Geomorphic Differences between Unmined and Surface Mined Lands in Southeastern Ohio

THESIS

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By

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Abstract

Surface mining for coal is a significant landscape disturbance that occurs throughout the United States, extending from the Appalachian Mountain Region in the eastern part of the country westward to Wyoming, Arizona, Texas and small portions along the West Coast. Surface mining and reclamation activities often result in dramatic physical reconfigurations of hillslope and stream channel networks, which in turn alter hydrologic and geomorphic processes across the terrestrial and fluvial regions of the landscape. To date, surface mining related research has focused on hydrological impacts with little attention to morphologic alteration.

This study quantifies terrestrial and channel geomorphic differences between mined sites reclaimed according to the 1977 Surface Mine Control and Reclamation Act (SMCRA), sites mined prior to SMCRA, and unmined sites. The research approach includes analysis of two watershed land uses, Pre-SMCRA mined (unreclaimed) and Post-SMCRA mined (reclaimed), as well as

unmined watersheds at three spatial scales, which include the terrestrial landscape (10^0 km^2), channel network topology (10^3m), and channel reach (10^1 m). Seven watersheds within each of the three land use groups (n=21; ~1km^2 each) were evaluated at the three scales using Geographic Information Systems (GIS) and field methods. Study sites were located on and adjacent to lands managed by American Electric Power (AEP) in southeastern Ohio, U.S. It was expected that Post-SMCRA sites would be more dissimilar to unmined sites compared to differences between Pre-SMCRA and unmined sites at all spatial scales. Specifically, Post-SMCRA sites were expected to have detectable differences characterized by smoothed and homogenized landscape topography and highly engineered channel network systems. At the landscape scale, Pre-SMCRA sites would have steep, varied topography similar to unmined sites, but exhibit geomorphic differences from unmined sites at the network topologic and reach scales. Hypotheses were created based on these expectations as well as the expected influence of broader spatial scales on finer reach scale channel morphology.

A combination of univariate methods (Kruskal Wallis) and multivariate methods that included Nonmetric Multi-Dimensional Scaling (NMDS), Permutational Multivariate Analysis of Variance (PerMANOVA) and standardized linear models were used for

analyses. Analyses generally support hypothesized differences between land use groups and linkages across spatial scales. At the landscape scale, Post-SMCRA sites were significantly different from unmined and Pre-SMCRA sites, with reduced mean terrestrial slope (KW, p=0.001), increased mean hillslope length (KW, p=0.003) and reduced profile roughness (KW, p=0.001). Pre-SMCRA sites were similar to unmined sites. At the network topology scale, the amount of open water area was found to be greater for all mined sites (Pre-SMCRA and Post-SMCRA), relative to unmined sites (KW, p=0.001) with correspondingly shorter distances between outlet reaches and the nearest upstream open water body (KW, p=0.038). At the outlet reach scale, Post-SMCRA sites were less sinuous than unmined sites (KW, p=0.049). Pre-SMCRA outlet reaches were similar to unmined reaches for all variables tested, although Pre-SMCRA sites had significantly smaller width/depth ratios than Post-SMCRA sites (KW, p=0.039). Multivariate analyses identify surface mining activity and the resulting formation of open water bodies as significant predictors of stream power at the outlet reach, providing evidence for the impact of land use at all spatial scales.

The reclamation of surface mined lands is a somewhat unique prospect in that the soils, topography, drainage networks and vegetation can be directly manipulated for a wide variety of

future land uses. Findings from this study provide surface mine reclamation practitioners with new information regarding topologic and geomorphic processes in reclaimed areas. SMCRA requires that mined lands be returned to approximate original contour, with prior conditions restored. Results from this study indicate a need for greater topographic and topologic complexity in SMCRA-reclaimed sites in order to more closely resemble geomorphic structure of unmined conditions. Further research is necessary to evaluate the geomorphic function of mined landscapes relative to unmined landscapes.

Dedication

To my wife Cassandra, for your unwavering support of my academic endeavors. I could not have done this without you.

and Bill Zeedyk, for showing me how water does its work.

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Table of Contents

Abstract ii

Dedication vi

Acknowledgements vii

Vita viii

List of Tables xii

List of Figures xiv

Chapter 1 - Introduction 1

Surface Mining in Ohio 1

Pre-SMCRA Practices 2

The Surface Mine Control and Reclamation Act 5

Post-SMCRA Practices 6

Headwater Channels and the Impact of Mining 7

Literature Cited 12

Chapter 2 - Geomorphic Differences between Unmined and Surface Mined Lands in Southeastern Ohio 20

Abstract 20

Introduction 23

Methods 30

Study region 30
Study Design 32
Site Selection 33
Data Collection 35
Data Analysis 43
Results 49
Differences between land use groups 49
Landscape Scale 50
Interactions across spatial scales 65
Discussion 74
Differences between land use groups 74
Implications for the movement of materials through the landscape 77
Interactions across spatial scales 79
Conclusion 81
Literature Cited 82
Chapter 3 – Conclusions 90
Implications for Land Managers 90
Future Research 92

Literature Cited 94

Bibliography 97

Appendix A: Site selection figures 109

Appendix B: Four direction photography example (from the mid-point of unmined reach #6). 111

Appendix C: Correlation Matrices 112

Appendix D: Spatial Scale Interactions (PerMANOVA results). ... 115

Appendix E: Tiered interactions model 118

List of Tables

Table 2.1: All variables collected for each spatial scale of analysis. Landscape and Network scale variables are GIS derived, while outlet reach scale variables are calculated from field-collected data. * denotes variables selected for use in statistical analyses. Variables were chosen at each scale such that instances of high correlation ($\rho>0.8$) were removed, while preserving variables that represent the greatest range of geomorphic processes. 36

Table 2.2: Summary of the six PerMANOVA models used to evaluate interactions across spatial scales. Each test utilizes 9,999 permutations. See complete model output in Appendix D.....47

Table 2.3: Site attributes which have significant differences ($p<0.05$) by land use group. Site attributes include conclusion of mining activities (Year), mean surface slope in percent rise (slope), mean hillslope length in meters (Hillslope), profile roughness in σ slope (Roughness), percentage of watershed area as open water (% water.), distance from outlet reach upstream to nearest open water (Dist. To water.), width/depth ratio m/m (W/D), and ratio of streambed length to Euclidean distance (Sinuosity). 50

Table 2.4: Landscape scale variables used for analysis.....51

Table 2.5: Ordination values for landscape scale NMDS. 53

Table 2.6: Network scale variables used for analysis. 56

Table 2.7: Ordination values for network scale NMDS. 58

Table 2.8: Reach scale variables used for analysis.....60

Table 2.9: Ordination values for network scale NMDS. 63

Table 2.10: Summary of significant interactions across spatial scales, as detected by multiple PerMANOVA tests. Comprehensive results in Appendix D. Pathways refer to those in figure 2.17.....67

Table 2.11: Results of linear model: Mean hillslope length as a function of network meander, by land use group.....69

Table 2.12: Linear model results for bankfull Q as a function of open water area (left panel, figure 2.19) and bankfull Q as a function of distance to water (right panel, figure 2.19).....70

Table 2.13: Tiered variable selection process with final summary model. Input variables without p-values were excluded from models via lowest AICc selection process. Mining and reclamation practices (including the construction of impoundments) are as impactful as channel dimensions on stream power at the outlet..73

List of Figures

Figure 2.1: Top-down hypothetical model structure. At the outlet reach scale, channel geometry is the product of upstream influences. Land uses may directly impact outlets via channel engineering, while having indirect influence via landscape and network alterations (such as the presence of surface waters in mined sites). 28

Figure 2.2: Location of twenty-one study sites in eastern Ohio, U.S. 33

Figure 2.3: Examples of DEM-derived surface slope layers. Slope is binned in 10% increments for display purposes while my dataset retains 1% resolution for statistical analysis. A remnant headwall is visible in the Pre-SMCRA site (red linear feature) while Post-SMCRA sites are visibly smoother, with reduced slopes evidenced by a dominance of green coloration. 37

Figure 2.4: Example of network meander ratio calculation. Total channel length (White)/Euclidean distances (Red)=network meander ratio. In this example, 6069m/5006m = 1.2. Watershed delineation (orange polygon) and channel nodes (red circles) also shown. 38

Figure 2.5: Google Earth imagery with a Pre-SMCRA watershed boundary delineated by dark blue polygon. Right panel shows

overlaid wetland delineations, from the USFWS National Wetlands Inventory (NWI) (pale blue shaded areas). NWI delineations correspond to open waterbody areas identified as dark gray or black features (left panel). 39

Figure 2.6: National Land Cover Dataset (clipped to watershed, prior to reclassification). 30m cell counts were converted to percentage of watershed area. In this example, 591 herbaceous cells/1098 total cells = 53.8% grassland cover. 40

Figure 2.7: Landscape scale univariate boxplots across the three land use groups. Box center lines indicate group median, box ends are the 25th and 75th percentiles; lines extend to the 5th and 95th percentiles. Different letters above boxes indicate significant differences ($p<0.05$) between land use groups, from Kruskal Wallis post-hoc pairwise tests. 52

Figure 2.8: Landscape scale NMDS. Horizontal axis is characterized by mean slope, down-slope roughness and hillslope length. Vertical axis is a combination of elevation range and mean hillslope length. Sites that plot in the left region of the plotting space are steeper and rougher. 53

Figure 2.9: Slope distributions by land use group, with 95% confidence bands (upper panel) and resulting pairwise differences (lower panel). 55

Figure 2.10: Network scale univariate boxplots. Box center lines indicate group median, box ends are the 25th and 75th percentiles; lines extend to the 5th and 95th percentiles. Different letters above boxes indicate significant differences ($p<0.05$) between land use groups, from Kruskal Wallis post-hoc pairwise tests. 57

Figure 2.11: Network scale NMDS. Horizontal axis is characterized by the percentage of open water area, the distance from outlets to the nearest open water body and the network meander ratio. Vertical axis is a combination of % open water and the distance from the outlet reach upstream to an open water body, as well as drainage density and channel node count. 58

Figure 2.12: Network complexity variation within Post-SMCRA group.....59

Figure 2.13: Outlet scale univariate boxplots. Box center lines indicate group median, box ends are the 25th and 75th percentiles; lines extend to the 5th and 95th percentiles. Different letters above boxes indicate significant differences ($p<0.05$) between land use groups, from Kruskal Wallis post-hoc pairwise tests. 61

Figure 2.14: Reach scale NMDS with central cluster of eight sites circled. These eight sites are significantly different at both the

landscape and outlet reach scales. Horizontal axis is most strongly determined by the percentage of bedrock, D90 particle size and the entrenchment ratio. Vertical axis is most strongly determined by W/D ratio and Sinuosity. 63

Figure 2.15: Comparing Inner and Outer groups from reach scale NMDS. Underlying geomorphic effects appear to act in unison with land use to determine outlet channel geometry. Greater vertical relief (landscape scale) yields narrower, steeper and less confined outlet reaches. 64

Figure 2.16: Cumulative particle size distributions of outlet reach sediments by land use group. X-axis is log-scaled and labelled with physical particle sizes. White lines indicate land use group mean values and shaded areas indicate 95% confidence intervals of the land use group distributions. 400 samples were collected at each outlet reach, for 2,800 samples per land use group. 65

Figure 2.17: Summary of spatial scale interactions as determined by multiple Bi-directional PerMANOVA tests. Interactions which were originally hypothesized are either supported or unsupported by PerMANOVA results. The influence of networks on landscapes were not predicted but are indicated in results. Letters refer to pathways in table 2.10. 67

Figure 2.18: Interaction of Network Meander Ratio and Mean Hillslope Length by land use group. 69

Figure 2.19: Quantity (% open water) and position (distance to water) of open water bodies vs. Bankfull Discharge, by land use. Unmined and Pre-SMCRA responses are linear but differentiated by land use group. Post-SMCRA group does not show detectable trends in these comparisons. 71

Chapter 1 - Introduction

Surface Mining in Ohio

The Central Appalachian Region in the eastern U.S., including Ohio, contains some of the richest coal reserves in North America (figure 1.1), (USDOE 1996). The presence of coal in Ohio was first noted in 1748, with the first recorded production (90t) in 1800 (Crowell, 2005). Coal comprises the bulk of U.S. and global energy sources; coal powered generating stations provided 39% of the nation's electricity production in 2013 (USEIA, 2015). Surface mining remains a primary coal extraction method accounting for more than 40% of the coal output for the Central Appalachian region (Kitts 2012). Over the last four decades, surface mining and reclamation represent the dominant driver of land cover land use change in this region (Townsend et al., 2009) serving as a significant landscape scale disturbance (Northington et al., 2011). Surface coal mining requires the substantial disturbance or removal of overlying vegetation, soil, and near surface geologic layers.

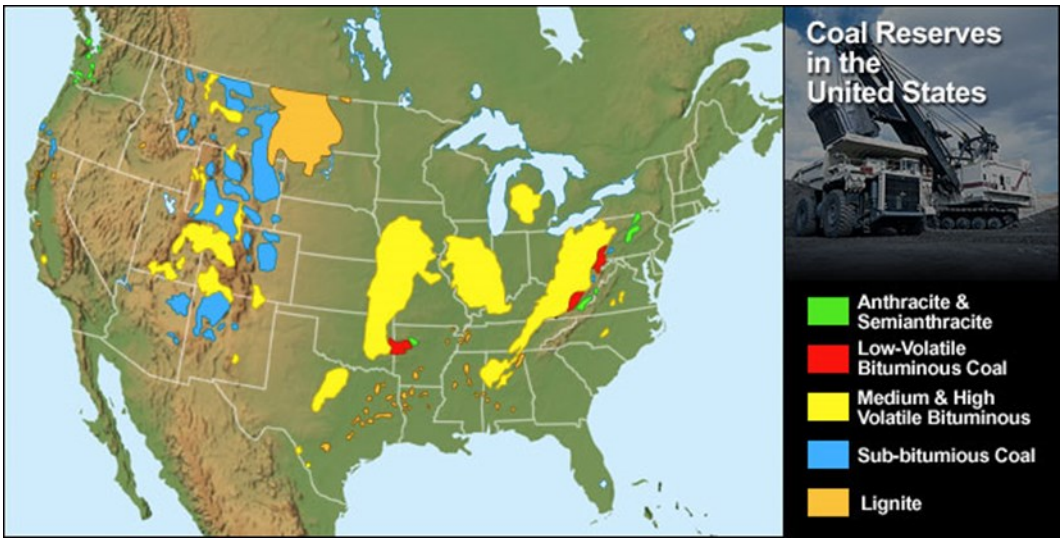

Figure 1.1: Coal reserves in the United States. (American Coal Foundation, 2014).

Pre-SMCRA Practices

Prior to 1977, regulation did not require controlled placement of mine spoils in Appalachian coal fields (Zipper et al., 2011). Mine spoils, commonly referred to as overburden, include the vegetation, soils and rock overlying a coal seam. Surface mining typically involved contour stripping, where relatively shallow (<50m) overburdens were displaced in order to access horizontal coal seams (figure 1.2). This method penetrates hillsides along a horizontal bench, resulting in a vertical face of native rock and exposed coal known as a headwall or highwall. Coal extraction continues, with the bench widening into the hillside until the headwall is as tall as the vertical reach of machinery on site, which can extend upwards of 45m. Overburden is placed behind the

earthmoving machinery as it continues forward. At the termination of an extraction run, the resulting trench along the headwall was often left unfilled. This combination of disturbances results in topographically irregular landscapes with some reconfiguration of channel networks and introduction of open water bodies as trenches filled with water.

When the Surface Mining Control and Reclamation Act (SMCRA) was passed in 1977, two thirds of all surface mined lands were unreclaimed. Reclamation refers to the act of returning an area to a former pre-disturbed or improved condition. In particular, unreclaimed areas within Pre-SMCRA mined lands in southeastern Ohio are characterized by irregular landforms, introduced open water areas via trenches, and substantially increased effective porosity in terrestrial portions of the watershed. Uncompacted surface mine spoil may have as much as 25% effective porosity compared to 1% for pre-mining conditions (Hawkins and Smoyer, 2011). Water-filled trenches may be lacking surface flow connections. In addition, many Pre-SMCRA sites were subject to land instability, sedimentation and surface water contamination as a result of uncontrolled spoil placement (Zipper et al., 2011). These issues led to the introduction of SMCRA.

Pre-SMCRA lands account for approximately 2,100 km^2 of all surface mined lands in the U.S. The federal Abandoned MineLand Inventory System (AMLIS) is a national database, which includes 1,352 km^2 of Pre-SMCRA mined lands (equivalent to 1.3% of Ohio's land surface area). Of these lands, 893 km^2 are listed as being in need of reclamation, yet lack the necessary funding. Approximately 126 km^2 of these unfunded sites occur in the state of Ohio (OSMRE, 2014).

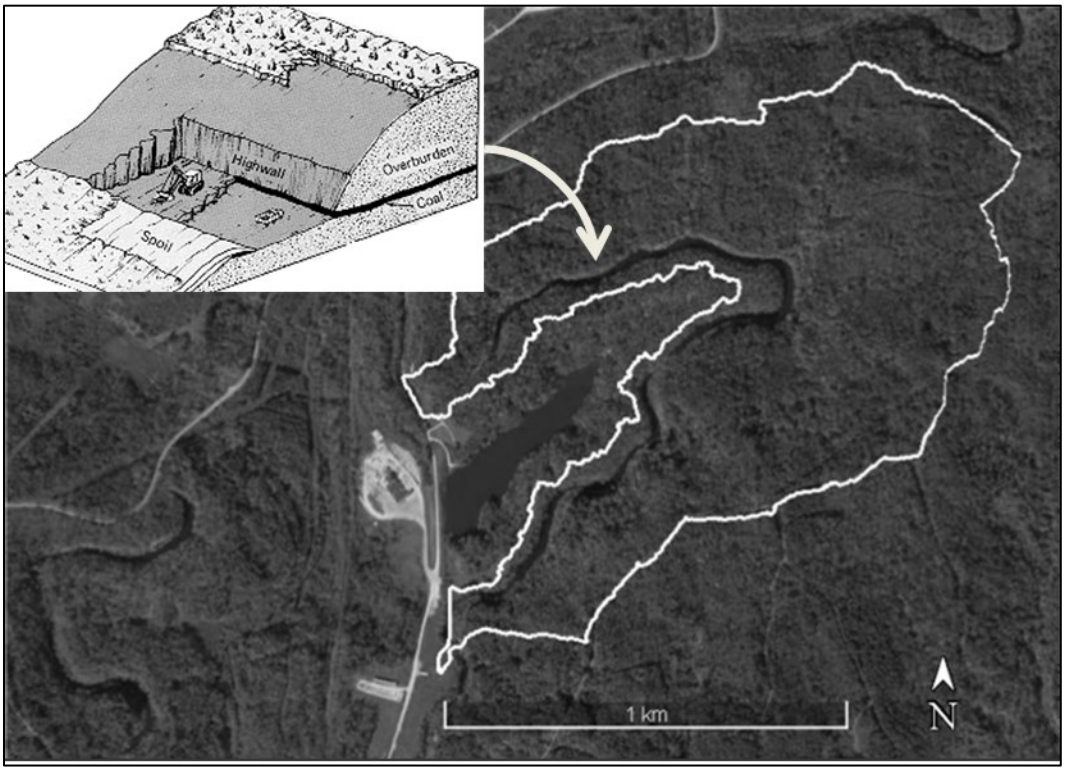

Figure 1.2: Pre-SMCRA watershed (white polygon) with remnant headwalls and water-filled trenches (dark linear feature). Following removal of vegetation and soils, trenches are excavated for coal extraction, resulting in the formation of vertical headwalls. Prior to SMCRA, neither re-contouring of excavated material (mine spoils) nor backfilling of trenches was required. Inset: Earthsci.org, 2015. Main: Google Earth, 2015.

The Surface Mine Control and Reclamation Act

The Surface Mine Control and Reclamation Act (SMCRA) of 1977 was drafted and enacted in response to growing concerns regarding the environmental and socioeconomic impacts of surface mining. The impacts of surface mines are officially recognized in Title 30 of the United States Code (Mineral Lands and Mining) which acknowledges the adverse effects of surface mining on commerce and public welfare *"by causing erosion and landslides, by contributing to floods, by polluting the water, by destroying fish and wildlife habitats, by impairing natural beauty, by damaging the property of citizens, by creating hazards dangerous to life and property by degrading the quality of life in local communities, and by counteracting governmental programs and efforts to conserve soil, water, and other natural resources."* [30 U.S.C. §1201]. Mining regulation bills were passed by U.S. Congress in 1974 and again in 1975. In both instances, the bills were vetoed by President Gerald Ford. A similar bill was later signed by President Jimmy Carter on August 3rd, 1977. After over six years in development, SMCRA was now a federal law. During the signing, President Carter expressed concerns about the strength of the bill but considered it to be "*a basis on which we can make improvements on the bill in years to come."* (Carter, 1977). Under SMCRA, bonds must be held against successful reclamation of surface mined lands, which must be

returned to approximate original contour (AOC) unless a site specific deviance is issued.

Post-SMCRA Practices

With the advent of SMCRA, post-mining strategies focused on the creation of stable landforms (Angel et al., 2006). In addition to SMCRA requirements to return the land to AOC, mining companies are also required to minimize disturbance to nearby hydrologic systems (Mishra et al., 2012). SMCRA-mandated hydrologic objectives are commonly achieved by replacing naturally branching channel networks with a combination of diversions and artificial, armored channels, both of which may connect via a series of reservoirs (Bonta et al., 1997) to address erosion and flooding issues.

From 1977 to 2011, almost 10,000 km^2 have been surface mined and reclaimed in the U.S. under SMCRA, which is equivalent to 9.4% of Ohio's land surface area. Approximately 60% of these lands are in the Appalachian Region (Zipper et al., 2011). In addition, the Abandoned Mine Land (AML) Program, also created under SMCRA, has funded the reclamation of almost 1,000 km^2 of Pre-SMCRA mined lands.

Recontouring of mined surfaces with heavy machinery can result in significant compaction of surface soils, which in turn has

resulted in the semi-permanent conversion of forested land to a pasture condition (McCormick and Eshleman, 2011) (figure 1.3). Further, Post-SMCRA surface mined lands are characterized by considerable homogenization of terrestrial landforms and removal of steep terrain (Maxwell and Strager, 2013, Wickham et al., 2013).

Headwater Channels and the Impact of Mining

Surface coal mining throughout the Appalachian Region is predominantly conducted in the uppermost portions of watershed areas. These areas contain headwater channels, which are a critical component of the fluvial network (Gomi et al., 2002). Headwaters account for 60-80% of the fluvial network in terms of total channel length (Leopold et al., 1964, Shreve 1969). Streamflow volumes received from headwater channels comprise the majority of flow in downstream channels (Alexander et al., 2007, MacDonald and Coe 2007) and approximately 50 to 73% of sediment delivered to the world's oceans is derived from headwater areas (Wilkinson and McElroy 2007). In addition, headwater channels provide habitat for endemic aquatic macroinvertebrate, mollusk, amphibian, and some fish species that do not occur elsewhere in the channel network (Wilkins and Peterson 2000, Finn et al., 2011).

Surface mining results in a landscape-scale reconfiguration of terrestrial landforms and drainage features where these headwater channels are located (figure 1.3). As previously identified, substantial alteration in upland topographic relief is a consequence of large-scale, earth-moving activities associated with surface mining. In addition, alterations to the channel network occur in both Pre-SMCRA and Post-SMCRA sites. On Pre-SMCRA sites, because lands were not required to be re-contoured, extraction areas often were not backfilled, resulting in sheer highwalls up to approximately 45m high (TEEIC, 2014) and adjacent trenches that filled with water over time. These rock-lined trenches are prominent features in Pre-SMCRA reclaimed sites. Lands reclaimed under SMCRA often feature engineered drainage networks in place of the original headwater channels. In both unreclaimed and reclaimed mine sites, the geomorphic complexity of channels may be reduced as a consequence of flow regulation from water filled trenches or constructed open water bodies. Channel complexity refers to the degree of variation in channel geometry from three perspectives: i) cross-section profiles ii) longitudinal profiles and iii) planform profiles (Laub et al., 2012). Channel complexity provides the physical template that supports diverse, robust ecosystem processes (Ward et al., 2001).

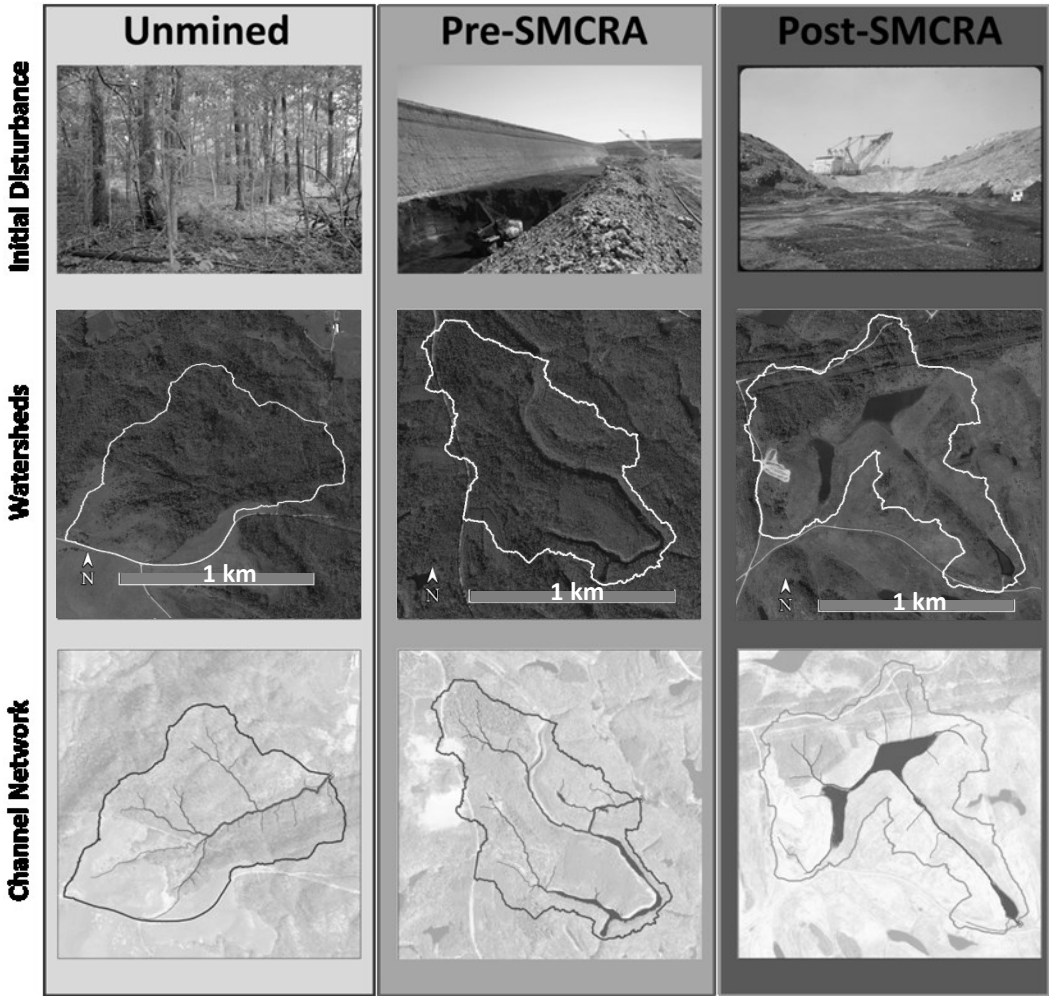

Figure 1.3: Comparison of unmined, Pre-SMCRA (unreclaimed) and Post-SMCRA (reclaimed) watershed topology and corresponding channel network structure. Pre-SMCRA sites are often characterized by remnant headwall trenches, which follow horizontal contours and capture runoff. Post-SMCRA sites are characterized by a series of open water bodies, fed by a partially engineered channel network.

Headwater channels are the primary conveyance mechanism for downstream delivery of water, sediment, and energy (e.g. nutrients, wood, biota) (Meyer et al., 2007, Wipfli et al., 2007). Changes to this conveyance mechanism can have important implications on the physical, chemical, and biological processes

occurring throughout the riverine network. Altered physical channel dimension and stream network configurations in the headwater portion of the network therefore may impact physical, chemical, and biological processes occurring throughout the larger riverine network. Downstream impacts may include flooding and/or water quality issues as well as altered ecosystem processes such as nutrient cycling and biodiversity. Studies that quantify the hydrologic effects of surface mining and reclamation have yielded mixed results, in part because of variability in mining and reclamation activities and the long-term periods of readjustment that occurs. Some have found that unreclaimed mined sites have a more rapid rainfall to runoff response, which manifests as increased storm flow volumes, peak runoff rates, and decreased time to peak flow (Bonta, 2000, Bonta, 2003, Ferrari et al., 2009, McCormick and Eshleman, 2011). These results have been attributed to the altered infiltration and storage capacities of mine soils (Curtis, 1977) and the surface compaction of re-contoured sites (Bonta et al., 1972). Bonta et al. (1997) also acknowledges that runoff and infiltration characteristics for mined/reclaimed surfaces undergo long-term periods of readjustment following disturbance. Other studies have found opposing results, where peak flows are diminished while base flows are increased (homogenization of flow) within Pre and Post-SMCRA reclaimed

sites (Borchers et al., 1991). Curtis (1979) later found evidence for the homogenization of flows within reclaimed sites and attributed this to the presence of retention basins within reclaimed areas. Other studies have demonstrated a net increase in water yield, especially in base flows, which have been also been linked to the presence and storage capacity of retention basins (Agnew and Corbett, 1973). Decreased evapotranspiration within Post-SMCRA (reclaimed) sites has also been reported (Dickens, 1989). Collectively, these studies reflect the large variation in topographic and channel network complexity within Post-mining watersheds. They provide evidence for fundamental differences between mined and unmined landscapes in terms of hydrologic and geomorphic function, which are responsible for the magnitude and transfer rate of materials through the landscape. The magnitude and direction of hydrologic and geomorphic differences remain unclear.

A crucial factor within the collective literature is the lack of consistency regarding experimental design. In a recent review of surface mining hydrology (Miller and Zégre, 2014), 27 separate studies were examined. No study in this group utilized more than six headwater basins for their comparisons. In addition, traditional land surface modeling fails to capture the complex interactions within reclaimed sites, where the sum of all land surface effects on hydrology may be offset or reversed by the presence of retention

basins (Miller and Zégre, 2014). Geomorphic studies in surface mined areas are scarce (but see Bonta 2000, Wiley et al., 2001, Touysinhthiphonexay and Gardner, 1984, Fox, 2009, Jaeger, 2015) relative to hydrologic studies. The study presented in this thesis will address the lack of knowledge regarding the extent and magnitude of topographic and channel network change in mined sites via a larger sample of similarly sized watersheds, which represent both the legacy of Pre-SMCRA methods and the outcomes of Post-SMCRA reclamation. In particular, this study will quantify morphologic differences between Pre-SMCRA, Post-SMCRA, and unmined watersheds across three spatial scales that include the landscape (10^0 km^2), channel network (10^3 m) and outlet reach (10^2 m) scales. This study will provide information to land-managers regarding the geomorphology of surface mined lands relative to unmined lands as well as the geomorphic impacts of reclamation.

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Chapter 2 - Geomorphic Differences between Unmined and Surface Mined Lands in Southeastern Ohio

Abstract

Surface mining for coal has been carried out in Ohio since the early 1800s. Surface mining involves the complete removal of vegetation, soils and geologic units (overburden) to expose underlying coal seams. This coal extraction method results in heavily disturbed landscapes, in what were historically forested or agricultural lands. The Surface Mining Control and Reclamation Act (SMCRA) of 1977 was enacted to address the environmental impacts of coal surface mining. Recent studies have examined the hydrologic impacts of surface mining but few have explored geomorphic impacts including potential linked impacts across spatial scales. This study identifies significant geomorphic differences between unmined, Pre-SMCRA and Post-SMCRA watersheds at the landscape, channel network and outlet reach scales. Geomorphic differences were quantified across the three

spatial scales in seven small watersheds (~1km^2) representing each of the three land use types (unmined, Pre-SMCRA, and Post-SMCRA, n=21) located in southeastern Ohio. It was expected that Post-SMCRA sites would be more dissimilar to unmined sites compared to differences between Pre-SMCRA and unmined sites at all spatial scales. Specifically, Post-SMCRA sites were expected to have detectable differences characterized by smoothed and homogenized landscape topography and highly engineered channel network systems. At the landscape scale, Pre-SMCRA sites would have steep, varied topography similar to unmined sites, but exhibit geomorphic differences from unmined sites at the network topologic and reach scales. Hypotheses were created based on these expectations as well as the expected influence of broader spatial scales on finer reach scale channel morphology.

Univariate Kruskal Wallis tests indicate reduced complexity in Post-SMCRA sites relative to Pre-SMCRA and unmined sites at the landscape scale, as well as some differences at the channel network and outlet reach scales. At the landscape scale, Post-SMCRA sites had reduced mean terrestrial slope (KW, p=0.001), increased mean hillslope length (KW, p=0.003) and reduced profile roughness (KW, p=0.001). At the network topology scale, the amount of open water area was found to be greater for all mined sites, relative to unmined sites (KW, p=0.001) with correspondingly

reduced distances between outlet reaches and the nearest upstream open water body area (KW, p=0.038). At the outlet reach scale, Post-SMCRA reaches were less sinuous than unmined reaches (KW, p=0.049) and exhibited higher variation in other reach-scale parameters than either Pre-SMCRA or unmined reaches. Post-SMCRA sites had significantly higher width/depth ratios than Pre-SMCRA sites (KW, p=0.039). Multivariate methods that include Nonmetric Multi-Dimensional Scaling, Permutational Multivariate Analysis of Variance and standardized linear models indicate some interactions between spatial scales, with land use influential at all scales. Multivariate analyses largely support the hypothesized influential effects of mining and reclamation across all spatial scales, via direct and indirect effects.

The simplification of Post-SMCRA landforms and drainage networks, coupled with the well-documented compaction and low soil fertility of recontoured lands has resulted in altered landscapes with altered geomorphic trajectories compared to unmined sites. Pre-SMCRA sites have attributes which are inconsistent with the goals of erosion control and water quality such as unconsolidated mine spoils, which contribute heavy sediment loads to the channel network and vertical headwalls that are prone to periodic failure. Despite these attributes, Pre-SMCRA sites resemble the geomorphic structure of unmined sites more closely than

reclaimed Post-SMCRA sites. These findings suggest a need for reclamation strategies that incorporate greater topographic and topologic complexity, to more closely resemble the structure of unmined conditions. Further research is needed to evaluate geomorphic function of these landscapes.

Introduction

Coal is a major source of energy in the United States, providing 39% of the nation's electricity production in 2013 (USEIA, 2015). The Central Appalachian Region, which includes Ohio, contains some of the richest coal reserves in North America (USDOE, 1996). In this region, surface mining yields over 40% of total coal output (Kitts, 2012). Surface mining involves the displacement of all vegetation, soils and geologic units (overburden), which overlie the coal seam. The manner in which overburden is redistributed after coal extraction dictates site topography following mining operations. This physical landscape reconfiguration includes alterations to land surfaces and stream channels, with subsequent altered hydrologic and geomorphic processes. Surface mining and reclamation collectively are dominant drivers of land use/cover change (Townsend et al., 2009) and thus a significant landscape scale disturbance throughout Central Appalachia (Northington et al., 2011).

In 1977, the Surface Mining Control and Reclamation Act (SMCRA) was introduced to address environmental impacts associated with surface mining. The act requires that mine operators mitigate threats to public health and safety as well as addressing land and water resources degraded by the adverse effects of coal mining practices (30 U.S.C. §1233). Reclamation under SMCRA requires that the approximate original contour of the landscape (at the lowest grade) be restored and a permanent vegetative cover be established (30 U.S.C. §1265). Consequently, the traditional strategy under SMCRA has resulted in the conversion of previously steep, rugged and often forested terrain into gently rolling hill/swale landforms, with compacted soils and a dominant cover of grasses (McCormick and Eshleman, 2011).

The environmental impacts of coal surface mining are diverse and long-lasting. Many Pre-SMCRA sites were not actively reclaimed, defined as act of returning an area to a former pre-disturbed or improved condition, following coal extraction. This has created a legacy of heavily disturbed landscapes. Unreclaimed sites are often characterized by steep and unstable slopes, exposed headwalls and the presence of water bodies within abandoned trenches. Open water bodies have been linked to hydrologic alterations within Pre-SMCRA watersheds (Curtis, 1979, Agnew and Corbett, 1973). These legacy sites have been associated with

downstream water quality issues including acid drainage (Zipper et al., 2011, Griffith et al., 2012). Unstable slopes and headwalls in unreclaimed sites may also pose a risk to public safety. Despite these geomorphic alterations, many Pre-SMCRA sites have exhibited timber yields similar to those on nearby forested unmined sites (Angel et al., 2006). Sites reclaimed under SMCRA (Post-SMCRA) exhibit reduced soil permeability that has been linked to increased downstream water yields and flooding peaks (McCormick and Eshleman, 2011). These hydrologic responses are likely a result of the collective impacts of topographic homogenization and compaction of terrestrial soils, limited tree recruitment and growth (Groninger et al., 2006) and the presence of surface retention basins constructed within SMCRA-reclaimed sites (Hoomehr, 2013).

The majority of surface mines in the Central Appalachian Region directly impact the headwaters by altering the physical landscape and local channel network onsite, with subsequent impacts downstream. Several analyses have quantified the effects of surface mining and reclamation on sediment transport and hydrology (reviewed in Miller and Zégre, 2014, Dick et al., 1986). Less attention has been given to the effects of surface mining and reclamation on landscape and channel morphology (but see Touysinhthiphonexay and Gardner, 1984, Wiley et al., 2001,

Maxwell and Strager, 2013, Wickham et al., 2013, Jaeger, 2015). This study compares the geomorphic attributes of three land use groups, Pre-SMCRA (unreclaimed), Post-SMCRA (reclaimed) and unmined sites at three scales: 1) terrestrial landscape (10^0 km^2); 2) network topology (10^3m); and 3) channel reach (10^1 m) scales. Seven watersheds within each of the three land use groups (n=21; ~1km^2 each) are evaluated at the three spatial scales using Geographic Information Systems (GIS) and field methods. Study sites are located on and adjacent to lands managed by American Electric Power (AEP) in southeastern Ohio, U.S.

This study has two objectives: (1) quantify geomorphic differences between mined and unmined landscapes across multiple spatial scales, and (2) identify significant geomorphic influences and interactions between spatial scales and assess their dependence on land use. It was hypothesized that land use groups would be identifiable by significant differences at all three spatial scales. At the landscape scale, I hypothesized similar landforms and topographic slopes in Pre-SMCRA and unmined site (H_{1a}) but significant differences between Post-SMCRA and unmined sites as a result of smoother landforms with reduced slopes in the mined watersheds (H_{1b}). Channel network topology in Pre-SMCRA and Post-SMCRA sites will differ from unmined sites, with shorter channel segments, increased open water area and higher

confluence frequency (H_{2a1}). In addition, channel networks in Post-SMCRA sites will have a less sinuous planform (H_{2a2}). Drainage density is hypothesized to be similar between Pre-SMCRA and unmined sites, but will be lower on Post-SMCRA sites (H_{2b}). Finally, outlet reach-scale geomorphic channel complexity will be lower in both Pre-SMCRA and Post-SMCRA sites relative to unmined sites (H_3).

The second objective is addressed through a set of top-down hypothesized causal relationships (figure 2.1) between land uses, physical attributes at each spatial scale and their collective impact downstream, using stream power at the outlet reach as a proxy of impact. Stream power, here defined as the product of the reach averaged stream channel gradient and bankfull discharge, is a measure of the potential for geomorphic work (Cooley, 2013) within each watershed. Land use group, as well as landscape and channel network variables, are hypothesized to influence outlet reaches directly, via physical alterations of the outlet reach. Indirect effects are also hypothesized, such as the presence of surface waters in mined sites, which may alter the hydrologic response and in turn, channel geometry at the outlet reach.

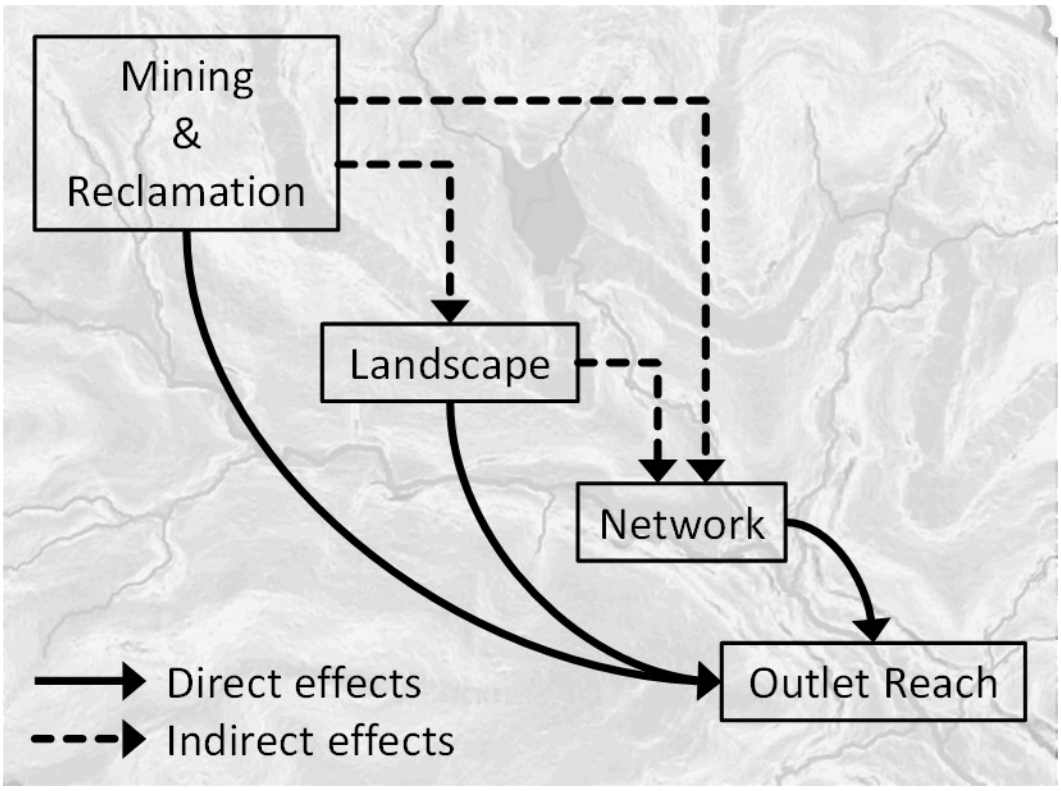

Figure 2.1: Top-down hypothetical model structure. At the outlet reach scale, channel geometry is the product of upstream influences. Land uses may directly impact outlets via channel engineering, while having indirect influence via landscape and network alterations (such as the presence of surface waters in mined sites).

The reclamation of surface mined lands is a somewhat unique prospect in that the soils, topography, drainage networks and vegetation can be directly manipulated in order to configure the landscape for its future intended use. Findings from this study provide surface mine reclamation practitioners with new information regarding topologic and geomorphic processes in reclaimed areas in order to continue the development of site and use-specific reclamation strategies. In particular, reclamation

strategies must incorporate greater topographic and topologic complexity in order to more closely resemble unmined conditions.

Surface mining remains a viable extraction method throughout the Appalachian region. As economic forces change, it may also be profitable to re-mine certain areas. Re-mining of unreclaimed mine lands provides an opportunity to address acid drainage issues and the legacy of dangerous headwalls while profitably extracting resources (Mauger et al., 2011). Surface mining will therefore continue in the U.S. for the foreseeable future.

Surface mining and reclamation both result in fundamentally altered topology, soil structure, groundwater interactions and surface water flows. Since "reclamation" can potentially take on many forms, this research is intended to identify the physical landscape and channel network characteristics associated with traditional metrics of outlet channel functionality and complexity. This study will provide information to land-managers regarding the geomorphology of surface mined lands relative to unmined lands as well as the geomorphic impacts of reclamation.

Methods

Study region

Seven watersheds within each of three land use types (unmined, Pre-SMCRA, and Post-SMCRA, n=21; ~1km^2 each) were selected within or adjacent to the mine lands owned by American Electric Power (AEP) approximately 15km NE of McConnelsville, in southeastern Ohio (Figure 2.2). Surface mining occurred in this area from the 1950s to the early 1990s thus spanning Pre- and Post-SMCRA eras. Today, AEP manages this land for a variety of recreational uses that include camping, fishing, hunting, canoeing and hiking. Remnant headwalls and trenches remain on Pre-SMCRA sites. The majority of Pre-SMCRA mined lands are used in forestry production, while Post-SMCRA reclaimed sites are generally grass covered to provide stock feed for nearby farms. Post-SMCRA sites have been returned to approximate original contour, with some portions of drainage networks being lined with angular rock material for long-term stability. Open water bodies are frequent and trees have been planted in patches throughout Post-SMCRA reclaimed sites but with marginal results due to highly compacted soils and the establishment of aggressive ground cover species (Groninger et al., 2006). Nearby unmined sites have historically been managed for various forest products and are

dominated by forest cover today. Some unmined sites incorporate portions of small-scale dairy farming operations along boundaries at higher elevations.

The region receives an average 1.07m of precipitation annually, with 0.51m as snowfall (climate-charts.com, 2015). Peak runoff events occur from January through May. Study site outlet reaches are 3rd or 4th Strahler order (Brooks et al., 2013) channels. Streamflow was present in all stream channels during field visits. Personal field observations, including flowing water >48 hours after rainfall and seeps/springs within outlet reaches suggest perennial flow regimes (FCSPD, 2003).

The twenty-one sites lie within Muskingum, Noble and Morgan counties. The study area is near the western edge of the Appalachian plateau and is characterized by Pennsylvanian-age interbedded sandstones, shales, coals and thin limestones (Coogan, 1996). Soils in unmined sites are highly variable, often in complexes and are elevation dependent. Unmined soils are generally silt loams. Pre-SMCRA sites are dominated by silty clay loams while Post-SMCRA sites are dominated by very stony clay loams (USDA, 2015). Outlet elevations range from 211 meters above mean sea level (AMSL) to 285m AMSL. The maximum

elevation of any site perimeter is 358m AMSL. All study sites lie within a 12km radius.

Study Design

Each of the twenty-one study watersheds is approximately 1km^2, with an outlet channel reach at least 50m long, or fifty times bankfull width. I began with the premise that surface mining results in substantially altered landscapes, with altered geomorphic processes. Also, the act of reclaiming mined lands results in further alterations, which may not necessarily resemble unmined conditions. All sites were selected for their close proximity to each other (within 12km radius), as well as their similar geology and climate, which contribute to geomorphic processes. This allows me to attribute potential differences to differences in land use (unmined, Pre-SMCRA mined-unreclaimed and Post-SMCRA mined-reclaimed).

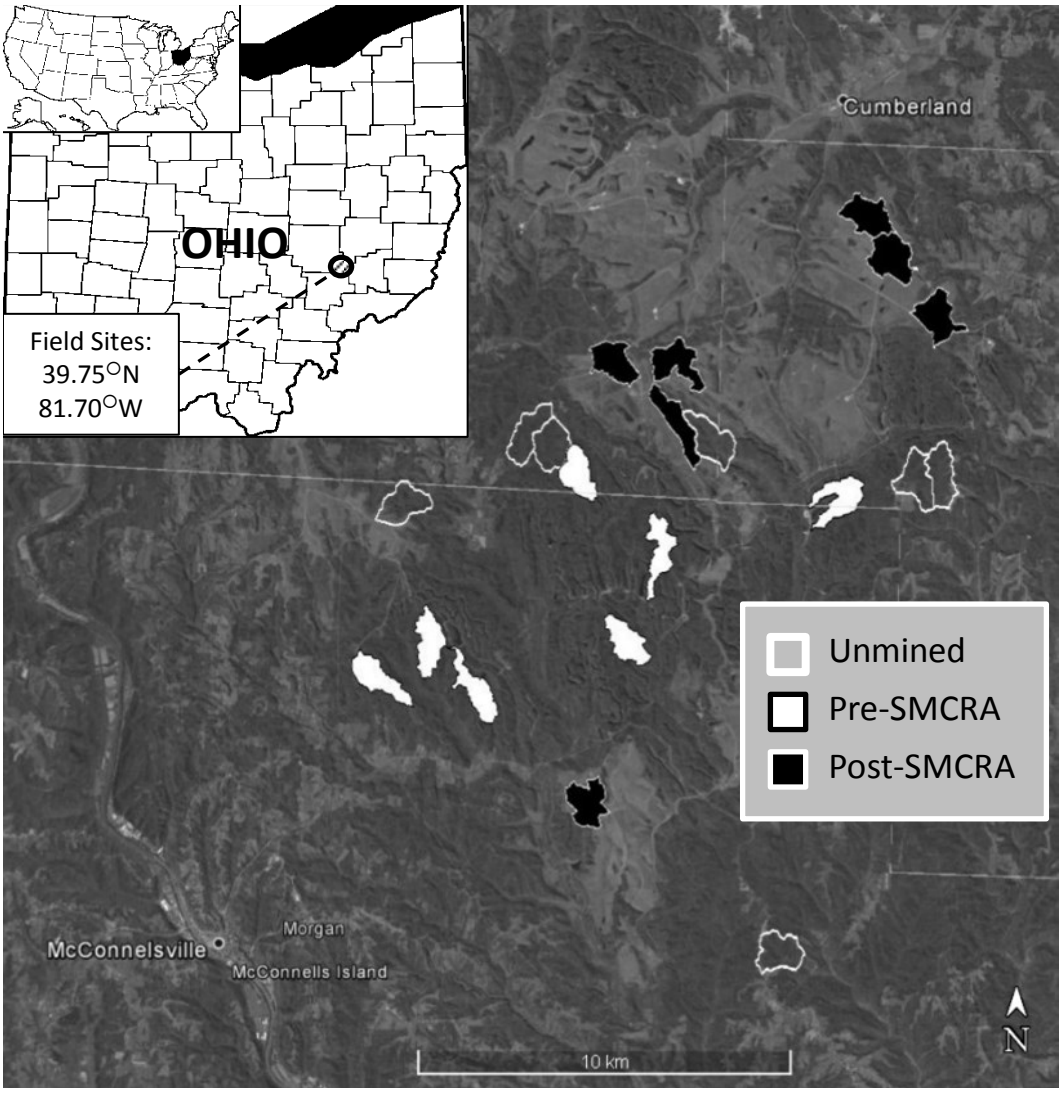

Figure 2.2: Location of twenty-one study sites in eastern Ohio, U.S.

Site Selection

A bounding rectangle (27km E-W by 33km N-S) was created in a GIS which enclosed the mined lands of interest and surrounding areas. A 30m Digital Elevation Model (DEM) (OGRIP, 2013) was clipped to this bounding rectangle and from this DEM, a flow accumulation layer, which calculates the contributing

upstream drainage area for each 30m grid square, was developed using the hydrology toolset in ESRI ArcMap (v.10). This layer was then reclassified such that points with 100ha+/-5ha flow accumulation were color coded (Appendix A, figure A1). These points represent the outlet reaches of 100ha (1km^2) watersheds. A 1.5 x 1.5km grid was overlaid on the geographic area of interest and was used to locate all possible watersheds, of approximately 1km^2, that satisfied the following criteria:

1) Must have an outlet reach that is a free-flowing open channel (not an impoundment) without significant tributaries, at least 50 times bankfull width in length.

2) Must have no detectable (DEM, imagery and site visit) infrastructure for inter-basin hydrologic transfers such as irrigation ditches, pumps or pipes.

While establishing candidate sites, surveyable reach length was estimated via the distance between impoundments and between tributaries (OGRIP, 2013). Reach endpoints were recorded with a GPS and approximate bankfull widths were measured during site visits to establish appropriate reach dimensions. The resulting candidate watersheds were then compared to mining permit GIS layers in order to identify the land use group. Eight watersheds in each land use group (unmined, Pre-SMCRA and Post-SMCRA) were

identified. Each outlet reach was visited in March 2014 to determine suitability and access. It was determined that one Pre-SMCRA site was unsuitable as the outlet reach was too short. One Post-SMCRA site was also eliminated because the outlet was located within a large depressional area that was periodically inundated. These two sites and a randomly selected unmined site were removed from the study group, leaving seven sites in each group (n=21).

Data Collection

Following site selections and field verification, each watershed was delineated via a LiDAR-derived 0.762m (2.5ft) resolution DEM. Watershed perimeter polygons were used to clip the LiDAR-derived base DEM, producing individual DEMs for each watershed. Clipping was necessary given the high resolution of the data (each watershed DEM contains ~$1.7*10^6$ data points). Landscape and network scale variables were derived using GIS, while outlet reach scale data were calculated from field-collected data. A summary of all variables considered for analysis is provided in table 2.1.

Table 2.1: All variables collected for each spatial scale of analysis. Landscape and Network scale variables are GIS derived, while outlet reach scale variables are calculated from field-collected data. * denotes variables selected for use in statistical analyses. Variables were chosen at each scale such that instances of high correlation (ρ>0.8) were removed, while preserving variables that represent the greatest range of geomorphic processes.

Landscape Topography	Network Topology	Outlet Reach
% Forest Cover	* Drainage Density (m/ha)	* Bankfull Discharge (m^3/s)
% Grassland Cover	* Network Meander Ratio	* Entrenchment Ratio
* Profile Roughness (σ slope)	* Channel Node Count	* Sinuosity (m/m)
Cross-slope Roughness (σ contour)	Channel Segment Count	Bed Roughness (R^2 linear fit)
* Mean Hillslope Length (m)	Total Channel Network Length (m)	* Mean Bed Slope (m/m
Mean Slope Variability (% rise/ha)	1st-4th Strahler Order Total Length (m)	* Width/ Depth Ratio
* Mean Terrestrial Slope (% rise)	1st-4th Strahler Order Segment Count	Mean Bankfull Depth (m)
* Elevation Range (m)	* Distance from Outlet to Open Water (m)	* Bankfull Width (m)
Minimum Elevation (m AMSL)	* % Open Water Area	Mean Particle Dia. (mm)
Maximum Elevation (m AMSL)		Geometric particle Sorting Ratio.
Total Area (km^2)		* % Bedrock (% of reach length)
		* D90 Particle Size (mm)
		D50 Particle Size (mm)
		D10 Particle Size (mm)

GIS data

Batch processing was used to run surface runoff direction, runoff accumulation and hillslope length modelling functions on watershed DEMs using spatial analyst tools within ESRI ArcMap (v.10). DEMs were also used to determine the surface slope distributions of all sites (figure 2.3). Slope data were binned in 1% rise increments, from 0-1% through to 99-100% and a >100% (>45 degrees) bin. Binned cell counts from GIS slope layers (~1.7×10^6 unique values per watershed) were converted into percentages of watershed area. Open surface waters were removed from these summaries so that the distributions describe dry land only.

Landscape surface roughness characteristics including profile and cross-slope roughness were derived via standard deviations in profile and contour elevations, sampled within a roving 1ha square window (~20,000 cells) (Cooley, 2013).

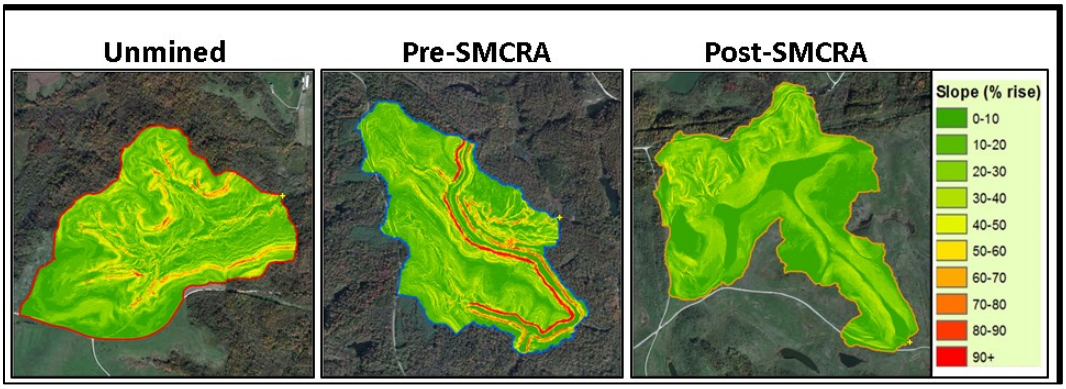

Figure 2.3: Examples of DEM-derived surface slope layers. Slope is binned in 10% increments for display purposes while my dataset retains 1% resolution for statistical analysis. A remnant headwall is visible in the Pre-SMCRA site (red linear feature) while Post-SMCRA sites are visibly smoother, with reduced slopes evidenced by a dominance of green coloration.

The network meander ratio reflects the planform complexity of the channel network (figure 2.4). The metric is the ratio of the total length of each stream network and the sum of Euclidean distances from node to node within the network. Channel network nodes or confluences were manually selected to eliminate erroneous connections arising within open water bodies.

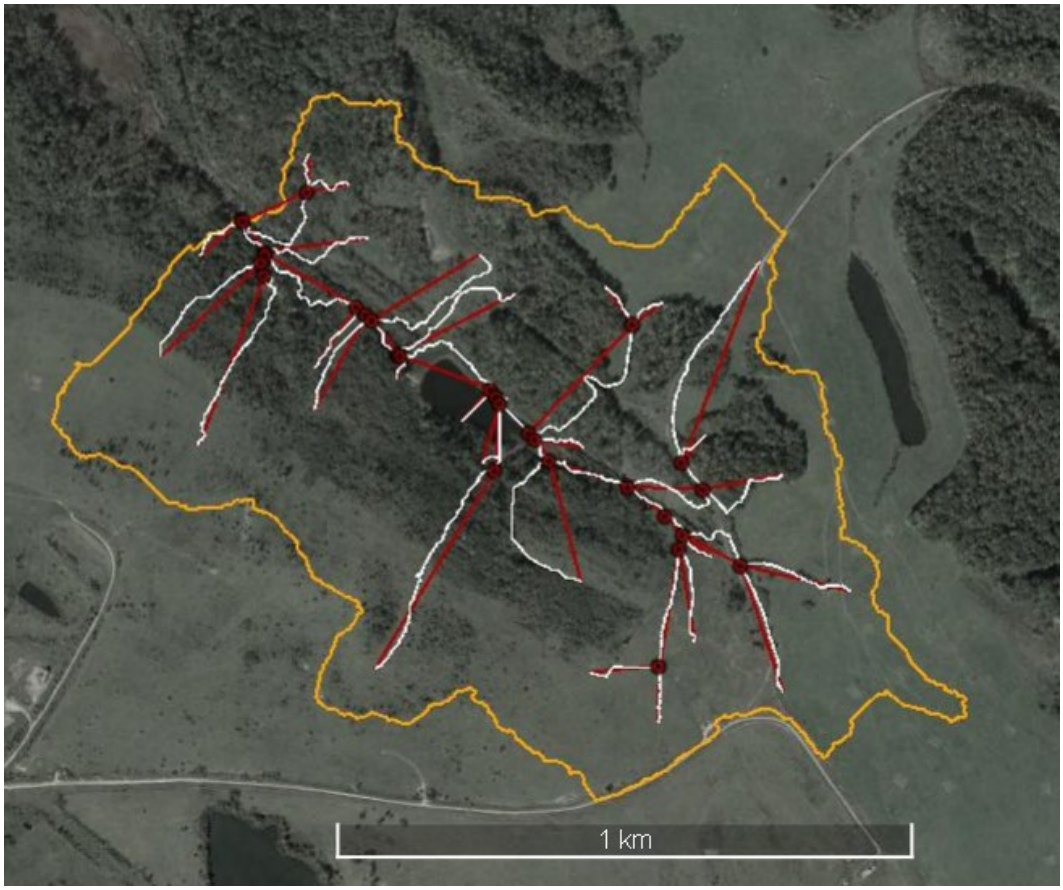

Figure 2.4: Example of network meander ratio calculation. Total channel length (White)/Euclidean distances (Red)=network meander ratio. In this example, 6069m/5006m = 1.2. Watershed delineation (orange polygon) and channel nodes (red circles) also shown.

The percentage of open water area was defined as the watershed area designated as wetlands by the U.S. Fish and Wildlife Service's National Wetlands Inventory (NWI) (USFWS, 2014). Originally, open water area, which includes detention basins and natural riverine wetlands, was calculated via remote sensing methods (supervised classification, ESRI ArcMap v.10) from a single false-color IR imagery layer (OGRIP, 2013) but this

method did not reflect seasonal trends, with many open waterbodies subject to cycles of expansion and contraction. Remotely sensed open waterbody area was found to strongly correlate to NWI wetland area (R^2=0.85) (figure 2.5). USFWS wetland calculations are more rigorous, involving remote sensing data from multiple seasons and years.

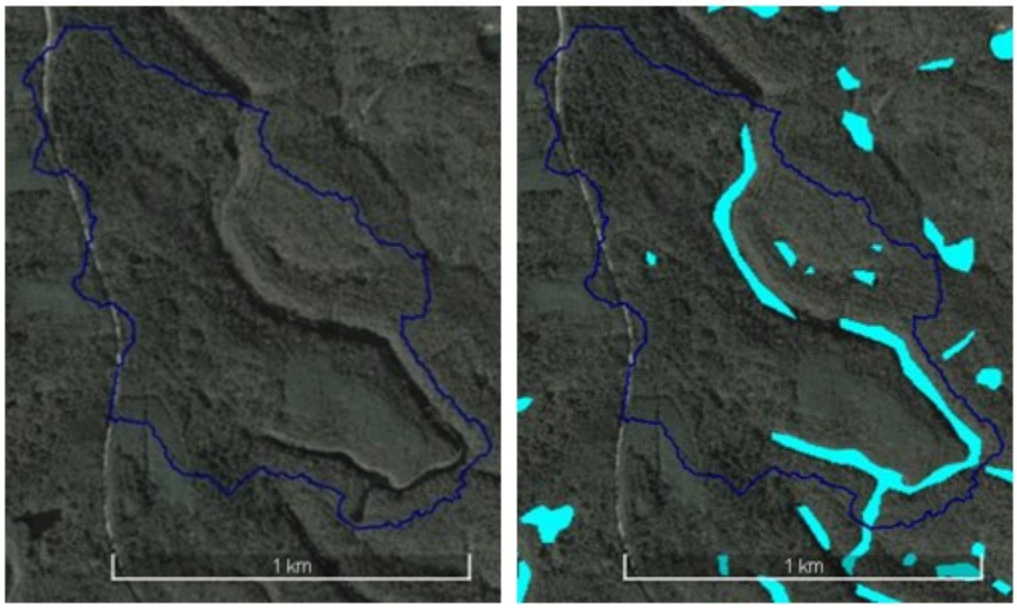

Figure 2.5: Google Earth imagery with a Pre-SMCRA watershed boundary delineated by dark blue polygon. Right panel shows overlaid wetland delineations, from the USFWS National Wetlands Inventory (NWI) (pale blue shaded areas). NWI delineations correspond to open waterbody areas identified as dark gray or black features (left panel).

Land cover types and areas were calculated using the most recent National Land Cover Dataset (NLCD)(MRLC, 2011). The NLCD utilizes a sixteen-class land cover classification scheme, at a resolution of 30m (figure 2.6). These classes were merged to create

four classes (forest, grasses, open water, other), which were used to calculate the percentage of watershed area covered by forests, grasslands and open waterbodies (figure 2.6). Since the NLCD has 30m resolution, derived from a single year of data, this method of open water quantification is considered less rigorous than the NWI. Land cover data were ultimately omitted from statistical analyses but provided qualitative evidence for the dominance of forest cover in unmined and Pre-SMCRA sites as well as the dominance of grassland cover in Post-SMCRA sites.

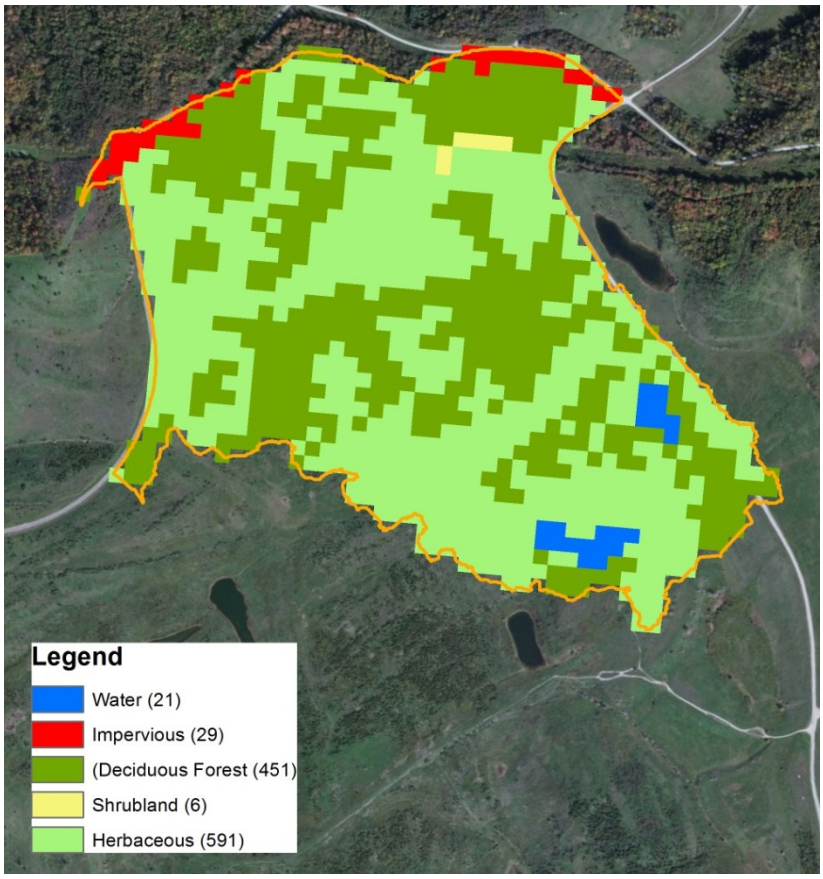

Figure 2.6: National Land Cover Dataset (clipped to watershed, prior to reclassification). 30m cell counts were converted to percentage of watershed area. In this example, 591 herbaceous cells/1098 total cells = 53.8% grassland cover.

Field collected data

The twenty-one outlet reaches of the study watersheds were evaluated via three types of data collection: 1) photography; 2) pebble counts; and 3) topographic surveys. The upstream and downstream extents of each study reach were identified and their geographic coordinates recorded with a handheld GPS (3-5m accuracy). Two cross-sections were identified that best described the geomorphic complexity of the reach. Photographs were taken at the upstream and downstream ends of the reach and at 10m intervals along the reach, facing upstream, downstream, left and right each time (Appendix B). Pebble counts to characterize streambed substrate were carried out by walking along the entire reach within the bankfull width in a zigzag pattern, collecting random samples (n=400) individually at approximately 1m intervals (Wolman, 1954, Bevenger and King, 1995) and measuring the intermediate axis of each clast using a gravelometer. Streambed substrate characteristics that include the D_{10} (the particle diameter at 10% in the cumulative distribution), D_{50}, D_{84}, D_{90} and geometric sorting ratio (Folk, 1980) were computed for each site with GRADISTAT v12.0 Grain Size Analysis Program (Blott, 2001).

Longitudinal and cross-section stream channel surveys were conducted using a laser theodolite (Gowin TKS-202, 2" angle or 0.5mm/100m accuracy), prism rod and standard surveying methods. Temporary benchmarks were installed as necessary to allow for re-positioning of the theodolite when required. While a clear view of the entire reach was sometimes possible, repositioning occurred frequently as a consequence of dense vegetation throughout many of the channel reaches. In all cases, back-sighting yielded consistently accurate results, with differences <5mm in the x and y axes; <20mm in the vertical z-axis. Elevations were recorded at every break in slope or at 1m intervals. Elevations were recorded more densely in cross-sections, at each break in slope or every 0.5m. Cross-section surveys were extended past the bankfull channel onto the floodplain or hillslope >5m beyond two times bankfull width.

For each cross section, bankfull stage, defined as the cross-section elevation with the smallest width/depth ratio, occurring at a natural break in bank slope (Wolman, 1955) was used to calculate channel width, depth, area and perimeter. The average values of the two cross-sections in each reach were used to describe that reach. Bankfull discharge (Q m^3/s) was calculated as

$$Q = VA \qquad (1)$$

where V (m/s) is reach averaged streamflow velocity and A is the surveyed cross-section area (m^2) at bankfull stage. Field parameters were used with Manning's (1891) equation to estimate V at bankfull stage

$$V = \frac{k}{n} R_h^{2/3} S^{1/2} \quad (2)$$

Where k=1 for SI units, n is the Manning's roughness coefficient, R_h is the hydraulic radius (cross-section area/wetted perimeter) and S is the local channel slope (m/m). Since all bankfull cross sections were free of vegetation, Manning's n was calculated via Limeniros' (1970) formula

$$n = \frac{(0.8204) {R_h}^{1/6}}{1.16+2.0 \log\left(\frac{R_h}{D_{84}}\right)} \quad (3)$$

which utilizes hydraulic radius and D_{84} computed from pebble counts.

Data Analysis

A combination of univariate and multivariate statistical methods were utilized to examine differences between land use groups and evaluate linkages across spatial scales. All statistical analyses were carried out in R v3.1.2 (R Core Team, 2014). First, correlation matrices were constructed for relevant variables at each

of the three spatial scales (Appendix C). Spearman's ρ, which is based on rank order, was used instead of Pearson's correlation since many variables were non-normal (Gibbons and Chakraborti, 2011). A subset of variables was chosen from each matrix such that instances of high correlation ($\rho>0.8$) were removed, while preserving variables that represent the greatest range of geomorphic processes. The only exception was the retention of both mean surface slope and profile roughness ($\rho=0.9$). From several roughness descriptors investigated, profile roughness was the least correlated to mean surface slope. Both variables were included in analyses since they describe distinctly different topographic properties, which influence hydrology in fundamentally different ways.

Differences between land use groups

The univariate Kruskal Wallis (KW) non-parametric test was used to detect significant differences ($\alpha=0.05$) between Pre-SMCRA, Post-SMCRA and unmined groups. Non-parametric methods were necessary since the majority of variables were non-normal and could not be normalized with a log, square root or power transformation. Post-hoc KW tests were used to identify significant pairwise differences between land use groups.

In addition, non-parametric multivariate methods were used to identify potential similarities and differences between sites within each land use group as well as the similarities and differences between groups. Non-metric multidimensional scaling (NMDS) was used to generate two-axis ordinations at each spatial scale. NMDS allows for the arrangement of multivariate data within one or more ordination axes, via a resemblance matrix (Legendre and Gallagher, 2001). In order to negate the effects of differences in scale and units of measure, all input variables were standardized for NMDS by converting each raw data value to its z-score,

$$z = \frac{x - \bar{x}}{\hat{\sigma}} \qquad (4)$$

which is based on the estimated standard deviation($\hat{\sigma}$) and sample mean ($\bar{x}$). Standardization does not alter the distribution of data but rescales the magnitude of data so that the relative differences between dissimilar variables can be explored.

A separate evaluation of slope distributions was carried out for all sites. Attempts to describe surface slopes according to pre-defined distributions (such as a Gamma distribution) did not capture the complexity of the data adequately. Differences were assessed graphically, where non-overlapping 95% confidence intervals represent regions where significant differences occur. KW

tests were not used because of the inter-related nature of the binned data, where all bins sum to 100% of the watershed area.

Interactions across spatial scales

Hypothesized spatial scale interactions were tested using nonparametric permutational multivariate analyses of variance (PerMANOVA) with 9,999 permutations per test. PerMANOVA are appropriate for data analyses that include both continuous and categorical variables, which may lack normality (Anderson, 2001). PerMANOVA can be sensitive to the scale of variables, with broader scales associated with lower p-values. This issue is addressed directly by standardizing all input variables such that mean=0 and $\sigma=1$. It is possible for PerMANOVA to attribute significance to a variable within a dataset having poor multivariate dispersion. The likelihood of false-positives is controlled effectively by ensuring that the PerMANOVA assumption of "similar multivariate dispersion of points" (Anderson, 2001) is met. To assess group dispersion, the betadisper function in the vegan R package was used (Oksanen, 2015). All multivariate data sets satisfied the equal dispersion assumption. With standardized data and proper multivariate dispersion, PerMANOVA provides a robust method of analysis (Anderson and Walsh, 2013). Both NMDS and PerMANOVA

(metaMDS and Adonis functions) analyses utilize the Vegan package in R (Oksanen, 2015).

PerMANOVA was used to test the strength of hypothesized interactions between spatial scales. Data were organized into three data frames, one for each spatial scale. For each test, a data frame is modelled by the variables from another data frame, plus a categorical variable for land use. These models were paired, to test for interactions in both directions (table 2.2).

Table 2.2: Summary of the six PerMANOVA models used to evaluate interactions across spatial scales. Each test utilizes 9,999 permutations. See complete model output in Appendix D.

Model	Data Frame (y)	Variables (~A+B+C…)
1a	Landscape	network variables + land use
1b	Network	landscape variables + land use
2a	Network	reach variables + land use
2b	Reach	network variables + land use
3a	Landscape	reach variables + land use
3b	Reach	landscape variables + land use

A tiered multivariate modeling process was used to explore the effects of mining and reclamation on stream power at the outlet reach of each site. A series of linear models, using standardized data, were selected from sets of possible models at each spatial scale to construct a pathway of significant connections from land use, through landscape, network and reach characteristics, to

stream power at the outlet. Stream power is a measure of the energy expended on the bed and banks of a channel, or the capacity for flowing water to do geomorphic work (Cooley, 2013). Stream power is a meaningful summation of outlet reach characteristics because it is derived from several measured attributes of the reach, including local slope, width, depth and D_{90} particle size.

The small sample size corrected Akaike Information Criterion (AIC_c) was used to select the most parsimonious model from each set of possible models (Burnham et al., 2011). In some cases alternative models with similar AIC_c values were identified but these required additional explanatory variables. The number of variables was critically important since the pathway model utilizes all variables previously selected at each spatial scale. This approach provides a physical basis for variable selection, as opposed to testing all possible combinations against stream power directly (Appendix E). The resulting model demonstrates the relative impacts of mining and reclamation on stream power, via the direct and indirect effects of landscape, network and reach scale interactions.

Results

Differences between land use groups

Univariate test results revealed several significant differences between unmined, Pre-SMCRA and Post-SMCRA sites. Significantly different variables are reported in table 2.3 and statistical analyses are shown in the following sections. Variables for which significant differences were found in KW tests are shown in table 2.3.

Table 2.3: Site attributes which have significant differences (p<0.05) by land use group. Site attributes include conclusion of mining activities (Year), mean surface slope in percent rise (slope), mean hillslope length in meters (Hillslope), profile roughness in σ slope (Roughness), percentage of watershed area as open water (% water), distance from outlet reach upstream to nearest open water (Dist. to Water), width/depth ratio m/m (W/D), and ratio of streambed length to Euclidean distance (Sinuosity).

			Landscape Scale			Network Scale		Reach Scale	
Land Use	Site:	Year	Slope	Hillslope	Roughness	% Water	Dist. to Water	W/D	Sinuosity
	Un-1	N/A	22.9	38.5	2.44	0.30	1582	10.1	1.18
	Un-2	N/A	23.6	34.6	2.43	1.47	1	65.2	1.05
	Un-3	N/A	21.0	34.7	2.31	0.00	1776	23.0	1.42
Unmined	Un-4	N/A	18.4	34.1	2.16	0.22	1450	15.7	1.19
	Un-5	N/A	21.6	30.6	2.58	0.00	1433	11.5	1.36
	Un-6	N/A	26.6	31.5	2.72	0.55	1049	36.7	1.14
	Un-7	N/A	24.4	34.4	2.45	0.18	1971	27.0	1.18
Unmined Mean		N/A	22.6	34.1	2.44	0.39	1323	27.0	1.22
	Pr-1	1969	24.1	28.5	2.77	2.33	2089	11.2	1.14
	Pr-2	1972	19.6	31.6	2.30	2.72	1298	8.3	1.20
Mined	Pr-3	pre 1960	26.6	38.3	2.93	8.34	1	13.6	1.18
(Pre-SMCRA)	Pr-4	pre 1960	26.8	35.5	2.97	8.97	15	18.2	1.05
	Pr-5	pre 1960	25.1	42.7	2.79	9.78	100	17.1	1.13
	Pr-6	1967	26.7	24.6	3.27	6.86	1100	12.4	1.10
	Pr-7	pre 1960	25.8	29.2	3.33	6.64	400	11.6	1.14
Pre-SMCRA Mean		N/A	25.0	32.9	2.91	6.52	715	13.2	1.13
	Po-1	1981	16.1	39.5	2.40	2.58	550	59.0	1.20
	Po-2	1981	7.9	37.6	1.14	1.85	1	61.4	1.05
Mined	Po-3	1984	12.0	62.6	1.49	1.07	626	12.5	1.06
(Post-SMCRA)	Po-4	2004	14.5	80.4	1.45	4.49	200	68.0	1.03
	Po-5	1995	18.4	57.2	1.45	8.86	1	28.1	1.06
	Po-6	2004	16.3	51.3	1.55	3.88	10	14.5	1.13
	Po-7	2004	20.3	67.5	1.31	6.14	1	30.8	1.02
Post-SMCRA Mean		1993	15.1	56.6	1.54	4.12	198	39.2	1.08

Landscape Scale

Landscape scale attributes were extracted from fine-scale (0.762m) DEMs and the National Land Cover Dataset (NLCD). From a larger set of variables (Appendix C), four were selected for statistical comparisons (Table 2.4).

Table 2.4: Landscape scale variables used for analysis.

Variable:	Description:
Profile Roughness	The standard deviation of changes in slope.
Mean Hillslope Length	Mean of all terrestrial areas within watersheds.
Mean Slope	Mean of all terrestrial areas within watersheds.
Elevation Range	Maximum – minimum (outlet) elevation (m)

Kruskal Wallis tests identified significant differences in Post-SMCRA sites compared to unmined and Pre-SMCRA sites for two of four landscape variables evaluated (Figure 2.7). Post-SMCRA sites have significantly lower surface slopes (KW, p=0.001) and longer hillslope lengths (KW, p=0.003). Post-SMCRA sites also had reduced downslope roughness (KW, p=0.001) compared to Pre-SMCRA sites and typically had smaller elevation ranges, though the difference is not significant (KW, p=0.059). Overall, unmined sites generally have the lowest variation at the landscape scale.

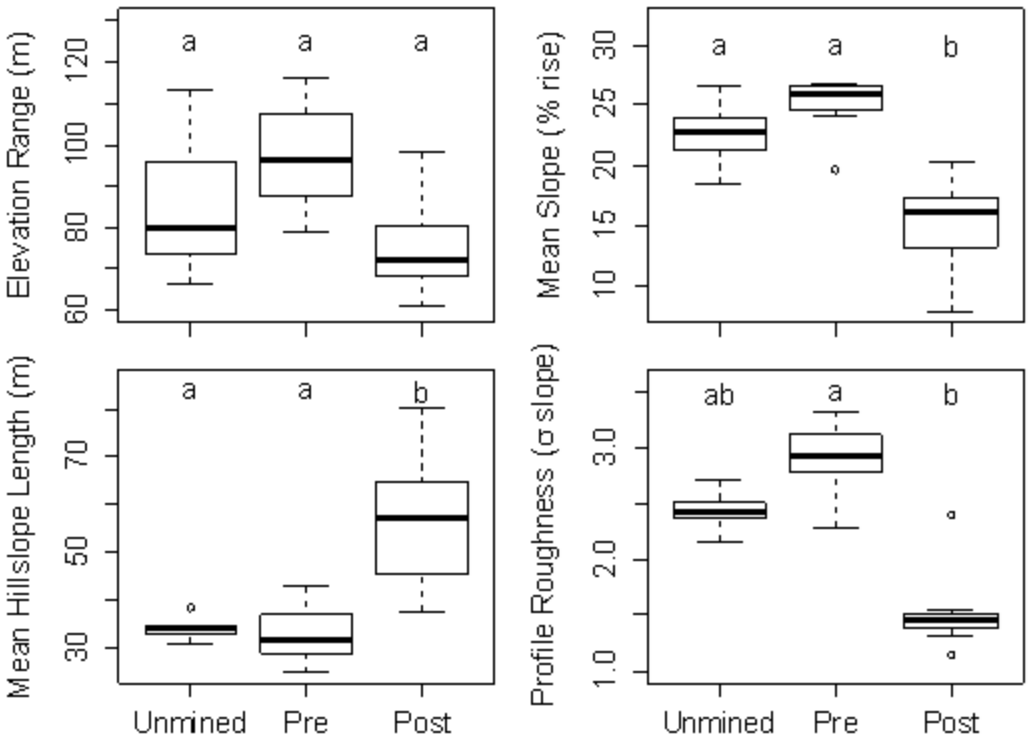

Figure 2.7: Landscape scale univariate boxplots across the three land use groups. Box center lines indicate group median, box ends are the 25th and 75th percentiles; lines extend to the 5th and 95th percentiles. Different letters above boxes indicate significant differences ($p<0.05$) between land use groups, from Kruskal Wallis post-hoc pairwise tests.

A NMDS ordination (with a linear fit of $R^2=0.986$), incorporating the four landscape variables in two ordination axes (table 2.5), demonstrates the dissimilarity of Pre- and Post-SMCRA sites in the x-axis. Sites that plot in the left region of the plotting space are steeper and rougher (figure 2.8).

Table 2.5: Ordination values for landscape scale NMDS.

Landscape NMDS ordination:

Variable	X axis	Y axis	R^2	p-value
Elevation range	-0.482	-0.876	0.91	0.001
Mean surface slope	-0.999	-0.042	0.77	0.001
Mean hillslope length	0.719	-0.694	0.81	0.001
Profile roughness	-0.940	0.341	0.91	0.001

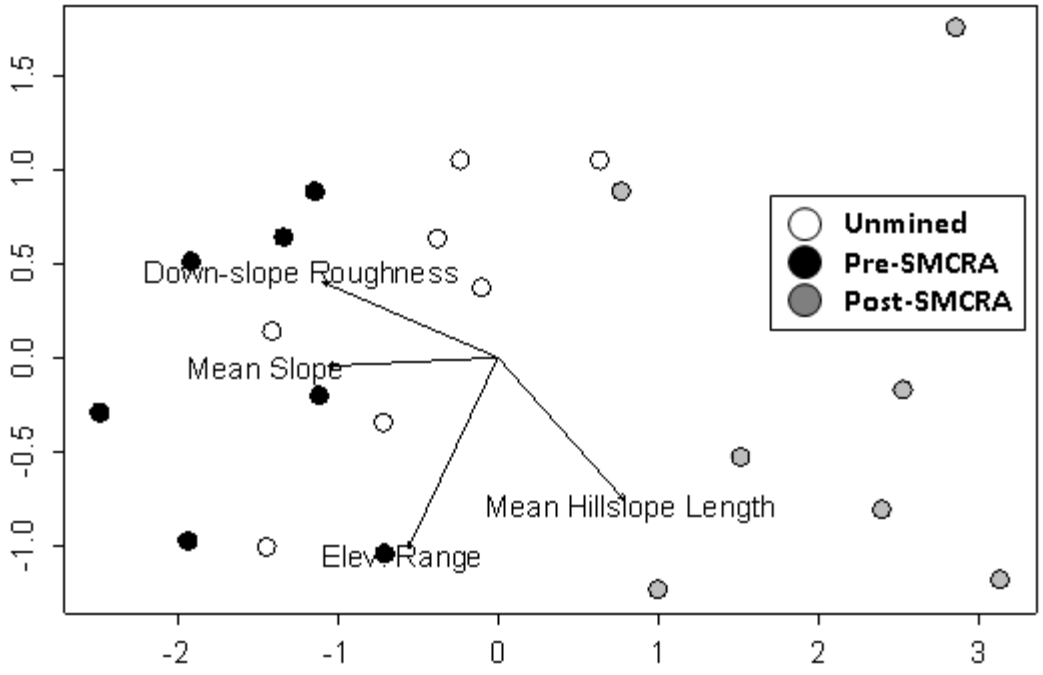

Figure 2.8: Landscape scale NMDS. Horizontal axis is characterized by mean slope, down-slope roughness and hillslope length. Vertical axis is a combination of elevation range and mean hillslope length. Sites that plot in the left region of the plotting space are steeper and rougher.

Surface Slope Distributions

The surface slope distribution plot (figure 2.9) shows distinct differences between the three land use groups. Unmined slopes follow approximate Gamma distributions, while Pre-SMCRA sites are similar but have more steep terrain (>60% rise). Much of this

steep terrain in Pre-SMCRA sites is attributed to remnant headwalls and spoil dumps. Post-SMCRA sites are dominated by low-angle landforms, as predicted. Bimodal Post-SMCRA slope distributions highlight the homogeneity of recontouring practices. Recontoured landforms are typically flattened (<7%), with 19-23% slopes, reflecting the requirements of the Ohio Surface Mine Law; unconsolidated materials must be recontoured to 18% slopes, or steeper if stabilized with thick vegetative cover (OAIMA, 2002). Post-SMCRA sites also have significantly less steep terrain than both Pre-SMCRA and unmined sites.

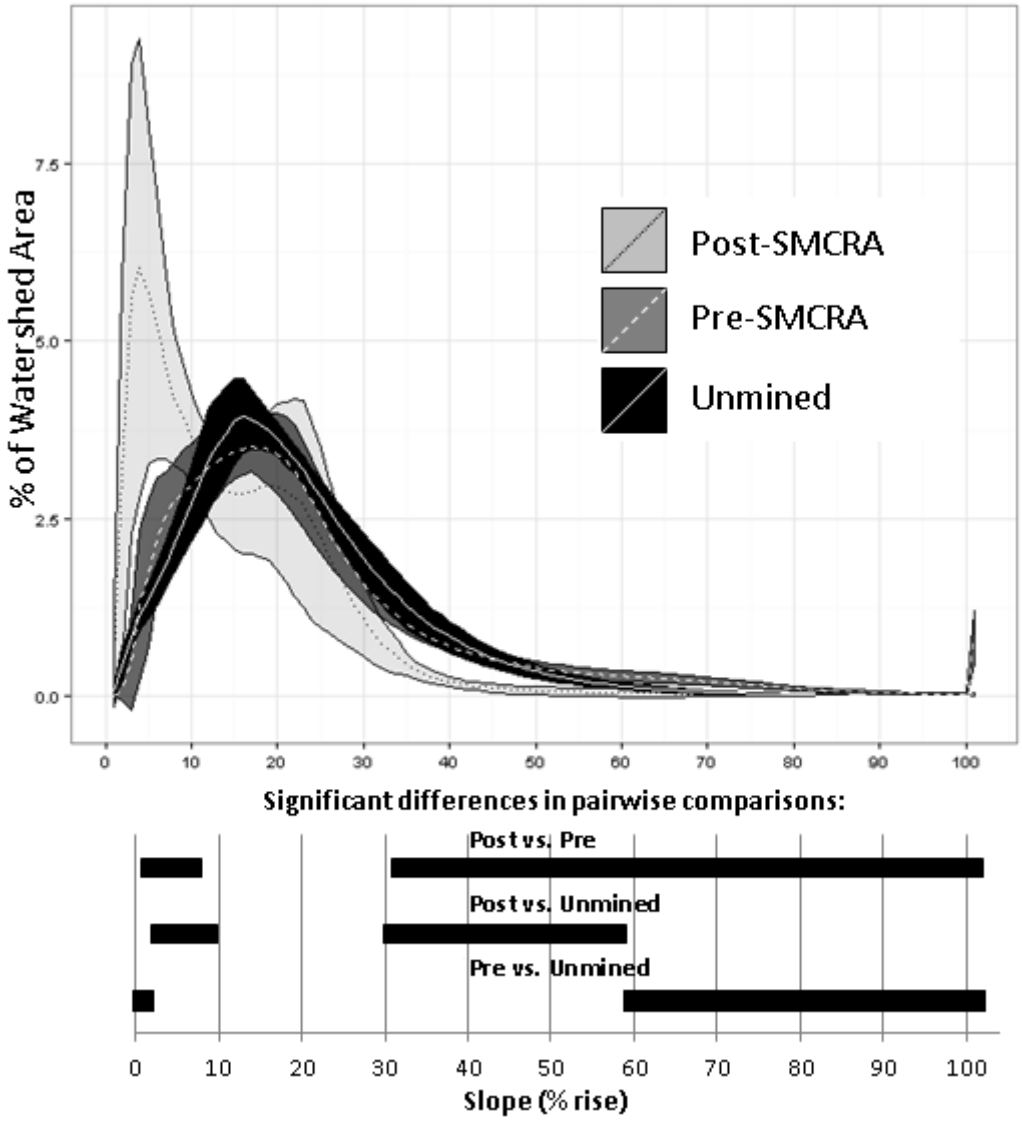

Figure 2.9: Slope distributions by land use group, with 95% confidence bands (upper panel) and resulting pairwise differences (lower panel).

Network Scale

A larger pool of fifteen variables was created for the network scale analysis, including several Strahler stream order metrics (Appendix C). These variables were developed from DEMs and the

National Wetlands Inventory (NWI). A subset of five variables (table 2.6) was chosen following removal of variables with high correlation ($\rho>0.8$), while preserving the greatest diversity of variables.

Table 2.6: Network scale variables used for analysis.

Variable:	Description:
Drainage Density	Mean value per watershed (meters/hectare).
Network meander	Ratio of stream path/Euclidean distances between nodes.
Node Count	Number of stream intersections in network.
Distance to water	Dist. (m) from outlet, upstream to nearest open water
% Open Water	% of watershed area identified as NWI wetlands.

Kruskal Wallis tests indicated that at the network scale, planform structures are similar across the three groups, but that mined sites have significantly more open surface waters relative to unmined sites (figure 2.10). The presence (KW, $p=0.001$) and position (KW, $p=0.038$) of open surface waters are the only significant factors separating mined sites from unmined sites. Consistent with the landscape scale, unmined sites generally have the lowest variation at the network scale.

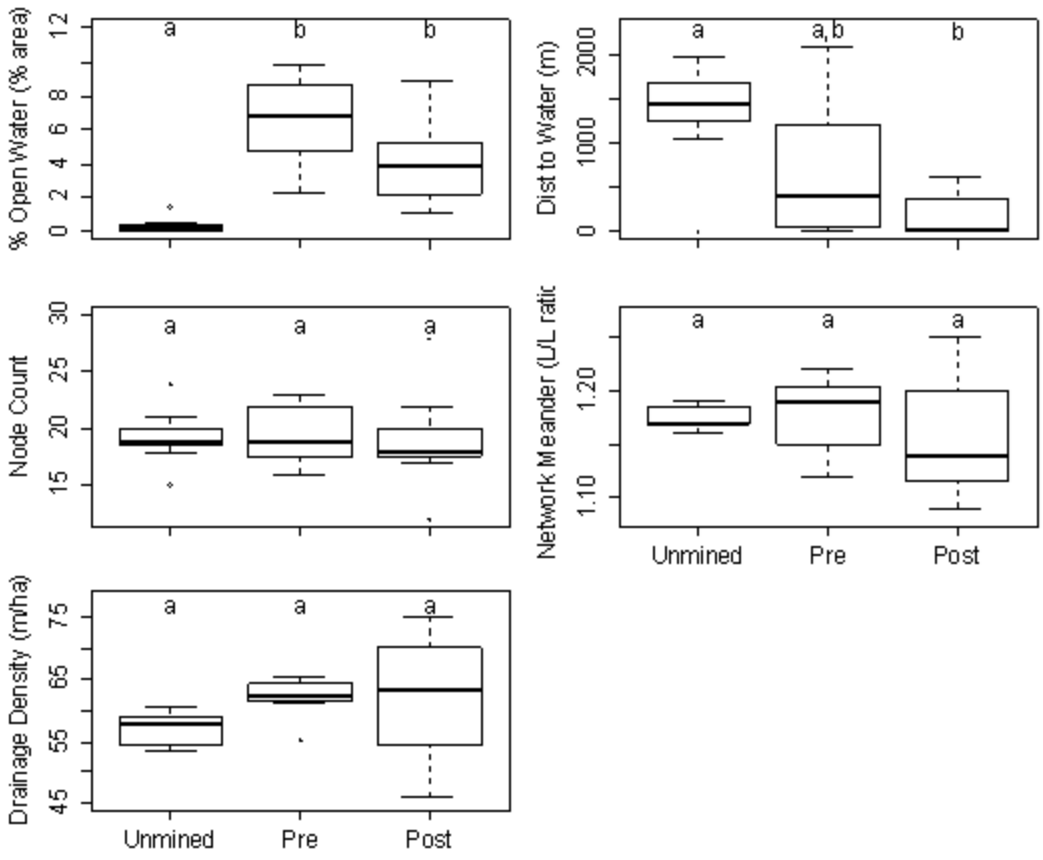

Figure 2.10: Network scale univariate boxplots. Box center lines indicate group median, box ends are the 25th and 75th percentiles; lines extend to the 5th and 95th percentiles. Different letters above boxes indicate significant differences ($p<0.05$) between land use groups, from Kruskal Wallis post-hoc pairwise tests.

The network scale NMDS, with linear fit of $R^2=0.947$ (table 2.7, figure 2.11) again shows separation of Post-SMCRA and unmined sites, as a result of the near absence of open surface waters in unmined sites. Pre-SMCRA sites appear to have network structures similar to unmined sites, with the addition of extensive open water bodies, which are also prevalent in Post-SMCRA sites. The network scale NMDS also shows that Post-SMCRA sites have the greatest network structure variability, particularly in terms of

drainage density, (Unmined σ=2.81, Pre-SMCRA σ=3.41 and Post-SMCRA σ=10.89). The large variability of Post-SMCRA networks is demonstrated visually in figure 2.12.

Table 2.7: Ordination values for network scale NMDS.

Variable	X axis	Y axis	R2	p-value
% Open Water	0.699	0.715	0.75	0.001
Dist. To Water	-0.700	-0.714	0.74	0.001
Channel Nodes	-0.774	0.633	0.65	0.001
Network Meander	-0.989	0.147	0.70	0.001
Drainage Density	-0.357	0.934	0.85	0.001

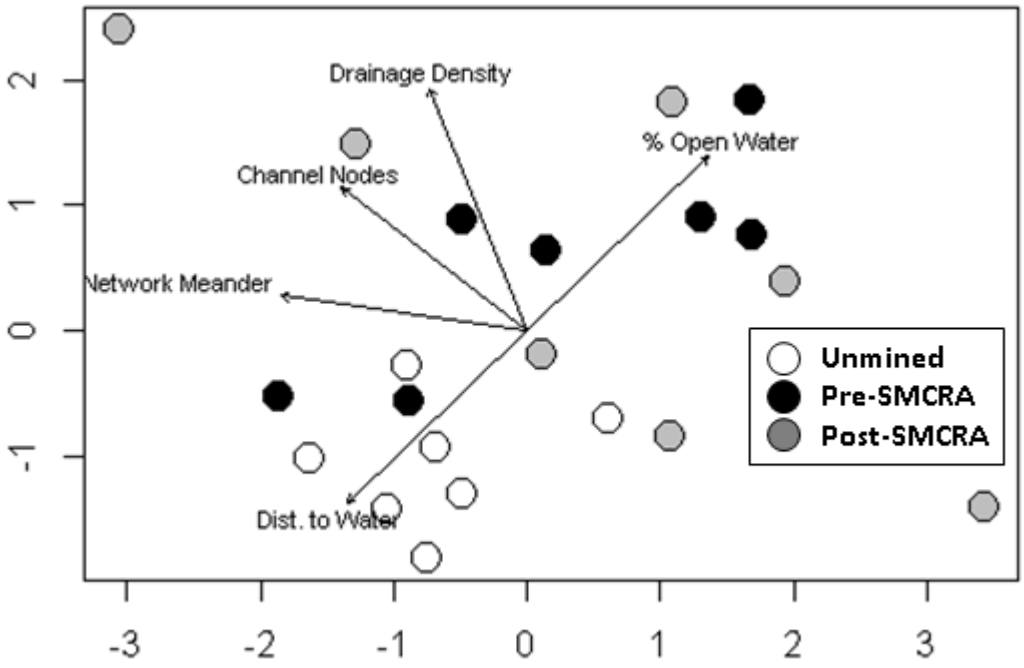

Figure 2.11: Network scale NMDS. Horizontal axis is characterized by the percentage of open water area, the distance from outlets to the nearest open water body and the network meander ratio. Vertical axis is a combination of % open water and the distance from the outlet reach upstream to an open water body, as well as drainage density and channel node count.

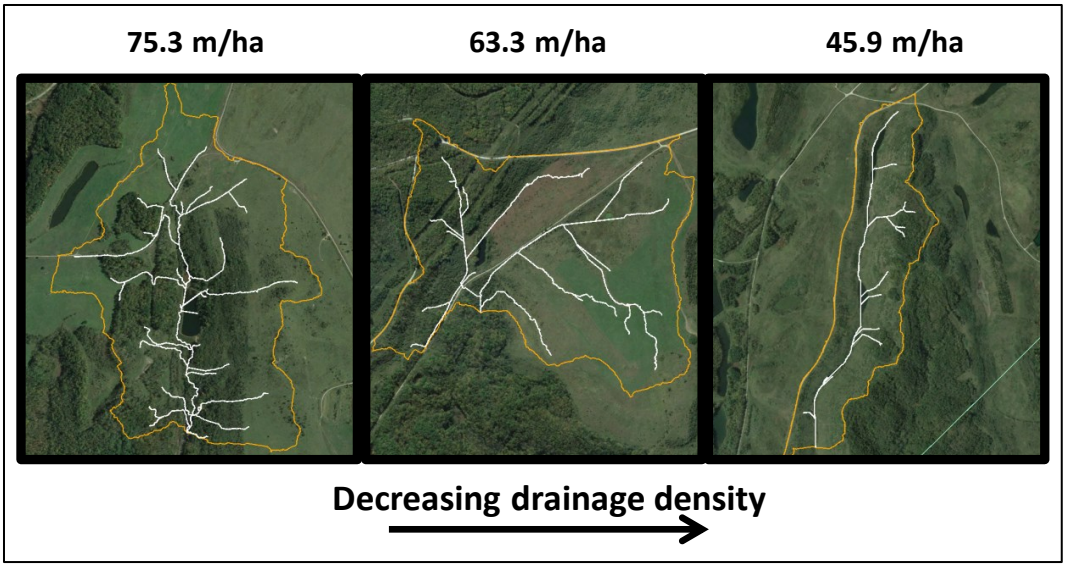

Figure 2.12: Network complexity variation within Post-SMCRA group.

Outlet Reach Scale

Reach scale variables were calculated from theodolite elevational survey data and pebble counts. From fourteen variables, eight variables (table 2.8) were chosen such that instances of high correlation ($\rho>0.8$) were removed, while describing the greatest complexity within outlet reaches.

Table 2.8: Reach scale variables used for analysis.

Variable:	Description:
Bankfull Q	Discharge estimate using field data (m^3/s).
Entrenchment	Ratio of bankfull width/2*bankfull width.
Sinuosity	Ratio of stream path/Euclidean distance.
Mean Bed Slope	Slope at thalweg of surveyed reach (m/m).
Width/Depth	Ratio calculated at bankfull stage (m/m).
Bankfull Width	Width at bankfull stage (m).
D_{90}	Particle diameter (mm).
% Bedrock	Percentage of reach length with exposed bedrock.

Univariate test results (figure 2.13) indicate that Post-SMCRA reaches are significantly less sinuous (KW, p=0.049) relative to unmined reaches. Pre-SMCRA reaches may be slightly steeper (KW, p=0.053) than both unmined and Post-SMCRA sites, with significantly smaller width/depth ratios (KW, p=0.039) compared to Post-SMCRA sites.

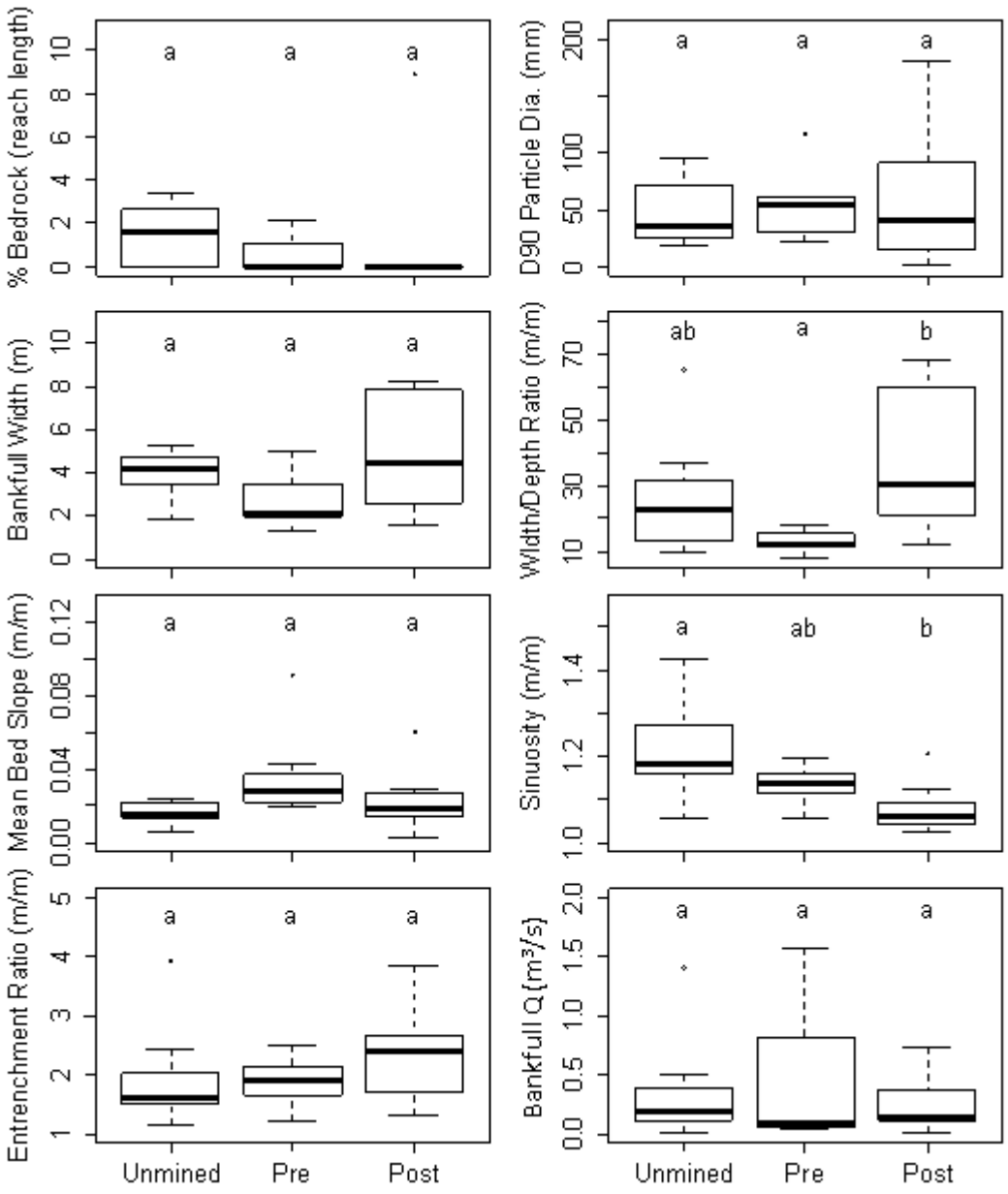

Figure 2.13: Outlet scale univariate boxplots. Box center lines indicate group median, box ends are the 25th and 75th percentiles; lines extend to the 5th and 95th percentiles. Different letters above boxes indicate significant differences ($p<0.05$) between land use groups, from Kruskal Wallis post-hoc pairwise tests.

The reach scale NMDS, with linear fit R^2=0.911 (table 2.9, figure 2.14) shows no clear separation by land use group. Rather, the NMDS shows a clustering of eight sites near the center of the

plot. This cluster, composed of three unmined, four Pre-SMCRA and one Post-SMCRA site is statistically separable from all other sites via several outlet reach and landscape scale variables (figure 2.15). The inner cluster of sites has outlet reaches that have significantly reduced bankfull width (KW, p=0.020), steeper mean bed slope (KW, p=0.043) and reduced entrenchment (KW, p=0.043) relative to the remaining sites. At the landscape scale, the inner cluster of sites has significantly steeper mean surface slope (KW, p=0.020), greater profile roughness (KW, p=0.020) and larger elevation range KW, p=0.017). No significant differences were detected at the network scale. Steeper, rougher landscapes tend to have outlet reaches that are steeper, narrower and less entrenched.

Table 2.9: Ordination values for network scale NMDS.

Variable	X axis	Y axis	R2	p-value
% Bedrock	0.989	-0.149	0.38	0.022
D90	0.816	0.578	0.56	0.001
Bankfull Width	-0.751	0.661	0.53	0.001
W/D Ratio	-0.185	0.983	0.70	0.001
Bed Slope	0.769	-0.640	0.60	0.001
Sinuosity	-0.251	-0.968	0.53	0.001
Entrenchment	-0.960	-0.279	0.33	0.033
Bankfull Q	-0.754	-0.657	0.55	0.001

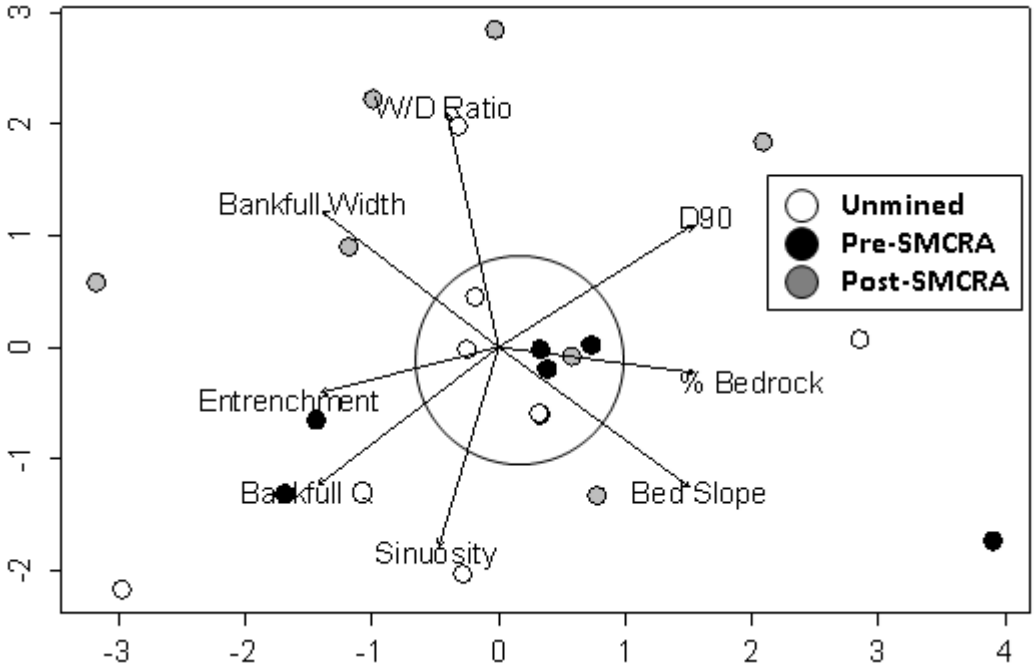

Figure 2.14: Reach scale NMDS with central cluster of eight sites circled. These eight sites are significantly different at both the landscape and outlet reach scales. Horizontal axis is most strongly determined by the percentage of bedrock, D90 particle size and the entrenchment ratio. Vertical axis is most strongly determined by W/D Ratio and Sinuosity.

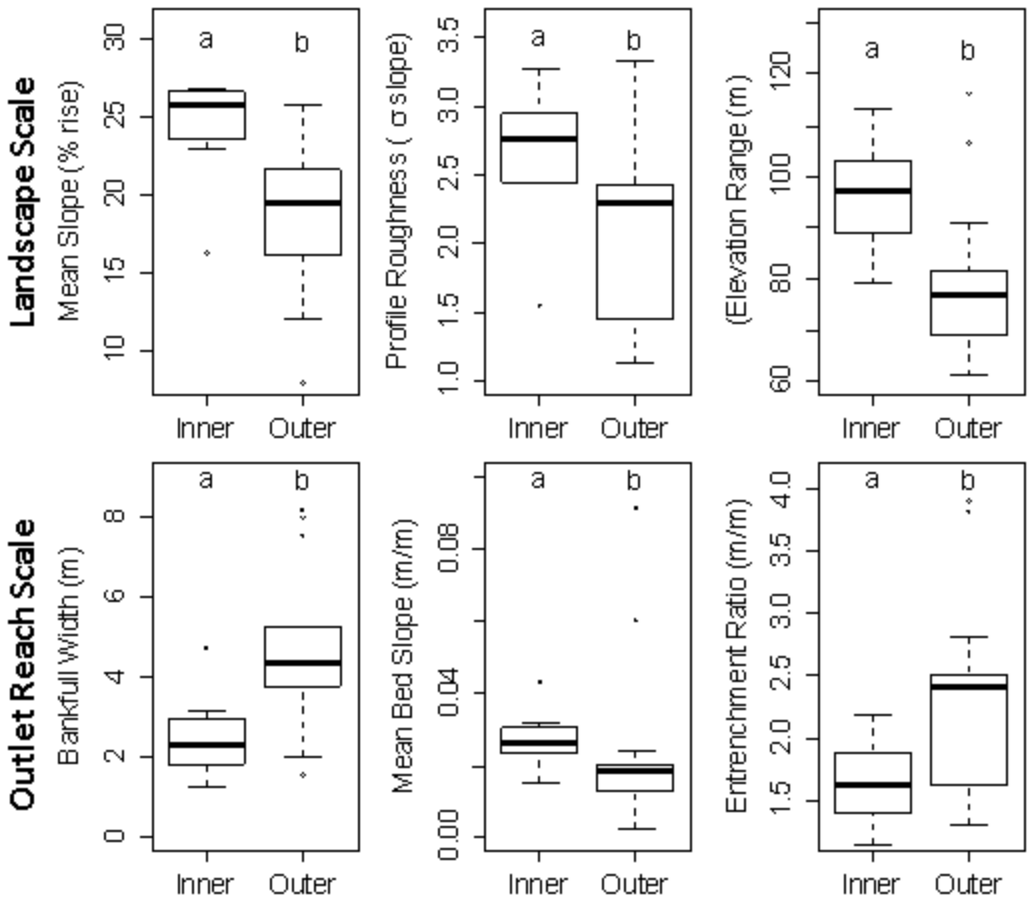

Figure 2.15: Comparing Inner and Outer groups from reach scale NMDS. Underlying geomorphic effects appear to act in unison with land use to determine outlet channel geometry. Greater vertical relief (landscape scale) yields narrower, steeper and less confined outlet reaches.

Outlet reach particle distributions

Pebble counts (n=400 per site) were used to describe the cumulative distribution of particle sizes by land use group (figure 2.16). Pre-SMCRA sites have distributions which are similar to unmined sites. Post-SMCRA sites may have more fine (0-4mm) sediments than both unmined and Pre-SMCRA sites but the large

variation of Post-SMCRA distributions suggests site-specific effects within the Post-SMCRA land use group.

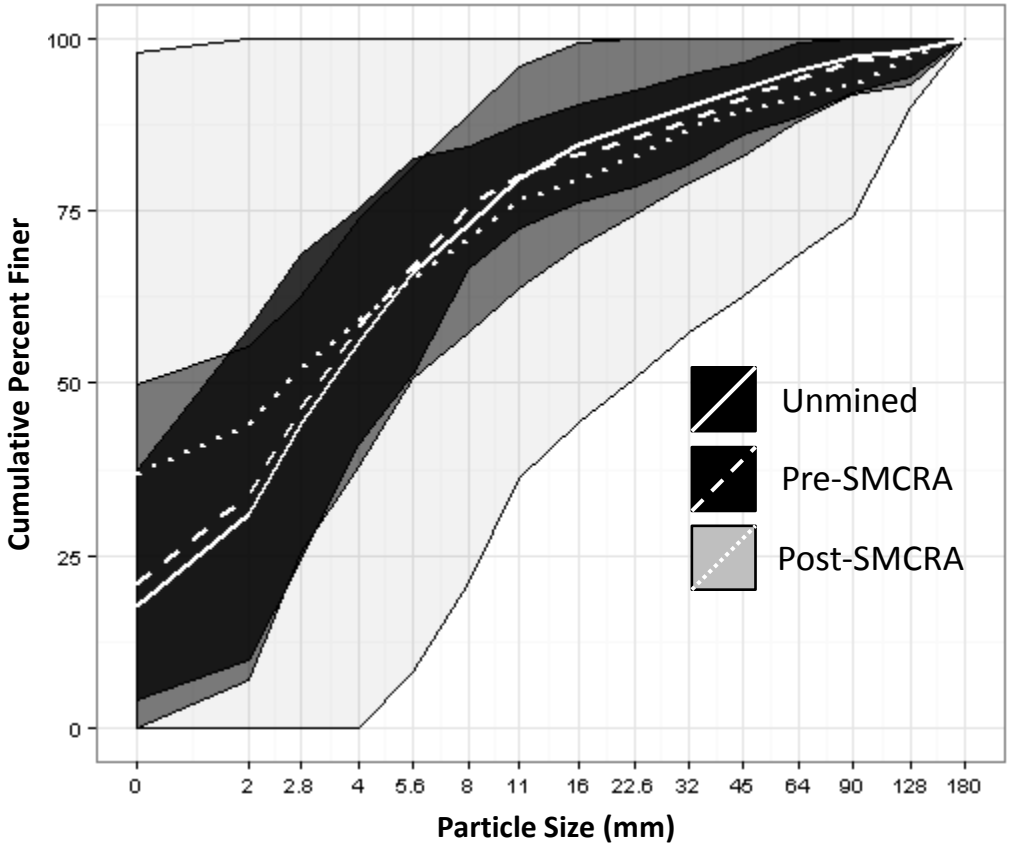

Figure 2.16: Cumulative particle size distributions of outlet reach sediments by land use group. X-axis is log-scaled and labelled with physical particle sizes. White lines indicate land use group mean values and shaded areas indicate 95% confidence intervals of the land use group distributions. 400 samples were collected at each outlet reach, for 2,800 samples per land use group.

Interactions across spatial scales

The relationships identified between landscapes and outlet reaches (landscapes with greater vertical relief yield narrower,

steeper outlet reaches) demonstrate some possible mechanisms whereby post mining strategies may impact landscapes, channel networks and outlet reaches. PerMANOVA tests were used to evaluate the influences of mining and reclamation on the morphology of study sites at each of the three spatial scales. Interactions between spatial scales were quantified with paired PerMANOVA tests (e.g. landscapes as a function of networks and vice versa).

The results generally validate the hypothetical interactions model, with some modifications (figure 2.17). Land use type is an influential factor at all three spatial scales. Landscape scale metrics appear to influence networks, which in turn influence outlet reaches. Landscape scale metrics do not appear to influence outlet reaches directly. Spatial scale interactions and their influential variables are summarized in Table 2.10. Comprehensive PerMANOVA results are shown in Appendix D.

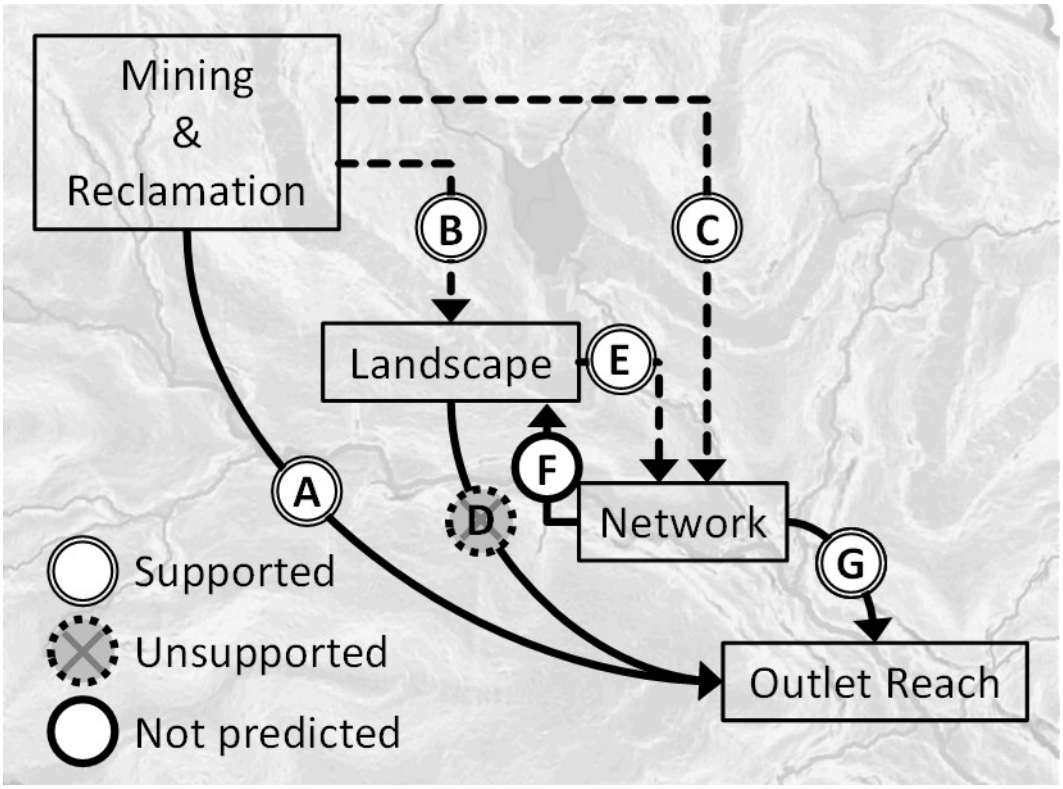

Figure 2.17: Summary of spatial scale interactions as determined by multiple Bi-directional PerMANOVA tests. Interactions which were originally hypothesized are either supported or unsupported by PerMANOVA results. The influence of networks on landscapes were not predicted but are indicated in results. Letters refer to pathways in table 2.10.

Table 2.10: Summary of significant interactions across spatial scales, as detected by multiple PerMANOVA tests. Comprehensive results in Appendix D. Pathways refer to those in figure 2.17.

Pathway	Interaction	Variable	P-value
A	**Land use** alters **outlet reaches** via:	Width/Depth Ratio	0.039
		Sinuosity	0.049
B	**Land Use** alters **landscapes** via:	Mean Slope	0.001
		Mean Hill-slope Length	0.003
		Profile Roughness	0.001
C	**Land use** alters **networks** via:	% open water	0.001
		Distance to Pond	0.038
D	**Landscapes** do not alter **outlet reaches**	N/A	
E	**Landscapes** alter **Networks** via:	Network Meander Ratio	0.034
F	**Networks** alter **Landscapes** via:	Mean Slope	0.045
		Profile Roughness	0.003
G	**Networks** alter **outlet reaches** via:	D_{90} particle size	0.013
		Bankfull Discharge	0.008

Channel networks appear to influence landscapes (and vice versa) in a complementary feedback mechanism. Network meander ratio is the network variable identified as having an influence on landscapes. The interaction of network meander ratio and mean hillslope length is evaluated with linear regression (table 2.11 and figure 2.18). For all mined sites, network meander ratio is inversely related to hillslope length (Post-SMCRA R2=0.85, Pre-SMCRA R^2=0.98) but the response in Post-SMCRA sites is unlike the Pre-SMCRA response. Land use appears to play an influential role in this interaction. Post-SMCRA sites have greater mean hillslope lengths for any given network meander ratio compared to all other sites. In unmined sites, there is insufficient variation of these two variables to demonstrate a relationship (R^2=0.000). Pre-SMCRA sites align very closely with unmined sites in this comparison but with greater variation in both variables.

Table 2.11: Results of linear model: Mean hillslope length as a function of network meander, by land use group.

Land use group	Intercept	Slope	p-value	Adj. R^2
Unmined	1.176	0.000	0.997	0.00
Pre-SMCRA	1.374	-0.006	0.000	0.98
Post-SMCRA	1.365	-0.004	0.003	0.82

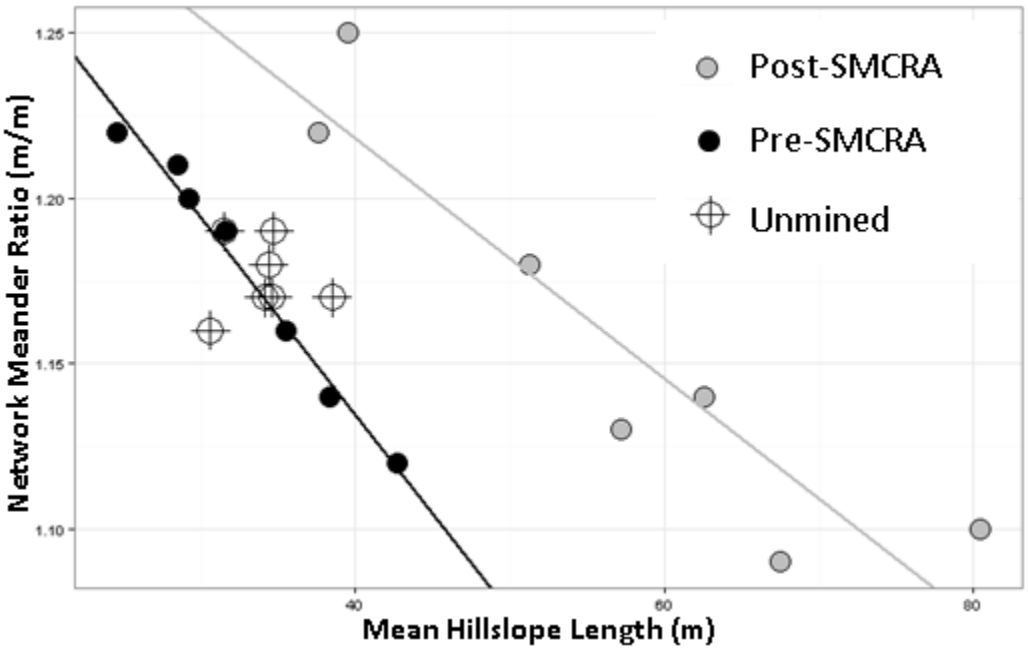

Figure 2.18: Interaction of Network Meander Ratio and Mean Hillslope Length by land use group.

Flow regulation plays an important role in watershed dynamics (McCormick and Eshleman, 2011). Open waters are expected to mediate high flows. Bankfull discharge (Q) at the outlet reach was expected to decrease as the percentage of open water area increases. Also, Q was expected to increase as the distance between the outlet reach and the nearest upstream open water

body increased based on the reasoning that the expected mediating effect of open waters on discharge diminishes with distance. Expected relationships were strong for unmined (adj. R^2=0.85 and 0.68) and Pre-SMCRA (adj. R^2=0.78 and 0.81) sites but not for Post-SMCRA (adj. R^2=0.01 and 0.05) sites (table 2.12 and figure 2.19).

Table 2.12: Linear model results for bankfull Q as a function of open water area (left panel, figure 2.19) and bankfull Q as a function of distance to water (right panel, figure 2.19).

Log(Q) as a function of % open water

Land use group	Intercept	Slope	p-value	Adj. R^2
Unmined	-0.277	-1.452	0.002	0.85
Pre-SMCRA	0.641	-0.214	0.006	0.78
Post-SMCRA	-0.747	-0.030	0.804	0.01

Log(Q) as a function of distance to water

Land use group	Intercept	Slope	p-value	Adj. R^2
Unmined	-2.223	0.001	0.014	0.68
Pre-SMCRA	-1.329	0.001	0.003	0.81
Post-SMCRA	-0.979	0.001	0.633	0.05

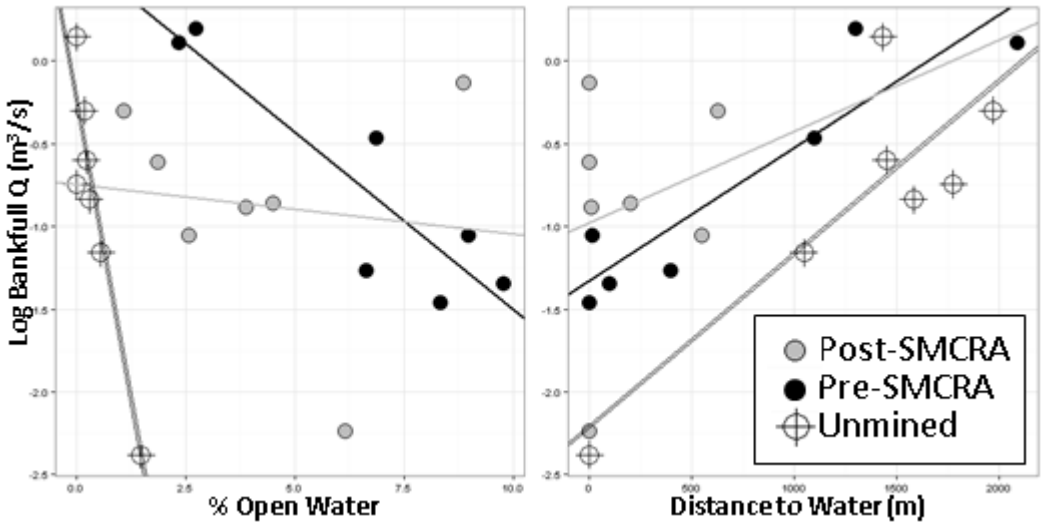

Figure 2.19: Quantity (% open water) and position (distance to water) of open water bodies vs. Bankfull Discharge, by land use. Unmined and Pre-SMCRA responses are linear but differentiated by land use group. Post-SMCRA group does not show detectable trends in these comparisons.

In order to test the top-down interactions of land use, landscapes, networks and reaches, a tiered modelling approach was used, which identifies mining and reclamation practices (including the construction of impoundments) as being impactful on stream power at the outlet.

The approach allowed selection of input variables at each spatial scale, ultimately seeking the most parsimonious set of predictors for stream power (table 2.13 and Appendix E). Landscape scale complexity is represented by down-slope topographic roughness, while network complexity is represented by the network meander ratio. Channel nodes, which is the number of channel junctions in the network, was considered as the

complexity metric but was rejected since it has little variance by land use as well as some outlying values. At each stage of the model, the small sample corrected Akaike Information Criterion (AIC_c) was used to select the smallest set of input variables with the greatest explanatory power. All physically plausible variable combinations within the model framework were tested (table 2.13). The final model, which utilizes all input variables from the tiered selection process, demonstrates that mining and reclamation practices (including the construction of impoundments) are as impactful as channel dimensions on stream power at the outlet.

Table 2.13: Tiered variable selection process with final summary model. Input variables without p-values were excluded from models via lowest AICc selection process. Mining and reclamation practices (including the construction of impoundments) are as impactful as channel dimensions on stream power at the outlet.

model	Input variables	p-value	Output variable	Adj. R^2
1	**Mined (categorical)**	0.005		
	Reclaimed (categorical)	0.000	Mean surface slope	0.82
2	Mined (categorical)	-		
	Reclaimed (categorical)	0.000	Mean hillslope length	0.58
3	Mined (categorical)	-		
	Reclaimed (categorical)	-		
	Mean surface slope	0.000		
	Mean hillslope length	0.115		
	Elevation range	-	Profile Roughness	0.96
4	**Mined (categorical)**	0.000		
	Reclaimed (categorical)	0.070	% open water	0.53
5	**Mined (categorical)**	0.119		
	Reclaimed (categorical)	0.248		
	% open water	0.002		
	Drainage density	-		
	Node count	-		
	Dist. To water	-		
	Profile Roughness	0.010	Network Meander	0.47
6	Mined (categorical)	-		
	Reclaimed (categorical)	-		
	Profile Roughness	-		
	Network Meander	0.068		
	Width/ depth ratio	0.000		
	Bankfull width	0.006		
	Entrenchment ratio	-		
	D_{90} particle size	-	Log(stream power)	0.57
Summary model:	**Mined (categorical)**	0.004		
	Reclaimed (categorical)	0.179		
	% open water	0.002		
	Width/ depth ratio	0.000		
	Bankfull width	0.006	Log(stream power)	0.71

Summary model residual standard error: 0.927 on 15 DF

Adj. R2=0.71

F-statistic: 10.74 on 5 and 15 DF, p-value: 0.000

Discussion

I compared reclaimed and unreclaimed watersheds which have previously been surface mined to sites which are unmined. My findings support many of my original hypotheses and suggest a need to incorporate a greater level of topographic complexity into future reclamation strategies to achieve geomorphic conditions similar to unmined watersheds.

Differences between land use groups

At the landscape scale, univariate tests identified Post-SMCRA landscapes as having significantly reduced surface complexity, compared to unmined sites which in turn are slightly less complex than Pre-SMCRA sites. Post-SMCRA terrestrial slopes and surface roughness are significantly reduced and hillslope lengths are increased. Post-SMCRA slope distributions highlight the homogeneity of recontouring practices. Recontoured landforms were flattened (<7 % slope), with 19-23 % side-slopes. In addition, the Post-SMCRA sites have significantly less steep terrain than Pre-SMCRA and unmined sites. These findings demonstrate the smoothing effect of reclamation practices, which emphasize the creation of stable landforms. The landscape scale NMDS shows that Pre-SMCRA sites are characterized by steeper and rougher terrain, while Post-SMCRA sites have longer and smoother

hillslopes. Combined, the landscape scale results support hypothesis 1a; *similar landforms and topographic slopes in Pre-SMCRA and unmined sites*, as well as hypothesis 1b; *significantly smoother landforms with reduced slopes in Post-SMCRA sites*.

Network topology analyses indicate significantly greater percentages of open waterbodies and a corresponding significant reduction in the distance from outlet reaches to the nearest open waterbody in all mined sites relative to unmined sites. These findings partially support hypothesis 2a1; *channel network topology in Pre-SMCRA and Post-SMCRA sites will differ from unmined sites, with shorter channel segments, increased open water area and higher confluence frequency.* My results do not support hypothesis 2a2; *channels in Post-SMCRA sites will have a straighter (e.g., less meandering) planform*. Instead, Post-SMCRA sites collectively have greater variation in network meander ratios ($\sigma_{unmined}$=0.011, $\sigma_{Pre\text{-}SMCRA}$=0.038, $\sigma_{Post\text{-}SMCRA}$=0.060). A similar result was obtained for drainage density, with Post-SMCRA sites having the greatest variation($\sigma_{unmined}$=2.81, $\sigma_{Pre\text{-}SMCRA}$=3.41, $\sigma_{Post\text{-}SMCRA}$=10.89) but no significant differences were detected. These findings partially support hypothesis 2b; *drainage density is hypothesized to be similar on Pre-SMCRA and unmined sites, but will be lower on Post-SMCRA sites*. The network scale NMDS shows separation of Post-SMCRA and unmined sites, due to the near

absence of open waterbodies in unmined sites. Pre-SMCRA sites appear to have network structures similar to unmined sites, with the exception of extensive open waters. Unmined sites have an average 0.39% open water area, compared to 6.52% in Pre-SMCRA sites and 4.12% in Post-SMCRA sites.

Outlet reach scale results indicate that Post-SMCRA outlet reaches have significantly greater width/depth ratios compared to Pre-SMCRA sites. Post-SMCRA reaches are also significantly less sinuous than unmined reaches. Pre-SMCRA reaches may be slightly steeper and narrower than both unmined and Post-SMCRA sites. The lower sinuosity of Post-SMCRA outlet reaches partially supports hypothesis 3; *outlet reach-scale geomorphic channel complexity will be lower in both Pre-SMCRA and Post-SMCRA sites relative to unmined sites*. The outlet reach NMDS indicated no separation of land use groups, although a central cluster of eight sites is significantly different from all others at both the outlet reach and landscape scales. Watersheds that are steeper and topographically rougher, having greater vertical relief, drain to outlet reaches that are steeper, narrower and less entrenched.

Sediment distributions in Post-SMCRA sites are highly variable, compared to unmined and Pre-SMCRA sites. This variability reflects the diversity of channels in Post-SMCRA sites,

with some channels being wide swales and others being steeper and rock-lined. The progressively reduced separation of land use groups in landscape, network and reach NMDS plots suggests that the influence of mining and reclamation activities may either diminish or be confounded by other geomorphic processes, such as the link between steeper terrain and steeper outlets, with increasing distance downstream.

Implications for the movement of materials through the landscape

Alterations at the landscape, channel network, and channel reach scale as a consequence of mining likely have significant consequences for the movement of water, sediment, and associated materials through a landscape. In other landscape scale studies that address surface mining, Maxwell and Strager (2013) and Wickham et al. (2013) report diminished topographic complexity in mountaintop mined watersheds. Their emphasis is on impacts of terrestrial diversity and some physical characteristics such as land surface temperatures. From a geomorphic perspective, reduced slopes and longer hillslope lengths in the Post-SMCRA landscape may indicate slower delivery of materials from the hillslope to the channel network relative to unmined or Pre-SMCRA landscapes. However this response may be mitigated by reduced surface roughness in Post-SMCRA watersheds that may facilitate greater,

and thus more rapid, hillslope connectivity to the stream channel network. Necessary future research includes studies that quantify the magnitude and rate of movement of water and sediment through the terrestrial portion of the landscape and into the channel network, which can shed light on the potentially confounding impacts of a smoothed landscape with longer hillslope lengths.

In the mined landscape, small wetlands and sinuous channels have been replaced by large impoundments interspersed with relatively straight channels as a consequence of reduced network meander ratios in Post-SMCRA watersheds and reduced reach scale sinuosity in Pre- and Post-SMCRA watersheds. In the unmined landscape, channel sinuosity serves to slow downstream movement of water and sediment. Natural wetlands in unmined landscapes also slow downstream movement, but residency of water and sediment in wetlands are limited by their small size. The collective result of introduced large impoundments and straighter channels is simultaneous increased residence times of water and sediment but potentially accelerated downstream transport in the stream channel portion of the network between impoundments. Although straighter stream channels imply more rapid downstream transport of water, sediment, and associated materials, the presence of large impoundments from water filled trenches and

engineered impoundments may dominate overall downstream flux. However, reduced residence time of water, sediment and materials in the channel likely has implications on the aquatic ecosystem of these streams channels in terms of nutrient retention and processing abilities (Benda et al., 2005).

Interactions across spatial scales

Interactions were hypothesized between land use, landscapes, channel networks and outlet reaches, with a top-down model structure created to test hypotheses. A set of six PerMANOVA tests provide evidence of several significant interactions across spatial scales. Importantly, land use is significant at all scales. A potential feedback mechanism was identified between the network and landscape scales, where network meander and mean hillslope length were found to be highly correlated in both Pre-SMCRA and Post-SMCRA mined sites. Post-SMCRA sites have greater mean hillslope lengths for any given level of network meander compared to all other sites, suggesting a land use effect on channel network layouts. Further investigation showed that in Pre-SMCRA sites, mean hillslope length generally increases as the portion of the channel network contained within headwall trenches increases. In Post-SMCRA sites, mean hillslope length increases as the amount of watershed

boundary determined by roads increases. In both Pre- and Post-SMCRA groups, anthropogenic impacts have resulted in altered channel network topology that is unlike the dendritic channel network layouts found in unmined sites. Self-evolving dendritic channel networks are very efficient for the transport of water and materials through a watershed (Gordon, et al., 2004). This efficiency may be compromised in all mined sites, particularly Post-SMCRA reclaimed sites, as a result of engineered open water bodies that serve as reservoirs that limit downstream movement of water, sediment, and associated materials.

A land use effect was also detected in comparisons of bankfull discharge to the amount and position of open waters within study sites, which underscores the potential impact of reduced geomorphic efficiency as a consequence of open waters. Unmined and Pre-SMCRA sites show a log-linear increase in bankfull discharge as open water area diminishes and the distance to the nearest water body increases.

Using stream power as an indication of potential geomorphic work, a tiered set of linear models was used to select variables from all spatial scales and quantify their relative impacts. While stream power is not significantly different between land use groups in KW tests, land use categorical variables do explain a portion of

the variance in stream power. Mining and reclamation (via the formation of open waterbodies) were found to provide predictive powers similar to those of channel dimensions for stream power at the outlet reach.

Conclusion

Unreclaimed surface mined lands represent significant environmental challenges, yet their complexity offers insights as to the potential geomorphic functionality of reclaimed mine lands. New reclamation methods are being explored that implement greater landscape complexity and address ecological/sustainability goals. Pre-SMCRA (unreclaimed) sites were found to be more physically similar to unmined sites than Post-SMCRA (reclaimed) sites, which had milder, smoother surface slopes and less sinuous outlet reaches. Surface slope distributions demonstrate the homogeneity of recontouring practices within reclaimed sites. Large variations in outlet reach variables, as well as widely varying particle size distributions within reclaimed sites may be indicative of a decoupling of fluvial geomorphic processes within Post-SMCRA reclaimed landscapes. It is expected that this variability will diminish in the long term but there is some evidence for the alteration of geomorphic processes within reclaimed lands. Altered processes could prevent reclaimed sites from approaching the form

and function of unmined sites. This study demonstrates that reclamation practices are significantly impactful at all spatial scales and have the potential to alter geomorphic responses in the long term, with implications on the downstream delivery of water, sediment and other channel transported materials. Further research will deepen our understanding of these complex systems and facilitate the continued development of reclamation practices.

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Chapter 3 – Conclusions

The Surface Mining Control and Reclamation Act (SMCRA) of 1977 set out federal guidelines for the reclamation of surface mined lands. For this study, twenty-one small watersheds (~1km^2), in three distinct land use groups (unmined, Pre-SMCRA and Post-SMCRA) were evaluated at the landscape, channel network and outlet reach scales. At each scale, significant differences between groups were detected. These differences provide evidence that Pre-SMCRA (unreclaimed) and unmined sites are more alike than Post-SMCRA (reclaimed) sites. Multivariate techniques identified significant interactions between land use, landscapes, networks and outlet reaches. These findings demonstrate that mining and reclamation are significantly impactful at all spatial scales.

Implications for Land Managers

Surface mining for coal will continue to be a viable method of resource extraction for the foreseeable future. The continuing development of efficient and effective reclamation strategies is in

the best interest of the public and the mining industry itself. When SMCRA was first introduced, there were concerns as to the economic impacts of reclamation. Costs associated with reclamation reduced coal output from surface mines by approximately 5% nationwide in the late 1970's (Randall et al., 1978). The subsequent 5% increase in sub-surface mine output helped offset the economic impact of SMCRA. The long-term legacy of surface mining was now a real, calculable cost in mining operations rather than an intangible cost passed on to the public.

The economic burden of reclamation was particularly impactful in the Midwestern United States, with less favorable combinations of overburden depth and coal-seam thickness. In Ohio, reclamation costs were estimated as 8.45% of the minimum acceptable selling price compared to 2.73% in Wyoming, currently the largest coal producing state in the U.S. (Misiolek and Noser, 1982). Operational costs will remain an important consideration when planning reclamation practices. Reclaimed lands have the potential for a variety of productive uses such as sustainable forestry (Burger and Zipper, 2011) and recreation (BLM, 2015, AEP, 2015). As our understanding of reclaimed landscapes and potential uses improves, land managers will increasingly consider their site-specific goals when planning reclamation strategies and

are likely to be the driving force behind innovative approaches, aimed at meeting a diverse set of future land-use needs.

Future Research

Much work has been done to understand the impacts of surface mining. Water quality issues, including acid-drainage and downstream impairments have been presented in scientific literature for decades (Branson, 1974, De Angelis et al., 1980, Brannon and Ramsey, 1988, Hopkins et al., 2013). Soil fertility and compaction on reclaimed sites has also received considerable attention (Miller et al., 2014, Srivastava et al., 2014). A greater understanding of mined lands as complex physical and ecological systems is needed. Reclamation offers an opportunity to design landscapes and channel networks, using natural forms as the template. Reclaimed landforms, which incorporate design elements from nature (geomorphic reclamation) are demonstrably stable and meet Approximate Original Contour (AOC) guidelines (Sears et al., 2012). Despite the technical and regulatory challenges of creating curvilinear landforms, their inherent long-term stability reduces long-term maintenance costs (Michael et al., 2010). Other avenues of research focus on improving already reclaimed lands for greater resource benefit. The Forestry Reclamation Approach (FRA) offers economically viable ways to reforest Post-SMCRA mined sites. The

key to FRA is minimal re-contouring, to avoid soil and substrate compaction. Failure to completely smooth (or stabilize) surfaces may seem problematic in terms of soil erosion, yet the enhanced complexity of FRA-reclaimed surfaces (micro-topography) demonstrably improves the recruitment and succession of forest communities (Gilland and McCarthy, 2014). Intensive re-contouring has been shown to increase soil erosion and decrease the growth rates of planted trees (Franklin et al., 2012). These examples highlight the importance of physical reclamation practices on long-term ecological outcomes.

More research which evaluates the effectiveness of land-use specific reclamation methods is needed. Considerations such as soils, aspect, slopes and drainage networks can all be treated as design parameters in a modern GIS framework. Exploring these possibilities as models and in practice will provide government agencies and land managers with the capacity to generate region, site and use-specific strategies. The study presented in this thesis and others (Mukhopadhyay, 2013, Gilland and McCarthy, 2014) have demonstrated the highly influential nature of reclamation practices on landscape morphology. Further work, which explores the complex interactions of mined landscapes, channel networks and ecological elements will empower regulatory authorities and mine operators to incorporate greater landscape complexity into

their reclamation designs, with emphasis toward future sustainable use of reclaimed lands.

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Appendix A: Site selection figures

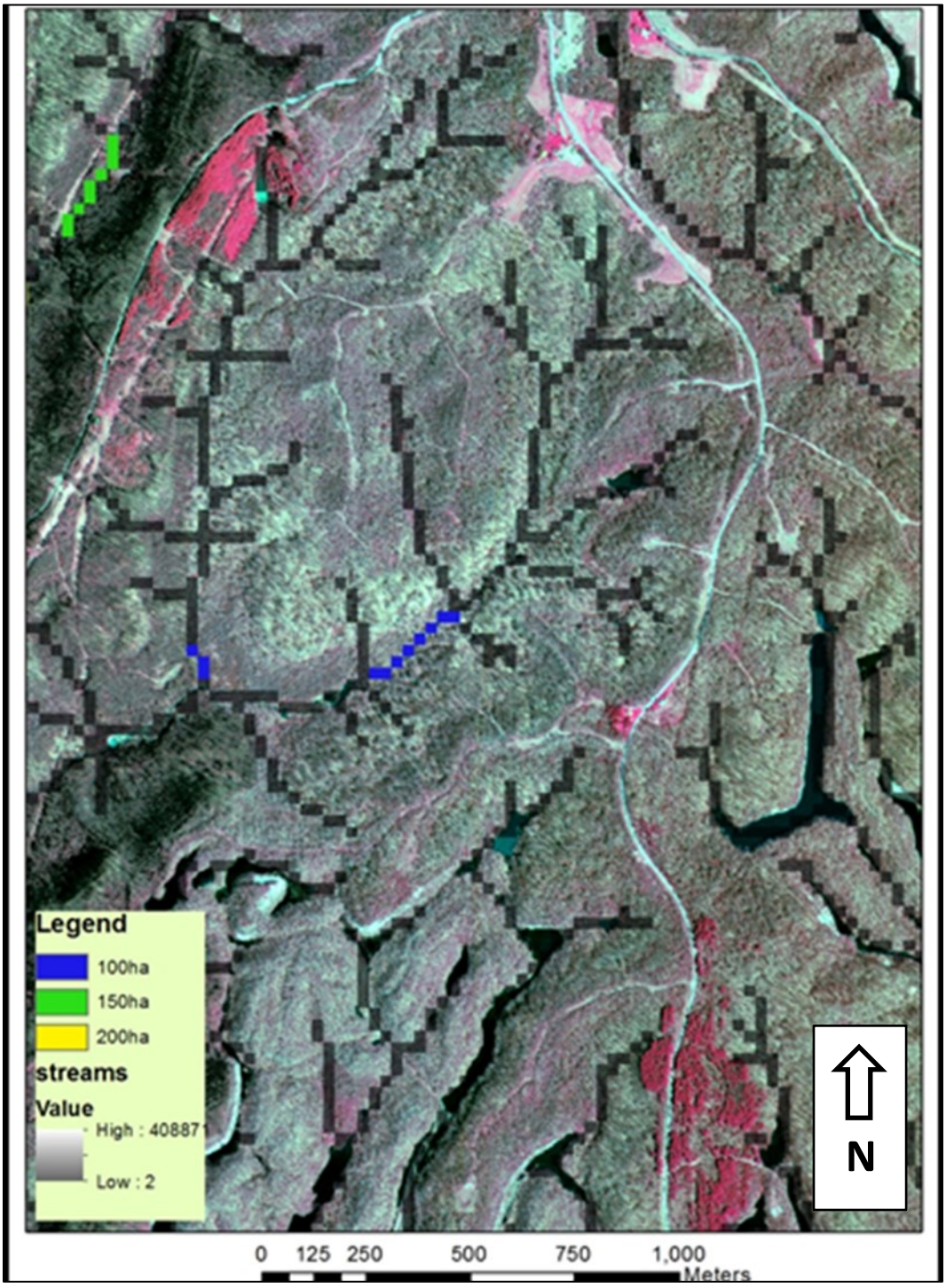


Figure A1: Flow accumulation grid layer (gray scale grid cells) with 0.95-1.05km^2 accumulations colored (blue) to identify potential outlet reaches. False-color IR imagery (OGRIP, 2013).

Figure A2: Watershed delineations (red) and stream networks (blue) for unmined sites 6 and 7 (derived from 0.762m DEM). DEM and imagery (OGRIP, 2013).

Appendix B: Four direction photography example (from the mid-point of unmined reach #6).

Appendix C: Correlation Matrices

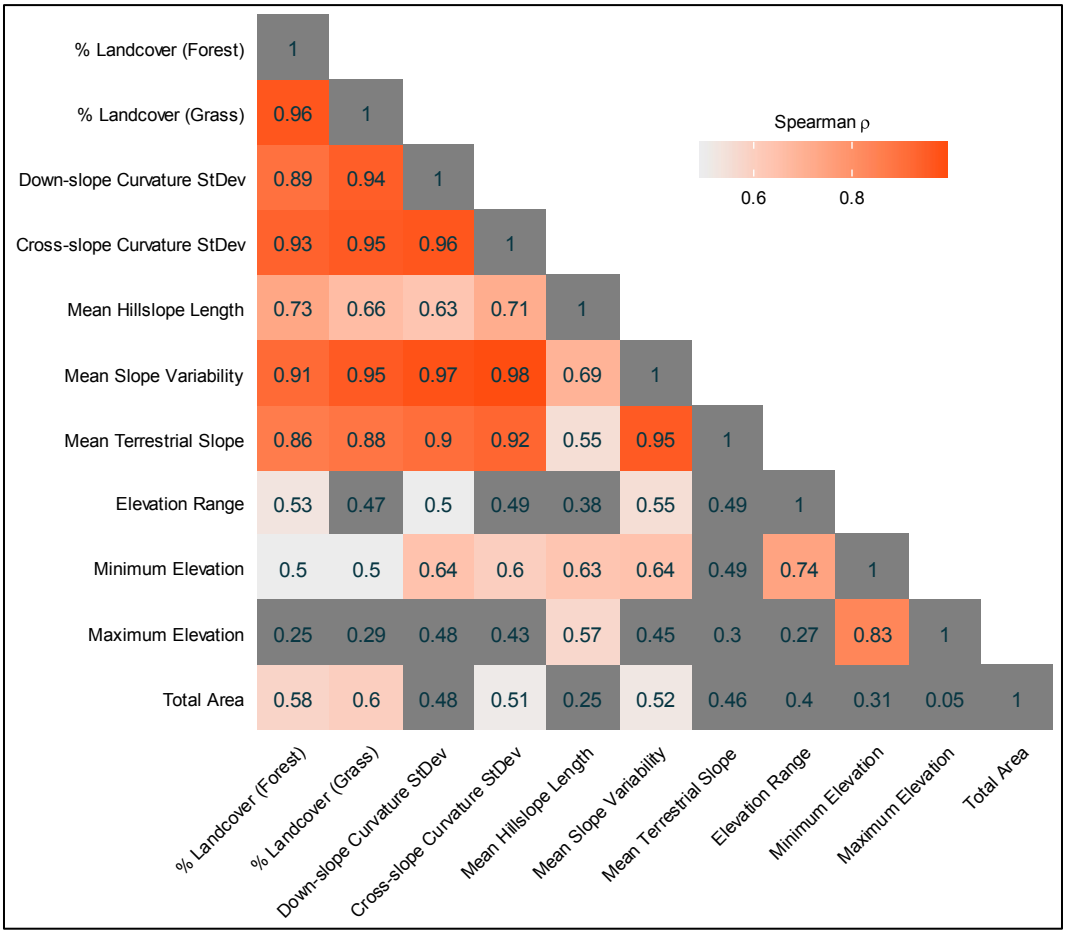


Figure C1: Correlation matrix of all landscape-scale variables. A subset of variables was chosen from each matrix such that instances of high correlation (ρ>0.8) were removed, while preserving the greatest diversity of variables.

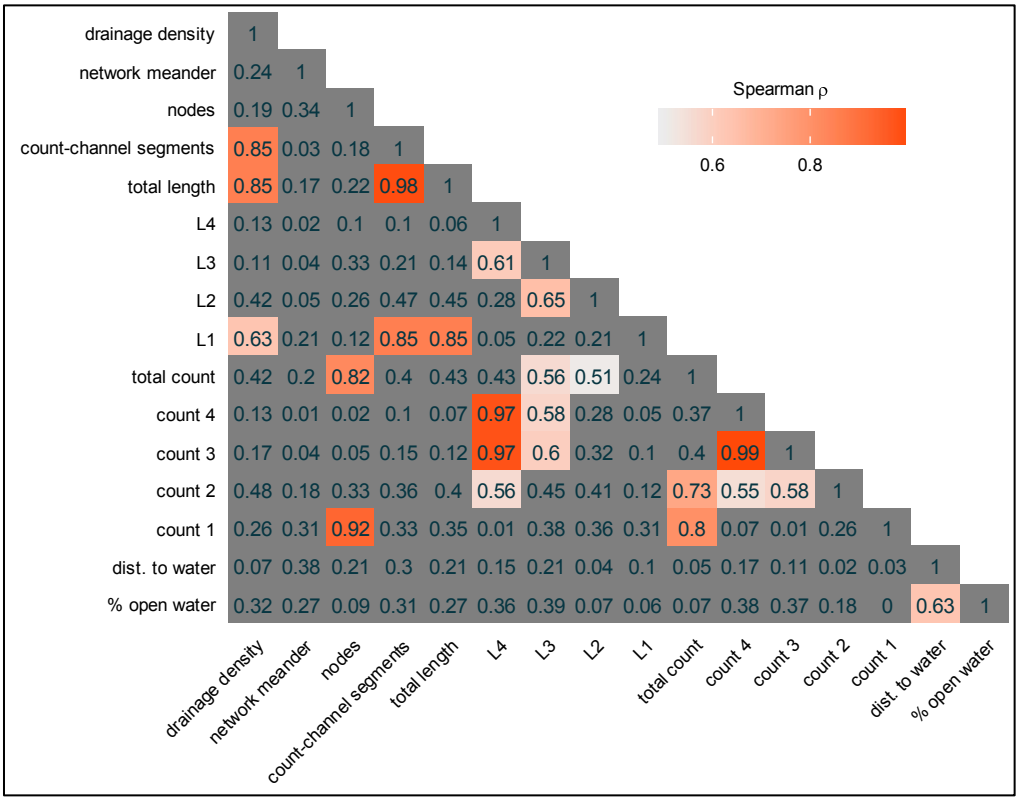


Figure C2: Correlation matrix of all network scale variables.

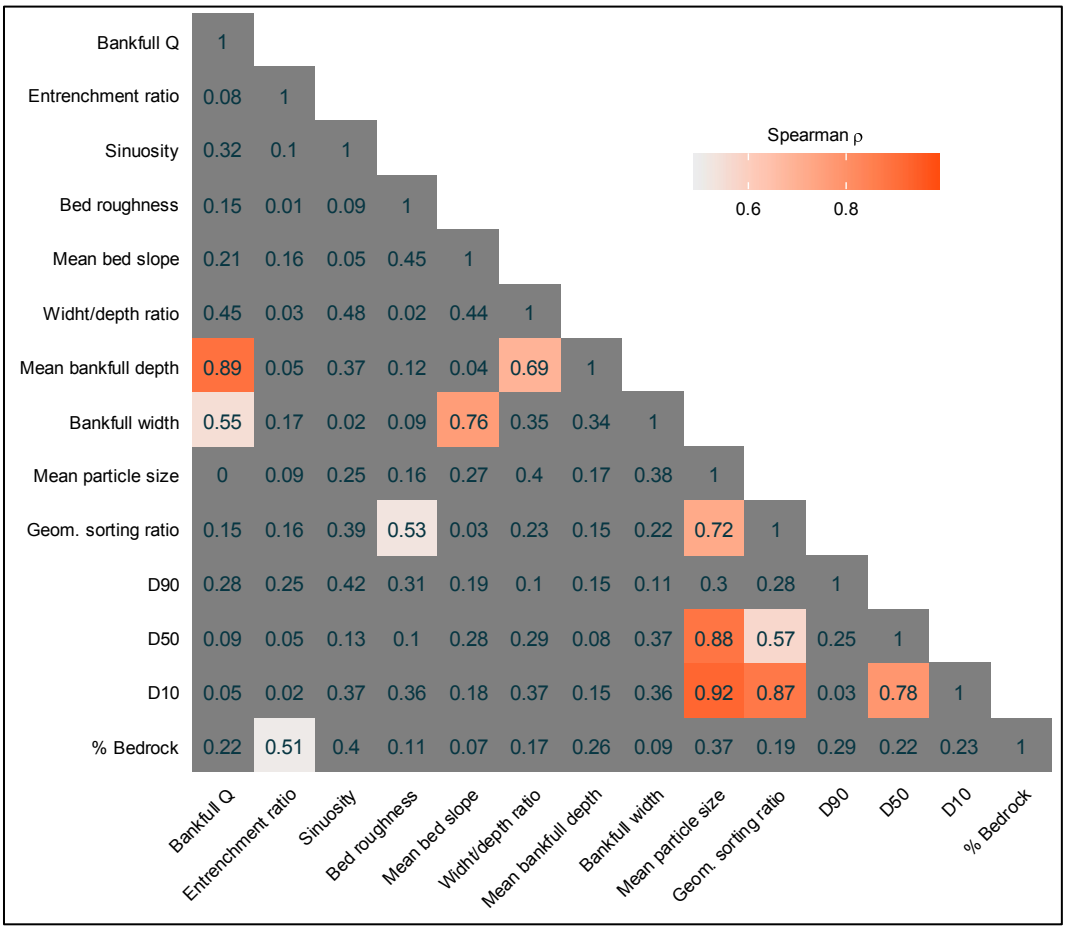


Figure C3: Correlation matrix of all outlet reach scale variables.

Appendix D: Spatial Scale Interactions (PerMANOVA results).

Table D1: Landscape-network scale interactions. Significant results in bold.

landscape variables and networks

	DF	SumsOfSqs	MeanSqs	F stat	R^2	p-value
Land use type	**2**	**1.070**	**0.535**	**5.422**	**0.26**	**0.012**
Elevation range	1	0.365	0.365	3.699	0.09	0.058
Mean surface slope	**1**	**0.371**	**0.371**	**3.760**	**0.09**	**0.045**
Mean hillslope length	1	0.047	0.047	0.481	0.01	0.587
Profile roughness	**1**	**0.846**	**0.846**	**8.573**	**0.21**	**0.003**
Residuals	14	1.381	0.099		0.34	
Total	20	4.080			1.00	

network variables and landscapes

	DF	SumsOfSqs	MeanSqs	F stat	R^2	p-value
Land use type	**2**	**0.114**	**0.057**	**12.834**	**0.50**	**0.000**
% open water	1	0.010	0.010	2.298	0.04	0.123
Dist. to water	1	0.014	0.014	3.121	0.06	0.065
Node count	1	0.005	0.005	1.214	0.02	0.306
Network meander	**1**	**0.017**	**0.017**	**3.922**	**0.08**	**0.034**
Drainage density	1	0.010	0.010	2.338	0.05	0.115
Residuals	13	0.058	0.004		0.25	
Total	20	0.229			1.00	

Table D2: : Network-outlet reach scale interactions. Significant results in bold.

network variables and outlet reaches

	DF	SumsOfSqs	MeanSqs	F stat	R^2	p-value
Land use type	2	0.300	0.150	1.835	0.15	0.128
% open water	1	0.102	0.102	1.247	0.05	0.303
Dist. to water	1	0.165	0.165	2.017	0.08	0.130
Node count	1	0.151	0.151	1.841	0.08	0.166
Network meander	1	0.090	0.090	1.097	0.05	0.350
Drainage density	1	0.090	0.090	1.098	0.05	0.356
Residuals	13	1.064	0.082		0.54	
Total	20	1.962			1.00	

outlet reach variables and networks

	DF	SumsOfSqs	MeanSqs	F stat	R^2	p-value
Land use type	**2**	**1.070**	**0.535**	**5.665**	**0.26**	**0.014**
% bedrock	1	0.038	0.038	0.405	0.01	0.656
D_{90} particle size	**1**	**0.551**	**0.551**	**5.831**	**0.13**	**0.013**
Bankfull width	1	0.059	0.059	0.625	0.01	0.494
Width/depth ratio	1	0.271	0.271	2.875	0.07	0.091
Mean bed slope	1	0.223	0.223	2.366	0.05	0.131
Sinuosity	1	0.083	0.083	0.882	0.02	0.392
Entrenchment ratio	1	0.134	0.134	1.415	0.03	0.242
Bankfull Discharge	**1**	**0.707**	**0.707**	**7.484**	**0.17**	**0.008**
Residuals	10	0.944	0.094		0.23	
Total	20	4.080			1.00	

Table D3: : Landscape-outlet reach scale interactions. Significant results in bold.

landscape variables and outlet reaches

	DF	SumsOfSqs	MeanSqs	F stat	R^2	p-value
Land use type	2	0.300	0.150	1.512	0.15	0.204
Elevation range	1	0.071	0.071	0.717	0.04	0.541
Mean surface slope	1	0.094	0.094	0.943	0.05	0.424
Mean hillslope length	1	0.041	0.041	0.416	0.02	0.729
Profile roughness	1	0.065	0.065	0.655	0.03	0.579
Residuals	14	1.390	0.099		0.71	
Total	20	1.962			1.00	

outlet reach variables and landscapes

	DF	SumsOfSqs	MeanSqs	F stat	R^2	p-value
Land use type	**2**	**0.114**	**0.057**	**9.472**	**0.50**	**0.000**
% bedrock	1	0.013	0.013	2.160	0.06	0.141
D90 particle size	1	0.001	0.001	0.139	0.00	0.898
Bankfull width	1	0.003	0.003	0.441	0.01	0.663
Width/depth ratio	1	0.010	0.010	1.653	0.04	0.199
Mean bed slope	1	0.004	0.004	0.654	0.02	0.536
Sinuosity	1	0.006	0.006	0.989	0.03	0.375
Entrenchment ratio	1	0.014	0.014	2.302	0.06	0.124
Bankfull Discharge	1	0.005	0.005	0.773	0.02	0.484
Residuals	10	0.060	0.006		0.26	
Total	20	0.229			1.00	

Appendix E: Tiered interactions model

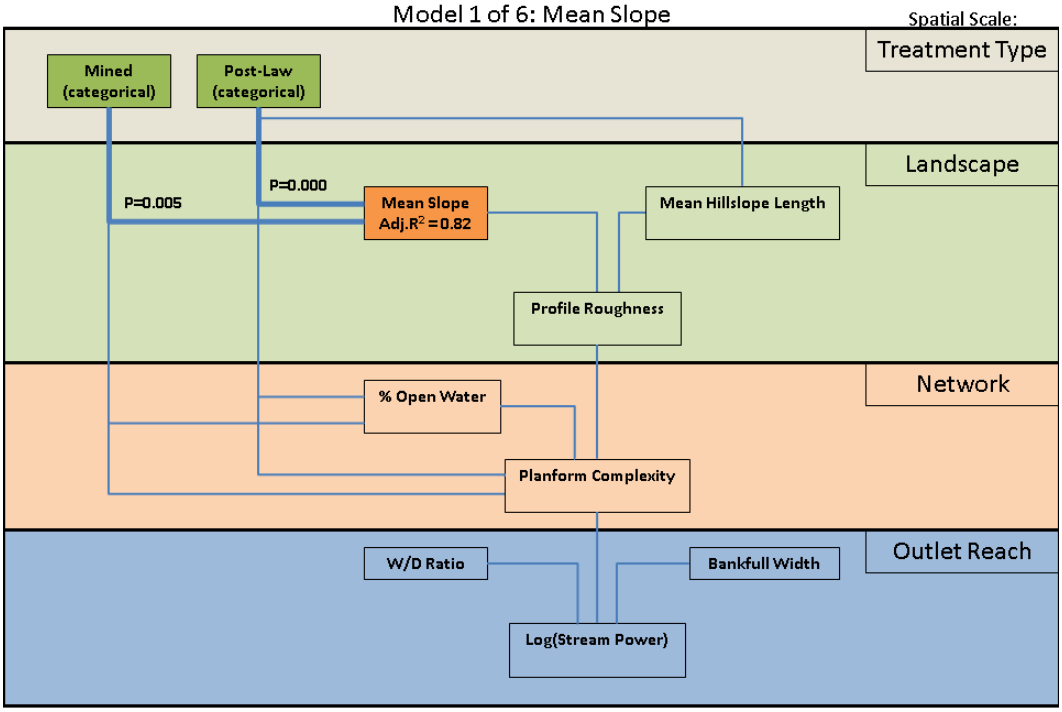
Table E: Tiered variable selection process with final summary model. Input variables without p-values were excluded from models via lowest AIC_c selection process. Mining and reclamation practices (including the construction of impoundments) are as impactful as channel dimensions on stream power at the outlet. Figures on following pages are a visual representation of these results.

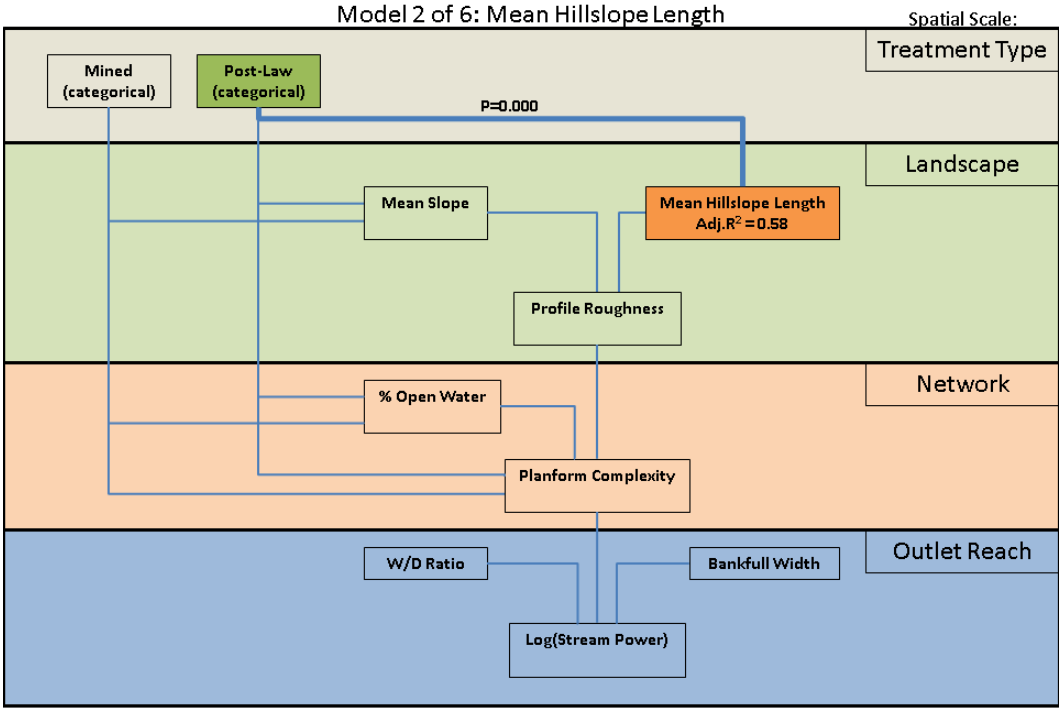
model	Input variables	p-value	Output variable	Adj. R^2
1	**Mined (categorical)**	0.005		
	Reclaimed (categorical)	0.000	Mean surface slope	0.82
2	Mined (categorical)	-		
	Reclaimed (categorical)	0.000	Mean hillslope length	0.58
3	Mined (categorical)	-		
	Reclaimed (categorical)	-		
	Mean surface slope	0.000		
	Mean hillslope length	0.115		
	Elevation range	-	Profile Roughness	0.96
4	**Mined (categorical)**	0.000		
	Reclaimed (categorical)	0.070	% open water	0.53
5	**Mined (categorical)**	0.119		
	Reclaimed (categorical)	0.248		
	% open water	0.002		
	Drainage density	-		
	Node count	-		
	Dist. To water	-		
	Profile Roughness	0.010	Network Meander	0.47
6	Mined (categorical)	-		
	Reclaimed (categorical)	-		
	Profile Roughness	-		
	Network Meander	0.068		
	Width/ depth ratio	0.000		
	Bankfull width	0.006		
	Entrenchment ratio	-		
	D_{90} particle size	-	Log(stream power)	0.57
Summary model:	**Mined (categorical)**	0.004		
	Reclaimed (categorical)	0.179		
	% open water	0.002		
	Width/ depth ratio	0.000		
	Bankfull width	0.006	Log(stream power)	0.71

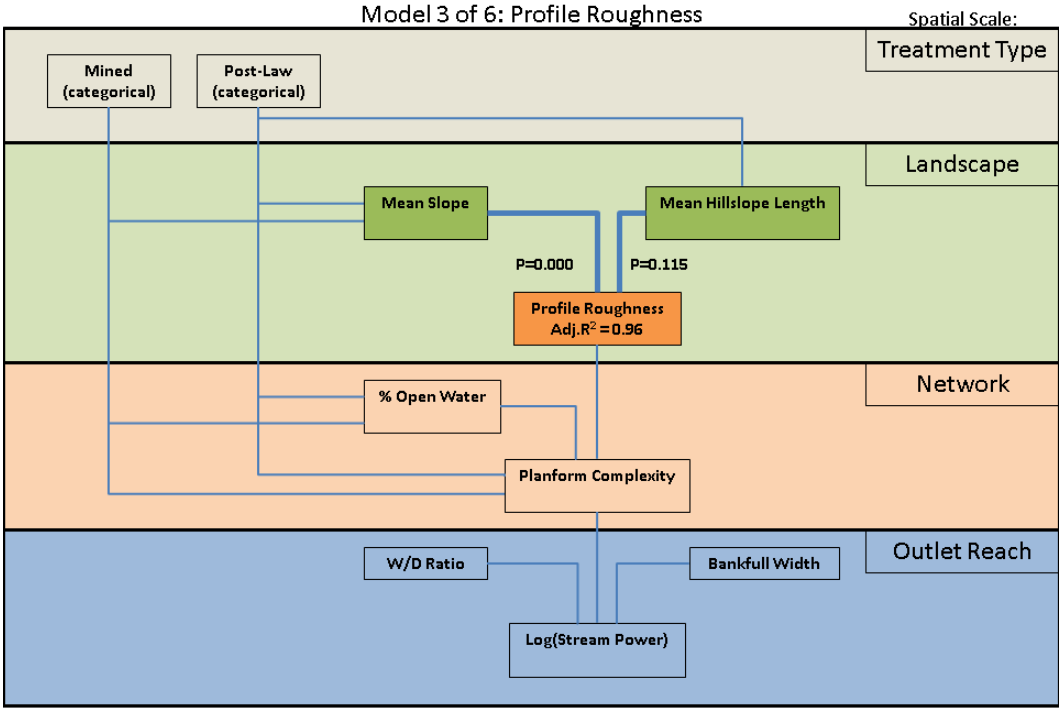
Summary model residual standard error: 0.927 on 15 DF

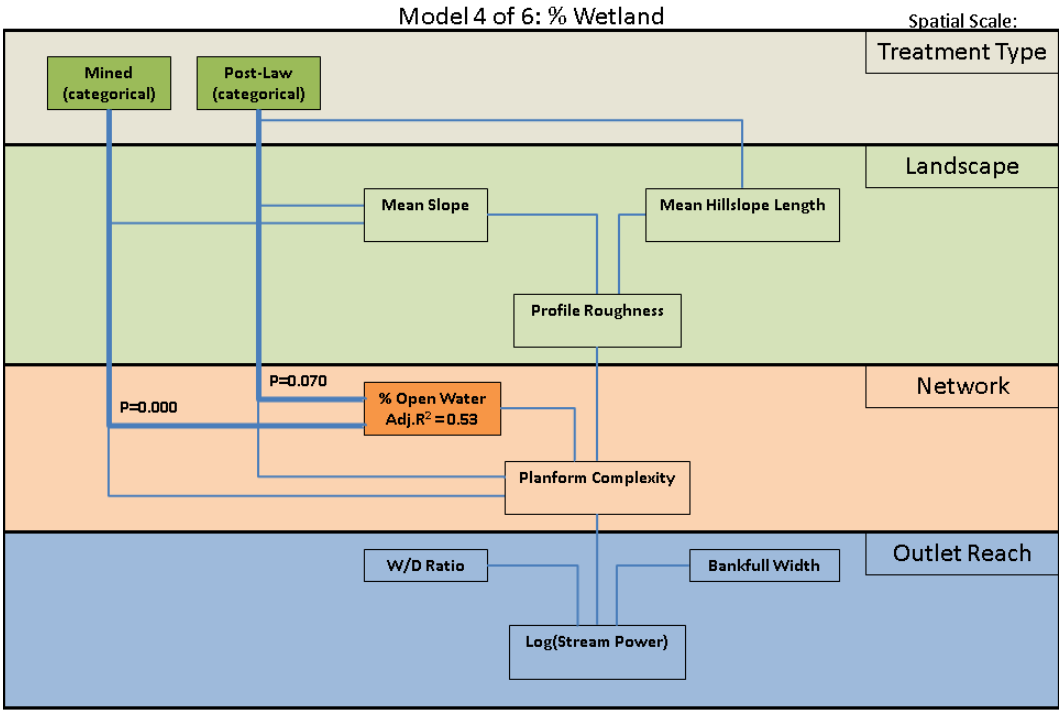
Adj. R2=0.71

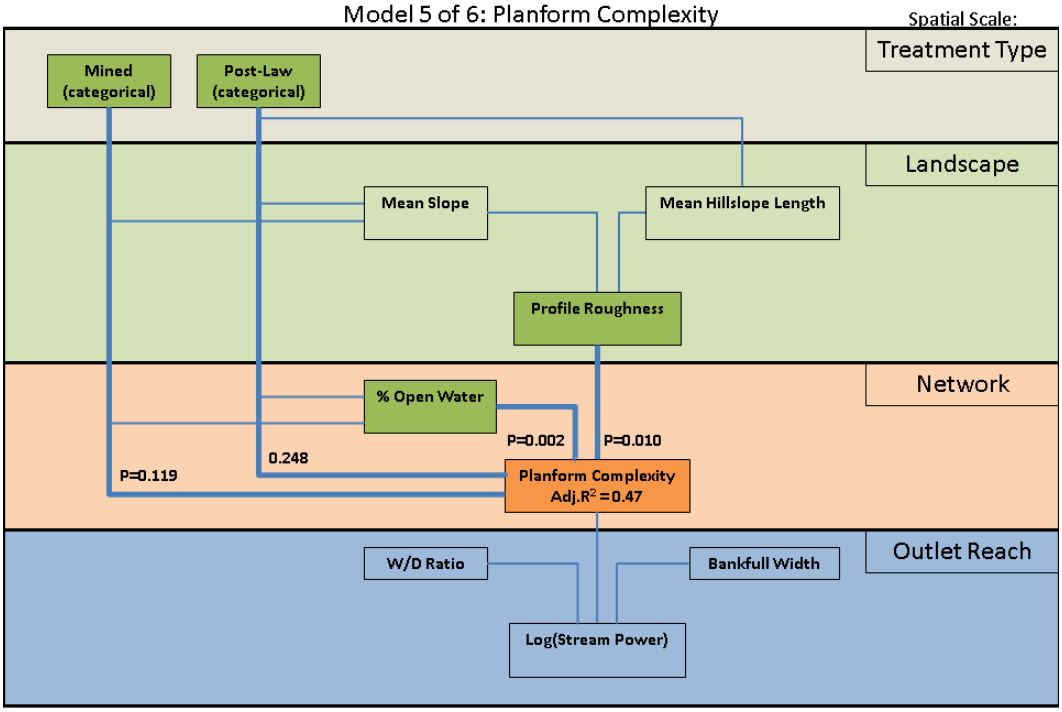
F-statistic: 10.74 on 5 and 15 DF, p-value: 0.000

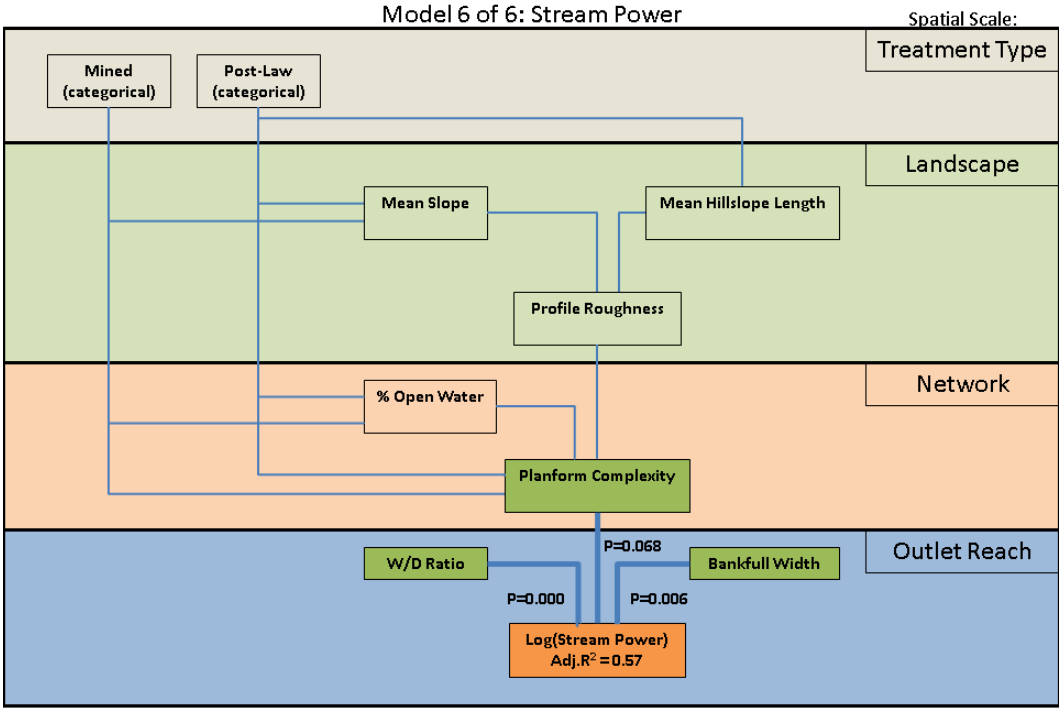

Model 1 of 6: Mean Slope
Spatial Scale:
Treatment Type
Landscape
Network
Outlet Reach
Mined (categorical)
Post-Law (categorical)
P=0.005
P=0.000
Mean Slope Adj.R² = 0.82
Mean Hillslope Length
Profile Roughness
% Open Water
Planform Complexity
W/D Ratio
Bankfull Width
Log(Stream Power)

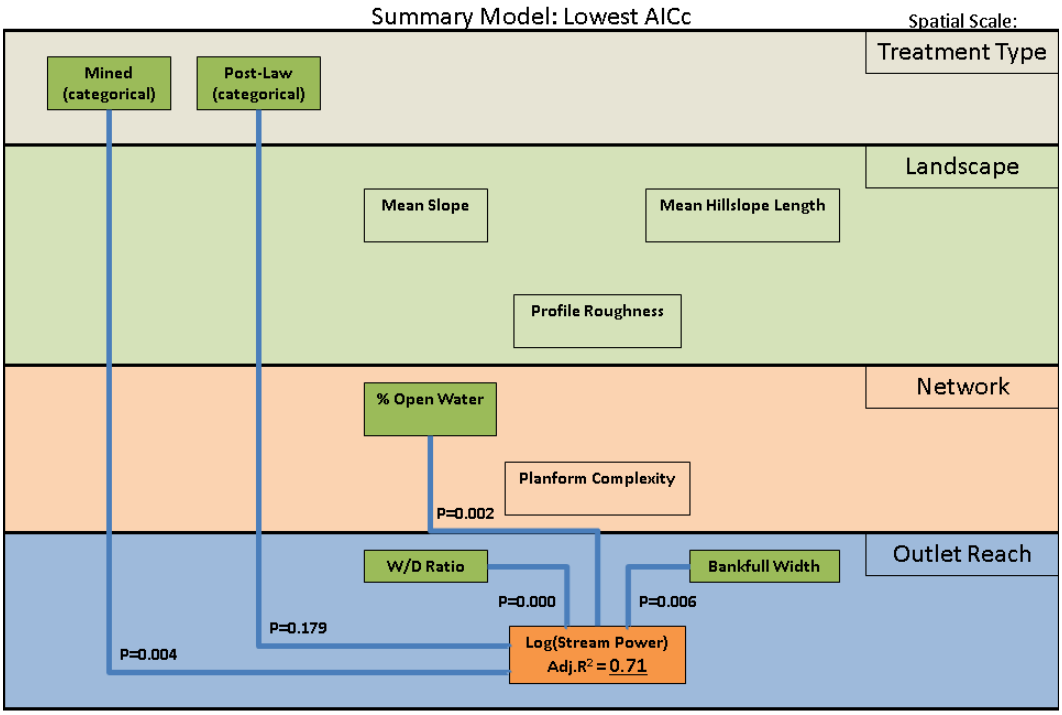

Model 2 of 6: Mean Hillslope Length
Spatial Scale:
Treatment Type
Landscape
Network
Outlet Reach
Mined (categorical)
Post-Law (categorical)
P=0.000
Mean Slope
Mean Hillslope Length Adj.R² = 0.58
Profile Roughness
% Open Water
Planform Complexity
W/D Ratio
Bankfull Width
Log(Stream Power)


Model 3 of 6: Profile Roughness
Spatial Scale:
Treatment Type
Landscape
Network
Outlet Reach
Mined (categorical)
Post-Law (categorical)
Mean Slope
Mean Hillslope Length
P=0.000
P=0.115
Profile Roughness Adj.R² = 0.96
% Open Water
Planform Complexity
W/D Ratio
Bankfull Width
Log(Stream Power)


Model 4 of 6: % Wetland
Spatial Scale:
Treatment Type
Landscape
Network
Outlet Reach
Mined (categorical)
Post-Law (categorical)
Mean Slope
Mean Hillslope Length
Profile Roughness
P=0.070
P=0.000
% Open Water Adj.R² = 0.53
Planform Complexity
W/D Ratio
Bankfull Width
Log(Stream Power)


Model 5 of 6: Planform Complexity
Spatial Scale:
Treatment Type
Landscape
Network
Outlet Reach
Mined (categorical)
Post-Law (categorical)
Mean Slope
Mean Hillslope Length
Profile Roughness
% Open Water
P=0.002
P=0.010
0.248
P=0.119
Planform Complexity Adj.R² = 0.47
W/D Ratio
Bankfull Width
Log(Stream Power)


Model 6 of 6: Stream Power
Spatial Scale:
Treatment Type
Landscape
Network
Outlet Reach
Mined (categorical)
Post-Law (categorical)
Mean Slope
Mean Hillslope Length
Profile Roughness
% Open Water
Planform Complexity
P=0.068
W/D Ratio
Bankfull Width
P=0.000
P=0.006
Log(Stream Power) Adj.R² = 0.57



The summary model utilizes the original input variables from the tiered variable selection process (models 1-6) to predict stream power at the outlet of each site.