Benthic Macroinvertebrate Community Temporal Dynamics and Their Response to Elevated Specific Conductance in Appalachian Coalfield Headwater Streams

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Introduction

Protecting integrity of benthic macroinvertebrate communities, which are used to assess stream condition in Appalachian coalfield headwater streams, is essential. Previous studies have suggested elevated total dissolved solids (TDS) and closely related specific conductance (SC) in streamwater have negative effects on sensitive benthic macroinvertebrates (Timpano 2011, Bernhardt et al. 2012, Cormier et al. 2013a, Cormier et al. 2013b), although effects varied based on selected metric, chosen effect level, and in some cases, potential influence of confounding water-quality- or physical-habitat conditions. Most importantly, previous studies have relied on point-in-time measurements of SC, which may not be representative of exposure levels in the days, weeks, or months prior to sampling of benthic macroinvertebrates.

Elevated TDS and SC occur in streams draining mining sites after large volumes of rock are exposed to weathering elements such as air and water, causing rapid dissolution of rocks and minerals into waters draining the site. Undisturbed rock in the Appalachian coalfields typically dissolves much more slowly. Elevated TDS in Appalachian mining-influenced streams is usually dominated by Ca, Mg, SO_4^{2-}, HCO_3^-, and is often referred to as increased salinity (Pond et al. 2008, Schoenholtz et al. 2011, Timpano 2011, USEPA 2011a, 2011b). The concentration of TDS is closely related to the electrical conductivity of the water, which is standardized at 25º C and referred to as specific conductance (SC). Measuring SC is faster and more cost-effective than measuring TDS directly.

We have been studying relationships between benthic macroinvertebrate community composition and elevated TDS/SC in four counties of southwestern Virginia. Similar to neighboring coal-bearing regions of Kentucky and West Virginia, southwestern Virginia's coalfields host an active coal mining industry. This report summarizes the two-year study intended to expand understanding of temporal variability within the benthic macroinvertebrate community in streams with elevated SC using family-level Virginia Stream Condition Index (VSCI) as the summary metric (Burton and Gerritsen 2003). Ten to fourteen benthic macroinvertebrate and water quality grab samples from each stream were collected and analyzed between June 2011 and November 2012, and continuous conductivity loggers were installed in each stream.

Background

Benthic macroinvertebrate community composition and SC effects are most often evaluated based on isolated point-in-time measurements of the macroinvertebrates and SC, which may not be indicative of SC exposure levels throughout the benthic macroinvertebrate lifespan. Within streams, SC varies temporally, and may be related to seasonal flow patterns in which higher flows during spring and winter periods are associated with lower SC, and lower flows of summer and fall are associated with higher SC (Figure 1). Understanding SC/macroinvertebrate associations is difficult without continuous conductivity monitoring because effect levels cannot be defined by isolated sampling events (Timpano 2011). Benthic macroinvertebrate community composition is likely influenced by SC levels days, weeks, and/ or months prior to sampling.

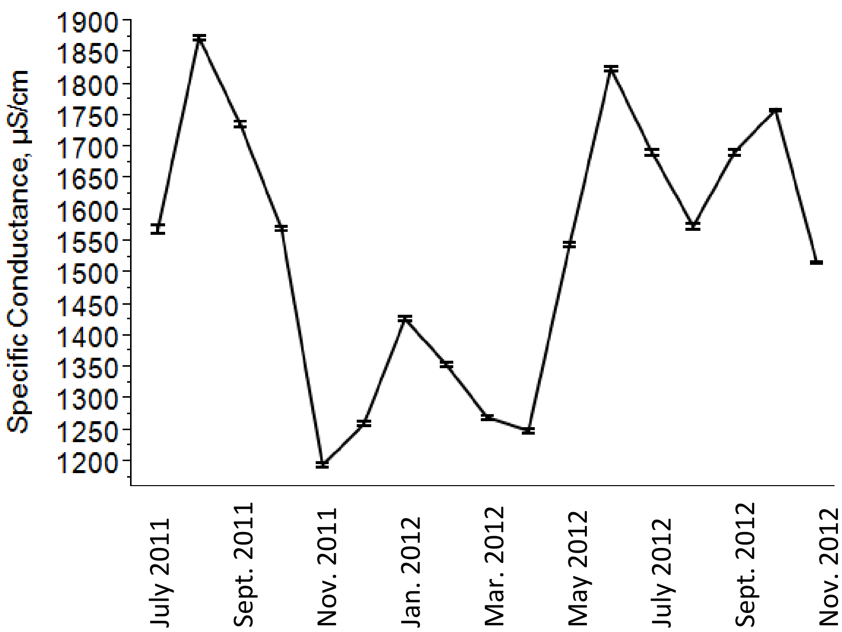

Figure 1: Mean specific conductance (SC) of the upper Powell River, Wise County, Virginia by month between July 2011 and November 2012. Each error bar is one standard error from the mean.

Additionally, benthic macroinvertebrate communities exhibit natural variation for many reasons. Communities respond to dynamic environmental variables including temperature, availability of food, water quality, flow regimes, and benthic macroinvertebrate community dynamics including predation and emergence (Resh and Rosenberg 1989). Benthic macroinvertebrate life cycles and residence time in streams vary, and include: fast-seasonal (days to weeks), slow-seasonal (months, with development extending over multiple seasons), and non-seasonal (weeks to years, in which several cohorts of the same benthic macroinvertebrate may inhabit the stream) life cycles (Hynes 1970). Therefore, isolating effects of anthropogenic stressors such as SC requires benthic macroinvertebrate assessment that accounts for potential confounding by natural community temporal variation (Resh and Rosenberg 1989, Linke et al. 1999, Šporka et al. 2006, Leunda et al. 2009, Álvarez-Cabria et al. 2010).

Consequently, this study approach was different from previous studies that involved isolated point-in-time samples of SC and macroinvertebrates, including Bernhardt et al. (2012), Pond et al. (2008 and 2010), Cormier et al. (2013a and b), and Timpano (2011). Multiple macroinvertebrate samples per index period (designated by the Virginia Department of Environmental Quality (VDEQ)) were collected, with additional samples collected outside of designated index periods.

Mining firms have not employed spoil handling methods intended to limit TDS generation because TDS/ SC has not been a regulatory concern in Central Appalachia until recently. The U.S. Environmental Protection Agency, however, has recommended a "benchmark" that indicated 300 μS/cm was protective of 95% of the native genera in their West Virginia-based study (USEPA 2011b). Consequently, this prompts the need for research investigating relationships between benthic macroinvertebrate community composition/ temporal variation and elevated SC/TDS *in situ*.

Research Objectives and Questions

Research Objectives: Quantify 1) temporal dynamics of benthic macroinvertebrate assemblages and 2) relationships between temporal dynamics of benthic macroinvertebrate assemblages in Virginia Coalfield headwater streams and three levels of elevated SC (Reference, Medium, and High).

Research Questions:

1. Do benthic macroinvertebrate communities vary temporally in Virginia Appalachian Coalfield streams (both elevated-SC sites and reference sites)?
2. Do benthic macroinvertebrate community composition metrics exhibit differences between months or specific index periods (e.g. fall vs. spring)?

Materials and Methods

Field Methods

This study included 1) streams with habitat and physiochemical parameters as close to reference condition as possible, with the exception of elevated SC, and 2) reference streams that have been minimally affected by human activities (Timpano 2011). Reference stream data were collected to identify and quantify biota present in relatively undisturbed conditions.

Twelve streams were selected for study along a gradient of SC, and locations spanned Wise, Russell, Dickenson, and Buchanan counties in southwestern Virginia (Figure 2); all were previously studied by Timpano (2011). *In situ* conductivity loggers (Onset HOBO U-24), were inserted in each stream between April and November 2011 in accord with the concurrent and complementary study (Schoenholtz et al. 2011). Loggers recorded SC every fifteen minutes, and data were downloaded at approximately monthly intervals. Mean SC data from continuous conductivity loggers were used to assign each stream to one of three categories, defined as "SC

Levels". Reference streams exhibited mean SC between 17-142 μS/cm, mean SC for Medium–SC Level streams was between 262-648 μS/cm, and mean SC for High-SC Level streams ranged from 756-1,535 μS/cm.

Ten to fourteen benthic macroinvertebrate and water samples from each study stream were collected according to the Timeline (Table 1). Benthic macroinvertebrates were sampled according to Virginia DEQ guidelines (VDEQ 2006). Water temperature, dissolved oxygen, SC, and pH were measured by a Hannah 9828 Probe at each sampling event. Water grab samples were collected and analyzed as part of collaborative research (Schoenholtz et al. 2011). Analyses included TDS, major anions, major cations, selected trace metals, and alkalinity (APHA 2005). Physical habitat quality was recorded during each sampling event according to Rapid Bioassessment Protocols (Barbour et al. 1999).

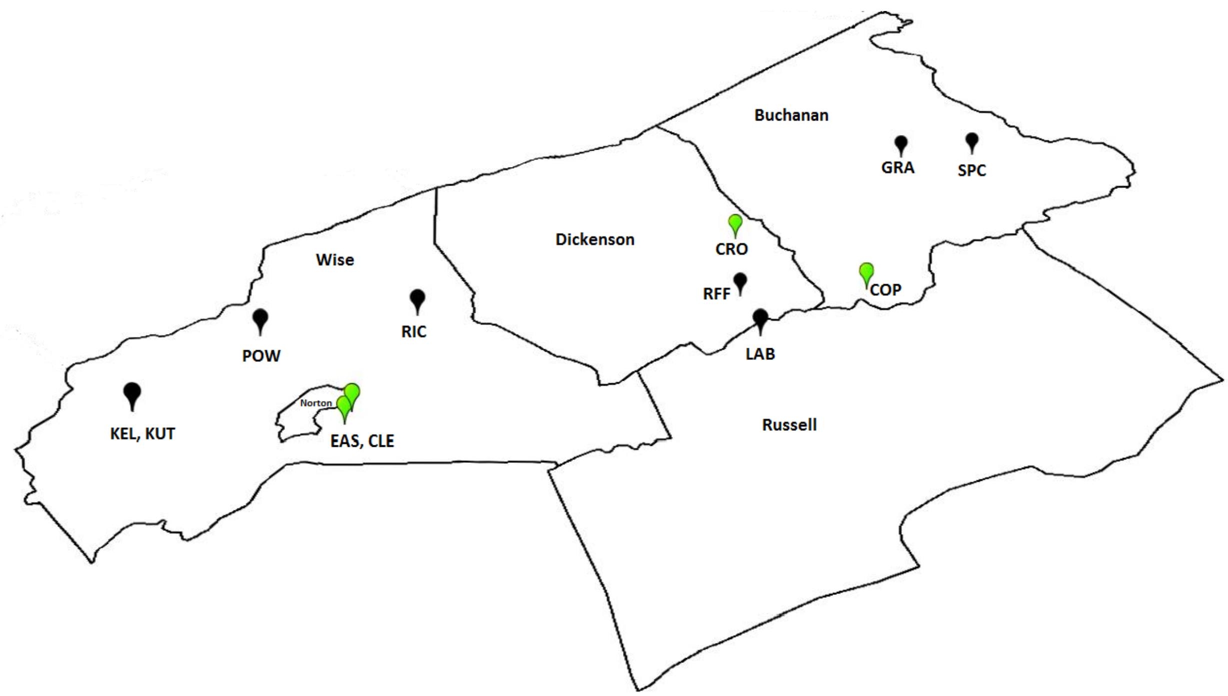

Figure 2: Map of study streams in the coalfields of southwestern Virginia. Eight test streams with elevated SC are shown in black and four reference streams are green. Four counties and the City of Norton are shown.

Table 1: Timeline for sampling benthic macroinvertebrates in headwater streams of the southwestern Virginia coalfields.

Time Period	Benthic Macroinvertebrate Samples per Site	Relevant Information
June-August 2011	2	Summer months typically exhibit low flow and corresponding elevated TDS/SC levels
September-November 2011	3	VSCI Fall Index Period. DEQ guidelines allow index period to extend into the first two weeks of December if weather/ flow conditions prevent completion of sampling during September, October, or November.
December 2011-February 2012	1	Winter months generally exhibit higher flows and subsequently lower TDS/SC. Weather conditions can create sampling difficulties.
March-May 2012	3	VSCI spring index period. DEQ guidelines allow index period to extend into the first two weeks of June if weather/ flow conditions prevent completion of sampling during March-May.
June-August, 2012	2	Summer #2
September-November 2012	3	Fall Index Period, Fall #2

Laboratory Methods

Benthic macroinvertebrates were sub-sampled in the laboratory at Virginia Tech following Rapid Bioassessment Protocol (Barbour et al. 1999) and VDEQ Standard Operating Procedures (VDEQ 2006) to a count of 200 (±10%) individuals using a rectangular sub-sampler with random number sets. Individuals were then identified to the lowest practical taxonomic level (usually genus, but in some cases family- or order- level when taxa were too immature, too small, or missing key features for further identification) using Merritt et al. (2008). Chironimidae, most Simuliidae, Ceratopogonidae, and Oligochaeta were not identified further.

Data Analysis

Raw data were entered into VDEQ's genus-level Ecological Data Assessment System (EDAS). EDAS is a Microsoft Access database that facilitates biotic metric calculations (VDEQ 2010) with pre-programmed macroinvertebrate taxa information. EDAS calculates a variety of biotic metrics including the multi-metric Virginia Stream Condition Index (VSCI), which is VDEQ's Index of Biotic Integrity for wadeable non-coastal streams (Burton and Gerritsen 2003).

The standard VSCI is calibrated for a 100 +/- 10% benthic macroinvertebrate sub-sample, normally identified to family level (Burton and Gerritsen 2003). Based on regional reference data, it assigns and averages scores for family-level Total Taxa Richness, EPT Taxa Richness, Hilsenhoff's Biotic Index, % Ephemeroptera, % Plecoptera and Trichoptera minus Hydropsychidae, % Scrapers, % Chironimidae, and % Top Two Dominant Taxa, generating one "score" for overall biotic integrity (Burton and Gerritsen 2003).

The EDAS database (VDEQ 2010) was used to generate values for 19 metrics, including the multi-metric VSCI using 200 +/- 10% individuals. Family-level VSCI was calculated with a rarified 100 +/- 10% individuals for this report, and was performed in EDAS (VDEQ 2010). Where applicable, EDAS calculated both family- and genus-level metrics. This report focuses on family-level VSCI scores from the 100 +/- 10% rarified subsample; other results are described by Boehme (2013).

Metric calculations were analyzed using JMP Pro 10.0.0 (SAS 2012). Individual and Total Habitat parameters were evaluated for differences between Reference, High-SC, and Medium-SC sites. Tukey's Honest Significant Difference (HSD) multiple comparison test was used to analyze differences among stream types and seasons (alpha = 0.05).

Trends in benthic macroinvertebrate metric scores were defined as ≥ three months of increasing or decreasing values, with significant differences between first and last months. Patterns were defined as being nominally different among months.

Results

Physical Habitat Parameters

Differences between total habitat scores by SC Level were not significant (p=0.8230), with means of 171, 171, and 167 for Reference, Medium-, and High-SC streams, respectively (Figure 3).

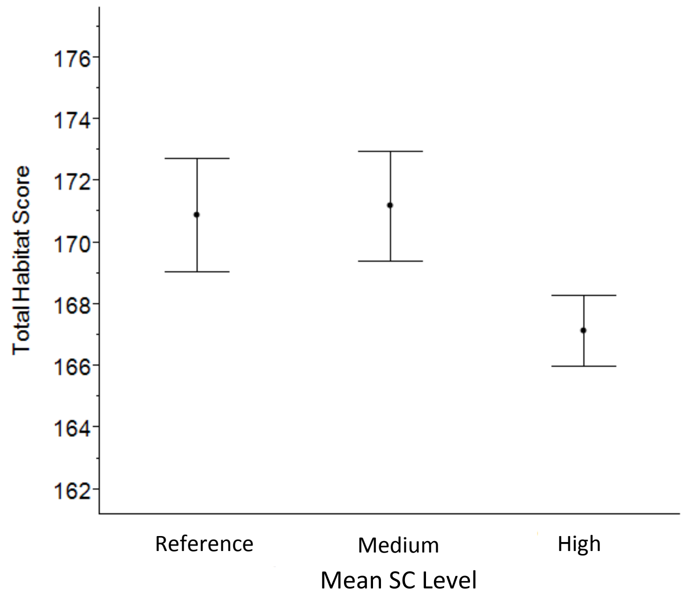

Figure 3. Total habitat score of selected streams by specific conductance (SC) level in southwestern Virginia. Maximum score is 200 points. Error bars are one standard error from the mean.

Physicochemical Parameters

Reference stream mean SC from continuous conductivity loggers ranged from 17-142 µS/cm. Medium- and High-SC stream mean SC ranged from 262-648 and 756-1,535 µS/cm, respectively (Figure 4). Overall means for SC levels were: 69, 423, and 1,021 µS/cm for Reference, Medium-, and High-SC streams, respectively.

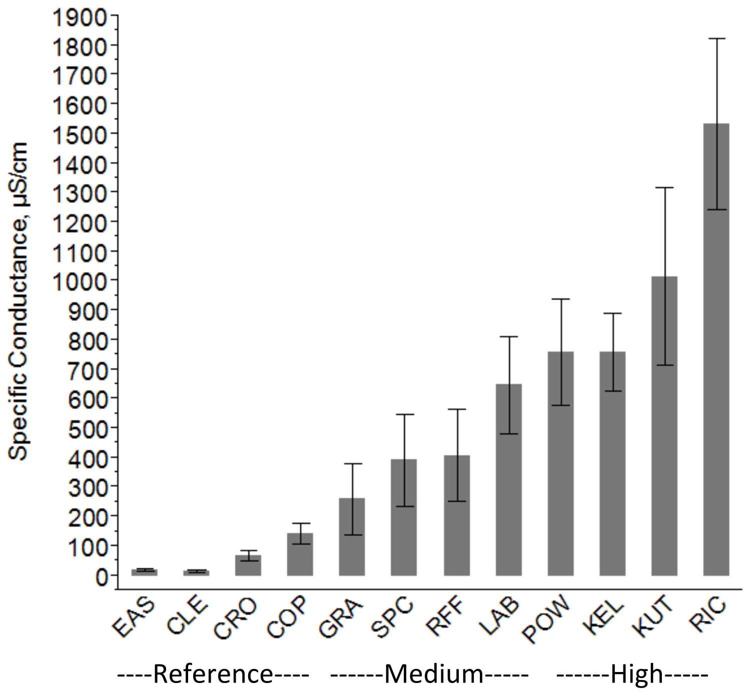

Figure 4. Mean specific conductance (SC) for the duration of continuous conductivity logger deployment by headwater stream and SC Level in the southwestern Virginia coalfields. Error bars are 1 standard deviation from the mean.

Significant differences among SC Levels were not detected for dissolved oxygen or point-in-time temperature (Table 2). Medium- (8.1) and High-SC stream (8.17) mean pH were significantly higher ($p=0.05$) than Reference (7.69) (Table 2). Point-in-time SC measurements were significantly higher ($p=0.001$) in High-SC streams (1,070) than Medium-SC (449) and Reference-SC (58) streams (Table 2).

Table 2. Mean streamwater physicochemical parameters by specific conductance (SC) Level in the coalfields of southwestern Virginia.

SC Level	Point-in-time Temp °C	S.E.[1] Temp	Point-in-time SC (µS/cm)	S.E. SC	pH	S.E. pH	Dissolved Oxygen (mg/L)	S.E. DO
Reference	13.12	0.7	58	7.0	7.69 [3]	0.1	8.59	0.2
Medium	13.48	0.7	449	25.5	8.1	0.0	9.51	0.2
High	13.02	0.5	1,070[2]	50.8	8.17	0.0	9.42	0.2

[1] Standard error of the mean.
[2] Mean is significantly higher than Medium- and Reference-SC Level means.
[3] Mean is significantly lower than Medium- and High-SC Level means.

Family-level VSCI (100 ± 10% individuals)

Family-level VSCI scores were significantly different by Month ($p<0.0001$) and SC Level ($p<0.0001$) (Table 3). Overall family-level VSCI scores were significantly higher in Reference-SC streams (71) and lower in High-SC streams (53) (Figure 5, Table 3). Medium-SC overall mean VSCI score was 61 (Table 3). Reference-SC VSCI scores were consistently highest and High-SC scores were consistently lowest, though there were no significant differences among SC Levels in August 2011, September 2011, and June-September 2012 and November 2012 (Table 3). During all months, Medium-SC VSCI scores were not significantly different from either High-SC or Reference-SC VSCI scores (Table 3).

High-SC VSCI scores were not significantly different by month (Table 4). In Reference-SC streams, April (80) and May 2012 (80) VSCI scores were significantly higher than August 2011 (64) and September 2012 (60) (Table 4). Medium-SC VSCI scores were significantly higher in March 2012 (73) than August 2011 (56), September 2011 (54), June 2012 (55), August 2012 (58), September 2012 (55), and October 2012 (57) (Table 4). In Medium-SC streams, September 2011 (54) was also significantly lower than April 2012 (69) and May 2012 (70); and June 2012 (55) was also significantly lower than May 2012 (70).

Mean VSCI scores in High-SC streams were consistently <60, whereas the mean VSCI scores for Medium-SC streams were <60 during June 2011 (59), August 2011 (56), September 2011 (54), June 2012 (55), August 2012 (58), September 2012 (55), and October 2012 (57). September 2011 and 2012, and October 2012 were within VDEQ sampling index periods.

Mean VSCI scores for Reference-SC streams exhibited rising trends for August 2011 (64) through November 2011 (76), and January 2012 (73) through April/ May 2012 (both 80) (Figure 5). A decreasing trend occurred in mean VSCI scores for Reference-SC streams between May 2012 (80) and September 2012 (60) (Figure 5). An increasing pattern was observed for mean VSCI scores in Medium-SC streams for September 2011 (54) through November 2011 (63) and September 2012 (55) through November 2012 (65). High-SC streams exhibited increasing patterns from October 2011 (48) through March 2012 (59) and September 2012 (49) through November 2012 (56). A decreasing pattern was observed in High-SC streams between May 2012 (59) and September 2012 (49).

Though not analyzed statistically, Reference-SC streams had the greatest range in VSCI scores throughout the study (20 points) followed by Medium-SC streams (19 points), and High-SC streams (10 points). In general, highest VSCI scores (sometimes nominally) occurred during the spring index period (March through May 2012).

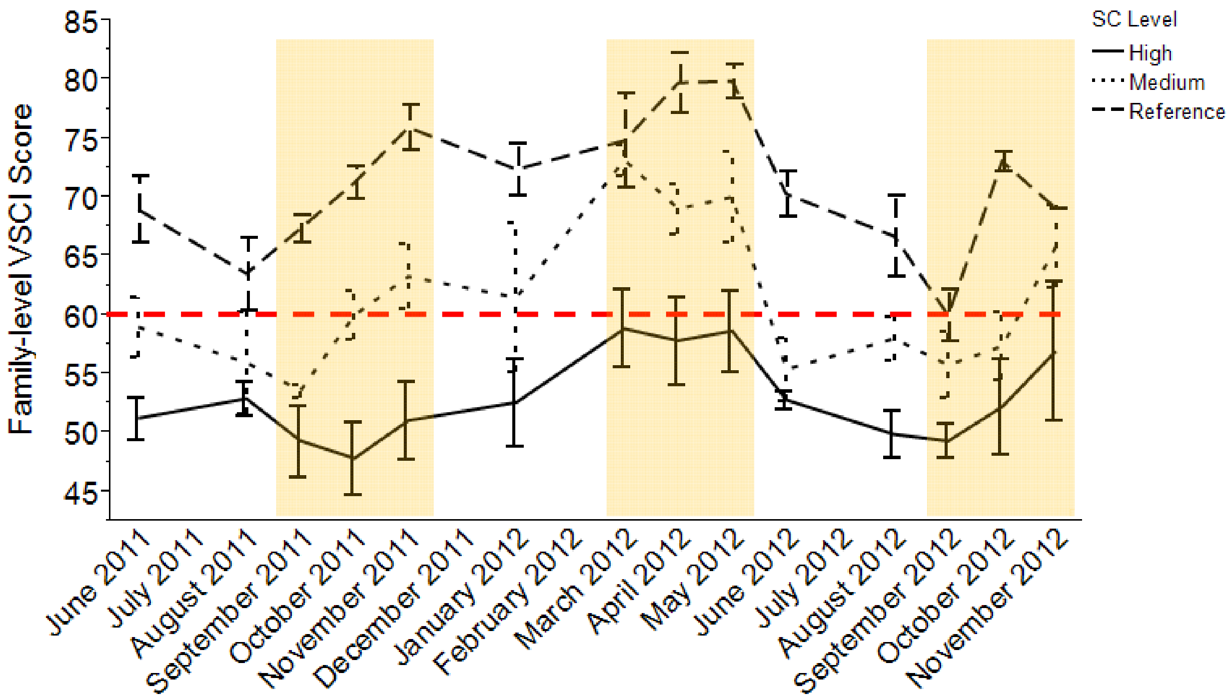

Figure 5. Mean Family Virginia Stream Condition Index (VSCI) scores by specific conductance (SC) level for headwater streams in the coalfields of southwestern Virginia. Each error bar is 1 standard error from the mean. The dotted red line is the Virginia Department of Environmental Quality (VDEQ) impairment threshold (VSCI score <60), although impairments are only defined if VSCI is <60 during the index periods (September – November and March – May, designated by tan boxes).

Table 3. Monthly mean Virginia Stream Condition Index (VSCI) scores of benthic macroinvertebrates in southwestern Virginia headwater streams by specific conductance (SC) Level.

	Reference			Medium-SC			High-SC		
	Mean		S.E.[1]	Mean		S.E.	Mean		S.E.
June 2011	69	a[2]	3.7	59	ab	2.7	51	b	2.7
August 2011	64	a	2.7	56	a	3.1	53	a	2.5
Sept. 2011	67	a	3.7	54	a	2.7	49	a	2.7
Oct. 2011	71	a	2.7	60	ab	2.7	48	b	3.1
Nov. 2011	76	a	2.7	63	ab	2.7	51	b	2.7
Jan. 2012	73	a	3.1	62	ab	3.1	53	b	2.7
March 2012	75	a	2.7	73	ab	2.7	59	b	2.7
April 2012	80	a	2.7	69	ab	2.7	58	b	2.7
May 2012	80	a	2.7	70	ab	2.7	59	b	2.7
June 2012	70	a	3.7	55	a	2.7	53	a	2.7
August 2012	67	a	3.1	58	a	2.7	50	a	2.7
Sept. 2012	60	a	3.1	55	a	3.1	49	a	2.5
Oct. 2012	73	a	3.1	57	ab	2.7	52	b	2.5
Nov. 2012	69	a	5.2	65	a	3.1	56	a	3.7
Overall Mean	71	a	1.5	61	b	1.4	53	c	1.4
Minimum	60			54			49		
Maximum	80			73			59		
Range	20			19			10		

[1]Standard error of the mean.

[2] Means followed by different letters within each row are significantly different (p=0.05) according to Tukey's HSD test.

Table 4. Effect of month within specific conductance (SC) Levels for mean family-level Virginia Stream Condition Index (VSCI) score within headwater streams in southwestern Virginia.

	Reference-SC			Medium-SC			High-SC		
	Mean		S.E.[2]	Mean		S.E.	Mean		S.E.
June 2011	69	A[1] B C	3.7	59	A B C D	2.7	51	A	2.7
August 2011	64	B C	2.7	56	B C D	3.1	53	A	2.5
Sept. 2011	67	A B C	3.7	54	D	2.7	49	A	2.7
Oct. 2011	71	A B C	2.7	60	A B C D	2.7	48	A	3.1
Nov. 2011	76	A B	2.7	63	A B C D	2.7	51	A	2.7
Jan. 2012	73	A B C	3.1	62	A B C D	3.1	53	A	2.7
March 2012	75	A B C	2.7	73	A	2.7	59	A	2.7
April 2012	80	A	2.7	69	A B C	2.7	58	A	2.7
May 2012	80	A	2.7	70	A B	2.7	59	A	2.7
June 2012	70	A B C	3.7	55	C D	2.7	53	A	2.7
August 2012	67	A B C	3.1	58	B C D	2.7	50	A	2.7
Sept. 2012	60	C	3.1	55	B C D	3.1	49	A	2.5
Oct. 2012	73	A B C	3.1	57	B C D	2.7	52	A	2.5
Nov. 2012	69	A B C	5.2	65	A B C D	3.1	56	A	3.7

[1] For each SC Level, means followed by different letters are significantly different (p=0.05), according to Tukey's HSD test.
[2] Standard error of the mean.

Discussion

This study intended to quantify benthic macroinvertebrate community temporal variation, and to investigate whether elevated SC influences this variation. Potentially confounding physical habitat and non-SC water-quality stressors were effectively minimized, as intended (Figure 3, Table 2). Although dissolved oxygen and pH were significantly different among SC Levels, measurements were within VDEQ reference recommendations. Reference-SC streams exhibited similar SC levels to previous studies of undisturbed Appalachian coalfield headwater streams (Lindberg et al. 2011, Timpano 2011, Bernhardt et al. 2012, Cormier et al. 2013b).

Previous research in these streams indicated dissolved ionic composition of streams with elevated SC was dominated by SO_4^{2-} (46%) and HCO_3^- (26%), followed by Ca^{2+} (13%), Mg^{2+} (7%), and Na^+ (6%), Cl^- (1%) and K^+ (1%), whereas Reference-SC streams were dominated by HCO_3^- (43%) and SO_4^{2-} (26%), followed by Ca^{2+} (11%), Cl^- (7%), Na^+ (6%), Mg^{2+} (4%), and K^+ (3%) (percentages are means as reported by Timpano 2011). Cormier et al. (2013a) suggested the mixture of ions in Central Appalachian coalfield headwater streams with elevated SC/TDS is the cause of extirpation of sensitive benthic macroinvertebrates. Consequently, findings of this study may be applicable to streams on a regional basis with similar dissolved ionic composition.

In this study, elevated SC was associated with negative effects on family-level VSCI scores, which was similar to previous research suggesting elevated SC acts as a stressor to benthic macroinvertebrate communities even in streams with reference-quality physical habitat and water-quality conditions (Timpano 2011). High-SC streams consistently scored <60 on the VSCI, with Reference-SC streams consistently ≥60. Medium-SC streams varied temporally above and below the VSCI = 60 level.

Streams of all three SC Levels exhibited temporal variability of VSCI scores, though VSCI score ranges and patterns of variability varied among SC Levels All three SC Levels tended to score higher on VSCI during the spring index period (March through May) than the fall index period (September through November). However, there were some exceptions to this general pattern. Additionally, VSCI scores increased from September through November in all SC Levels, with the exception of Reference in November 2012. All three SC Levels exhibited low scores in September, which is one of the fall index period months for sampling in Virginia. Results from this study suggest quantification of benthic macroinvertebrate community temporal variability is important, particularly in streams that may score impaired during part of an index period or year, and score not-impaired during sampling events at other times.

In a previous study of these streams, Timpano (2011) also found spring VSCI scores to be higher than fall, although the VSCI development study deemed differences between fall and spring index periods negligible (Burton and Gerritsen 2003). However, the VSCI development study reached that conclusion by analyzing data from throughout central and western Virginia, with just a small fraction of total samples obtained from Virginia's coalfield region where our study took place. It is important to note that both the VSCI development study and the current study had limited sample size of Reference streams. Additional Reference sites and multiple seasons are recommended for robust quantification of community temporal variation. However, this study suggests timing of sampling is important, which is consistent with findings of Linke (1999), Alvarez-Cabria et al. (2010), Kosnicki and Sites (2011), and Johnson et al. (2012) who conducted research on macroinvertebrate temporal variability in Canada, Spain, Missouri, and Kentucky, respectively.

Conclusions

Coal remains as an important fuel for electricity generation, and coal mining commonly causes elevated SC in streams that drain mine areas. Similar to a number of prior studies, this research has found that some components of benthic macroinvertebrate communities as represented by the VSCI are negatively associated with elevated SC. Results of studies such as this one can assist understanding of whether observed benthic macroinvertebrate community variation is caused by anthropogenic stressors, such as SC, or is occurring due to natural community variability. Timing of benthic macroinvertebrate sampling in Appalachian coalfield headwater streams is important, particularly in streams with elevated SC/TDS that may score impaired during some portions of sampling index periods and unimpaired during others.

Report of Activity: Research Presentations and Thesis

Boehme, Elizabeth, 2013. Temporal Dynamics of Benthic Macroinvertebrate Communities and Their Response to Elevated Specific Conductance in Headwater Streams of the Appalachian Coalfields. M.S. Thesis, Virginia Tech.

Boehme, E.A., S.H. Schoenholtz, C.E. Zipper, D.J. Soucek, A.J. Timpano. 22 May 2013. Temporal Dynamics of Benthic Macroinvertebrate Communities and Their Response to Elevated Specific Conductance in Headwater Streams of the Appalachian Coalfields. 61ST Annual Meeting of the Society for Freshwater Science (formerly North American Benthological Society). Jacksonville, FL. (Poster)

Boehme, E.A., S.H. Schoenholtz, C.E. Zipper, D.J. Soucek, A.J. Timpano. September 2012. Temporal Dynamics of Benthic Macroinvertebrate Communities and Their Response to Elevated Specific Conductance in Headwater Streams of the Appalachian Coalfields. Powell River Project Symposium. Wise, VA (Talk)

Boehme, E.A., S.H. Schoenholtz, C.E. Zipper, D.J. Soucek, A.J. Timpano. 27 March 2012. Characterizing Temporal Dynamics of Benthic Macroinvertebrate Communities and Their Response to Elevated Specific Conductance in Appalachian Coalfield Headwater Streams. Forest Resources and Environmental Conservation Graduate Research Symposium. Blacksburg, VA. (Poster)

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