A preliminary assessment of ecosystem function in Virginia coalfield streams

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Introduction

The United States possesses one-fourth of the world's coal resources, with more than 260 billion tons of recoverable reserves (USDOE 2009). Given political instability in world regions from which the US imports energy supplies, national security concerns demand continued use of domestic energy supplies. The Appalachian coalfields, including southwest Virginia, are a primary coal-producing region in the US, and are projected by the US Department of Energy to remain as such over the coming decades (USDOE 2009). Coal production to date has disturbed >0.6 million hectares and impacted > 2000 km of headwater and low order streams in Appalachia (USEPA 2005).

Prior to the European settlement of southwestern Virginia, the headwater streams of this region were closely connected to the forests of their watersheds and provided important ecosystem services. These forests provided shade, which limited in-stream photosynthesis and moderated stream temperature. These forests provided inputs of leaves, the primary nutritional source for aquatic invertebrates and, indirectly, fish. The forests and streams acted as filters, preventing sediments and nutrients from being transported downstream. Streams and rivers in this region of central Appalachia have also been recognized as a globally significant biodiversity resource, having some of the most significant concentrations of rare, threatened, and endangered aquatic species in North America. Even before coal mining, the forests had been cleared or selectively logged. Important tree species such as chestnut had been lost to disease. Farming and woodland grazing had greatly modified the function of forests and streams. Many of the streams and their watersheds have now been further degraded or lost completely as a result of surface coal mining.

Restoration of coal-mine sites is required by federal law. In response to increasing public concern and the expanding scale of coal-mining operations, there is an increase in the legal requirements for environmental restoration by mining operations. Coal mine operators are now being asked to restore the physical and biological structure of streams, and to consider the restoration of stream function. A major difficulty with this task is that there is little information in existence to guide and evaluate such efforts.

Our research is intended to assess the effectiveness of stream restoration activities in an area of central Appalachia that is faced with the challenge of managing current energy extraction that is vital to the economic sustenance of local communities. Sustainable development of these areas demands that the structural and functional characteristics of water resources damaged or lost to surface mining operations be re-established. It is unlikely that pre-settlement state of stream function can ever be achieved by watershed and stream restoration, but with the paucity of data, a survey of current practices is vital. Our primary objective in this study is to identify headwater streams that have undergone restoration efforts following coal mining in the southwestern Virginia coalfields and conduct field and laboratory studies aimed at measuring selected structural and functional attributes. In terms of structure, we evaluated habitat quality, along with biotic assemblages present in these streams. Important ecosystem functions, including nutrient uptake and ecosystem metabolism, were also assessed.

Methods

Site Selection- Site selection occurred during Autumn 2008 and Winter 2008-2009 in the coal mining region of southwest Virginia, including the counties of Dickenson, Russell, Wise, and Buchanan. Because of a drought during the summer of 2008, many streams in this region of Virginia had no surface water flow, which impeded our ability to find an adequate number of streams initially. After sufficient rainfall had occurred during the winter of 2008, six restored and three unrestored sites were chosen for this study (Table 1), all of which had been historically disturbed by coal mining activities or logging. Restored sites generally refer to those streams that have undergone Natural Stream Channel Design methods, with the exception of Critical Fork. In contrast, Critical Fork, the oldest restored stream, was reconstructed by the coal mining operation as a purposeful effort to restore natural stream channel conditions. Although the in-stream restoration of these streams was mostly consistent, the landscape from which they were created varied (Photos 1 – 3). Critical Fork is a reconstructed channel that currently drains a sediment retention pond. Portions of Chaney Creek, Stonecoal Creek, and Laurel Branch were created from drained sediment retention ponds, whereas Left Fork was created as a new channel (Lance DeBord, personal communication). Lick Branch is the only site that is fed by active deep-mine effluent discharge. Additionally, the riparian zones were rebuilt and planted with vegetation in a manner that varied from site to site, leading to unique drainage and infiltration patterns across the 6 restored streams (personal observation). Unrestored sites have undergone no in-stream or riparian restoration, but do have disturbance including past coal mining in their catchments. Two of the three unrestored sites (N. Laurel and N. Chaney) were upstream segments of streams with restored study sites.

Within each stream, a 100-meter reach was delineated for habitat, biological, and functional measurements outlined below.

Habitat Assessment- Assessment of each stream took place during June 2009, and followed protocol outlined in Barbour et al. (1999) and VDEQ (2008). In brief, for each 100-meter reach of stream sampled (along with an additional 100-m section upstream from the top of the experimental reach), in-stream habitat and riparian structure were assessed using a variety of physical metrics. In-stream, visual evaluations of substrate cover, embeddedness, velocity regime, sediment deposition, channel flow status, channel alteration, and riffle/bend frequency were completed, with each being assigned a score ranging from 0-20 points. Riparian features for each bank, including bank stability, vegetative protection, and riparian zone width were also assessed and scored similarly to above. Maximum scores of 200 points could be obtained, with stream condition being classified as Poor, Marginal, Suboptimal, or Optimal, which represent <25%, 25-50%, 50-75%, or 75-100% of the total score possible based on metrics noted above.

Abiotic Parameters- Abiotic parameter measurements were taken throughout the sampling period. An estimate of discharge in each stream was determined using a NaCl slug (Webster and

Valett 2006). Dissolved oxygen and pH were measured using a portable sonde (Hydrolab Quanta, Hach Instruments, Loveland, CO), while specific conductance and temperature were taken with a conductivity meter (YSI, Inc., Yellow Springs, OH). Grab samples were collected for analysis of total dissolved solids (TDS) following Standard Methods (APHA 1998). Samples were transported and stored at 4°C prior to filtration and drying at 180°C in the laboratory. Methods for obtaining ammonium (NH_4^+), nitrate (NO_3^-), and phosphate (PO_4^{-3}) are outlined below.

Macroinvertebrate Collections- Stream surveys for aquatic macroinvertebrates in all streams took place during 9-10 June 2009. As per methods outlined in Barbour et al. (1999) and VDEQ (2008), six ~0.3m^2 kicks (2m^2 composite total) were taken with a 500 micron d-frame net for 30 seconds at each site. All material collected during sampling were placed in containers of 95% ethanol for transport back to the lab for identification. Laboratory processing of biological samples followed Virginia DEQ protocols (VDEQ 2008). Organisms were separated from debris using a randomized subsorting procedure to obtain 110 (+/- 10%) organisms for identification. Standard taxonomic keys (Merritt et al. 2008) were used to identify organisms to the family/lowest practicable level. Benthic macroinvertebrate metrics were calculated and Virginia Stream Condition Index (VSCI) scores obtained following formulae detailed by Burton and Gerritsen (2003). Aquatic life impairment status was determined based on each site's VSCI score. Sites scoring < 60 are considered impaired and sites with scores ≥ 60 are unimpaired. (VDEQ 2007).

Nutrient Uptake- The ability of stream biota to process nutrients for growth and maintenance is an important function of stream ecosystems. Movement of nutrients downstream between organic and inorganic compartments is termed "nutrient spiraling" (Webster and Patten 1979, Newbold 1992), with more efficient streams assimilating nutrients at a much faster rate as a result of biotic demand (i.e. tighter nutrient spirals; Allan and Castillo 2007). More efficient streams are able to better process nutrient loads, as opposed to simply acting as a "pipe" sending excess nutrients farther downstream into rivers and estuaries. As such, we measured ammonium uptake lengths (Webster and Valett 2006) during the dormant (Autumn/Winter 2008-2009) and growing seasons (Summer 2009) at each of the 9 sites. A co-injection of ammonium (as NH_4Cl) and a conservative tracer (NaCl) were added to the streams at a constant rate using a metering pump. A conductivity meter was used to monitor the conservative tracer. After the conservative tracer had reached equilibrium, samples were taken at seven transects within a study reach of approximately 100 m length, depending on flow at the time of the study. Triplicates of stream water were collected and filtered through a 0.7µm glass fiber filter at each of the seven sites along the reach. Samples were analyzed for chloride and nitrate, using ion chromatography (DX 500 IC, Dionex Corp., Sunnyvale, CA), and ammonium and phosphate, using flow injection analysis (Lachat QuickChem 8500, Lachat Instruments, Loveland, CO). Uptake length (S_w) was calculated as the negative inverse of the regression slope of flow-corrected ammonium concentration versus distance. We also calculated uptake velocity (v_f) and areal uptake (U) (Webster and Valett 2006).

Ecosystem Metabolism- Another major function of stream ecosystems is their ability to process organic matter (Allan and Castillo 2007). We measured stream metabolism (gross primary production and ecosystem respiration) at each of the 9 sites using standard whole-stream/open channel methods with conservative gas (SF_6) injections for estimating site-specific reaeration coefficients (Bott 2006). Dissolved oxygen, water temperature, and conductivity were measured at 2-min intervals over a 36-h period at each site using Hydrolab mini-sondes (Hach Environmental, Loveland, CO). Metabolism was calculated using the single station method (Bott 2006, Grace and Imberger 2006).

Results

General Stream and Macroinvertebrate Measurements- Restored sites used in this study ranged in age from 1- 10 years, with most sites completed within the past four. Based on EPA (Barbour et al. 1999) and VDEQ (2006) ratings, half of the restored sites were optimal in terms of habitat, whereas the other three were suboptimal (Table 1); all unrestored sites were classified as optimal (Table 1). Difference in mean habitat scores between restored and unrestored sites were not significant (t-test, $p > 0.1$)

Abiotic stream measurements were more variable across sites, although all pH values were circumneutral. Summertime discharges of streams were generally greater than in the autumn/winter, except for Stonecoal, North Chaney, and North Laurel Branch, where the opposite was true (Figure 1). Stream temperatures were consistently higher in the summer as well (Figure 2). Specific conductance varied across sites and seasons, but lower values were recorded in the summer for six of the nine sites (Figure 2). Stonecoal had the lowest measured specific conductance (159.3 ± 0.6, 265.6 ± 0.8 uS cm^{-1} in autumn/winter and summer, respectively), whereas Critical Fork had the highest (1,617.9 ± 1.2, 1,220.1 ± 3.2 uS cm^{-1} in autumn/winter and summer, respectively). Total dissolved solids also showed high variation (Table 2), with restored Critical Fork having the highest concentration (1,223.6 mg L^{-1}); overall, restored and unrestored sites did not demonstrate significantly different mean TDS concentrations (t-test, $p > 0.1$). In terms of background nutrient levels, ammonium was below analytical detection limits except in both reaches of Chaney Creek, whereas nitrate was detectable in each stream (Table 2). Phosphate was below analytical detection limits in all streams (<2 µg L^{-1}).

Virginia Stream Condition Index (VSCI) analyses provided fairly consistent results across all nine streams (Table 3), with restored and unrestored sites not significantly different (t-test, $P > 0.05$). All restored sites demonstrated a level of stress in terms of the macroinvertebrate assemblages found, except for Lick Branch, where severe stress was noted. Among the unrestored sites, only the macroinvertebrate assemblage in North Chaney Creek indicated stress, whereas the other unrestored sites scored "good" conditions (SCI>60). Habitat scores in all sites were significant predictors of VSCI (linear regression, $r^2 = 0.60$, $p = 0.01$), whereas total dissolved solids was not as strong ($r^2 = 0.37$, $p = 0.08$; Figure 3). Similar regressions on data from only restored sites demonstrated relationships between VSCI vs. habitat scores ($r^2 = 0.47$, $P = 0.13$) and VSCI vs. TDS ($r^2 = 0.58$, $P = 0.08$), but these relationships were not significant at $p<.05$ (Figure 3).

Ammonium Uptake- Streams showed seasonal variation in discharge and uptake parameters, while no distinct patterns were noted for restored and unrestored sites within the same season. Ammonium uptake lengths were variable across sites and seasons. Uptake velocities also demonstrated a high degree of variability (0.1-4.4 mm s^{-1} in autumn/winter and 0.2-3.5 mm s^{-1} in the summer), with higher velocities occurring during the summer in all but 1 restored site and the unrestored Powell River site. Uptake rate was also variable but showed a similar pattern as described for uptake velocity. Lick Branch consistently had the greatest uptake velocity and rate among sites during both seasons.

Ecosystem Metabolism- Both gross primary productivity (GPP) and ecosystem respiration were variable across sites over the study period. Respiration estimates were consistently greater than those for GPP, leading to productivity/respiration (P/R) ratios consistently < 0.5, except for Stonecoal Creek, during the summer of 2009.

Discussion and Conclusions

Inconsistencies in restoration methods and the overall impacted nature of all nine sites likely produced the wide variation in much of the data that we collected. Most of the streams that we used for this study contained macroinvertebrates indicative of impaired environments (noted by both the VSCI scores and the low numbers of EPT taxa, Table 3), regardless of habitat suitability. Habitat is a factor that may be manipulated through mine reclamation and reconstruction/restoration processes, and, as it is a significant predictor of VSCI, should be at the forefront of future projects on impacted streams in this region. Woody canopy was a major differentiating feature among stream-type habitats, as all non-restored streams were under mature woody canopy. Although woody canopy was developing within the riparian zones of most restored streams, that development was many years shy of the mature woody canopy that characterized the non-restored sites.

As postulated by the River Continuum Concept (Vannote et al. 1980), small headwater streams should have a net heterotrophic status because of a predominance of canopy cover and reliance on allochthonous materials to drive energy flow within the system. The nine streams assessed in this study appear to be net heterotrophic across seasons. Although rates of GPP were higher in some streams during the growing season, increased respiratory demand diminished the impact of this production. Only Stonecoal showed a P/R >1 during the growing season. In this stream, discharge was extremely low leading to a large portion of the benthic area being exposed to air. A possible reason for this result is the presence of multiple deep pools (0.5-1m) that may act as a hotspot of primary production (Freeman et al. 1994, Lake 2003).

Nutrient limitation may have also hindered primary production in these streams during the summer, even though streams appeared to have ample amounts of nitrogen and all restored streams had an open canopy. We measured phosphate in our stream samples on all occasions, and consistently found values below the detection limits of our analyses, suggesting a possible P-limitation.

Our major objective in this study was to gather information on the structural and functional attributes of restored streams in the coal mine regions of southwest Virginia to enhance our understanding of these systems. We were able to collect valuable baseline data in this survey that will contribute to the knowledge of restoration practices and their effects on stream function in this region. Even so, we were not able to truly discriminate between restored and unrestored streams, as all functional measures varied independently of stream type. Restoration practices could be classified as a form of disturbance, such that studies in other regions have noted a lack of return to satisfactory ecological condition even a decade or more post restoration (Charbonneau and Resh 1992, Kondolf 1995). The variation in our data also point out the innate diversity of streams, regardless of how similar restoration practices attempt to make them. Given time, these restored streams may return to a more ecologically functional condition, but our data demonstrate that more work should be done to better understand restoration and the effects on all aspects of stream ecosystems.

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Photo 1. The restored stream channel at Chaney Creek, in June 2009.

Photo 2. Critical Fork in June, 2009.

Table 1. Site descriptions of study streams in southwestern Virginia.

Site	Location	Site Type (age)	Habitat Score[1]	Condition
Chaney Creek	Russell County	Restored (3 y)	160	Optimal
Critical Fork	Wise County	Restored (>10 y)	145	Suboptimal
Laurel Branch	Russell County	Restored (4 y)	171	Optimal
Left Fork	Dickenson County	Restored (2 y)	133	Suboptimal
Lick Branch	Wise County	Restored (3 y)	136	Suboptimal
Stonecoal Creek	Russell County	Restored (1 y)	162	Optimal
North Chaney Creek	Russell County	Unrestored	154	Optimal
N. Laurel Branch	Russell County	Unrestored	170	Optimal
Powell River	Wise County	Unrestored	170	Optimal

[1] Habitat assessment scores were based on habitat metrics outlined in Barbour et al. (1999) and adapted for VDEQ (2008), stream condition may be classified as Poor, Marginal, Suboptimal, or Optimal, representing habitat score of <25%, 25-50%, 50-75%, or 75-100% of the total score possible.

Table 2. Abiotic parameters for restored (R) and unrestored (U) study streams in southwestern Virginia.[1]

Site	Site Type	DO ($mg\ L^{-1}$)	pH	TDS ($mg\ L^{-1}$)	NH_4^+ ($\mu g\ L^{-1}$)	NO_3^- ($mg\ L^{-1}$)
Chaney Creek	R	7.6	7.9	319.6	8.1	0.2
Critical Fork	R	9.3	8.1	1223.6	BD	3.0
Laurel Branch	R	8.4	7.7	551.6	BD	0.7
Left Fork	R	8.1	7.6	922.0	BD	0.8
Lick Branch	R	8.8	8.4	906.8	BD	1.1
Stonecoal Creek	R	7.5	7.9	119.2	BD	0.2
N. Chaney Creek	U	7.2	7.7	324.2	12.1	0.1
N. Laurel Branch	U	8.3	7.9	558.4	BD	0.7
Powell River	U	9.2	7.9	706.8	BD	1.3

[1]Dissolved oxygen (DO), pH, and total dissolved solids (TDS) were measured from 9-10 June 2009. Ammonium and nitrate were measured during 2009 summer sampling period. Minimum detection limit for ammonium=5 $\mu g\ L^{-1}$. BD=below detection limit. Phosphate was below analytical detection limits (2 $\mu g\ L^{-1}$) in all streams.

Photo 3. Laurel Branch in 2008.

Table 3. Biotic indices for study streams in southwestern Virginia. [1]

Site	Abund.	# taxa	# EPT	VSCI	ALU tier
Chaney Creek	98	12	5	58.2	Stress
Critical Fork	110	7	3	45.4	Stress
Laurel Branch	116	10	7	56.7	Stress
Left Fork	130	9	4	54.0	Stress
Lick Branch	102	3	1	38.8	Severe Stress
Stonecoal Creek	107	13	6	59.2	Stress
N. Chaney Creek	116	14	7	58.8	Stress
N. Laurel Branch	108	16	7	62.9	Good
Powell River	108	10	6	66.2	Good

[1]Included in this table are the total abundance (Abund.), total numbers of taxa (# taxa), Ephemeroptera-Plecoptera-Tricoptera taxa (EPT), Virginia Stream Condition Index Scores (VSCI), and aquatic life use (ALU) tiers (VDEQ 2006, 2008).

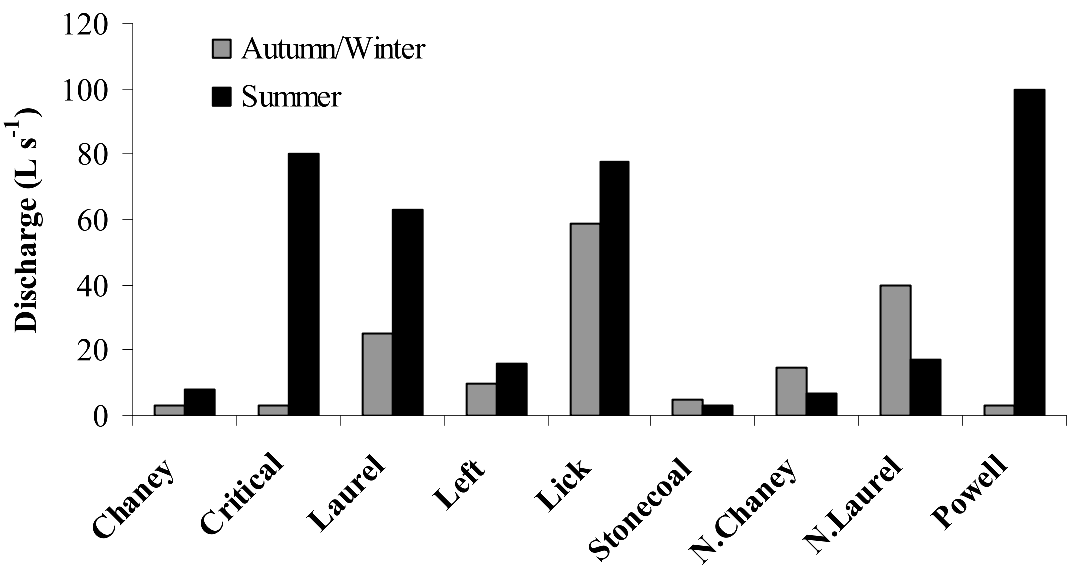

Figure 1 Seasonal discharge for the nine study streams in southwestern Virginia. Restored sites are to the left (Chaney to Stonecoal). The three unrestored sites are to the right (North Chaney to Powell River).

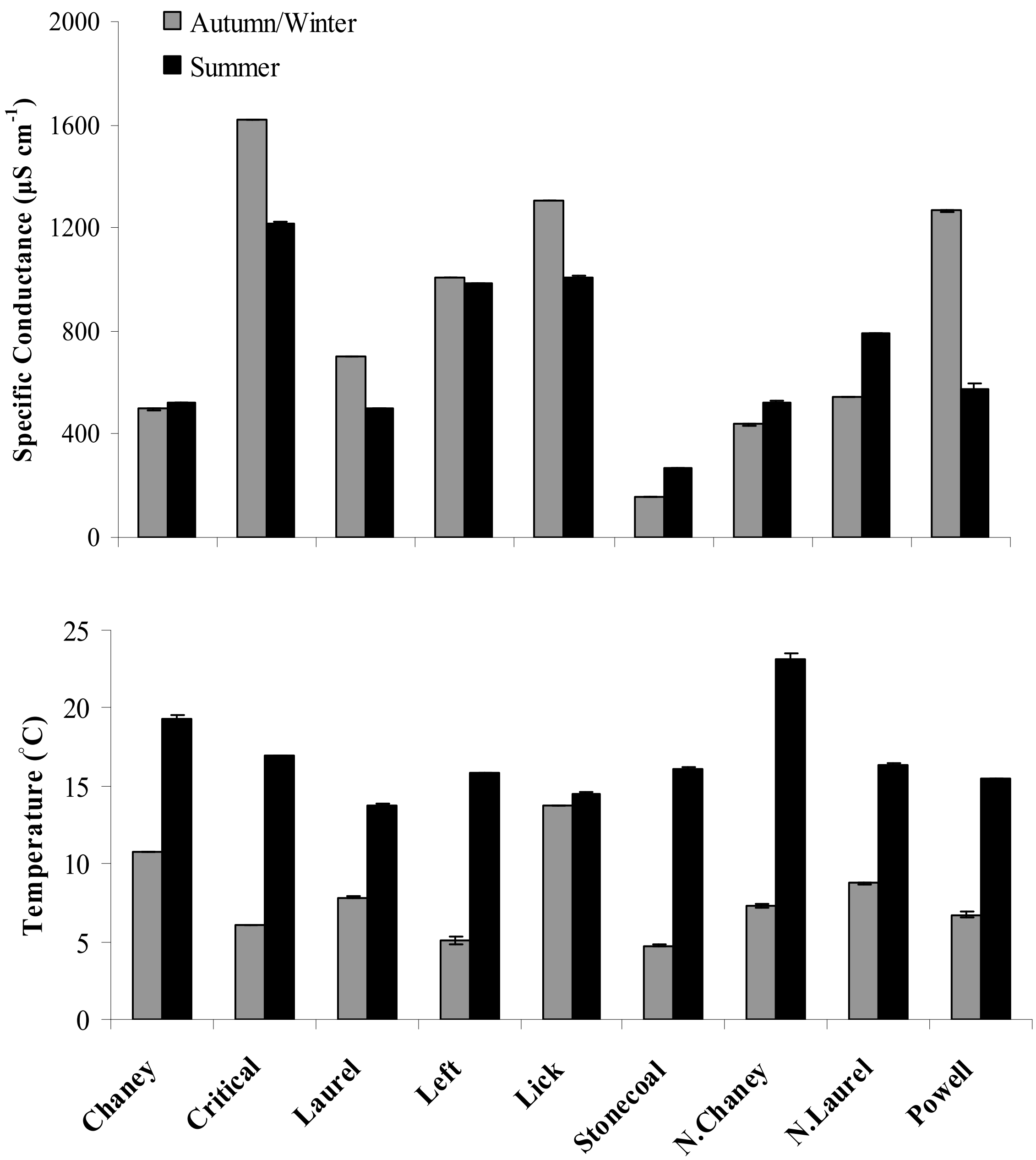

Figure 2. Specific conductance and temperature for the nine study streams in southwestern Virginia. Error bars represent ± 1 SD. Restored sites are to the left (Chaney to Stonecoal). the three unrestored sites are to the right (North Chaney to Powell River).

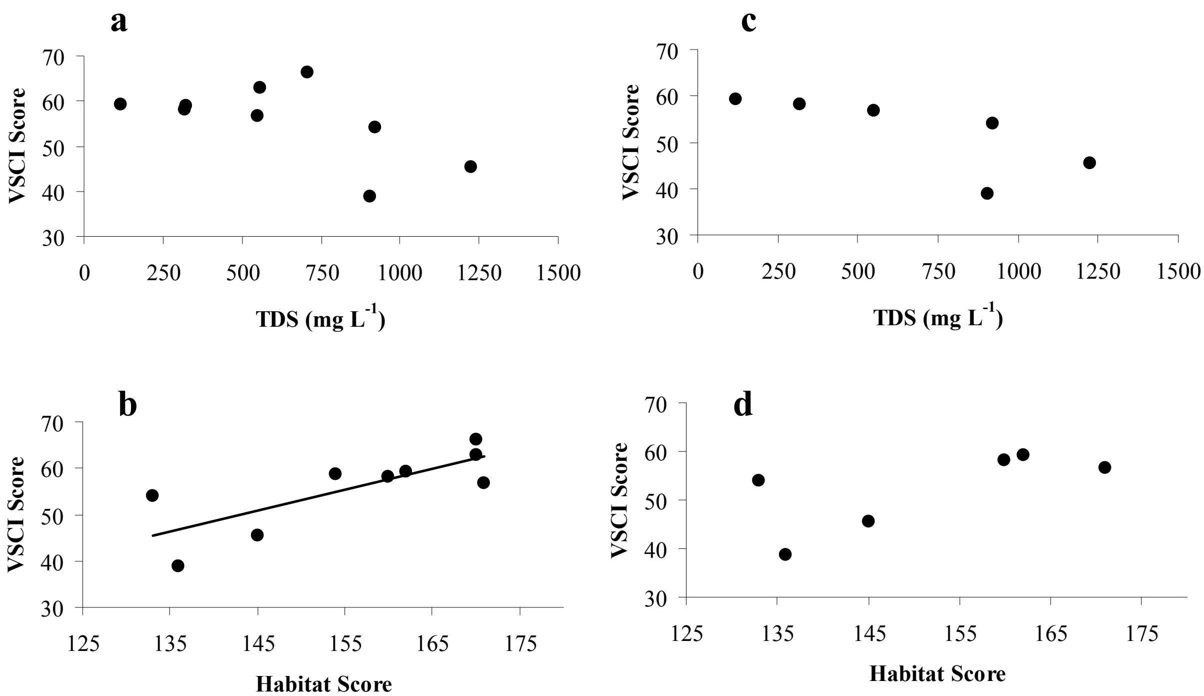

Figure 3. Linear regressions between a) TDS vs. VSCI in all sites, b) Habitat Score vs. VSCI in all sites, c) TDS vs. VSCI in the 6 restored sites, and d) Habitat Scores vs. VSCI in the 6 restored sites. Plots showing regression lines were significant at $\alpha = 0.05$.