements and provide visualizations of the spatial relationship between landscapes of the past and present.

This study reconstructs the relatively undisturbed terrain of Butte in the late 1800s to early 1900s by georeferencing a U.S. Geological Survey (USGS) map of 1895–1903 and building a terrain model from this source. This landscape is then combined with digital elevation models (DEMs) from a 1989–1991 survey to document volumetric variations associated with mining activities in Butte. A factor of particular interest is the extensive amount of material removed from the Berkeley open-pit copper mine (Berkeley Pit). Much of this material was used in the construction of the Yankee Doodle tailings dam, although other deposits of mine tailings and waste rock are distributed throughout the area.

METHODS

This study focused on changes in the landscape of the Butte Mining District, which began with placer mining in 1864. Although much of the most intensive changes did not occur until the open-pit copper mining phase, which created the Berkeley Pit between 1955 and 1982, this study was designed to document as much historical change as possible. Thus, an initial DEM of Butte was based on a USGS topographic map surveyed in 1895 and published in 1897, with extensions surveyed in 1903 and published in 1904. This map was surveyed using plane table and alidade, with distances measured with stadia crosshairs and rods (stadia intercept method), and elevations measured by measurements from a Beaman arc reduced to the station level. All of these methods were common at the time, but they are naturally crude compared to modern-day photogrammetric methods, and fraught with potential error. Figure 1 shows the portion of this map that later became the Berkeley Pit, including Butte Hill, the topographic high in the central portion of the map capped by the Mountain View mine.

This topographic map, a part of the Butte Special Folio of the *Geologic Atlas of the U.S. States* (U.S. Geological Survey, 1897), has a contour interval of 20 ft (6 m). It also shows benchmarks, hydrologic features, roads, railroads, and buildings. This map was separate from a geologic map of the area in the same folio, which included geologic units and outcrops of copper and silver veins. The 1895 (1897) topographic map was extended and revised in 1903 and published in 1904. This extended version of the topographic map was scanned for use in the volumetric model.

The 1897 and 1904 edition maps were in the polyconic projection commonly used by the USGS at that time. It was first necessary to georeference the scanned map image to this coordinate system. An affine transformation based on 13 control points including benchmarks and section corners was used for optimal placement. Affine transformations are linear operations that allow for scaling, rotation, or shearing of the original and entire map; no non-linear transformation was used, nor was any additional transformation applied to specific portions of the map. Although the paper source map was more than a century old, the georeferenced map achieved a root mean square error (RMS) of 3.14 m (10.3 ft).

Once georeferenced to the coordinates of the paper map, the 20 ft (6 m) contours, benchmarks, roads, and railroads were digitized into a GIS. These data layers were then projected from the USGS polyconic to the Montana (North American datum 1983) state plane coordinate system. These GIS layers were overlain with and compared to well-controlled federal, state ,and local GIS layers. Butte road layers based on U.S. Census Bureau (2010) TIGER files were especially useful for comparisons with historical roads.

It was necessary to include an offset in the x and y directions to account for issues with the original map. Benchmarks and other control points used in the 1895

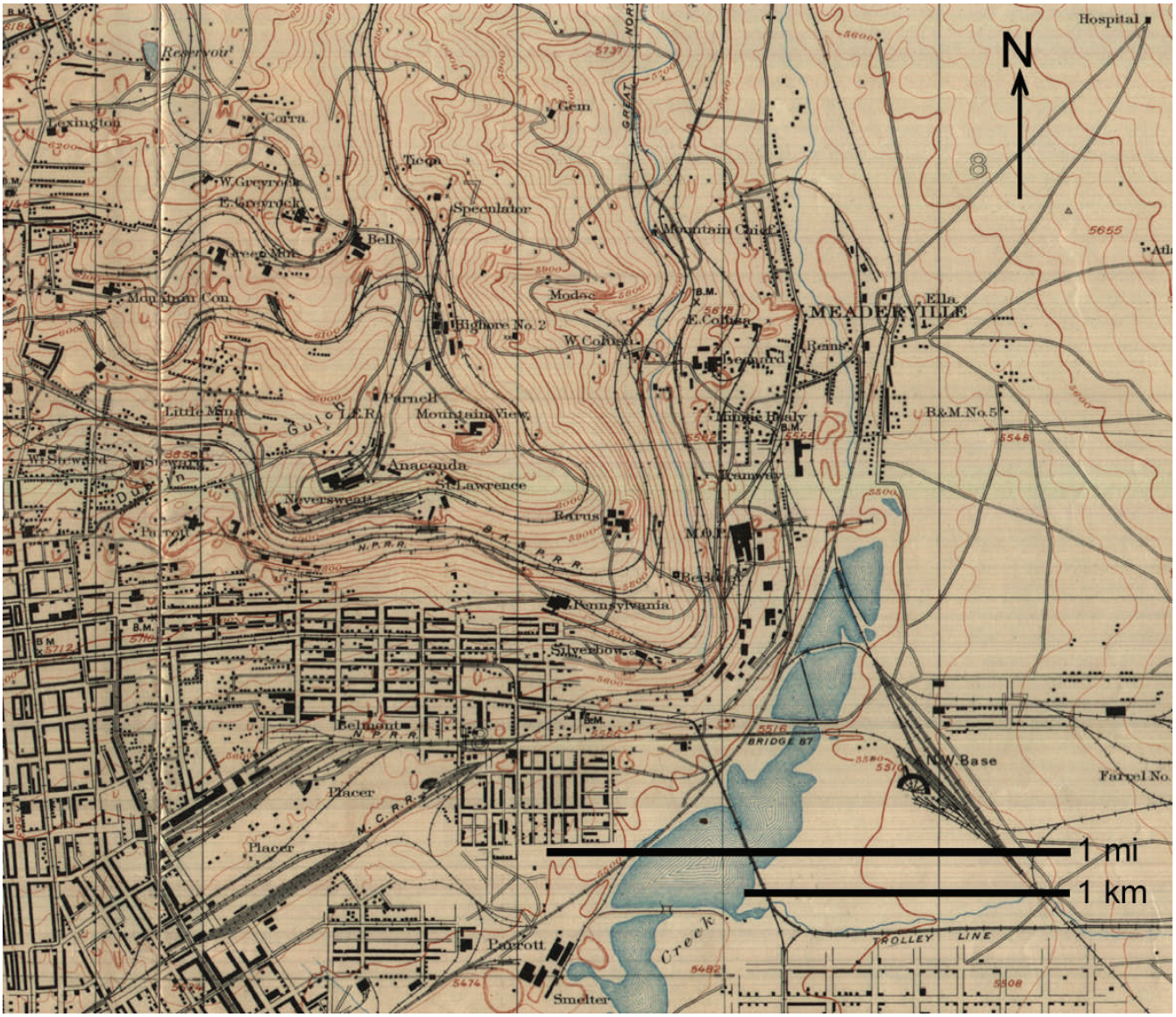

Figure 1. A portion of the topographic map included in the Butte Special Folio of the *Geologic Atlas of the United States*, published by the USGS in 1897 at a scale of 1:15,000. The portion of the map is centered on Butte Hill and the Upper Silver Bow Creek Valley. The 20 ft (6 m) elevation contours are shown in brown.

and 1903 surveys were assigned coordinates before the first North American datum of 1927 and were based on historical surveying techniques in a local area. By plotting a number of these control points in their 1983 datum position, it was possible to calculate average offsets in the x and y directions of -88 m and 223 m, respectively. Offsets showed variability, but applying these average corrections to the projected map resulted in a satisfactory fit, without requiring any variable offsets within the map area, a procedure called ''rubber sheeting.'' Such a process is necessary to fit historical data or data that are poorly referenced spatially (e.g., Shimizu and Fuse, 2003). Indications of quality of fit were examined by matching road centerlines on the 1904 edition to those roads still present in Butte and documented in the U.S. Census Bureau TIGER files.

One efficient method to calculate volumetric changes is to compare elevation grids from two different times. A simple example is included in Figure 2, where the original (A) and final (B) elevation data are stored as grids covering the same location at different times. A volumetric map (C) can easily be calculated as the difference between the old and new grids. In Figure 2C, areas of decreased volume (cut) are represented by hachured patterns, and areas of increased volume (fill) are represented by stippled patterns. Another geographic data model, the trian-

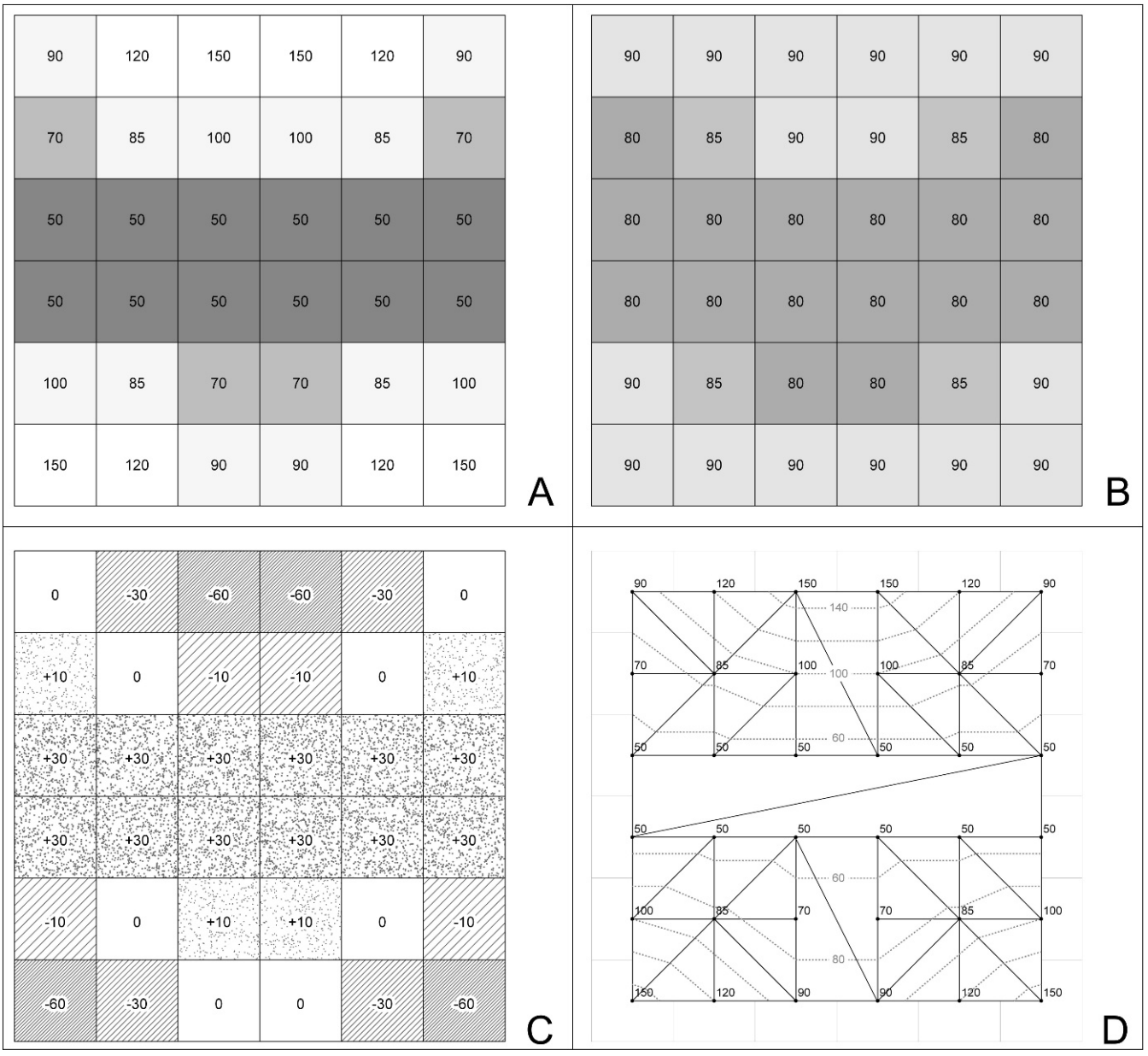

Figure 2. Various GIS data models used to represent terrain. Original topography is represented by a regular grid in (A), with values equal to elevation. Altered topography is represented by a similar grid in (B), but with new elevation values related to addition or removal of material. Volume differences are shown in (C), with areas of decreased volume (cut) represented by hachured patterns, and areas of increased volume (fill) represented by stippled patterns. The triangulated irregular network (TIN) data model is useful for transitioning between grid and contour formats. The TIN shown in (D) is an alternative representation of the original topography grid (A). Areas lacking slope or with constant slope can be represented by fewer, larger triangles.

gulated irregular network (Weibel and Heller, 1991; Clarke, 1995; Price, 1999; and DeMers, 2003) or TIN, is often used to convert grids to contours, or contours to grids. Figure 2D is a TIN representation of Figure 2A. In this example, centers of grid cells are potential vertices of triangles. Flat areas or areas of constant slope require fewer, larger triangles.

In a similar manner, the 20 ft (6 m) contours from the 1904 map were transformed into a TIN and then into a grid for more efficient comparison with a modern-day DEM. The TIN uses digitized points along the contour lines to build a continuous mesh of triangles of various types and sizes. This operation linearly interpolates elevations between points or vertices of known value, essentially creating triangles of constant slopes. Each resulting triangle has a known orientation (slope and aspect) in three-dimensional (3D) space.

Although TINs are efficient at storing topographic data (McCullagh, 1998), they do not offer the optimal

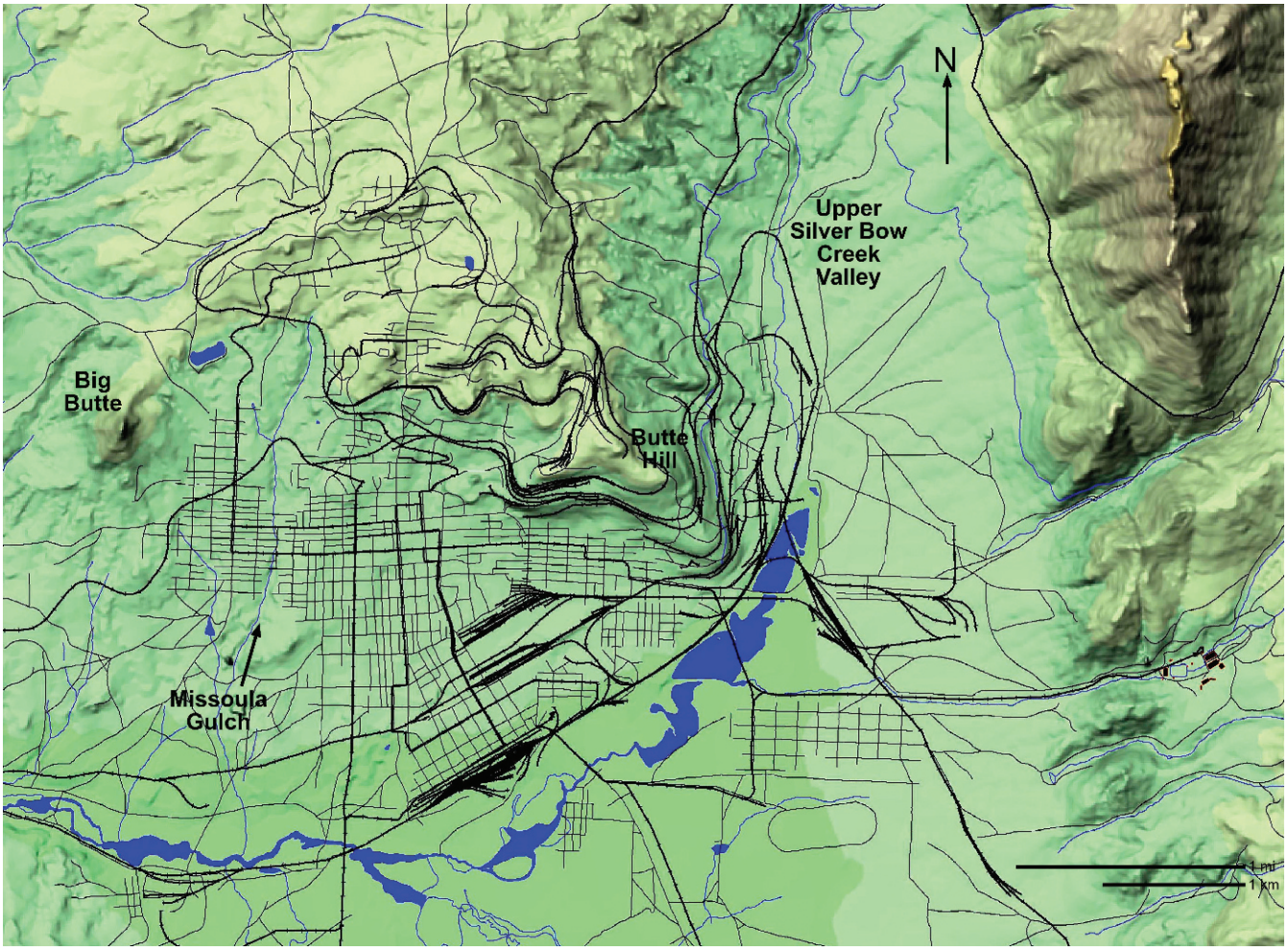

Figure 3. A map displaying the relatively unmodified landscape of the Butte Mining District circa 1897. A gridded digital elevation model (DEM) was derived from a triangulated irregular network (TIN) built from the historical elevation contour lines shown in Figure 1. The terrain was layer tinted and hill shaded for improved visualization. Butte Hill is the promontory at the southeast end of the topographic high. The Upper Silver Bow Creek follows the central blue line to the east of Butte Hill.

data model for comparing surfaces made from different data sources (Chang, 2009; Longley et al., 2011). The TIN was thus converted to a grid format, consisting of a regular pattern of 10 m by 10 m grid cells or pixels, each assigned to an interpolated elevation value from the TIN. Using this DEM, overlain with hydrology, roads, and railroads from the 1904 edition map, it was possible to create the terrain map of the Butte Mining District of 1897/1903 shown in Figure 3. The DEM shows color varying with elevation, a method called layer tinting (Imhof, 1982; White, 1985; and Kennelly and Kimerling, 2004), and changes in slope and aspect are shown with variable shades of gray, a method called hill shading (Yoeli, 1965; Horn, 1981; Robinson et al., 1995; and Slocum et al., 2008).

The most detailed elevation data for the Butte Mining District was collected by Horizon, Inc., in 1989 and 1991. With the use of photogrammetry, the resulting data set consisted of 2 ft (0.6 m) contours in the Montana state plane coordinate system. These contours were converted to a TIN and then a grid using the same methodology described previously (Figure 4).

The only locale within the mapped area for which the Horizon data were not the most detailed available was beneath the water surface of the flooded portion of the Berkeley Pit. Once open-pit copper mining ended in 1982, active pumping of water to keep the pit dry was discontinued (Gammons et al., 2006a). As a result, the Horizon surveys of 1989–1991 show elevations for the top of the water level at that time in the central pit area (purple area in Figure 4), but not the bathymetry beneath. To complete the modern terrain model, 100 ft (30.5 m) contours from blue line maps compiled in 1977 by the Anaconda Mining Company (AMC) were used. These contours were combined with the Horizon 1989–1991 data by the

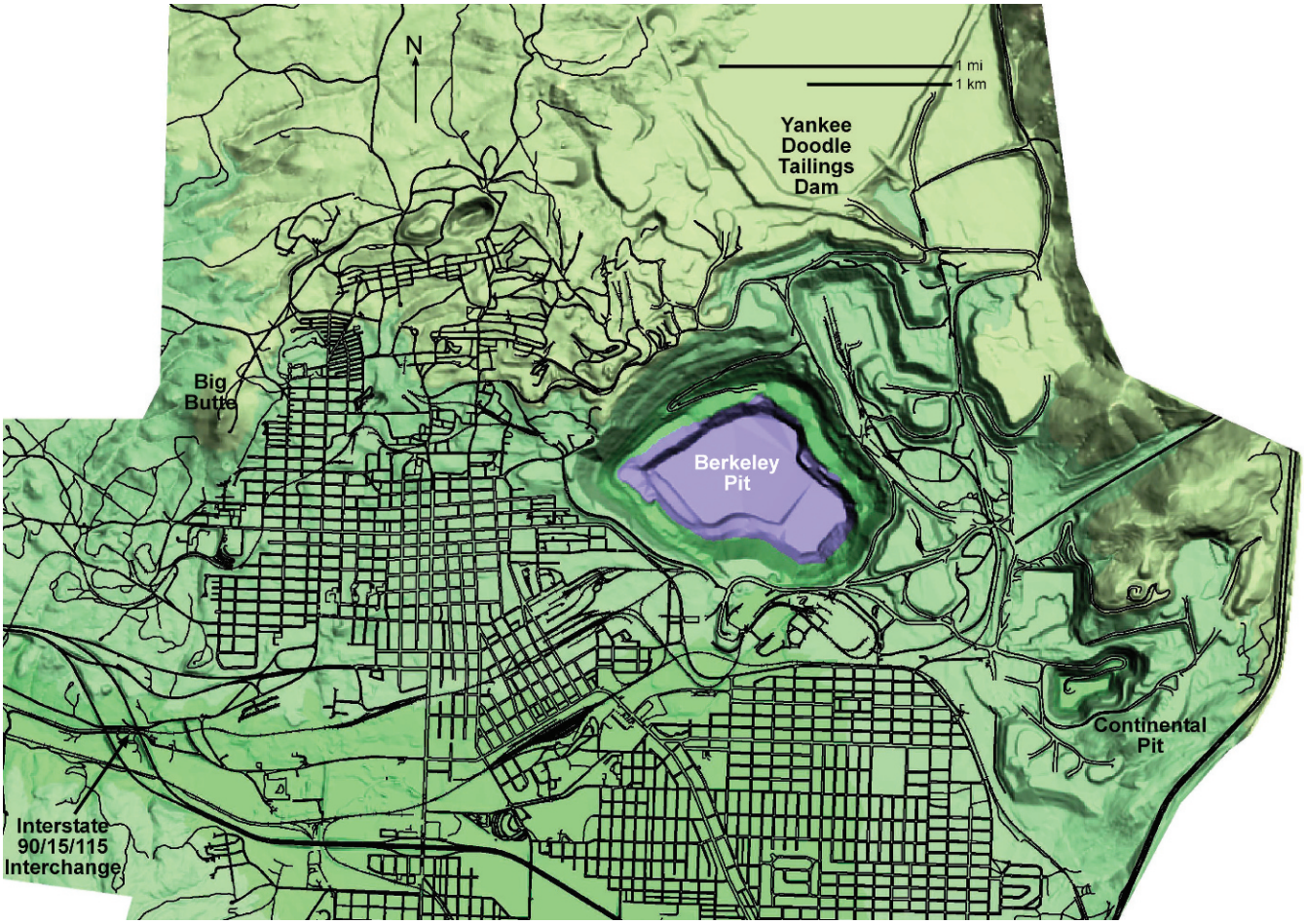

Figure 4. A map displaying the highly modified landscape of the Butte Mining District circa 1991. A gridded DEM was derived from a detailed survey conducted by Horizon, Inc., between 1989 and 1991. The lake in the Berkeley Pit is colored in purple and represents the water level near the time of the Horizon survey.

Montana Natural Resource Information System (NRIS).

Two separate grids were created from the combined contours. One grid was created using 10 m grid cells so that each grid cell of the Horizon data would directly overlie a cell in the grid created from the 1904 edition map. A second, more detailed grid was generated to show variations that are solely a function of the current terrain mapped by Horizon, Inc. The map shown in Figure 5 is the result of combining the Horizon and AMC contours using 1 m grid cells.

For visualizing the modern terrain, however, it is desirable to show as much detail as possible. The map shown in Figure 5 was created with the same Horizon and AMC contours, but it was mapped with 1 m by 1 m grid cells. This represents the most detailed rendering possible of the current morphology of the Berkeley Pit's topography and bathymetry. The unlabeled white lines in Figure 5 are 20 ft (6 m) contours from the USGS 1897 map, and they include the highest portion of Butte Hill from Figure 1.

RESULTS

Subtraction of the DEM from the Horizon survey from the DEM created from the 1904 USGS edition map creates a volumetric model of the Butte Mining District (Figure 6). The geographic extent of the model was determined by the Horizon survey, which fell within the extent of the USGS map shown in Figure 3.

In creating a volumetric map display, it is important to consider the accuracy of both data sets. The Horizon data, mapped at a scale of 1:6,400 and a 2 ft (0.6) contour interval, should easily be the more accurate of the two. The USGS map is at a scale of 1:15,000 and has a contour interval of 20 ft (6.1 m). The accuracy of the elevation data from the USGS 1904 map is uncertain, since it was generated prior to the U.S. National Map Accuracy Standard of 1941. This standard states that 90 percent of all elevation data should be within one half the contour interval used for mapping, and there is no reason to believe it meets this criterion. The resulting map (Figure 6) uses

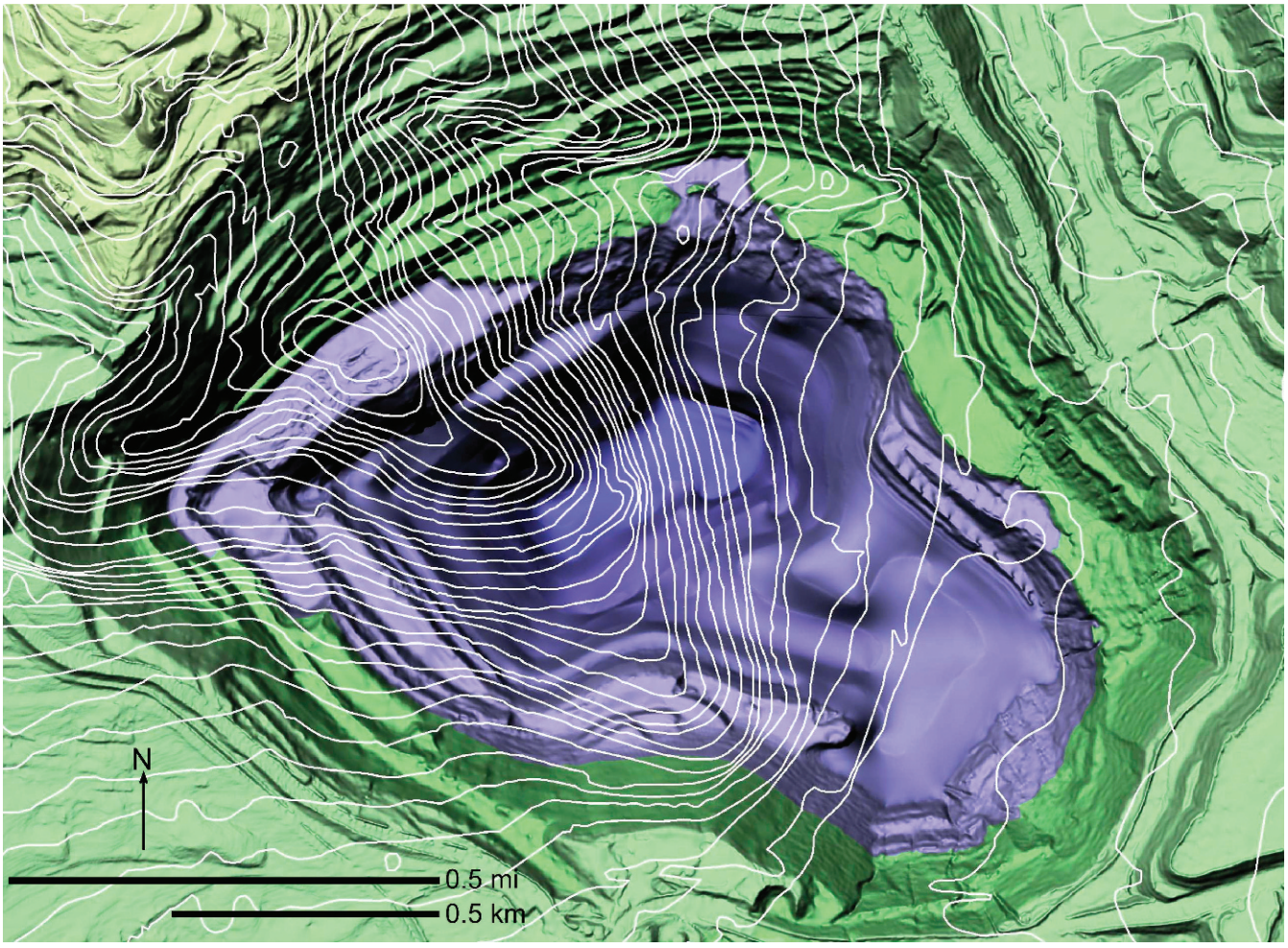

Figure 5. A detailed map of the topography and bathymetry of the Berkeley Pit. The hill shading reveals detail from the 2 ft (0.6m) Horizon, Inc., contours above the pit lake level of 1991. Beneath this level, the smoother, less detailed shading represents surveys contoured at a 100 ft (30.5 m) interval by the Anaconda Mining Company in 1977, when the Berkeley Pit was being excavated and had not yet begun to fill with water. Overlying unlabeled white contours are from the 20 ft (6 m) contours from the 1897 USGS topographic map of the area and are used to show original topography of Butte Hill.

color to show changes in volume for areas with 10 ft or more vertical change; areas with less difference display the underlying terrain. Areas of current lower and higher elevation are assumed to be associated with volumes removed and added, respectively. These changes are classified and shown in darker shades of red for the former and blue for the latter in Figure 6.

Many features of the Butte landscape are readily apparent in this map. The dark-blue area to the northeast is the Yankee Doodle tailings dam. The Berkeley Pit is the large red area just to the southwest of this dam. The area in the east-central portion of the map shows volumetric changes associated with the Continental open-pit mine (Continental Pit) as of 1991. Much smaller open-pit mining operations are evident in the northern portion of the map.

Two areas allow for simple visual inspection of the relative accuracy of the volumetric model. Missoula Gulch, which is shown in Figure 3, was an historical drainage along the western edge of early uptown Butte. In the first half of the 1900s, storm sewers were installed along the gulch and overlain with waste rock from underground mining. The Missoula Gulch drainage is delineated on the USGS map, and the thickness of the fill has been estimated at 40 ft (12 m) by comparing elevation values within and above the storm sewers. Figure 7 shows the current volume of material filling Missoula Gulch, as well as the location of the creek in 1897. The pattern of the fill and its maximum thickness correspond closely to the morphology of the gulch and measured thicknesses of material above the storm sewers.

An example not related to mining in Butte is earthworks cut-and-fill associated with highway construction. Figure 8 shows two maps of the Interstate 90/15/115 interchange on the southwestern

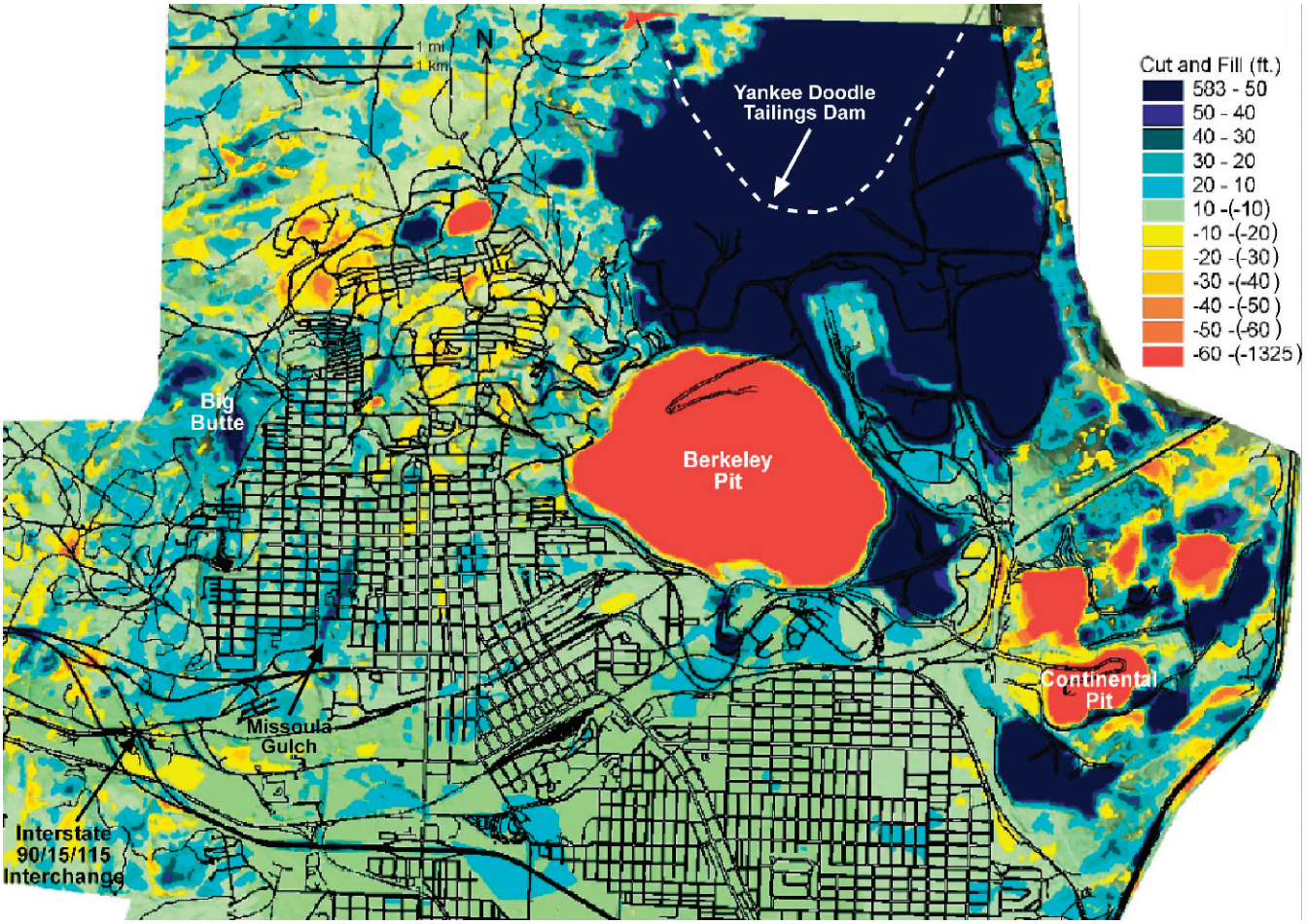

Figure 6. A volumetric model of landscape change in the Butte Mining District. Areas in which more than 10 ft (3 m) of volume have been added are shown with increasingly darker shades of blue. Areas in which more than 10 ft (3 m) of volume have been removed are shown with increasingly darker shades of red. Areas experiencing less than 10 ft (3 m) of change generally appear in green.

edge of Butte, without (Figure 8A) and with (Figure 8B) volumetric changes and modern roads. The model correctly predicts that there is no ($\pm$10 ft [3 m]) elevation change over most of this area. It also correctly highlights most areas of cut-and-fill, with these areas corresponding closely to those evident from the hill-shaded map of the area. Volumetric changes result in differences in elevation ranging from 10 ft (3 m) to 50 ft (15 m) in this area of extensive alteration.

The volumetric model appears to be of sufficient accuracy to provide estimates of the largest changes in the Butte landscape, such as the Berkeley Pit. These volumetric estimates indicate that 423.5 M m^3 (million cubic meters) of material were removed from the pit. Because the top and bottom of this volume are represented by the surfaces mapped by USGS 1904 edition and Horizon 1989–1991 data, respectively, it is possible to visualize this volume using these DEMs. Two 3D perspective views of the Butte Hill, before the Berkeley Pit and after pit operations ceased, are shown in Figure 9A and B, respectively. Because the more detailed grid is used for displaying the base, the top is of noticeably coarser detail.

Using a density of 2.68 g/cm^3, 1.251 billion tons of material are estimated to have been removed by open-pit mining. By comparison, Anaconda Mining Company haulage estimates indicate 1.324 billion tons were removed. The GIS-based estimate does not include material removed by subsurface mining in the first half of the 1900s before open-pit copper mining began. This may constitute 5.3 M m^3 of material, or about 1.25 percent of the total volume of material removed in open-pit mining (Duaime et al., 2004). This volume would be associated with the underground workings coincident with the present 3D extent of the Berkeley Pit. These underground mine workings, originally mapped by the Anaconda Mining Company, were digitized in a GIS format by the Montana Bureau of Mines and Geology (Duaime et

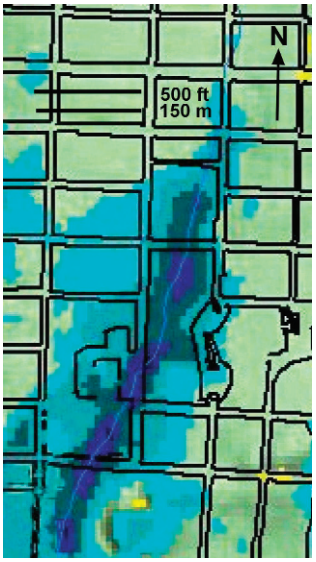

Figure 7. The pattern of fill shown in blue associated with the historical Missoula Gulch. The hydrology is from the 1897 USGS topographic map of the area. The morphology and thickness of the gulch's fill closely match the expected pattern and values. See legend of Figure 6 for values of fill.

al., 2004). A 3D perspective view (Figure 10) shows the spatial relationship of these underground workings previously located in the Berkeley Pit.

Most of the mine tailings and waste rock resulting from mining the Berkeley Pit were deposited in the Upper Silver Bow Creek Valley, with a portion used to construct the Yankee Doodle tailings dam. The dam is named after Yankee Doodle Creek, which flowed into the Upper Silver Bow Creek Valley just to the east of Butte Hill (Figures 1 and 3). Above the dam, there is a tailings pond (which is currently in use for operations at the Continental Pit), which can be seen in the aerial photograph in Figure 11. The historical path of the creeks and associated ponds along this drainage can also be seen in the lowest areas of Figure 1. The other two blue lines that appear to run along the slopes on either side of the Upper Silver Bow Creek Valley were ditches dug in the 1860s to provide water for placer mining operations.

Unlike the Berkeley Pit, it may be more difficult for modern observers to appreciate the volume or extent of the Yankee Doodle tailings dam. Figure 12A shows a 3D perspective view of the Butte Mining District as of 1897, including the valley that contained the historical Silver Bow Creek. Figure 12B shows the same 3D view, but it now includes the volume of waste rock and tailings associated with the Yankee Doodle tailings dam in yellow and orange. Because the Horizon survey does not extend to the northern end of the Yankee Doodle tailings dam and its adjacent waste rock dumps, these data do not allow

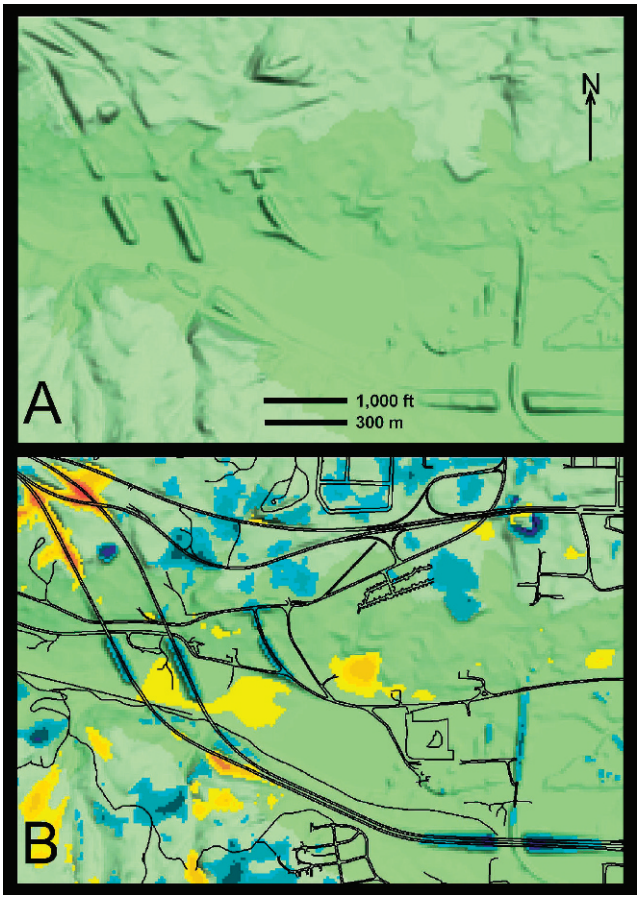

Figure 8. Patterns of earthwork associated with the Interstate 15, 90, and 115 interchange to the southwest of Butte, showing: (A) present-day terrain and (B) present-day terrain with predicted cut and fill of more than 10 ft highlighted in red and blue, respectively, and with present-day transportation infrastructure.

for an estimate of total fill volume. By comparing changes in elevation of the DEM from 1904 to the 1989–1991 Horizon DEM, however, the height of the dam in 1991 can be estimated at 168 m. This is comparable with the 1998 height estimate of 174 m from the International Commission of Large Dams (ICOLD) survey (Marchuk, 2000). The estimate of fill height from the GIS model seems reasonable, especially because some additional tailings were added in the years between 1991 and 1998.

DISCUSSION

The topographic and volumetric models created in GIS for this study are useful for various purposes. From a volumetric perspective, this cut-and-fill model is the only rigorous effort to verify the quantity of material removed from the Berkeley Pit during open-pit mining. This is important because there is no way to directly verify the completeness or accuracy of the AMC haulage records. This volumetric model arrives

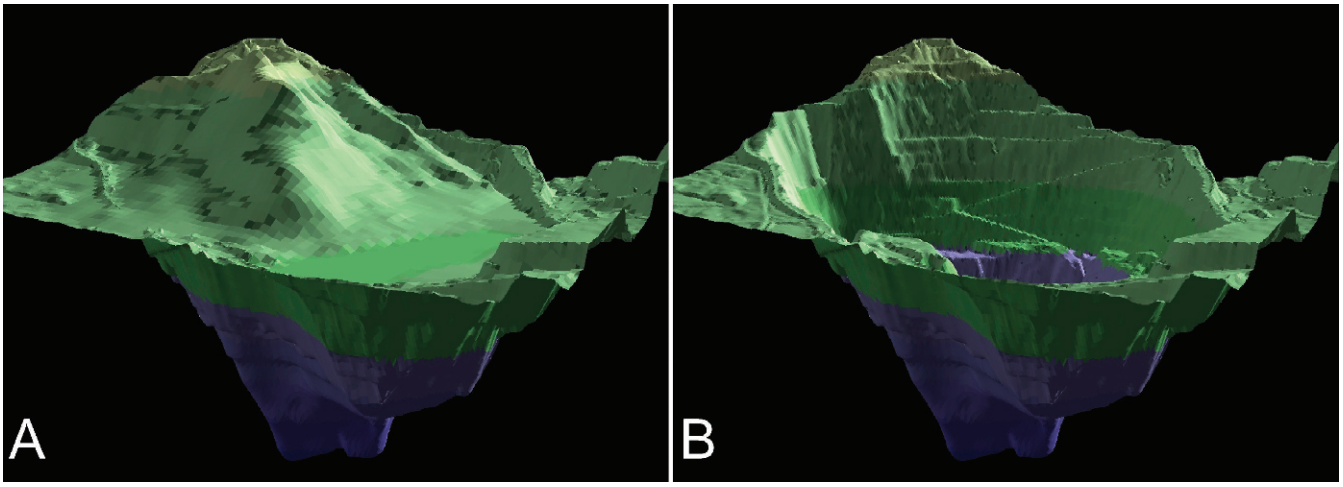

Figure 9. (A) A 3D visualization of the Berkeley Pit using a vertical exaggeration of 3×, and with the topography from 1897 added on top. (B) The same view of the pit, but without the topography from 1897 added on top.

at an independent estimate within 8 percent of previously reported values, even while using very general assumptions and a topographic map produced in 1897/1904.

Volumetric estimates from this study are also of use in reconnaissance of portions of the Butte Mining District overlain with waste rock or mine tailings. It is important to recognize prior land-use practices before

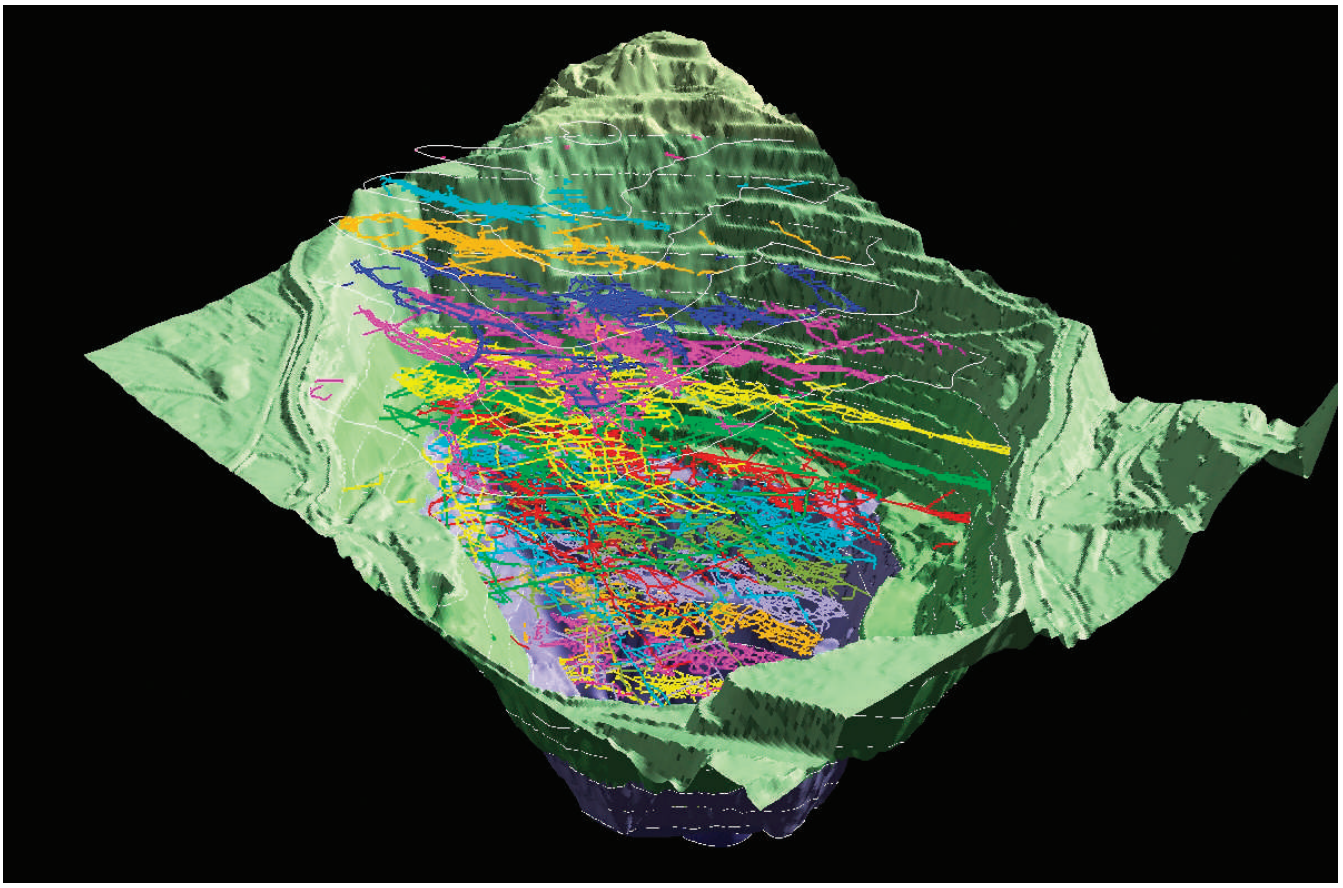

Figure 10. A 3D visualization of the Berkeley Pit, including the location of underground mine workings excavated during open-pit mining (colors represent depth levels from Anaconda Mining Company maps), using a vertical exaggeration of 3×. White contours at an interval of 100 ft (30.5 m) represent the elevation of the base of the pit and the 1897 topography, as illustrated by the volumetric model in Figure 9A.

Figure 11. An aerial photograph (looking northeast) of the uppermost portion of the Yankee Doodle tailings dam and the associated tailings pond (courtesy of Ted Duaime, Montana Bureau of Mines and Geology).

planning and developing current facilities. As an example, a skateboard park in Butte was proposed but not built on a mine tailings site. While material from open-pit mining associated with the Berkeley Pit is relatively well documented from 1955 to 1982, much material from underground and small open-pit operations was dispersed throughout the area in the late 1800s and early 1900s with little or no documentation. Although site visits could be used to identify the presence of such waste rock or tailings, the volumetric model offers a first-pass assessment of areas where larger volumes of such material are most likely to be encountered.

A practical application for this model is being used is in the maintenance of infrastructure. In some areas of Butte, sewer and water lines are buried in mine waste. In general, these lines undergo more rapid degradation than those not buried in such material. The groundwater in this type of fill is of higher acidity and contains leached metals, which are able to corrode cast iron sewer lines and culverts. Recent efforts in Butte to replace thousands of feet of such lines used this volumetric study to help identify areas where lines would most likely be buried in mine waste.

Perhaps the more important utility of this model, however, is the ability to visually represent historical and present-day terrain, as well as the volume of material displaced. Although no new information regarding the location of past or present features was discovered, this study has merit in visually integrating landscape features from Butte's past and present. Such displays offer a simple way in which to understand spatial relationships, and they are well suited to education and outreach. For example, displays of Butte's changing morphology are used in tours of Butte conducted by faculty at Montana Tech of the University of Montana, the Montana Bureau of Mines and Geology, and the Clark Fork Watershed Education Program.

Butte Hill was the heart of underground mining operations in the early to mid-1900s, and it was a landform that could be seen throughout Butte. With mining of the Berkeley Pit, however, the highest portion of Butte Hill has been removed. Observers unfamiliar with the pre-pit morphology may have difficulty visualizing its location and extent. Images such as Figure 3 and 5 show Butte Hill's original morphology and its relationship to the Berkeley Pit as a promontory on a northwest-southeast–trending highland. This ridge trended at a right angle to the deepest portion of the Berkeley Pit, which reflects the northeast-southwest orientation of numerous copper veins in the area. Also, Butte Hill did not directly overlie the deepest portion of the Berkeley Pit, but was located to its northwest. The steep northern wall of the pit was a lower portion of the northwest-southeast–trending ridge.

For outreach and educational purposes, many people have a difficult time comprehending large volumes or areas. Attempts to comprehend a volume of 423.5 M m^3 could be confounded by not being able to visualize the upper surface of material removed.

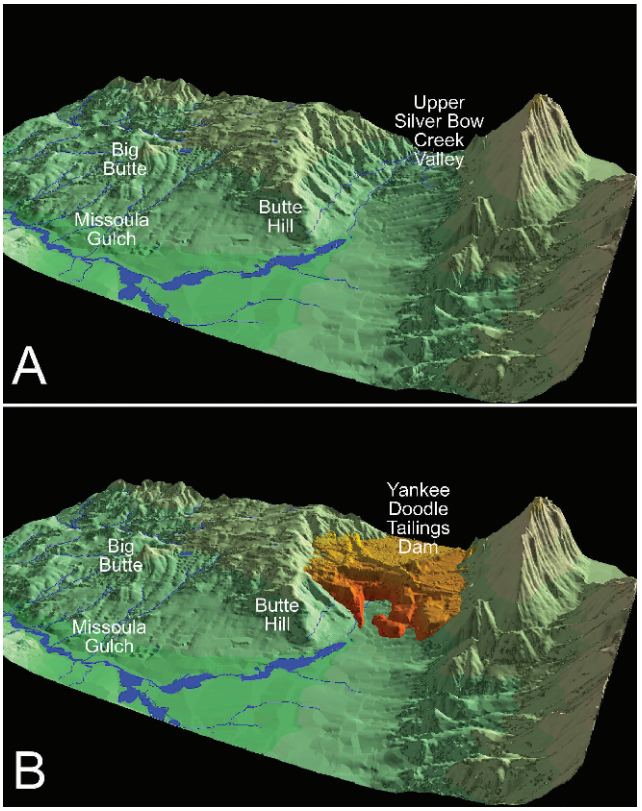

Figure 12. Two 3D visualizations looking up the valley of Upper Silver Bow Creek using a vertical exaggeration of 3×. (A) The volume in orange and yellow represents tailings and waste rock used to create the modern-day Yankee Doodle tailings dam and those adjacent to it. (B) The same view, with the volume of tailings from Figure 12A removed. View (A) would reflect the landscape of the Upper Silver Bow Creek Valley in 1897. The middle blue line flowing into the ponds is Silver Bow Creek. The other two blue lines that appear to run along the valley slopes were ditches dug in the 1860s to provide water for placer mining operations.

The total volume removed is not the Berkeley Pit of Figure 9B filled to its rim; it is the volume represented by Figure 9A. A model capable of being rotated, explored, and animated, as is made possible by this study, may further help people to visualize such large volumes.

The image in Figure 10 underscores the interconnectivity of the Berkeley Pit with the extensive 3D underground mine workings that occur throughout the Butte Mining District. Such images can also be useful for outreach and education about issues regarding interactions of groundwater with water in the Berkeley Pit and the complex network of flooded underground mine workings (Gammons et al., 2006b).

Various environmental issues of concern to the public can arise with tailings dams. These problems range from contamination due to seepage (Rosner and van Schalkwyk, 2000) to dam failure. Visual displays such as Figure 12 can be used for educational and outreach purposes to aid in the understanding of the importance of dam morphology to such issues. In the case of the Yankee Doodle tailings dam, Figure 12 highlights the large volume of fill material, which may be difficult to assess from modern-day topography (compare with Figure 4). It also highlights the relationship between the tailings and historical drainages. These areas may be more prone to seepage of contaminants, since they are localized lows, are composed of higher-permeability tailings, and have higher concentrations of metals, which are more susceptible to leaching.

In discussing the utility of such volumetric models, it is important to point out the limitations of working with data derived from historical maps. Although an RMS error of 3.14 m indicates good accuracy of location throughout the map, there is no systematic way to measure overall accuracy of elevation. This study highlights areas in which comparisons with current elevations and a prior knowledge indicate useful levels of accuracy, but other areas are more suspect. One example is the undisturbed area of Big Butte (Figures 3 and 4), which is an eroded remnant of a small volcanic vent that sits on the edge of a much larger volcanic field and which has associated lava deposits that lack the surficial copper and silver veins prevalent throughout the surrounding area. Figure 6 shows extensive areas of added volume on its slopes, often in excess of 20 ft (6 m), although no fill is known to have been placed there. There is also an elevation difference in the summit of 9 ft (3 m). Unlike the area of Missoula Gulch or the Interstate 90/115/15 interchange, the volcanic rocks of Big Butte contained no copper or silver veins. As a result, this area may not have been as sharp a focus of accurate mapping as more copper- and silver-prone areas during the 1895/1903 surveys.

CONCLUSIONS

This model of volumetric changes in the Butte Mining District illustrates a practical application of GIS technology that can also be used to quantify and visualize extensive landscape changes. The results found here using maps from near the beginning and end of the 1900s show how historical maps can be useful in volumetric studies. This study concludes that many resulting patterns of cut-and-fill are consistent with landscape features such as the Missoula Gulch fill, the Interstate 90/15/115 earthworks, and the Yankee Doodle tailings dam. Additionally, the model can be used to make independent volumetric estimates of material removed from open-pit mining of the Berkeley Pit. Finally, visualizations of historical

terrain and volume changes are useful in illustrating important alterations in the Butte Mining District for outreach and educational purposes.

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