Changes in the extent of surface mining and reclamation in the Central Appalachians detected using a 1976–2006 Landsat time series

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Abstract

Surface mining and reclamation is the dominant driver of land cover land use change (LCLUC) in the Central Appalachian Mountain region of the Eastern U.S. Accurate quantification of the extent of mining activities is important for assessing how this LCLUC affects ecosystem services such as aesthetics, biodiversity, and mitigation of flooding. We used Landsat imagery from 1976, 1987, 1999 and 2006 to map the extent of surface mines and mine reclamation for eight large watersheds in the Central Appalachian region of West Virginia, Maryland and Pennsylvania. We employed standard image processing techniques in conjunction with a temporal decision tree and GIS maps of mine permits and wetlands to map active and reclaimed mines and track changes through time. For the entire study area, active surface mine extent was highest in 1976, prior to implementation of the Surface Mine Control and Reclamation Act in 1977, with 1.76% of the study area in active mines, declining to 0.44% in 2006. The most extensively mined watershed, Georges Creek in Maryland, was 5.45% active mines in 1976, declining to 1.83% in 2006. For the entire study area, the area of reclaimed mines increased from 1.35% to 4.99% from 1976 to 2006, and from 4.71% to 15.42% in Georges Creek. Land cover conversion to mines and then reclaimed mines after 1976 was almost exclusively from forest. Accuracy levels for mined and reclaimed cover was above 85% for all time periods, and was generally above 80% for mapping active and reclaimed mines separately, especially for the later time periods in which good accuracy assessment data were available. Among other implications, the mapped patterns of LCLUC are likely to significantly affect watershed hydrology, as mined and reclaimed areas have lower infiltration capacity and thus more rapid runoff than unmined forest watersheds, leading to greater potential for extreme flooding during heavy rainfall events.

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1. Introduction

Quantifying the temporal and spatial patterns of land cover/land use change (LCLUC), as well as its consequences for ecological, hydroclimatological, and socioeconomic systems on Earth, is a central focus of land change science (Turner et al., 2003). Among the variety of different land conversions (e.g., deforestation, urbanization, etc.) that has received scientific attention, the removal of forest cover has been shown to dramatically affect hydrological processes such as evapotranspiration, canopy interception, and runoff at scales ranging from small plots to large river basins (Eshleman, 2004). In the case of urbanization, the loss of vegetative cover in combination with changes in soil infiltration capacity due to disturbance, has been shown to significantly enhance the flood generation potential of watersheds with substantial consequences for human well-being (Beighley & Moglen, 2002; Hollis, 1975; Rose & Peters, 2001; Sauer et al., 1983).

Modern techniques of surface mining using heavy equipment can produce dramatic alterations in land cover, both ecologically and hydrologically (Simmons et al., 2008). In forested regions such as the Appalachian Mountains, surface mining for bituminous coal since World War II has led to a widespread transformation of the mountainous landscapes. Reclamation of surface mines, as mandated by the Surface Mine Control and Reclamation Act of 1977 (SMCRA), has not resulted in restoration of pre-mining hydrologic characteristics (Negley & Eshleman, 2006) or ecological functions (Simmons et al., 2008). SMCRA requires mine operators to reclaim strip mines to the approximate original contours of the landscape, and to restore appropriate permanent vegetation types. In general, reclamation has thus involved replacement and grading of the overburden (topsoil and other near-surface materials) using large earthmovers, followed by seeding with grasses and other herbaceous vegetation. The end result is the transformation of native forests and their associated soils into predominantly herbaceous-covered minelands with reduced soil infiltration capacity due principally to surface compaction (Bell et al., 1994; Bussler et al., 1984; Chong & Cowsert, 1997; McSweeney & Jansen, 1984; Negley & Eshleman, 2006).
Although comparative hydrological research in the Appalachians shows relatively minor changes in annual water balances (e.g., annual evapotranspiration and annual runoff) due to deforestation and surface mining (Simmons et al., 2008), several studies show higher peak and total storm runoff from mined compared to forested Appalachian watersheds (Bonta et al., 1997; Negley & Eshleman, 2006). These results raise the specter that surface mining and reclamation in the Appalachian Mountain region may be increasing the risk of flooding hazards, thus underlining a need for more careful, objective, and quantitative estimation of the trajectory and spatial dimension of mined land conversions in this region. Knowledge of the extent of mining and reclamation within watersheds is critical to managing or mitigating the potential impacts of surface mining on downstream settlements. However, spatial data necessary to characterize the timing and extent of mining and reclamation in the region are either unavailable or unreliable. For example, the most reliable information – GIS layers of state issued mine permits – have imprecise boundaries and omit many areas identifiable as mines on aerial photographs or satellite imagery. Moreover, these mine permits identify only the date permits were issued and not the actual onset of mining activity, which may occur many years (a decade or more) after the issuance of the permit.

Remote sensing has been used widely to characterize land cover changes relevant to hydrologic functioning. In particular, remote sensing is especially useful for detecting the conversion (e.g., deforestation) of natural vegetation cover to land cover types having higher rainfall runoff rates (de Fries & Eshleman, 2004; de Smedt et al., 2004; Foley et al., 2007; Foody et al., 2004; Genux et al., 2006; Griffith, 2002; Miller et al., 2002). Likewise, maps of urbanization and surface imperviousness derived from remotely sensed data provide critical inputs for understanding the nature of hydrologic changes and changes in flood dynamics in watersheds experiencing LCLUC (Carlson, 2004; Finch et al., 1989; Shuster et al., 2005; Weng, 2001).

Comparatively fewer studies have comprehensively examined the use of remote sensing to map surface mine extent through time, and as such, there are few studies that incorporate maps derived from remotely sensed data into analyses of the broad-scale effects of mining on watershed hydrology. Rathore and Wright (1993) reviewed some of the early papers and conference proceedings that used Landsat MSS and TM data to map mining and reclamation, and found that the methods for mapping active mines were relatively straightforward and accurate, especially in areas where similar barren cover types are not present. Two papers (Anderson & Schubert, 1976; Anderson et al., 1977) delineated and inventoried active strip mines using MSS data in western Maryland, but found high variability in spectral signatures of mines. Band ratios were found to be most effective for discriminating mined areas. Other studies have used time series Landsat TM and similar image sources to map changes interpreted as having resulted from coal mining (Prakash & Gupta, 1998) and there is an extensive literature on mapping industrial open pit mines and associated tailings (e.g., Hagner & Rigna, 1998; Latifovic et al., 2005), but most studies are generally qualitative and do not report map accuracy.

Despite success at mapping active mines using satellite imagery, the mapping of mine reclamation has been considerably more troublesome (Rathore & Wright, 1993). The most successful studies for mapping reclaimed mines have used aerial photography, in which context and pattern have been used to infer process. However, Irons and Kennard (1986) demonstrated some capacity for Landsat TM imagery from Pennsylvania to distinguish bare mine spoil, grass on mine spoil and trees on mine spoil from agriculture, water and forest on a single image date, although overall map accuracy rates were low (62%). Also in coal mining areas of Pennsylvania, Guertert and Gardner (1989) used SPOT data to map classes associated with differing infiltration rates on mines and reclaimed mines (70% accuracy), but did not attempt to distinguish mined/reclaimed areas from other cover types. Parks, Petersen, and Baumer (1987) found that MSS was useful for monitoring active mines, and that TM and simulated SPOT imagery could be used to characterize the spectral characteristics of reclaimed mines, though not necessarily the spatial pattern.

Several broad-scale studies have attempted to quantify overall rates of land cover change during the Landsat era (Loveland et al., 2002 and related papers). Loveland et al. (2003, Figure 6–3) demonstrated through this approach that conversion to mining was the single largest land cover change in the Central Appalachian region between 1973 and 2000. Other major types of land cover change during that time include conversion to clear-cut/regeneration and to grass/shrub (possibly indicative of mine reclamation), indicating that forest clearance accounted for more than two-thirds of the landscape conversion in the region during the last three decades. However, the methods and accuracy for mapping mined lands as presented in Loveland et al. (2003) are not presented, but are presumed to be based on the 1992 National Land Cover Classification (NLCD) map following Loveland et al. (2002) and Griffith et al. (2003). The NLCD maps (Vogelmann et al., 2001) for U.S. Environmental Protection Agency Ecoregion 3 (Central Appalachians) have a commission error of 65% and omission error of 48% for mine-relevant classes, pointing to the limitations of using NLCD for characterizing land cover processes associated with mining.

Although studies have documented the use of remote sensing to map surface mining with varying levels of success, maps of mine reclamation are rare, in large part because reclaimed mines are spectrally indistinguishable from grasslands or pastures. From the hydrologic perspective, however, reclaimed mines do not function like natural grasslands or pastures, and retain many of the hydrologic properties of impervious mines. The biological, chemical and physical process required for soil development to pre-mining conditions occurs very slowly over century time scales. As such, the mapping of reclaimed mines is at least as important as mapping active mines for studies of watershed hydrology. Active mines are generally transient features of landscapes, and are typically minor in extent at any given time (Negley, 2002). In contrast, reclaimed mineland is generally persistent, with the area gradually increasing as new mines are opened and subsequently reclaimed. Although reclaimed mines may not be distinguishable from pastures or grasslands based on spectral characteristics alone, a logical approach using temporal sequences of land cover change could be used to properly label reclaimed mines and other grass-dominated cover types. This suggests the use of logical decision trees to identify land use classes based on transition trajectories of land cover maps through time. Although such an approach has not been used for mapping surface mine reclamation, the approach has been used to label classes based on their cover transition in studies of LCLUC in areas experiencing other types of land conversion (e.g. Wolter et al., 2006).

The objective of our study is to quantify patterns of LCLUC (e.g. conversion of forest to mined and reclaimed mine lands) in eight study watersheds within the Central Appalachian Region of the Eastern U.S. during a 30-year time period (1976–2006). This work provides the basis to understand changes in hydrologic response through time in these river basins as a consequence of continued mining and mine reclamation. To distinguish active mines and reclaimed minelands from spectrally similar classes, we developed simple land cover classifications on four image dates (1976, 1987, 1999 and 2006) and employed a logical decision tree based on class transitions and ancillary data such as GIS layers of mine permits (from the 1950s to the present), wetlands, and urban land cover.

2. Approach

2.1. Study area

The Appalachian Mountain region forms the headwaters for several major U.S. rivers, including the Potomac, Susquehanna, and
Ohio Rivers, and provides water resources to tens of millions of residents throughout the eastern and central U.S. The Central Appalachian Ecoregion (Fig. 1) in western Pennsylvania, western Maryland, eastern West Virginia, southwestern Virginia, eastern Kentucky, and north-central Tennessee is also rich in other natural resources: (1) wood from productive temperate forests that dominate the land cover of the region; and (2) extensive coal seams that have been mined since the 1800s and that fueled U.S. economic development through most of the 20th century. These deposits still contain billions of tons of recoverable, bituminous coal that continue to sustain a major portion of electricity generation in the U.S. In contrast to most of the rest of the Eastern U.S., LCLUC in the Central Appalachians is driven largely by natural resource extraction rather than suburban and exurban development fueled by accelerating population growth (Brown et al., 2005). Although the landscape remains mostly forested, the loss of tree cover to mineland in steep, mountainous Appalachian watersheds has the potential to result in widespread flooding (Eisenbees et al., 2007). Many rural communities in the region are plagued by water resource problems as a legacy of environmental degradation, including poor water quality from acid mine drainage and economic losses and personal hardship from persistent flooding. It has been suggested that extreme floods in this mountainous region can be attributed to a variety of hydrometeorological factors including the occurrence of intense orographically-enhanced rainfall or snowmelt, wet antecedent soil moisture conditions, and possibly loss of forest cover due to land use change or forest management activities (Eisenbees et al., 2007; Graybeal & Leathers, 2006; Hicks et al., 2005; Smith et al., 1996; Sturdevant-Rees et al., 2001).

Our study area includes eight river basins with relatively long streamflow records that we are studying as part of a larger study to determine the effects of surface mining on the magnitude and frequency of flooding in the Central Appalachian Ecoregion (Fig. 1). The watersheds exhibited a wide range in potential extent of mining based on the “area permitted for surface mining” data from Pennsylvania, West Virginia, and Maryland state mine bureaus. All of these basins are located within the Pittsburgh coal bed, the thickest and most widespread coal seam in the central Appalachians (Fig. 1). The Pittsburgh seam has been deep-mined continuously for more than two centuries, with strip mining having become prominent following the development of large earth-moving equipment in the 1950s. Our study and the results we present focus on land cover changes in the subset of eight watersheds rather than the ecoregion as a whole; as such, the general trends in mining and reclamation that we identify are representative of the region, but not the specific percentages of mined areas.

2.2. Image data

We employed a single-date classification approach that used images from each of the last four decades to map the change through time of mined and reclaimed areas. We used a Landsat 2 MSS image from 13 September 1976, a Landsat 5 TM image from 18 August 1987, a Landsat ETM+ image from 13 September 1999, and a Landsat 5 TM image from 2 May 2006 (closer anniversary date imagery was not available due to

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**Fig. 1.** Study area showing the eight watersheds for which the land use land cover change analyses were conducted. Shaded area on main map indicates location of the Pittsburgh coal seam, while the shaded area on the inset denotes the larger ecoregion.
cloud cover). All images were orthorectified to UTM coordinates using a 30 m digital elevation model and GeoCover imagery (http://glcf.umiacs.umd.edu/portal/geocover/) with RMSE values of less than 0.4 pixels. For each image date, we derived several spectral indices that we hypothesized would increase the separability of mined and reclaimed areas from other cover types, including the Normalized Difference Vegetation Index (NDVI) and Tasseled Cap indices (Brightness and Greenness for MSS and TM/ETM+, adding Wetness for TM/ETM+, Crist & Cicone, 1984; Huang, Wylie, Yang, Homer, & Zylstra, 2002; Kauth & Thomas, 1976), as well as the first three principal components computed for each image.

2.3. Ancillary geospatial data

GIS data layers of mine permit extent were acquired from the Pennsylvania and Maryland Mine Bureaus and the West Virginia Department of Environmental Protection. The GIS permit data show polygons for which individual mining companies have been granted approval to excavate soil and remove minerals (i.e. coal). We also acquired maps of wetland extent (from the National Wetlands Inventory; NWI, www.fws.gov/nwi/) and land cover from the 1992 and 2001 NLCD projects (Homer et al., 2004; Vogelmann et al., 2001). To assess classification accuracies, we used 2005 NAIP (National Agriculture Imagery Program, http://165.221.201.14/NAIPhtml) color orthophotos (midsummer acquisition, 1 m spatial resolution) and color infrared digital orthophotographs from the states (April acquisition, 1 m pixels) produced between 1995 and 1997. To assess the mine maps derived from 1976 and 1987 imagery, we used GIS coverages of mined and reclaimed areas in the Georges Creek watershed mapped by Negley (2002) via manual photo interpretation of aerial photographs from 1962 and 1982.

2.4. Basic classification method

Our objective was to map urban areas, forest, grasslands (including crops and pasture), active mines and reclaimed mines. Ultimately, our processing approach yielded five additional classes (for a total of ten classes). Reclaimed mines were split into three classes: reclaimed grassland, reclaimed woodland (<50% forest cover), and reclaimed forest (>50% forest cover). However, the discrimination of the three classes of reclaimed mines was not an objective of the study, but rather was a consequence of our mapping approach. The subclasses of reclaimed mines are retained in the results to illustrate the degree to which our method can be extended. We also mapped open water and reclaimed mines are retained in the results to illustrate the degree to which our method can be extended. We also mapped open water and

2.5. Mined-areas mask

The mined-areas mask was constructed using ancillary data (mine permits) and the basic land cover classifications to first label as potential mines all pixels falling within the mine permit boundaries. Although the permit areas usually align with known coal seams, the entire permitted area often is not mined completely if no coal is present in some areas. Remote sensing becomes a useful tool to map differences between areas of potential and actual mines. In addition, areas not within permit boundaries are also sometimes mined. As such, the area of potential mines was expanded by including areas outside the permit boundaries that exhibited:

1. single-date NDVI values more than three standard deviations below the mean NDVI;
2. NDVI difference values between two consecutive dates that decreased by more than three standard deviations below the mean NDVI difference;
3. class transitions (a) from or to Bare/Urban; and (b) from Forest to Pasture on two consecutive dates.

This processing step identified mines that were not in the mine permit data, but clearly could be identified as strip mines from aerial photography. Upon review, these areas were almost entirely locations adjacent to existing mines or mine permits. We verified these additions to the mined-areas mask using ancillary aerial photography and supplemented the mine permit layer with the resulting polygons.

2.6. Decision tree

The decision tree was programmed in C and employed the mined-areas mask in conjunction with the time series of spectral maps to label cover types. The basic spectral classes from each time step were analyzed according to their transitions in class membership during the four time steps. Transitions were evaluated two years at a time (i.e. 1976→1987, 1987→1999, 1999→2006), as detailed graphically in Fig. 2. The majority of the pixels were unchanged through time (e.g., forest at all four intervals, symbolized as F→F→F→F). For the remaining pixels that experienced one or more class transitions across the four image dates, the decision tree labeled cover conversions to active mines and then reclaimed mines based on logical transitions for areas inside the mined-areas mask. As such, a class transition within the mined-areas mask mapped as F→B→G→G would be labeled a location that was forest in 1976, actively mined in 1987, and reclaimed grassland in 1999 and 2006. Another area intersecting with the mined-areas mask mapped F→G→G→G would be labeled as forest in 1976 and reclaimed grassland in 1987, 1999 and 2006. It would be assumed that the location was mined and reclaimed between 1976 and 1987.

We considered that the signal of mining and logging could be confused in some instances, particularly in cases where both mining and reclamation occurred between image dates. In these instances (e.g. F→G→G→F), we relied upon the mined-areas mask to separate reclaimed mines from areas of logged forest. Areas of logged forest (e.g. F→F→G→F) occurred in areas not coincident with mined-areas mask, and generally reverted to forest after just one time interval as “grass.” Through an exhaustive set of logical operators, we were able to

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use the class transition data to properly label areas as actively mined, reclaimed grassland and reclaimed forest. For locations to be designated reclaimed forest, they needed to exhibit at least two dates classified as forest following mining (e.g., B→G→F→F). Areas with only one date classified as forest (e.g., B→G→G→F) were labeled to the reclaimed woodland class. This designation derived from our observation (from aerial photographs and on the ground) that tree/shrub cover was generally sparse (<50% forest cover) compared to places mapped as forest for more time periods. By doing this, we retained the information content about the transition; however, for practical purposes the reclaimed woodland class may be indistinguishable from reclaimed forests. The analyses followed all possible combinations of the three general cover types (and intersecting with the ancillary data), yielding 162 potential classes, but the vast majority of the pixels in the study area (>99%) could be labeled to classes based on change transitions.

Imperfect image co-registration and the differing spatial resolutions of Landsat MSS (79 m) and TM (30 m) imagery caused a very small number of pixels (<0.01%) to exhibit illogical transitions (e.g., F→G→F→F or G→F→F→G). Errors caused by imperfect image registration were ignored because they had a minimal effect on the overall calculation of land cover area within watersheds (although some single pixels may have been misclassified). Errors caused by differing spatial resolutions were dealt with by allowing the 1987 Landsat TM classification to take precedence over the 1976 Landsat MSS classification in locations where the 1976–1987 transition was illogical (e.g., B→F). Unlike the 2001 NLCD maps, we did not “burn” in urban areas from ancillary data sets. Areas mapped as urban that could not otherwise be identified as another cover type remained classified as urban.

### 2.7. Accuracy assessment

Two sets of accuracy assessments were conducted: one for all basins for 1999 and 2006, and a second on the Georges Creek watershed for the entire period. Classification accuracy was evaluated using the best available air photo data. However, it should be noted that validation for the earlier dates (1976 and 1987) was limited by data availability, and ancillary data for the later dates (1999 and 2006) were not timed exactly to the year of the Landsat imagery. For the 2006 classification, we used the 2005 NAIP orthophotos, while for 1999, we used digital orthophotoquads produced between 1995 and 1997. Accuracy assessment for the 1976 and 1987 maps used data developed and reported by Negley (2002) for the Georges Creek watershed, in which manual photo interpretation of aerial photographs from 1962 and 1982 was used to map mined and reclaimed areas. Because the aerial photographs used by Negley were not closely timed to our maps, we developed transition maps for the period 1962–1987 covered by our maps and Negley’s maps (1962 Negley→1976 MSS→1982 Negley→1987 TM) to identify areas in which the transitions could be considered logical. Any transition that was determined to be illogical in our classification was labeled as a classification error in either the 1976 or 1987 map. The original Landsat imagery and mine permit maps were consulted as needed to assess inconclusive areas, and to address potential inaccuracies in the Negley (2002) maps. All sample points were selected using a stratified random sampling design, with approximately 300 points selected for the assessment of the entire study area (1999 and 2006) and 100 points for the analysis of Georges Creek alone.

### 3. Results

#### 3.1. Land cover change

Across our eight study watersheds, the area of active mines was highest in 1976 (1.8% of the land area) and relatively stable in 1987 and 1999 before declining to 0.5% in 2006 (Table 1, Fig. 3). In the most heavily mined watershed, Georges Creek in Maryland, active mines...
peaked at 5.4% around 1976, declining to around 2% or slightly less in later years (Table 1). Reclaimed mines increased in area following 1976, balancing the decline in active mines and forest area. The amount of reclaimed land in particular is directly attributable to the mandate to reclaim all mined lands following the passage of the SMCRA in 1977. As such, the area of active plus reclaimed mines increased steadily through time, balanced by a loss in forest area (Table 1). Across all watersheds, mined areas increased from 3.3% to 5.8% of the area, whereas the total mined area (sum of active and reclaimed mines) increased from 10.3% to 17.2% of the land cover in the Georges Creek watershed (Table 1, Fig. 3). These results illustrate the continued expansion of surface mining that began in the 1950s. It is notable that urban area also increased from 1987 to the present, but at a much lower rate than active/reclaimed mines (Table 1). Finally, the development of the mined-areas mask identified areas that were mined, but not mapped in the permit data (Fig. 4).

Table 1

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Active mines</th>
<th>Reclaimed</th>
<th>Forest</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redstone Creek, PA</td>
<td>1.0 0.6 0.6 0.3</td>
<td>0.7 1.7</td>
<td>2.3 53.4</td>
<td>53.7</td>
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<tr>
<td>Savage River, MD</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Georges Creek, MD</td>
<td>5.4</td>
<td>2.1</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>North Branch Potomac River, MD/WV</td>
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<td>1.6</td>
<td>1.3</td>
<td>0.7</td>
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<tr>
<td>Blackwater River (at Davis), WV</td>
<td>5.7</td>
<td>1.3</td>
<td>1.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Blackwater River (near Davis), WV</td>
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<td>0.0</td>
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<td>0.0</td>
</tr>
<tr>
<td>All Watersheds</td>
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<td>0.8</td>
<td>0.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Fig. 3. Landscape change in Georges Creek watershed, MD, 1976–2006.
3.2. Accuracy assessment

Accuracy for our classifications was high, and considerably higher for mined areas than has been reported for widely available land cover data sources (e.g. NLCD) or in other studies (Guebert & Gardner, 1989; Irons & Kennard, 1986). The accuracy assessments are reported hierarchically (Tables 2 and 3), with per-class accuracies reported for all mined cover types together, then with all mines split into active and reclaimed mines, followed by reclaimed mines split into reclaimed grasslands and reclaimed forests, and finally with reclaimed forests further divided into reclaimed woodlands and forests. The contingency tables on which Tables 2 and 3 are based are provided in Appendices A and B. Urban areas, forests, grasslands (agriculture and pasture) and all mines were mapped with a very high level of accuracy, with accuracies for all mined types above 90% for 1999 and 2006, and around 85% or higher for Georges Creek in 1976 and 1987. Separating reclaimed from active mines yielded accuracy rates generally above 75%, although accuracy was somewhat lower for reclaimed mines in 1976 (Table 3). Lower accuracy in 1976 may result from several factors, including (1) mixed pixels due to the larger MSS pixel size, (2) inaccuracies in the mine permit maps, or, most likely, (3) the lack of reliable ground truth data for 1976 (1976 accuracy was assessed using aerial photographs from 1962 and 1982). However, two of our watersheds overlap with the area mapped by Anderson and Schubert (1976) using 1972 ERTS-1 (MSS) imagery and our total area mapped as mined compares favorably with their study (12.58 km² in 1972 vs. 14.39 km² in 1976). Some errors in the accuracy assessment are likely due to the mismatch in timing of validation data and satellite imagery.

Table 2
Percent user's and producer's accuracy of mapped cover classes for all watersheds, 1999 and 2006

<table>
<thead>
<tr>
<th></th>
<th>1999</th>
<th></th>
<th>2006</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Producer</td>
<td>User</td>
<td>Producer</td>
<td>User</td>
</tr>
<tr>
<td>Urban</td>
<td>78.8</td>
<td>100.0</td>
<td>92.5</td>
<td>94.9</td>
</tr>
<tr>
<td>Forest</td>
<td>90.1</td>
<td>82.0</td>
<td>85.8</td>
<td>89.8</td>
</tr>
<tr>
<td>Grass/pasture/agriculture</td>
<td>84.9</td>
<td>94.8</td>
<td>87.1</td>
<td>84.4</td>
</tr>
<tr>
<td>Mined (active or reclaimed)</td>
<td>94.3</td>
<td>86.8</td>
<td>95.6</td>
<td>91.5</td>
</tr>
<tr>
<td>Active mine</td>
<td>66.7</td>
<td>76.9</td>
<td>77.8</td>
<td>82.4</td>
</tr>
<tr>
<td>Reclaimed mine</td>
<td>87.3</td>
<td>76.2</td>
<td>88.0</td>
<td>81.5</td>
</tr>
<tr>
<td>Reclaimed grassland</td>
<td>80.6</td>
<td>67.6</td>
<td>80.8</td>
<td>67.7</td>
</tr>
<tr>
<td>Reclaimed forest</td>
<td>70.8</td>
<td>65.4</td>
<td>70.8</td>
<td>73.9</td>
</tr>
<tr>
<td>Reclaimed woodland</td>
<td>54.5</td>
<td>27.3</td>
<td>40.0</td>
<td>28.6</td>
</tr>
<tr>
<td>Reclaimed forest</td>
<td>7.7</td>
<td>25.0</td>
<td>42.9</td>
<td>66.7</td>
</tr>
</tbody>
</table>
Further division of the reclaimed mine class to reclaimed forests and reclaimed grasslands produced accuracy rates from 65% to over 80% (Tables 2 and 3). Confusion between reclaimed grasslands and forests resulted from mixed pixels linked to the spotty nature of tree regeneration, growth and survival on reclaimed mines. Where it occurs, natural forest regeneration on reclaimed mines is sparse. Where trees are planted on mines, growth is slow and mortality is generally high. It is therefore unsurprising that there is some confusion between reclaimed grasslands and reclaimed forests, and accuracy levels may be sensitive to the timing of the aerial photos used for validation (in terms of both the year and season of acquisition). Our attempt to address this by further distinguishing reclaimed woodlands (>50% tree cover) from reclaimed forests and grasslands yielded mixed results, suggesting that there is a gradient in vegetation dynamics on reclaimed mines that may be hard to capture using hard classes. As such, reclaimed woodlands and reclaimed forests are best treated as one class for most applications, although information about distinctions between these classes may be of utility for landscape monitoring, even if accuracy is low (Czaplewski & Patterson, 2003).

4. Discussion

The ability to map the extent of active mines and reclaimed mines is essential to understanding the long-term ramifications of mining on ecosystem services (Simmons et al., 2008), especially those associated with watershed hydrology (Guebert & Gardner, 1989). In related research within our study area, Negley and Eshleman (2006) found infiltration rates nearly two orders of magnitude higher in unmined forests compared to reclaimed grasslands (30 cm h⁻¹ vs. 0.3 cm h⁻¹); infiltration on active mines is assumed to be nil. Sloan (2006) observed infiltration rates of 1.2 cm h⁻¹ on recently reclaimed mines, and 2.8 cm h⁻¹ on a 25-year old reclamation with vigorous vegetation on it. Additional data collected by Sloan (unpublished data) showed intermediate rates of infiltration in reclaimed forests. These data suggest that – despite reclamation – the increased area of reclaimed mines within heavily mined watersheds of the Appalachians is likely to have significant effects on storm runoff responses in these areas (Negley & Eshleman, 2006).

A retrospective remote sensing approach provides the opportunity to map both mines and mine reclamation, as well as to estimate the time since reclamation based on the temporal trajectory of land cover. This may be important to identify changes in the impacts of mining and reclamation on hydrology through time, especially if reclaimed areas show gradual increases in infiltration as vegetation and soil develop. It is possible that indices derived from multispectral data (e.g., NDVI) could be used to estimate infiltration-relevant properties on areas mapped as reclaimed mines. The long time series of remote sensing imagery from Landsat provides an unparalleled opportunity to detect land cover changes and describe them in terms of environmentally relevant land uses. For instance, our approach offers the capacity to discriminate reclaimed mines from other grasslands, a distinction that is important for the hydrological assessment of Appalachian watersheds.

Despite the success of our approach, broad-scale reconstructions of mining and reclamation using a retrospective approach remain a challenge. Good ancillary GIS data (wetland inventories, mine permits, maps of urban areas) can enhance classification accuracy, but may be unavailable or, as in our study, inaccurate over large areas. However, these data were important to our study, as reclaimed grasslands and pasture cannot be definitively separated based on spectral properties alone. Likewise, the confusion between urban areas and mines may be pronounced (as in the NLCD data), although logical decision tree classifiers can generally be used to distinguish such areas. In particular, by comparing different versions of our logical decision tree (data not shown), we found that changes in NDVI through time were especially useful for discrimination among transition classes through time. In addition, our work illustrates the need to carefully evaluate ancillary data sources, as the NDVI data were important for identifying areas of mines that were not delineated as such in the permit data (Fig. 4).

We attempted to discriminate reclaimed grasslands, woodlands and forests, all of which are apparent from aerial photography (Fig. 5). However, the accuracy levels for these subclasses of reclaimed mines were less than 80% in most instances, although the accuracy levels for reclaimed mines as a whole were mostly above 80%. The errors for the subclasses likely result from several factors. First, variations between levels of tree cover may be difficult to detect in a consistent manner from time period to time period using imagery at the Landsat spatial resolution. In addition, our results may have been affected by the seasonal timing of imagery or lack of temporal coincidence of imagery with training data. Growing season imagery is essential for mapping mines and reclamation, so that confusion between areas of bare soil and either mines or reclaimed mines is minimized. Image availability was an issue for our study, and we presume that it would be for many of the coal mining regions in the U.S., which are largely in mountainous regions and are especially cloudy during spring and summer months. For this study, we used a 2 May 2006 image for the latest year in our time series. For this date, we observed some confusion related to bare agricultural fields that would not have occurred had a later image been available. For the other dates, the use of multi-seasonal imagery (both leaf-on and leaf-off) may have improved the discrimination among reclaimed mine classes, but due to persistent cloud cover in the Appalachian region, we were unable to find suitable image pairs from the same year for such an analysis. In future studies, object-oriented methods or approaches that exploit image texture may prove helpful for mapping different reclamation types. Finer resolution imagery may also improve mapping, although little such data are available over the Appalachians, especially considering issues with cloud cover in the region. The best prospects for mapping reclaimed minelands in the Appalachians ultimately will come from regular synoptic imagery such as from the Landsat instruments. This points to the importance of maintaining a Landsat-type data record for landscape monitoring.
Finally, it should be noted that the classification accuracy assessment may include errors resulting from imperfect validation data, especially for the earlier dates in which reliable independent validation data was not available. We expect that it is likely that some areas mapped as reclaimed mines using satellite imagery may in fact have been reclaimed, but were identified as active mines on the aerial photos since the aerial photos were imaged earlier (as much as two years) than the satellite imagery. This is certain to happen in situations in which active mines are reclaimed between the date of the aerial photographs and the satellite imagery. As such, the accuracy assessment results we have reported should be considered conservative; actual accuracy was likely higher than reported in Tables 2 and 3. As with all change detection studies, additional errors may have resulted from misregistration of the image time series, but we saw little evidence of this in the results (e.g., systematic, one-pixel wide linear change features).

The use of a temporal signature of change transitions in the classification process was central to the work. This allowed us to identify and label likely changes related to mining (as well as changes unrelated to mining, such as logging and urban expansion). Analogous to a spatial filter, this temporal filter facilitates identification of the most likely cover class based on temporal context. The analyses and accuracy would likely have been improved by inserting (if available) additional images at five-rather than ten-year intervals. This should reduce confusion (especially between pastures and reclaimed grasslands) by ensuring that most active mines are mapped at some point, rather than being inferred from transitions between dates. For instance, differences at any given time step between the sum of active mines prior to that time step (including reclaimed mines at the first time step) and reclaimed area can be attributed to reclaimed mines that were never mapped as active because the entire active mining fell between mapping periods. Finally, we recommend monitoring of mine activity at 5-year intervals for future studies to better characterize the timing of mining and reclamation activities as they relate to hydrologic responses.

Our research has revealed patterns of surface mining and reclamation that are likely representative of the larger Central Appalachian region comprising northern West Virginia, Maryland and Pennsylvania. It is notable that the area of active mining in our study area declined sometime after 1976 and remained steady or declined slightly thereafter. We attribute this largely to the gradual depletion of the Pittsburgh coal seam shown in Fig. 1. The decrease in area of active mines tracks national and regional trends in declining numbers of permits, production and employment in surface mining. From 1978 to 2006, nationwide employment in surface mining declined 58.7% (and over 71% in all sectors of coal mining), while the total number of active strip mines declined 58.7% (and over 71% in all sectors of coal mining), while the total number of active strip mines declined 58.7% (and over 71% in all sectors of coal mining), while the total number of active strip mines declined 58.7% (and over 71% in all sectors of coal mining), while the total number of active strip mines declined 58.7% (and over 71% in all sectors of coal mining), while the total number of active strip mines declined 58.7% (and over 71% in all sectors of coal mining), while the total number of active strip mines declined 58.7% (and over 71% in all sectors of coal mining). In the three counties in West Virginia covering our study area, surface coal production has declined from 1.05 million tons in 1996 to practically zero in 2007 (with associated declines in employment (West Virginia Office of Miners’ Health Safety and Training, http://www.wvmsa.gov/ACCINJ/accinj.htm), while in the two western Maryland counties the number of active mines declined 75% between 1978 and 2006. Surface-mined coal production in western Maryland has varied substantially during that time with major declines after the early 1980s and a recent increase in the early 2000s. However, the general trend of declining or level coal production in the northern part of the Appalachians is not mirrored in southern West Virginia, where the area of active surface mining and coal production has actually increased (as much as threefold in some counties) due to the emergence of mountaintop removal mining (MTM). Our methods for mapping active mines should work equally well (if not better) in areas with MTM since the transformations of the landscape are at a considerably larger scale.

Despite the general decline in area of active mines since 1976, the important (and somewhat obvious) result of our work is that the overall area of mined lands (active plus reclaimed) continues to increase. Hydrologically, reclaimed mines behave more like active...
mines than the pre-existing cover types, suggesting that methods to characterize the area of mine reclamation is of critical importance to landscape monitoring in flood-prone Appalachian watersheds.

5. Conclusion

Surface mining for coal and subsequent mine reclamation has been extensive in watersheds throughout the Appalachian Mountains. Our watersheds are likely representative of the larger region, but should be generalized with caution because some areas, especially in southern West Virginia, are in fact experiencing much more widespread surface mining. Application of a Landsat-based, temporal filtering approach to assessing LCLUC in these and other heavily mined areas worldwide could greatly facilitate assessments of mining impacts on ecosystem services. In particular, the LCLUC data generated by our study will be useful for assessing the extent to which mining has resulted in flooding and associated expenses to structures and human livelihood. Effective management must target areas of potential risk, which in the long run will rely upon good LCLUC maps that do not yet exist in regions such as the Appalachians that have long histories of surface mining. Although it is unlikely that a fully automated remote sensing approach could identify and correctly label all classes related to mine activity, our results show that a long Landsat time series can be used to accurately track mining activities through time.

Acknowledgements

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Appendix A. Contingency tables for accuracy assessment of all watersheds

<table>
<thead>
<tr>
<th>Year</th>
<th>Map data</th>
<th>Ground data</th>
<th>Total</th>
</tr>
</thead>
<tbody>
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<td>Urban</td>
<td>Forest</td>
<td>Grass</td>
</tr>
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<td>1976</td>
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<td>0</td>
</tr>
<tr>
<td>1987</td>
<td>16</td>
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<td>0</td>
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</tbody>
</table>

Appendix B. Contingency tables for accuracy assessment of Georges Creek watershed

<table>
<thead>
<tr>
<th>Year</th>
<th>Map data</th>
<th>Ground data</th>
<th>Total</th>
</tr>
</thead>
<tbody>
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<td>Urban</td>
<td>Forest</td>
<td>Grass</td>
</tr>
<tr>
<td>1999</td>
<td>14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2006</td>
<td>16</td>
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<td>0</td>
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</table>

References


