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IMPACTS OF SURFACE MINING AND "AOC" RECLAMATION ON SMALL STREAMS AND DRAINAGE NETWORKS[1]

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Abstract. Many Appalachian drainage networks have been extensively altered by surface mining and reclamation. Mine sites reclaimed after passage of the Surface Mine Control and Reclamation Act (SMCRA) of 1977, must meet SMCRA Approximate Original Contour (AOC) requirements. However, investigations at three north-central West Virginia study show AOC is far removed from original landscape form and function. Specific drainage transformation varies greatly with reclamation style. Small stream drainage density decreased in all cases, but declines were less where sediment trenches act as low-gradient streams. Many reclaimed slopes lack small streams, relying on groundwater and overland flow to deliver water to larger streams. Thus, many headwater streams in unmined uplands are severed from the rest of the drainage system.

Slopes below truncated headwater streams are prone to instability. Groundwater and sheet flow lack capacity to handle moderate- to high-magnitude runoff from intense rainfall. Steep slopes commonly showed significant gully erosion very soon after reclamation and these gullies fore-tell long-lived channel paths across reclaimed slopes. Most constructed drainage was designed for extreme runoff, and lacks the "channel within a channel" cross-sections that promote stability during formative bankfull flows that occur every year or two. Constructed channels are poor matches to natural streams with respect to gradient, sinuosity and bed materials. Oversize channels may not fail during the reclamation bond period, but inevitably most will face sedimentation or lateral erosion problems.

Existing reclamation practices inadequately address the important roles of small streams in storm-water conveyance and sediment transport, and virtually eliminate ecological functions critical to the biological viability of all streams throughout a watershed. Long-term stability of reclaimed slopes and ecological sustainability of streams will require designs that accommodate both moderate bankfull flows and large infrequent floods.

Additional Key Words: fluvial geomorphology, hydraulic geometry, drainage density, stream restoration, slope stability, Appalachian Plateaus, West Virginia.

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Introduction

Along with various preceding state regulations, the Surface Mine Control and Reclamation Act (SMCRA) of 1977 marks an important watershed in the integration of environmentally responsive surface-mining practices (Plass, 2000). Under SMCRA, most surface mines must be reclaimed to a state described as Approximate Original Contour (AOC), in which the post-reclamation land surface at any given point differs from pre-mining topography by no more than 50 feet (15 m). AOC landscapes are indisputably superior to unreclaimed slopes in regards to slope erosion, stream sediment concentrations, ecological function and aesthetics. However, AOC requirements do not ensure reclaimed landscapes maintain natural stream and slope functions as well as their pre-mining predecessors.

The most critical functions of streams and slopes are not obvious throughout most of the year. In fact, if flowing water is used as a visual indicator of where streams exist, most streams are not apparent except during and immediately after rainfall or snow-melt events. Fluvial geomorphologists consider a stream to be any part of the landscape where channeled flow, no matter how infrequent, is the dominant erosion and sediment transport process acting on the underlying landform.

Slope and channel stability are foremost concerns for most reclamation practitioners. The basic geomorphology principles of hydraulic geometry underpin the emerging discipline of natural stream restoration, providing conceptual guidelines for sound surface-mine reclamation design. The most important principle of natural stream design is the tenant that the pattern, profile and cross-sectional geometry of streams are controlled by “bankfull” flows, levels reached on average only once every year or two (Wolman and Miller, 1960; Wolman and Gerson, 1978; Leopold, 1994; Rosgen 1996). Wolman and Miller (1960) have shown that bankfull conditions are the most effective flows at transporting sediments in most steams, and subsequent studies (Costa, 1974) have concurred that the hydraulic geometry of Appalachian streams is determined by bankfull flows. More frequent flows lack the energy to significantly modify the channel and adjacent landforms (at least under natural conditions), and rare extreme floods occur too infrequently to dominate channel form.

Put in more straightforward terms, bankfull flows are the most appropriate target conditions for designed stream channels because bankfull discharge is the channel-forming discharge. In contrast, over-sized or under-sized channel dimensions almost always lead to instability and bad things happening in the channel, which may lead to instability of adjacent slopes. In time, adjacent riparian vegetation will adjust to bankfull flow conditions (Hupp, 1988) further enhancing stability.

Delimiting bankfull channels in the field is a subtle talent because bankfull conditions on small streams occur less than 0.1 percent of the time, usually associated with some of the worst weather for field observation. To the untrained eye, low-flow conditions give very little insight into the nature of the most important events: bankfull flow. Several field-based methodologies for assessing stream dimensions (Harrelson and others 1994; Rosgen, 1994; 1996) require identification of geomorphological criteria to reconstruct bankfull stage, such as low depositional surfaces that mark the floodplain (Stream Systems Technology Center, 2003). Although mastery of fluvial geomorphology requires years of experience and well-honed observational skills, identification of bankfull channels can be made by field practitioners with as little as a few weeks experience.

Although most observers readily understand that perennial streams have important natural functions controlled by channeled flow, the importance of intermittent and ephemeral streams is commonly glossed over because these streams lack flow during significant intervals throughout the year. However, all streams are merely a part of the “River Continuum” in which tiny ephemeral and intermittent streams transport food energy produced throughout the watershed to the easily recognized perennial streams (Vannote et al., 1980).

Most Appalachian stream ecosystem food-energy flow begins as leaf litter falling or washing into small streams, which shredder invertebrates convert into fine organic matter that, in turn, feeds collector organisms. Shredders and collectors provide food for predator invertebrates and fish, which may be eaten by larger predators. If a normal input of organic matter into perennial streams is interrupted, the base of the food chain must be met by in-stream photosynthesis by algae and aquatic plants. The surface area occupied by perennial channels is tiny compared to the large watershed area that would normally contribute to the food chain, so Appalachian streams severed from their headwaters are unlikely to support the rich, diverse ecosystems that would exist under natural conditions.

Pragmatically, many streams in surface mined areas are so impaired by poor water quality that food-energy flow is, at most, a secondary limitation on the aquatic ecosystem. However, problems like acid mine drainage are geologically short-lived phenomena, so severance of small ephemeral and intermittent headwater streams from larger streams may emerge as the most important factor limiting stream ecosystem production while water quality recovers in coming decades and centuries.

Purpose, Objectives and Methodology

The purpose of our research is to analyze mining impacts by quantifying and describing alterations of drainage networks due to mining and reclamation. Specifically, research has focused on headwater segments of fluvial systems where reclaimed contour strip mining has intercepted small ephemeral streams. Larger streams are a secondary focus, largely because only one was directly impacted by mining and reclamation in our study sites.

The objectives of this project were met using the following methods:

1. Drainage networks were mapped from pre-mining and topographic maps and post mining field study using Global Positioning System (GPS) survey, in addition to tape and compass measuring.
2. Stream orders were assigned to network components. Total stream lengths and basin area for each stream order were calculated and compared between pre-mining and post-reclamation networks in each study area.
3. Comparisons of pre-mining and post-reclamation values for total stream lengths, mean length of a given order stream, bifurcation ratio, and drainage density were made between different watersheds within each study area.
4. The length-slope (LS) factor from the Universal Soil Loss Equation (USLE) was employed to determine how this factor related to observed channel erosion on backfill.
5. The hydraulic geometry and stability of one intermittent reclaimed stream was compared to that of an unmined analog reference reach.

Study Sites

This study focused on the fluvial geomorphology of three reclaimed surface-mine sites and a control area within Dents Run watershed, 7 to 10 km west of Morgantown, north-central West Virginia (Fig. 1). All sites are located within the Appalachian Plateaus physiographic province (Lessing, 1996) and Surface Mining Province #2, where bedrock is flat-laying and acid mine drainage frequently develops in response to mining activity (Skousen, 2001). Pre-mining drainage patterns were dendritic, excluding permit area #1006-98, which exhibited a trellis drainage pattern. In all areas, original topography consisted of narrow valleys with steep slopes ranging from 22 to 31 percent. The three study sites and control area share similar geology and climate. Waynesburg Coal, typically 3 to 4 m thick, was mined at each reclaimed surface mine site. Post-mining land use for the reclaimed study sites is pastureland, whereas the control area is mostly in timber.

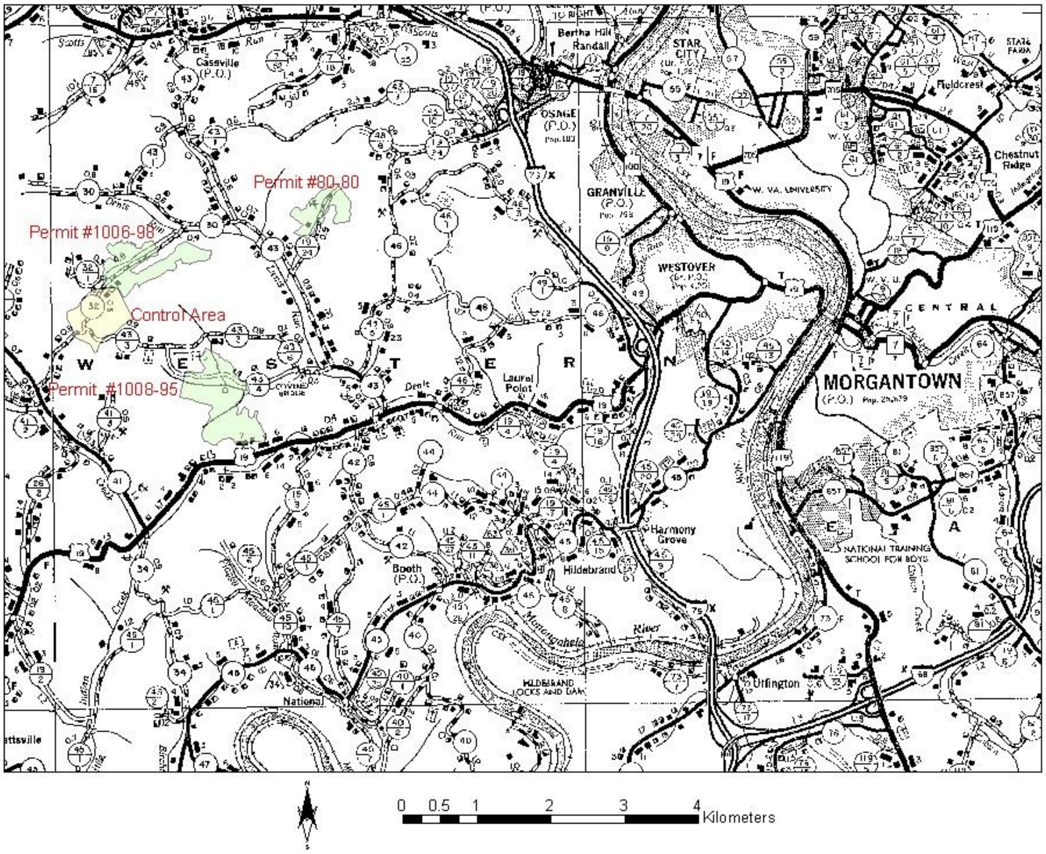

Figure 1: Study sites and control area location map. Map from Smith, 2003.

The oldest of the reclaimed sites, permit area #80-80 was mined and reclaimed in the early 1990's (Jeff Skousen, 2001, personal communication). Permit area #1008-95 was mined and reclaimed from 1997 to 1999 (Jeff Skousen, 2001, personal communication). This is the only area where valley fills were created during reclamation: two are located along the central eastern edge of the area. Permit area is #1006-98 is the most recently mined area. Dents Run, a sixth order stream at this location, flows through the center of site #1006-98, dividing it in half. The northern half was mined in 1998 and reclaimed in 1999, when some engineered structures, such as a hillside fill and two channels, were created during reclamation. The southern half was mined in 1999 to 2000 and reclamation was completed in early 2001. The control area, adjacent to permit #1006-98, was selected because it has not been mined within the last 60 years, and has not experienced significant surface mining.

Stream Order

Horton (1945) and Strahler (1954) established a system for stream order designation as a quick and dirty approximation of stream size. In Strahler's currently accepted scheme, a first-order stream is the uppermost tributary in the drainage network; no other channel contributes flow to a first-order stream. A second-order stream is created by the junction of two or more first-order streams, and stream orders increase only when streams of equal order join.

Despite the level of specificity in Strahler's hierarchy for drainage networks, there is no standard method for identification of first-order channel heads. An internet poll of active researchers showed that many create their own protocols to determine where a first-order stream begins (Smith, 2003). Definitions of channel heads are adjusted according to the research's focus or the study area's climate and geomorphology.

Our map analysis of pre-mining drainage followed one of the more widely used protocols by Lubowe (1964), which established criteria for defining first-order streams on 1:24,000 topographic maps (Mark, 1983). In Lebowe's protocol, contour crenulations define a stream where three or more consecutive crenulations occur with inflection angles ≤ 150° or where two consecutive crenulations occur with inflection angles of ≤ 100° (Fig. 2). Mark (1983) showed Lubowe's protocol for topographic maps under-represents the drainage networks as shown by field mapping, although detailed maps allow reasonably accurate reconstruction of drainage. In order to maximize comparability between pre-mine and post reclamation data we used 1:6,000 scale, five-foot contour permit maps to determine the pre-mine drainage network for two study sites and the control area. The permit map for the oldest mine site (80-80) was based on an

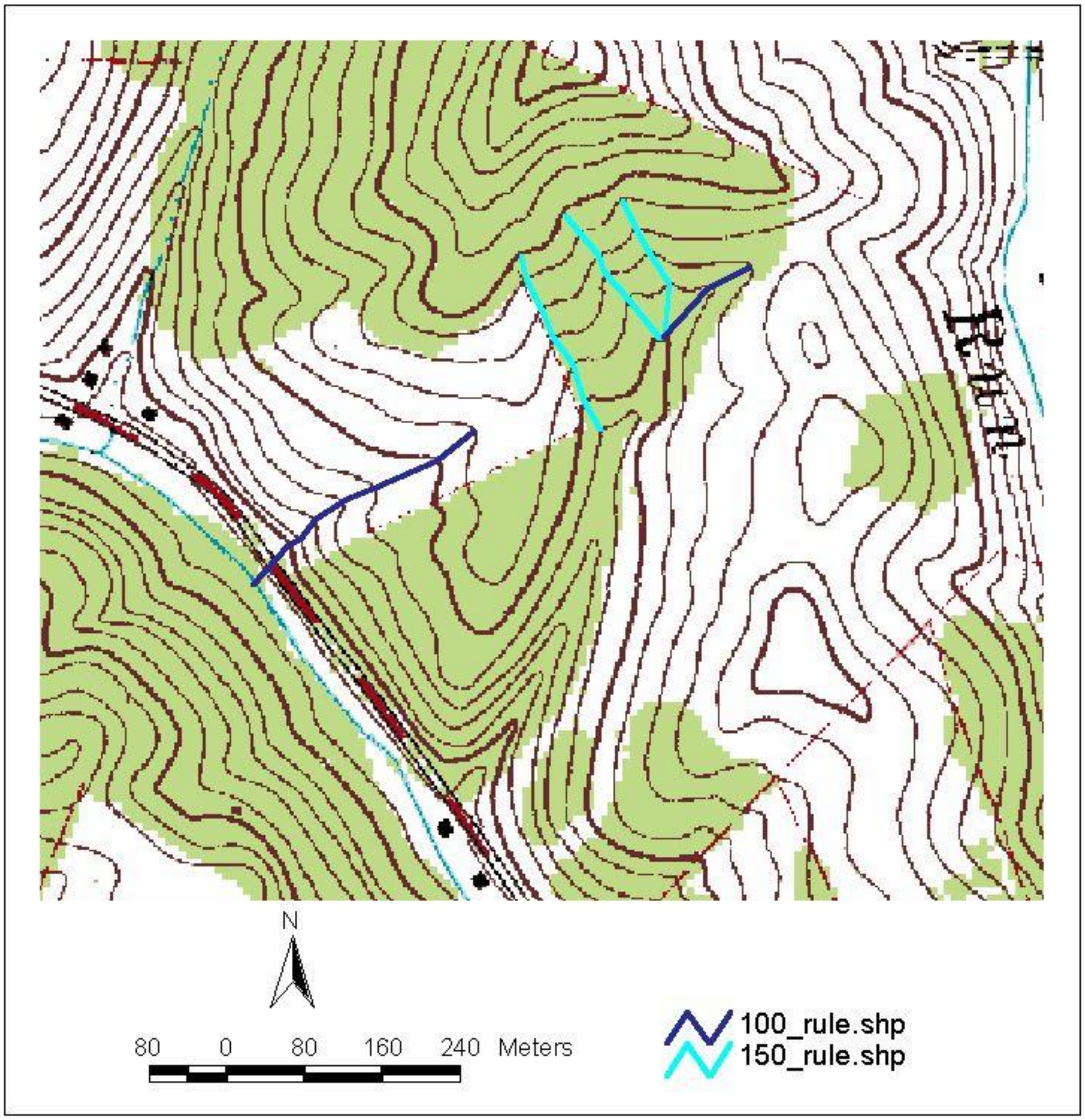

Figure 2. Illustration of Lubowe’s 1964 stream network mapping rules.

Streams are mapped on the 1:24,000 scale Osage topographic quadrangle. Dark blue lines indicate streams located using Lubowe’s two or more consecutive contour line crenulations with inflection angles $\leq$100°.

Light blue lines indicate streams that were located using three or more consecutive crenulations with inflection angles < 150°. Map from Smith, 2003.

enlarged portion of the 1:24,000 scale, ~6 m (20 ft) contour interval, USGS Osage quadrangle. The topographic detail provided by this map is significantly reduced compared to the other maps, and so, the pre-mining stream network mapped for this permit area is likely to be the least accurate.

Field and GIS Work

Post-reclamation data were acquired through field traverses across the three mined sites and the control area from September 2001 through June 2002. Locations of all landforms were marked on paper copies of the permit maps. Channels and other significant points were mapped using a Garmin 12 channel handheld GPS unit, with a precision of $\underline{+}$10 m under adequate satellite coverage (Garmin Corporation, 2002). GPS points were only recorded if the satellite coverage provided an estimated error of less than 12 m (40 ft).

Stream channels were identified wherever a feature exhibited two or more of the following characteristics**:** (1) surface water flowing in channels, (2) evidence of recent channeled flow, such as imbricated sediments or eroded substrate, (3) well-defined banks, (4) linear landform at a slightly steeper gradient than surrounding topography. Commonly, a bowl-shaped concavity was indicative of a channel head location. Channel heads were identified at groundwater seeps in a few instances where there was no evidence of a channel upslope from the seep.

Distances along channels were measured using a 50 m tape measure, and locations of junctions between channels were noted to within 0.1 m. Descriptions and UTM coordinates of other features, such as man-made channels, backfill slumping, landslide scars, and severe gullying or rilling, were noted on-site. Slope-angle measurements were taken with an inclinometer.

All maps and most data analysis were produced using ArcView 3.2 (ESRI, 1999). GPS field data were entered in a Microsoft Excel database (.dbf) file, and imported into ArcView. The ArcView “Length” tool was used to verify that the length of the digitized stream channel was similar to the length measured in the field. If the two values differed by more than 12 m, a new channel was digitized whose length more closely matched the field value. As a result, stream lengths measured in the field were more accurate than the stream lengths determined using ArcView 3.2 and the mapped waypoints.

Pre-mining drainage networks for the four study areas were generated using the permit maps to digitize the links between inflection points on contour crenulations. Channel heads were identified at the uppermost definitive crenulation. Channel junctions were digitized on the inflection points of the uppermost crenulation where two or more series of crenulations merge into one series. The ArcView "Calculator" function was used to calculate stream lengths for both pre-mining and post-reclamation data sets.

Study areas were subdivided into watersheds, typically second-order, although several third and fourth-order watersheds were identified. Stream data were analyzed at the watershed level, and then tabulated for each study site. Pre-mining and post reclamation drainage networks are shown in Fig. 3 to 8.

Data Analysis

Total stream lengths in the control and permit areas were calculated for each stream order using ArcView 3.2. Lengths were summed for each area and for individual watersheds. Post-reclamation stream network lengths were summed in three different categories: natural stream channels, all reclaimed channel lengths, and reclaimed engineered structures. Drainage density was calculated as the sum of channel lengths in a watershed, divided by watershed area.

The length-slope (LS) factor from the Universal Soil Loss Equation was used to assess where gulleys are likely to develop on reclaimed slopes. First, the change in elevation between the top of each watershed and the uppermost backfill was calculated using the permit map contours. Horizontal distance was measured using the ArcView "Length" tool. The change in elevation was divided by the horizontal distance between points to yield percent slope. A nomogram showing percent slope and slope-length (Dunne and Leopold, 1978) was used to determine the length-slope (LS) factor, an important variable used in the Universal Soil Loss Equation.

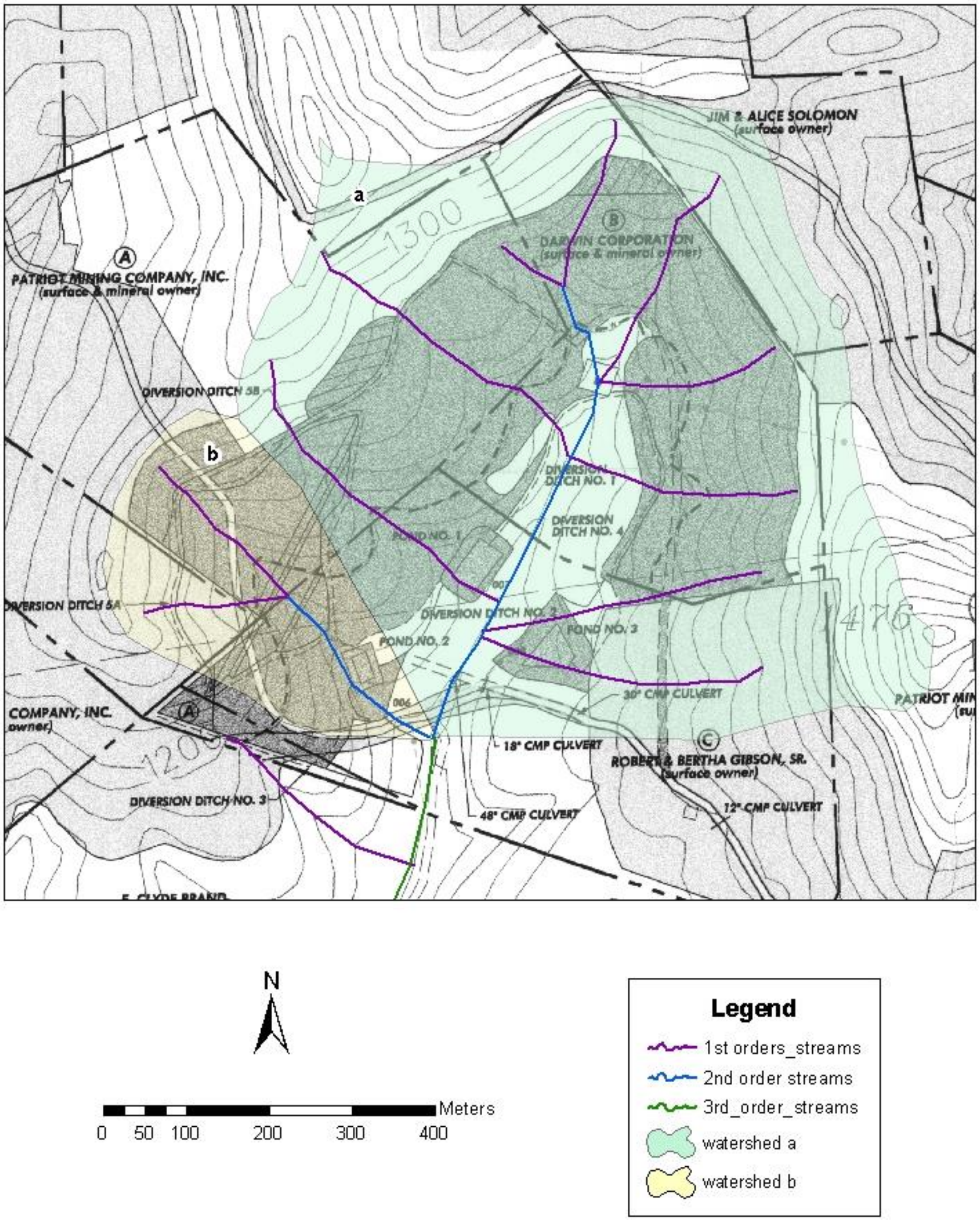

Figure 3. Pre-mining stream network at study site 80-80. The third-order stream that exits this site is an unnamed tributary to Dents Run. Map from Smith, 2003.

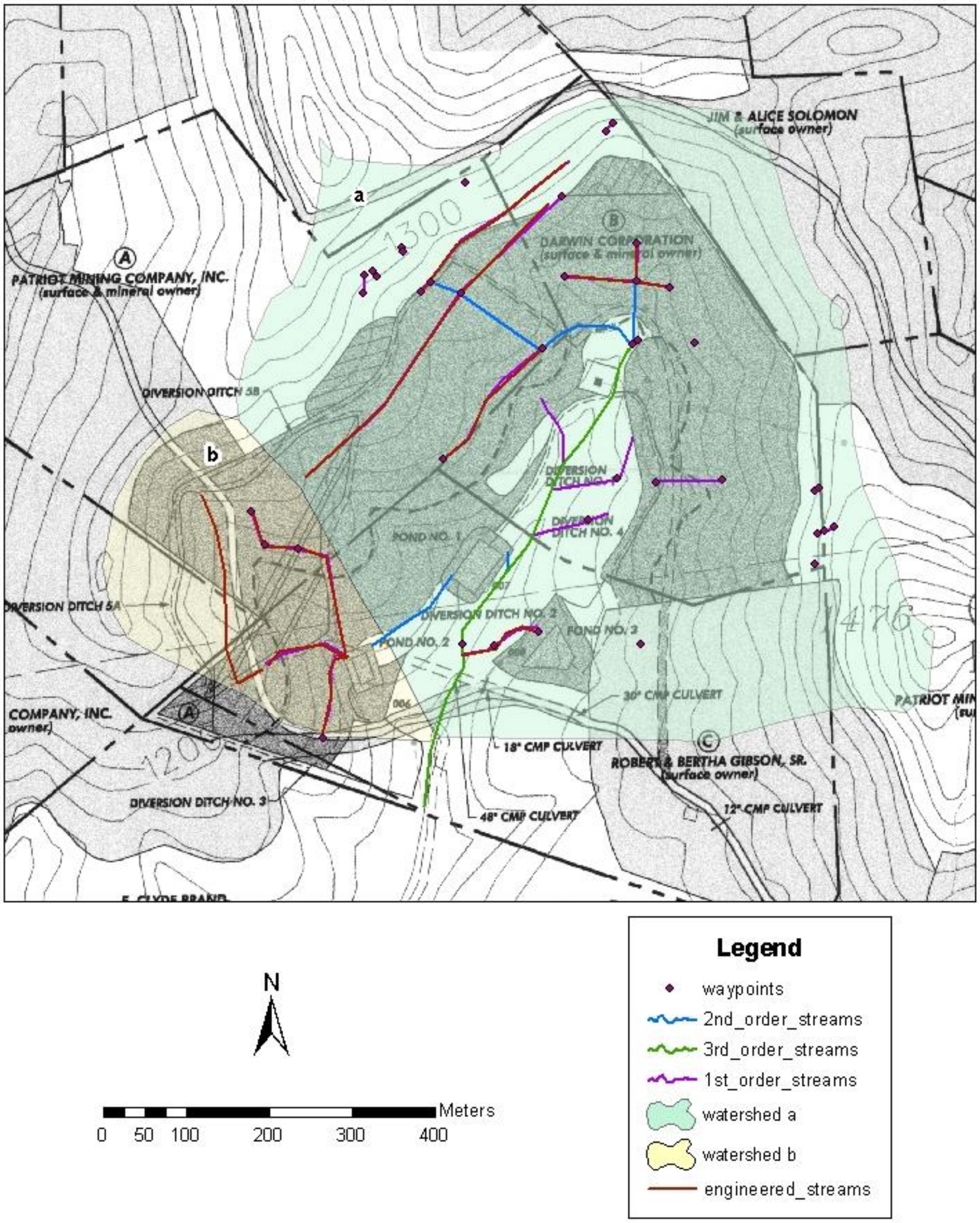

Figure 4. Post-reclamation stream network at study site 80-80. This permit area has the largest percentage of engineered drainages of all the reclaimed areas. Map from Smith, 2003.

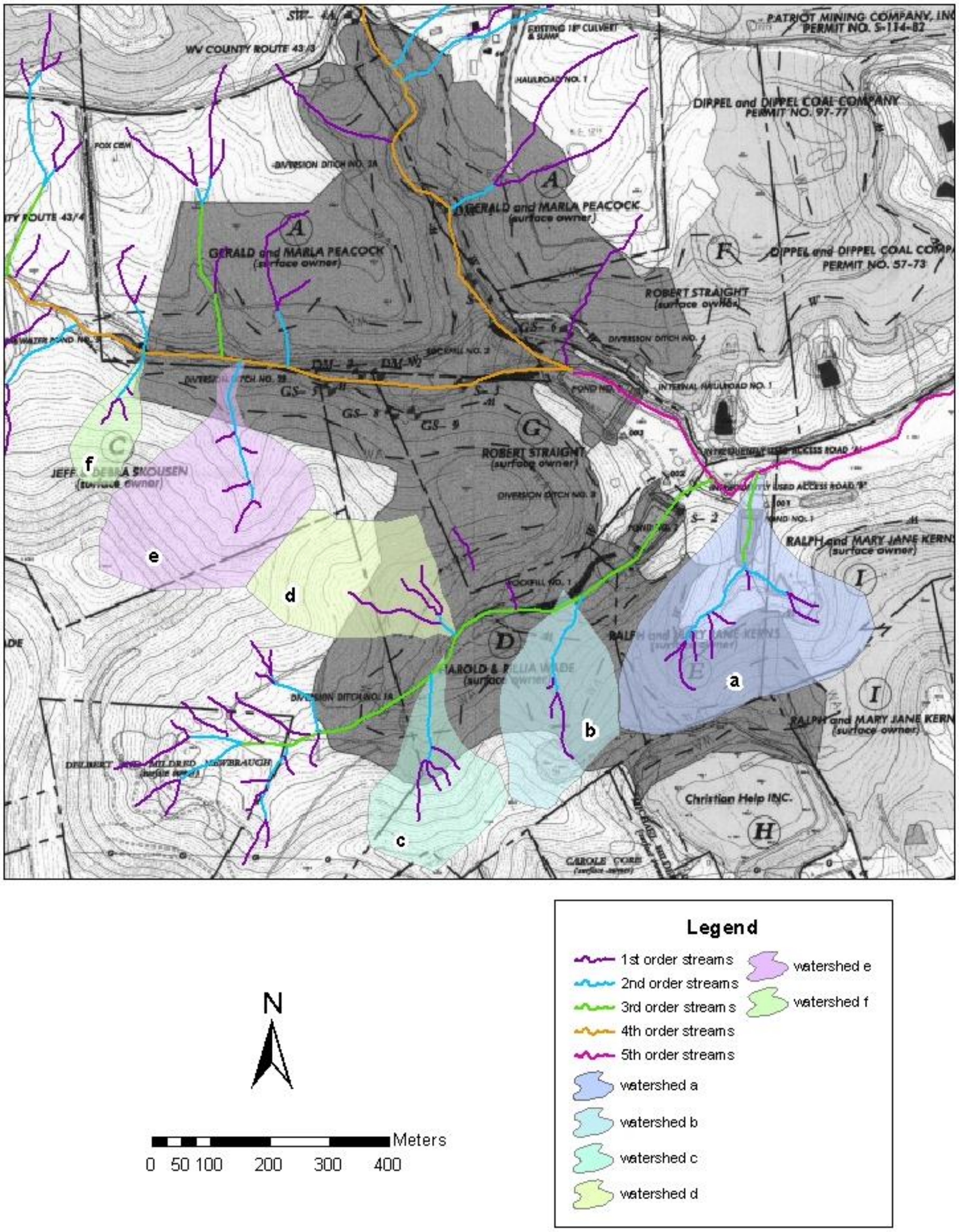

Figure 5. Pre-mining stream network at study site 1008-95. Map from Smith, 2003.

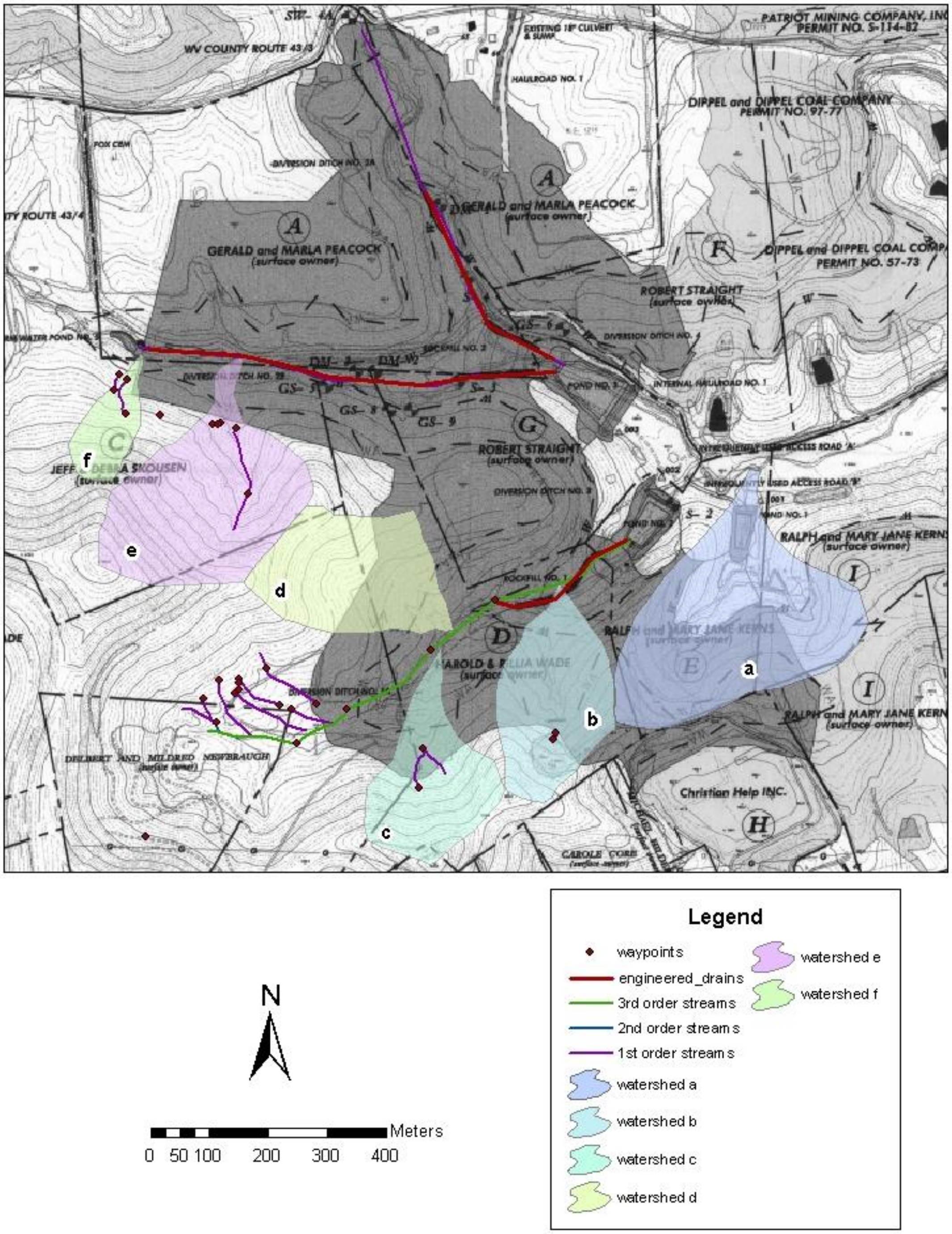

Figure 6. Post-reclamation stream network at study site 1008-95. Map from Smith, 2003.

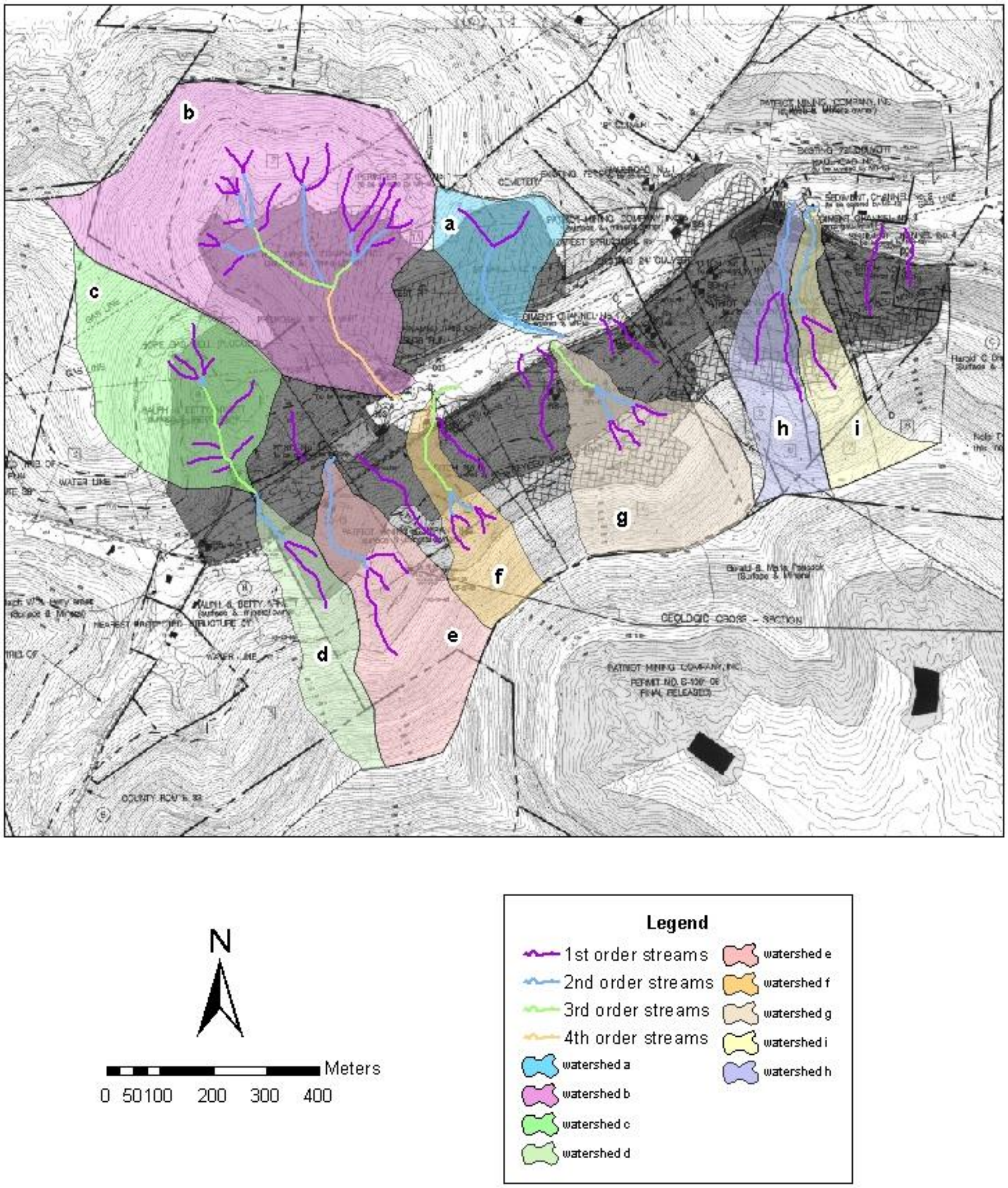

Figure 7. Pre-mining stream network at study site 1006-98. Map from Smith, 2003.

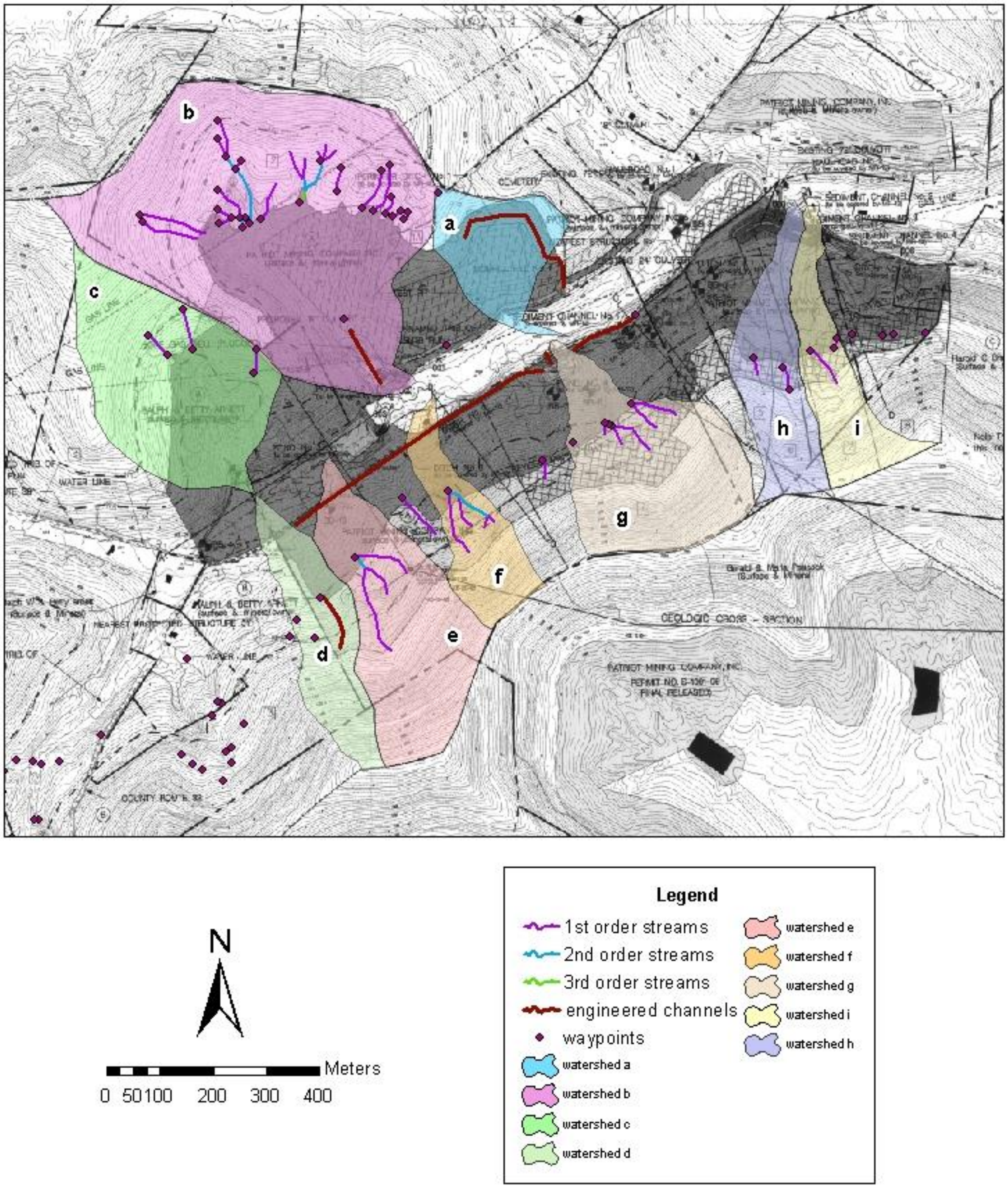

Figure 8. Post-reclamation stream network at study site 1006-98. Map from Smith, 2003.

Results

Total Stream Lengths and Drainage Density

Total stream channel lengths and drainage density for each reclaimed area decreased after mining and reclamation (Table 1). However, the amount of decrease varied significantly between areas. Total stream channel lengths have a direct relationship to drainage density; therefore, any change in the first value will impact the latter value proportionally.

Table 1. Summary of area, total stream lengths, and drainage density for reclaimed surface mine sites and control area.

Permit #	Base Map Scale	Water-shed Area (km^2)	Pre-Mining Lengths (km)*	% Engi-neered Channels	Drainage Density (km/km^2)	Length & Drainage Density Change
80-80 Pre-mining	24,000	0.562	3.887	-	6.92	
80-80 Post-Reclamation	24,000	0.562	3.191	69.2	5.68	-17.9 %
1008-95 Pre-mining	6,000	0.345	2.748	-	7.90	
1008-95 Post-Reclamation	6,000	0.345	0.435	0.0	1.25	-84.2%
1006-98 Pre-mining	6,000	0.806	5.088	-	6.31	
1006-98 Post-Reclamation	6,000	0.806	3.324	13.1	4.12	-34.7%
Control Map Based	6,000	0.346	1.866	-	5.40	
Control Field Mapped	6,000	0.346	1.881	0.0	5.44	+0.7%

* Pre-mining stream lengths were determined from contour crenulations; post-mining stream lengths were field mapped. Data revised from Smith (2003).

Permit area 80-80 retained the greatest total stream lengths and drainage density, experiencing only a 17.9 percent reduction. This decrease is relatively small because over 2200 m of bermed or boulder-armored engineered channels occur in the study area. Nearly parallel to slope contour, these bermed channels, or sediment trenches (Fig. 9, 10, and 11), are common at mine sites, where they are used as sediment control structures during construction. The drainage network at site 80-80, however, was enhanced because the operator did not follow the standard

Figure 9. Bermed channels, or sediment trenches, at study site 80-80. J.S. Kite photo.

Figure 10. Bermed channel on a south-facing slope at study site 80-80. Channels have been incised by knick-point erosion. J.S. Kite photo.

Figure 11. Gulley at study site 1006-98. Gulley occurred downslope of a truncated 3rd order stream in watershed f in October 2000, a few weeks after reclamation. J.S. Kite photo.

procedure of removing these structures after vegetation is well established (Jeff Skousen, personal Communication, 2003). Field observations confirm water regularly flows through these low-gradient channel structures.

Site 1008-95 had the largest decrease in total stream channel lengths: 84.2 percent, indicative of a reliance on a few over-sized armored channels fed by ground-water under normal low-flow conditions. Several sub-watersheds in permit area #1008-95, were reclaimed without any surface drainage. Although portions of permit area #1006-98 were reclaimed without surface drainage, two sub-watersheds actually had increases in total length of stream channels.

The control area showed little overall discrepancy between total stream length and drainage density calculated using the two different approaches, at face value, suggesting the significant decreases observed in surface-mined areas do not stem from methodological error. However, discrepancies of up to 20.5 percent were noted in sub-watersheds that comprise the control area, indicating that drainage networks derived from contour crenulations do not entirely correlate to those mapped in the field.

Bifurcation Ratios

In each reclaimed study area, post-reclamation bifurcation ratios were greater than the pre-mining ratios, reflecting less integrated drainage networks after mining and reclamation (Table 2). Bifurcation ratios changed least at permit area #80-80, where many armored drainage segments were constructed. Bifurcation ratio at permit area 1008-95 rose to infinity because of a complete lack of drainage integration. A small increase in first order-second order bifurcation ratio at the control area reflects recognition of three additional first order streams through field mapping. Bifurcation ratios between 3 and 4 are normal for the Appalachian Plateaus, with the small watershed size, ratio changes of 1.0 unit may not be significant, but the dramatic increases at sites 1008-95 and 1006-98 clearly show poorly connected drainage networks.

Table 2. Bifurcation ratio data for reclaimed surface mine sites and control area.

Permit #	1st Order	2nd Order	3rd Order	4th Order	Ratio: 1st/ 2nd Order	Ratio: 2nd/ 3rd Order	Ratio: 3rd/ 4th Order
80-80 Pre-mining	11	2	1	0	5.5	2.0	-
80-80 Post-Reclamation	22	3	1	0	7.3	3.0	-
1008-95 Pre-mining	26	7	1	0	3.7	7.0	-
1008-95 Post-Reclamation	7	0	0	0	∞	*	-
1006-98 Pre-mining	44	15	4	1	2.9	3.8	4
1006-98 Post-Reclamation	42	6	1	0	7.0	6.0	∞
Control: Map Based	13	5	2	0	2.6	2.5	-
Control: Field Mapped	16	5	2	0	3.2	2.5	-

The ∞ symbol denotes zero streams in larger order; * symbol denotes zero streams in either order; but the - symbol is used in lieu of ∞ or * where pre-mined ratio was ∞.

Length-Slope (LS) Factor

Topographic maps were used to determine LS values were for slopes immediately above surface mines in the three study sites (Table 3). LS factors are used in the Universal Soil Loss Equation to assess the impact of slope geometry on gulley erosion; in this study LS factors serve as a potential predictor of spontaneous initiation of new drainage links where channels were not provided during reclamation. Field observations show that gully erosion has occurred since reclamation at all sites, but is most pronounced at site 1006-98, even though reclamation at this site was only a few weeks old at the onset of this study. Unsurprisingly, this site has both the highest mean LS factor and the greatest number of slopes with factors “off the chart” (i.e. >20). At sites 1008-95 and 1006-98, backfills below slopes with LS factors of ≥17 tend to experience slumping.

Table 3. Summary of Length-slope factor for each reclaimed area.

Permit #	Mean Slope	LS Factor Minimum	LS Factor Maximum	LS Factor Mean	% Slopes w/ LS Factor ≥ 20
80-80	22.2 %	4.0	12.5	7.8	0
1008-95	21.0 %	3.0	>20	>10.4	25
1006-98	31.2 %	13.0	>20	>17.0	60

An LS factor of >20 is the highest value given on Dunne and Leopold’s (1978) LS factor nomogram.

Hydraulic Geometry of Engineered Channels

Field observations suggest engineered channels were constructed on our study sites for three reasons; (1) to conduct water to settling ponds, (2) to protect roads from runoff and erosion by creating drainage ditches (3) to reconstruct fourth order or larger streams that were destroyed or impaired during mining and reclamation. These channels are lined with large boulders and geotextiles. Some of these channels appear to remain dry year round, but a channel at permit area #1008-95 has imbricated cobbles and a lack of in-channel vegetation indicating occasional flow.

Ideal channel design allows conveyance of flood runoff at the right velocity to prevent either sediment deposition or channel erosion (Rosgen, 1996). Actual constructed channel dimensions are limited by factors such as steepness of terrain, available equipment, and mine soil characteristics (Lyle, 1987). With very few exceptions, an unnatural trapezoidal design was used for engineered drains at the reclaimed study areas. This shape may be related to standard operating procedures on the relatively large bulldozers used to create drainage.

Almost all engineered channels within our reclaimed study areas are visibly over-sized, in that their cross sectional area is much greater than is needed to convey bankfull flows typical of the region (Fig. 12). A minimal number of engineered channel dimensions were measured. Comparison to regional curves of hydraulic geometry for streams in the eastern United States (Dunne and Leopold, 1978) indicate that channel width is not far from widths expected for bankfull dimensions on in the region, but that depths were much greater than found on natural analogs (Smith, 2003). Width-depth ratios > 3.0 are much greater than seen on natural channels in analogous settings.

Figure 12. Typical over-sized armored constructed channel. Located at study site 80-80., channel is lined with large sandstone boulders. Approximate bankfull dimensions are 0.5 m deep, 1.4 m wide across the channel bed and 2.6 m wide at top of channel. J.S. Kite photo.

One exceptional ~100 m long reach at site 1008-95 appears to have been reclaimed fortuitously with a bankfull channel nested within a large high-flow channel (Fig. 13). The smaller cross-section appears properly sized to convey bankfull flows, and this reach has experienced sediment transport without excessive erosion or deposition during high flows. In contrast erosion and deposition problems occur on either end of the same reach, where the smaller bankfull channel is either absent or too large to be effective (Fig. 14).

Figure 13. Constructed channel at site1008-95 appears correctly sized for bankfull flow. Flow was directed toward the camera. Imbricated cobbles and pebbles show that this reach has experienced sediment transport although erosion is minimal. J.S. Kite photo.

The upshot of over-size channels is that the engineered structures are unlikely to have sufficient flow velocity during bankfull flow conditions to transport a balanced sediment supply and maintain channel dimensions.

Discussion

Maps of post-reclamation drainage networks reveal that the decrease in drainage density and increase in bifurcation ratios reflect truncations of small natural channels at the upslope limit of mining (Fig. 11 and 15), where groundwater infiltration is sufficient to handle “normal” flows. However, infiltration is insufficient to transmit bankfull flows conveyed by the undisturbed channel above the mine, leading to gulley development where LS factors are high. Channel truncations also are associated with landslides related to weakening of thick backfills with excessive soil moisture. If unchecked by mitigation, gulley erosion will ultimately lead to development of a channel system at equilibrium with upslope runoff; however, the erosion required to reach this equilibrium may produce acute negative short-term environmental impacts and significant operator or land owner mitigation costs. No matter how well backfill infiltration into unchanneled backfill seems to be working during fair weather, properly-sized channels based on bankfull flows will prove more cost effective in long term!

Figure 14. Channel at site 1008-95 downstream from correctly sized channel. Flow direction is away from the camera. Moderate flows have exceeded capacity of channel, scouring left side of channel. J.S. Kite photo.

It is beyond the scope of this study to assess the significance of decreased stream lengths and drainage density as well as the widespread stream truncations evinced by increased bifurcation ratios. Clearly, sediment transport and food energy flow have been disrupted by mining and reclamation, but water quality may be a more limiting factor on these ecosystems. In settings where a large stream flows relatively unimpeded through a mine area, such as Dents Run at site 1006-98, there may be ample upstream supplies of food energy to allow the stream to function

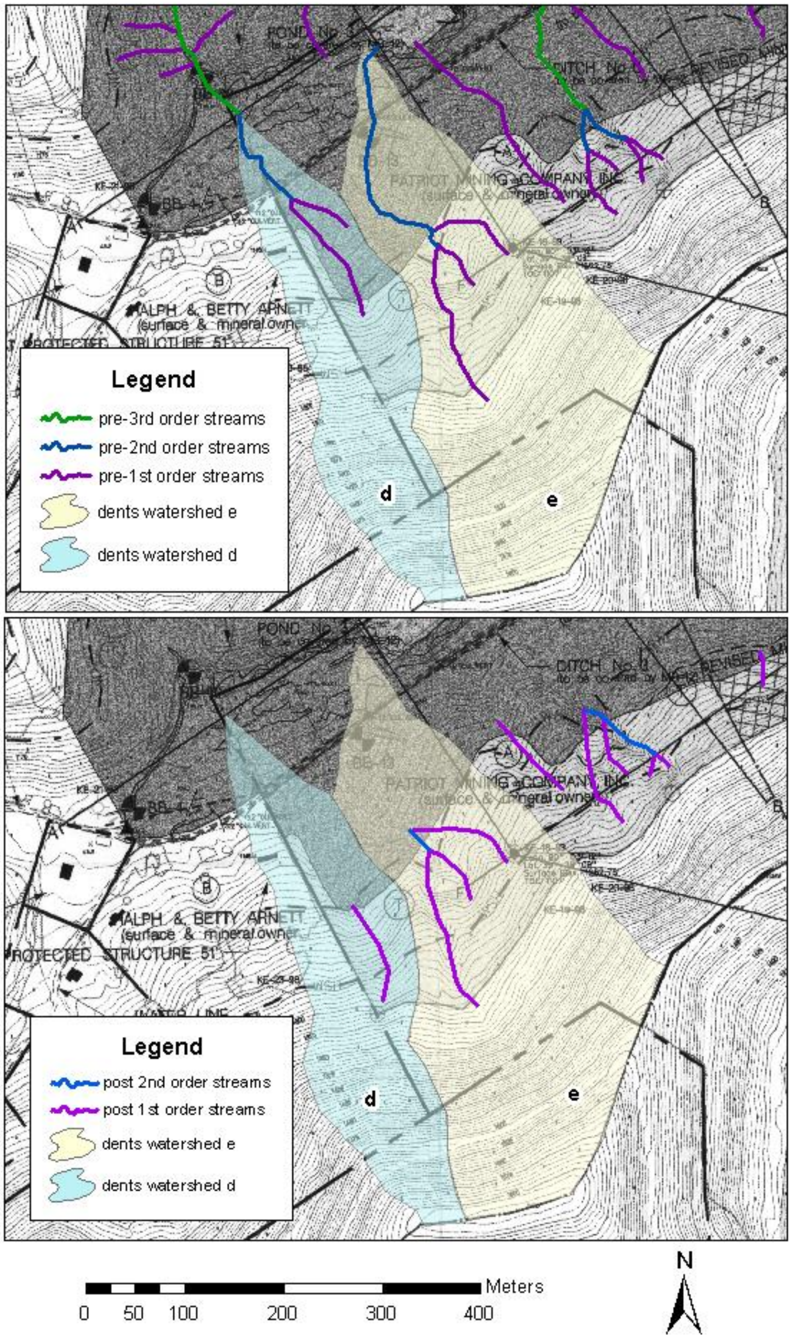

Figure 15. Example of channel truncations at permit area #1006-98. Top image shows pre-mining drainage network; bottom shows post-reclamation network. Channels in the post-reclamation watersheds d and e are abruptly terminated at the upper edge of the mine backfill (dark gray color). Figure by Smith (2003).

naturally. However, food energy and sediment flow may severely limit ecosystem productivity in streams whose entire watershed has been mined, such as the unnamed tributary at site 80-80. Although hypothetical impacts of disrupted drainage networks on fresh-water ecosystems are apparent, additional study may be needed before relying on ecological arguments as a basis for using natural stream design principles over existing reclamation practices. Ultimately, we expect holistic interdisciplinary approaches that involve geomorphologists, ecologists, and reclamation engineers, to lead to more environmentally sound and cost-effective reclamation of small streams and adjacent slopes.

There is a clear role for fluvial geomorphology in surface-mine reclamation. Mine engineers must understand that design of stable, functional drainage requires more than accommodating extreme events, such as 50 or 100 year floods. Long-standing geomorphological measures of drainage networks, such as stream order, drainage density and bifurcation ratios, can assist in demonstrating how existing surface mine reclamation departs from the natural drainage networks that have been stable while supporting rich aquatic and riparian ecosystems for thousands of years. Obviously, observations and measurements made on pre-mining landscapes can't be blindly applied to radically altered reclaimed mine lands, but the pre-mining drainage network is likely to show the basic forms that will be stable in an intact watershed through time. Balancing long-standing engineering practices with fluvial geomorphology principles appears to best way to guarantee that reclaimed drainage networks will be stable during and well beyond a project's bond period.

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