ARKANSAS WATER RESOURCES CENTER | PUBLICATION MSC375
FUNDED BY ARKANSAS GAME & FISH COMMISSION | PROJECT RG12153

MONITORING WATER RESOURCES OF THE GULF MOUNTAIN WILDLIFE MANAGEMENT AREA TO EVALUATE POSSIBLE EFFECTS OF NATURAL GAS DEVELOPMENT

2015 July

ARKANSAS WATER RESOURCES CENTER

DIVISION OF AGRICULTURE
RESEARCH & EXTENSION
University of Arkansas System

Monitoring Water Resources of the Gulf Mountain Wildlife Management Area to Evaluate Possible Effects of Natural Gas Development

Bradley J. Austin[1], Erin Scott[2], Sally Entrekin[3], Michelle A. Evans-White[4], Brian E. Haggard[5]

[1] Post-Doctoral Research Associate, Biological and Agricultural Engineering Department, University of Arkansas, Fayetteville, Arkansas: bjaustin@uark.edu
[2] Project Manager, Arkansas Water Resources Center, UA Division of Agriculture, Fayetteville, Arkansas: erins@uark.edu
[3] Associate Professor, Biology Department, University of Central Arkansas, Conway, Arkansas: sentrekin@uca.edu
[4] Associate Professor, Department of Biological Sciences, University of Arkansas, Fayetteville, Arkansas: mevanswh@uark.edu
[5] Director and Professor, Arkansas Water Resources Center, UA Division of Agriculture, Fayetteville, Arkansas: haggard@uark.edu

Executive Summary

Energy dependence and the search for alternative fuels have increased exploration and recovery of natural gas (NG) in the United States, and Arkansas has an area of extensive NG production in the Fayetteville Shale. The Arkansas Game and Fish Commission (AGFC) released the rights in the Scott Henderson Gulf Mountain Wildlife Management Area (GMWMA) for NG exploration, and concerns about potential impacts on water resources, public health and the environment existed in the vicinity of the gas well drilling sites. Therefore, the purpose of this project was to establish baseline assessment of water quality at the South Fork of the Little Red River (SFLRR), evaluating physical, chemical and biological data over four years. We use this information to evaluate if NG production influenced the physical, chemical or biological quality of water resources within the GMWMA. Our report incorporates data collection that began in fall of 2010 through the data collected specific to this funding agreement. Four sampling sites were established along the SFLRR from the most western to eastern edge of GMWMA. Physical, chemical and biological data were assessed before and after the construction of 3 NG well pads and associated pipelines within the GMWMA. All data reported are publically available either through the U.S. Geological Survey or the Arkansas Water Resources Center.

The US Geological Survey (USGS) Arkansas Water Science Center provided continuous water quality and discharge monitoring at the most upstream (USGS 07075250) and downstream (USGS 07075270) sites (sites 1 and 4, respectively), both sites measure and record stage, precipitation, turbidity, specific conductance, temperature, dissolved oxygen and pH at 15 minute intervals and transmit these data through satellite transmission once every hour. The USGS also measured discharge across the flow regime to develop the rating curve used to predict instantaneous and daily discharge. These values are displayed in near real time at https://waterdata.usgs.gov/ar/nwis/rt.

The Arkansas Water Resources Center (AWRC) collected water samples at the four sites along the SFLRR, which were analyzed at AWRC certified water-quality laboratory. The collected samples, duplicates and blanks were analyzed for conductivity, turbidity, chloride (Cl), nitrate (NO_3-N), sulfate (SO_4), soluble reactive phosphorus (SRP), total suspended solids (TSS), total organic carbon (TOC), and metals. The concentrations of all constituents measured in the SFLRR were low suggesting that this river and tributaries are of high water quality with regards to water chemistry relative to other streams and rivers across Arkansas. The physico-chemical conditions did not significantly change over time across the four sites spanning the SFLRR as it flows through the GMWMA, using techniques to flow adjust parameters

and evaluate monotonic changes over time. However, boron showed a significant increase after spring 2012 across all four sites relative to the watershed activities which included clear cutting and NG infrastructure development using a before-after-control-impact (BACI) statistical analysis on the flow-adjusted values.

The University Of Arkansas Biology Department determined benthic sediment composition, algal biomass, on all four sites and gross primary production (GPP) at the most upstream and downstream sites on the SFLRR. A BACI design was used to examine whether implemented BMPs mitigated NG development impacts in SFLRR within GMWMA, where the upstream site or study reach (site 1) served as the control and the downstream sites or study reaches (sites 2, 3 and 4) downstream of the activities within the GMWMA. The level of development was low (0.13±0.01 wells km^{-2}) compared to that of the surrounding Fayetteville Shale landscape (1.39±0.31 wells km^{-2}). There were no significant BACI interactions for algal biomass, GPP or fine organic and inorganic sediments in the SFLRR. While the BMPs appear to have been effective in the GMWMA, the level of NG development was relatively low and the sites along the SFLRR have relatively large drainage areas representing many potential landscape influences on benthic sediment, algal biomass and GPP.

The University Of Central Arkansas (UCA) collected macroinvertebrate samples from the same four study sites on the SFLRR and identified the collected organisms to the lowest practical taxonomic level. The same BACI design as described above was used to test effects of NG development on aquatic biota. There were several taxa sensitive to changes in water quality, including sixty-three genera belonging to 27 families of Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa. Overall, there was no change in macroinvertebrate density downstream from site 1 (i.e., the control site). However, a decrease in EPT taxa density was detected at the most downstream site where the SFLRR flow out of the GMWMA (site 4), potentially in response to NG activity and or logging activity occurring in the watershed downstream of site 1.

This project collected data on the physical, chemical and biological quality of the SFLRR, showing that water quality (based on the measured parameters), with the exception of EPT taxa, did not change over the four year study (2010 through 2014) in response to the low density of NG activities that occurred within the GMWMA. However, this study funded by the AGFC provided essential baseline information that can be used to evaluate water quality at the SFLRR in the future should NG activities expand within the GMWMA. The SFLRR flowing through the GMWMA is a unique water resource with chemical concentrations and biological diversity reflective high water quality.

Introduction

In the past decade, technological advances in horizontal drilling and hydraulic fracturing (fracking) have rocketed natural gas (NG) to the forefront of energy production in the United States (U.S.) (Malakoff 2014). These two processes have made the recovery of NG from unconventional sources, such as shale formations, economically feasible. While NG production from other unconventional sources, such as coal bed methane, tight gas and oil associated NG, have been prominent in the past, the contribution of these sources to annual NG production is waning and the extraction of NG from shale formations is increasing and is projected to meet almost half of the global energy demand by 2050 (Rahm and Rhia 2014; Malakoff 2014). This is primarily due to the widespread distribution of shale formations throughout North America and the world (U.S. EIA 2013; Rahm and Rhia 2014). In addition to its ubiquity and abundance, NG produces one-third less carbon dioxide (CO_2) than oil and half as much as coal per unit energy, making it a potential "bridge fuel" to more environmentally sound energy sources (Shahidehpour et al. 2005; Kintisch 2014). By utilizing this previously untapped NG source, the U.S. may reduce its demand for imported oil while increasing exports (Malakoff 2014).

Despite the economic and potential atmospheric environmental benefits associated with utilizing unconventional NG resources, the development of NG infrastructure has outpaced environmental regulation and research leading to a paucity of studies exploring environmental impacts. Only within the past 2-3 years have possible issues begun to be addressed in the literature. Some of these studies have focused on methane (CH_4) emissions from NG infrastructure (Alvarez et al. 2012; Allen et al. 2013; Miller et al. 2013; and Kintisch 2014) and consequences for atmospheric chemistry and climate change. Water quantity issues may arise due to over use of ground and surface water resources for hydraulic fracturing (fracking) (Entrekin et al. 2011). Additionally, water quality issues may result from improper storage and disposal of fracking fluids and flowback water and through sediment erosion from construction activities (Williams et al. 2008; Entrekin et al. 2011; Olmstead et al. 2013). With unconventional NG resources so widespread in the U.S. and the world, these potential environmental impacts will expand as more states and countries begin to extract this resource if proper regulation is not in place to mitigate impacts.

Best management practices (BMPs) are often implemented to prevent or reduce sediment migration from areas disturbed by NG construction activities. Best management practices, such as mulching, covers exposed soils, slowing overland flow and filtering out sediments before water reaches nearby stream channels (USFWS 2007; 2009). Additional BMPs specify where and how transmission pipelines should cross stream channels, specifically horizontal directional drilling (HDD) should be used to install pipelines under streams (USFWS 2009). Within the logging industry, similar BMPs have been found to be highly effective at preventing soil erosion into nearby streams (Prud'homme and Greis 2002). While BMPs are becoming more widely used in the NG industry, their implementation has trailed NG infrastructure development in the region by several years and, to date, few efforts have been undertaken to assess their effectiveness. The monitoring of multiple water quality parameters and biological indicators [e.g. algal biomass and production (Austin et al. 2015) and macroinvertebrate abundances (Johnson et al. 2015)] allow for the assessment of implemented BMPs within this region.

In the winter of 2010, we set out to examine the effects of unconventional NG activities on stream nutrients and trace elements, fine benthic sediments, algal biomass and gross primary production (GPP), and macroinvertebrates within the Scott Henderson Gulf Mountain Wildlife Management Area (here after, GMWMA) within the Fayetteville shale region of north central Arkansas (Figure 1). This area was selected due to the anticipated NG infrastructure development starting in the summer of 2011. Arkansas Game and Fish Commission (AGFC) officials were present throughout the construction of infrastructure and the implementation of BMPs. Four sites along the main stem of the South Fork Little Red River (SFLRR) were selected to establish baseline conditions for the variables listed above and examine potential short terms impacts associated with NG activity within the GMWMA. These sites were sampled before and after the installation of 4 wells on 3 well pads, and a major NG transmission pipeline within the GMWMA section of the SFLRR. Site 1 occurred just upstream of the landscape disturbance and acted as a reference site. Additionally, we wanted to assess the effectiveness of BMPs implemented within the region. We predicted that effective BMPs would result in no detectable differences between control and impacted sites before and after the disturbance for SFLRR sites.

Methods

Study area and sampling sites

This study was conducted in the GMWMA located in northcentral Arkansas, roughly 130 km North West of Little Rock, Arkansas (Figure 1). The GMWMA covers approximately 60 km^2 of land within the Boston Mountain Ecoregion adjacent to the eastern extent of the Ozark National Forest (Birdsong 2011). Forest composition consists of 65% oak hardwood (red and white oak *Quercus rubra and Q. alba*) and 35% pine (loblolly and longleaf pine; *Pinus taeda, P. palustris*) (Birdsong 2011) and the landscape is drained by two major catchments, the South Fork Little Red River (SFLRR) drainage in the north and the Point Remove drainage in the south (Figure 1). The geology of this region is Middle Pennsylvanian-Morrowan with the primary rock types consisting of sandstone and shale. The GMWMA is managed by the Arkansas Game and Fish Commission (AGFC) for wildlife-oriented recreation, such as hunting and site-seeing. Throughout the extent of the NG development in the GMWMA, AGFC officials enforced the implementation of BMPs across impacted areas.

The SFLRR was sampled at four locations starting in December of 2010 and continued each spring and winter through December 2013. The most upstream (site 1) and downstream (site 4) stations were at USGS monitoring stations (07075250 and 07075270, respectively). Both upstream and downstream sites occurred just outside of the GMWMA. Two additional sites were located within the GMWMA and occurred upstream (site 2) and downstream (site 3) of the confluence of Cedar Creek with the SFLRR (Figure 1). Land use and land cover was consistent across all four SFLRR sites with all having approximately 90% forested land cover (Table 1). The catchment area of all sites ranged from 123-193 km^2. All sites were impacted to some extent by NG activity occurring outside of the GMWMA. The major landscape impacts occurring within the time frame of this study includes the installation of transmission and lateral NG pipelines during the spring and summer of 2012, as well as from clear-cut logging (0.40 km^2) practices occurring downstream of site 1 during the same time frame as of the pipeline installation.

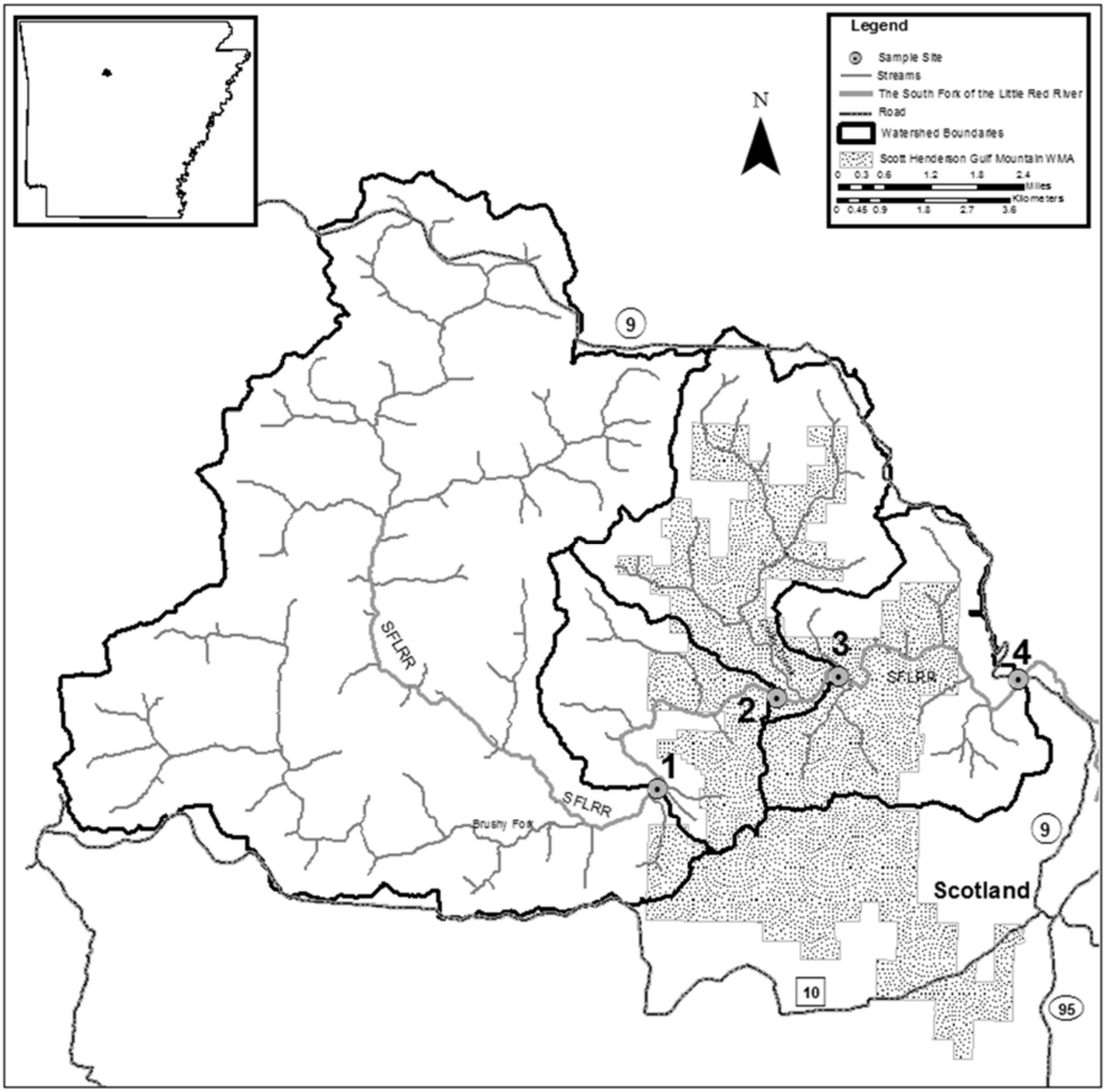

Figure 1. Map of the South Fork Little Red River watershed outlined in black. Gray polygon highlights the Scott Henderson Gulf Mountain Wildlife management area, managed by the Arkansas Game and Fish Commission. Sampling locations are labeled 1 through 4.

Sampling and analysis

At each of the four study reaches along the SFLRR, a 200 m reach was delineated for sampling of abiotic and biotic variables. A total of 5-6 cores were collected for benthic in-organic and organic sediments, 10-12 cobbles were collected for determination of algal biomass, and 5 Hess samples were collected and preserved for identification and quantification of macroinvertebrate densities, during each sample period at the 4 sample reaches along the SFLRR. Base flow water

Table 1. Landscape scale characteristics for each of the South Fork Little Red River sites for study 2. Pipeline and well pad densities are based on natural gas activity within the Gulf mountain wildlife management area only.

Site	CI[a]	Catchment Area (km^2)	% For[b]	% Past[c]	% Urb[d]	Pipeline (km/km^2)	Well Pad ($\#/km^2$)
1	Up	122.72	90	8	2	0.000	0.000
2	Down	140.03	91	8	2	0.005	0.007
3	Down	168.77	90	7	2	0.005	0.006
4	Down	192.67	91	7	1	0.008	0.010

[a]CI=upstream (*up) or downstream (*down) of the landscape disturbance ; [b]For=Forested; [c]Past=Pasture; [d]Urb=Urban

samples were collected monthly for analysis of water quality parameters.

The two USGS real-time monitoring stations on the SFLRR uploads data for stage (ft), discharge (CFS), turbidity (NTU), specific conductance ($\mu S\ cm^{-1}$), dissolved oxygen ($mg\ L^{-1}$), pH and water temperature (°C) (measured in stream every 15 min). These data were accessed through the USGS website at http://ar.water.usgs.gov. Daily values for all measured parameters were obtained by averaging the 15 min interval data for each day. Monthly averages for all parameters were then calculated using daily values.

At approximately monthly intervals, during base flow conditions, 1 L of water was collected from the vertical centroid of flow (VCF) at each site. A field duplicate was collected approximately every other sampling and a field blank was collected once every five samplings. Samples were stored on ice and delivered to the Arkansas Water Resource Center's (AWRC) certified water-quality laboratory for analysis of conductivity, chloride (Cl), sulfate (SO_4), turbidity, total suspended solids (TSS), metals, nitrate (NO_3-N), and soluble reactive phosphorus (SRP). All samples were analyzed following standard methods, details of which are available of AWRC's website, (http://-arkansas-water-center.uark.edu/waterquality-lab/2015July-MethodsForWaterAnalysisAnd-LabHoldingTimes.pdf; access date 10/21/2015).

A 19.5 cm diameter corer was used to collect benthic sediments at 6 locations within each 200 m sampling reach. All samples were stored on ice until returning to the laboratory where they were stored at 4 °C until being processed within 48 h of collection. In the laboratory, samples were sieved to separate sediments in to 6 size classes (>500 µm, 250-500 µm, 120-250 µm, 64-120 µm, 37-64 µm, and 1-37 µm). Sieved samples were placed into pre-combusted aluminum weigh boats, dried (50 °C), weighed to determine dry mass, combusted (500 °C), wetted with DI water, dried (50 °C), and weighed again to determine ash mass (Steinman and Lamberti 1996). The organic component or ash free dry mass (AFDM) of the samples was determined as the difference between the dry mass and the ash mass. The inorganic component of the sediments is equivalent to the ash mass. For the purpose of this study only fine (< 250 µm) benthic inorganic and organic sediments were examined in statistical analyses.

During the spring sample periods of 2011, 2012, and 2013 duplicate sediment samples were collected at each of the four sites and returned to the laboratory for determination of trace elements and water extractable total dissolved phosphorus. Sediment samples were dried (47.5 °C) to a constant mass and then sieved (< 2 mm). Trace elements were extracted from sediment samples using melich 3 extraction at the University of Arkansas Agriculture diagnostic laboratory (http://www.clemson.edu /sera6/MethodsManualFinalSERA6.pdf; access date 10/21/2015).

Cobbles were collected for the determination of algal biomass in the form of Chl *a* and total periphyton biomass measured as AFDM. At the headwater sites, two cobbles were collected at each of three riffles and three pools for a total of twelve cobbles. For the SFLRR study, two cobbles were collected near each of the sediment cores. All cobbles collected were stored on ice and transported back to the laboratory and frozen (-20 °C) until processing for Chl *a* and AFDM. Each cobble was thoroughly scrubbed with a stiff bristle brush to remove all periphyton from the surface. A subsample of the resulting slurry was filtered onto a pre-combusted pre-weighed filter (Pall GF/F) and then stored at -20 °C until Chl *a* extraction was performed. Chlorophyll *a* was extracted from filters using 10 ml of 95% ethanol and incubated at 78.5 °C for 5 min as described by Sartory and Grobbelaar (1984), and stored in the dark at 4 °C for 24 h, after extraction absorbance was measured on a Genesys 10 VIS spectrophotometer (Thermo Fischer Scientific inc., Waltham, MA) as described in APHA (2005). After the Chl *a* analysis, filters and extract were poured into pre-combusted, pre-weighed tins and placed in a drying oven (50 °C) and then combusted (500 °C, 3 h) for determination of AFDM (see detailed methods above). Surface area of each cobble was determined using the aluminum foil method as described by Lamberti et al. (1991) and used to standardize estimates of both Chl *a* and AFDM per unit area.

Gross primary production (GPP) was determined through the measure of diel curves of dissolved oxygen (DO) at a single station following Owens (1974) and Bott (1996) at sites 1 and 4. Dissolved oxygen data was measured at 15 min intervals continuously in association with the USGS monitoring stations listed previously. Air to water gas exchange (ko_2) was estimated using a night time regression of the DO fluctuation, whereby the slope of the regression between the changes in DO concentration and the oxygen deficit, is equal to the reaeration coefficient (Wiley et al. 1990, Young and Huryn 1996). Dissolved oxygen, reaeration coefficients and mean depth were used to calculate an areal rate of change in DO as (g O_2 m^{-2} min^{-1}) following calculations described in Bernot et al. (2010). Areal rates of oxygen change were then converted to rates of carbon change (g C m^{-2} min^{-1}) following equations described by Bott (1996). Rates of carbon change were then used to calculate GPP.

Macroinvertebrates were sampled with a 32 cm diameter Hess sampler with a 250 µm mesh. We took samples at five meter marks along each reach at points randomly selected with a random number generator. We preserved macroinvertebrates in 70% ethanol. In the laboratory, we separated macroinvertebrates into 1 mm and 250 µm size classes using nested sieves. We sorted macroinvertebrates larger than 1 mm by eye and subsampled macroinvertebrates less than 1 mm using a sample splitter with subsamples having at least 100 individuals (Waters 1969). We counted and measured all macroinvertebrates to the nearest millimeter and identified all taxa to genus or lowest practical taxonomic resolution (Stewart and Stark 1988, Wiggins 1996, Merritt et al. 2008).

LOESS regression procedures were used to flow-weight water quality parameters for each of the river reaches. A three step approach was used where first both water quality parameters and discharge data were log transformed. Second, the log transformed water quality parameters were flow-weighted against the log trans-formed discharge using LOESS smoothing tech-nique (Richards and Baker 2002). Finally, the residuals from the smoothing technique were regressed against time and evaluated for trends. A more thorough description of the methods can be found in White et al. (2004).

Sampling started prior to the installation of NG infrastructure within the GMWMA and continued until after the development was complete. This allowed us to examine the biological (algal biomass, GPP, and macro-invertebrate) and sediment data utilizing a paired reach Before-After Control-Impact (BACI) analysis (Green 1979). SFLRR sites were analyzed using the paired BACI analysis approach, where site 1 was always the control site and was compared with each of the downstream sites individually. An uneven two-way repeated measures analysis of variance (2-way rmANOVA) was utilized to examine the interaction term between the factors "Before-After" and "Control-Impact" (here after BA and CI respectively) for all response variables; whereby a significant interaction term ($p<0.05$) indicates impact by the disturbance. Visual inspection of box plots and scatter plot matrices were used to check that the data for each response variable met the assumptions of independence, homoscedasticity, and normal distribution prior to running the 2-way rmANOVA. Data not fitting the assumptions of the analysis were transformed and re-assessed to verify assumptions were met prior to conducting the statistical test.

Results and Discussion

USGS real-time monitoring

Mean annual discharge for each water year was lowest for the 1st water year of the project at 34.3 CFS and highest the 2nd water year of the project at 76.9 CFS for site 1, while site 4 was lowest during the 4th water year at 116.4 CFS and highest the 2nd water year at 128.1 CFS. The highest discharge measured at site 1 was during the second year at 1435 CFS, while site 4 was during year 1 at 7357 CFS (Figure 2A). These values were calculated from mean daily estimates, so they do not necessarily represent actual maximum instantaneous discharge values. Low flow conditions consistently occurred from June-October at both sites, with reported discharge values less than 0.1 CFS.

Temperature followed a typical seasonal pattern with the lowest values occurring in the winter months and highest values in the summer months. Mean daily temperature at site 1 ranged from 1.3 – 27.7 °C and from 0.6–30.0 °C at site 4. The slightly warmer temperatures in the winter and cooler temperatures in the summer at site 1, suggests that groundwater inputs likely influence site 1 to a greater extent than site 4.

Annual mean specific conductance was consistently higher at site 4 ranging from 30–36 $\mu S\ cm^{-1}$ and from 25–30 $\mu S\ cm^{-1}$ at site 1. Daily mean specific conductance ranged from 12–81 $\mu S\ cm^{-1}$ at site 1 and from 16–73 $\mu S\ cm^{-1}$at site 4. Peaks and valleys in the daily mean values of specific conductance coincide with valleys and peaks in discharge (Figure 2A and C). This is as would be expected, with low specific conductance during high flow due to dilution and greater specific conductance during low flow due to evapotranspiration.

Annual mean turbidity was relatively low and ranged from 4.5–6.9 FNU at site 1 and from 4.2–7.0 FNU at site 4. Overall, daily maximum values were higher at site 1 than site 4 (216.2 vs. 173.1 FNU, respectively; Figure 2F).

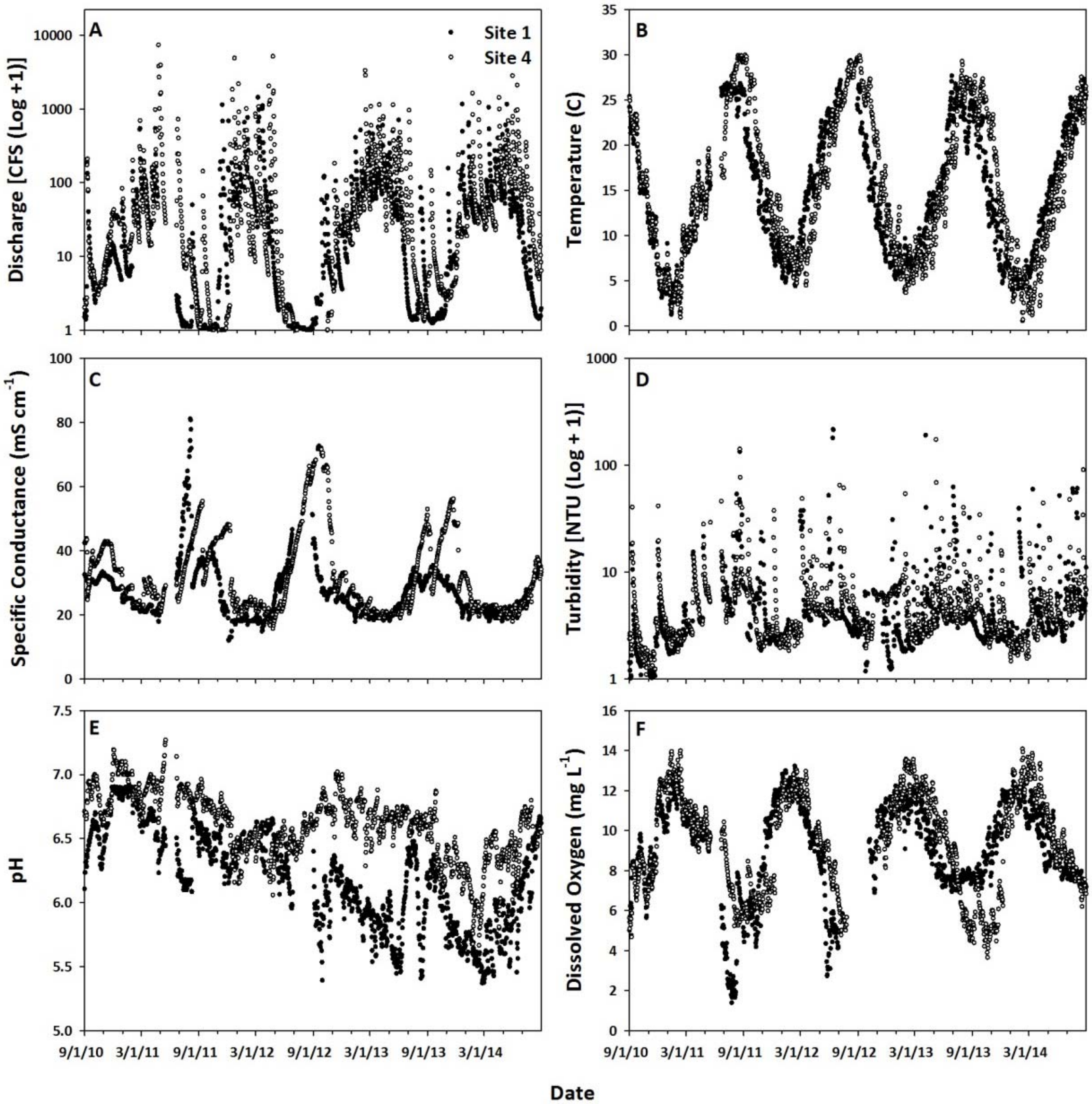

Figure 2. Scatterplots of recorded parameters from USGS gaging stations along the South Fork of the Little Red River at Site 1 (USGS 07075250; ●) and Site 2 (USGS 07075270; ○) versus time during the study period for discharge (A), Temperature (B), specific conductance (C), turbidity (D), pH (E) and dissolved oxygen(F).

Daily mean DO was greatest in the winter months, likely due to higher solubility than in the summer months at both sites. In general DO measurements were similar between sites with site 1 ranging from 1.4 mg L^{-1} measured in July of 2011 to 13.3 mg L^{-1} measured in January of 2011, while site 4 ranged from 3.7 mg L^{-1} to 14.1 mg L^{-1} measured in September of 2013 and January of 2014, respectively.

Daily mean pH was fairly consistent throughout the extent of the study ranging from 5.4–6.9 at site 1 and from 5.7–7.3 at site 4. However, there was a declining trend in pH at both sites; therefore, LOESS was used to correct pH for variable discharge, then flow adjusted pH values were regressed across time. For both sites pH decreased (became more acidic) during the extent of the study (R^2=0.50; P<0.001 for site 1 and R^2=0.37; P<0.001 for site 4).

Water quality

Annual geometric means of specific conductance were low across all sites and sample periods relative to that observed in more developed watersheds (e.g., Peterson et al. 2014) and ranged from 24.8 µS cm^{-1} at site 1 in 2011 to 41.4 µS cm^{-1} at site 4 in 2010. A BACI analysis of flow adjusted specific conductance revealed that there were no differences between the reference site and downstream sites (P>0.05 for all three comparisons), nor were there any significant interaction terms between the BA and CI factors for any of the pairings (P>0.05). However, the BA factor was statistically significant for all three pairings (P<0.05; Appendix C; Figure 3A). This indicates that while there was no detectable effect of the landscape disturbance occurring within the GMWMA, there was an environmental change that promoted changes in specific conductance across all of the sites.

While chloride concentrations were variable between years, in general they were relatively low across all sites and sample periods (0.950–4.061 mg L^{-1}), especially when compared to streams draining more developed watersheds (mean concentrations 4.38–10.59 mg L^{-1}; Bailey et al. 2012) or downstream of effluent discharge (mean concentrations greater than 16 mg L^{-1}; Bailey et al. 2012). Geometric mean annual chloride concentrations were not different across sites (P>0.05); however, there was a statistically significant effect of year (P<0.001) with the flow adjusted values

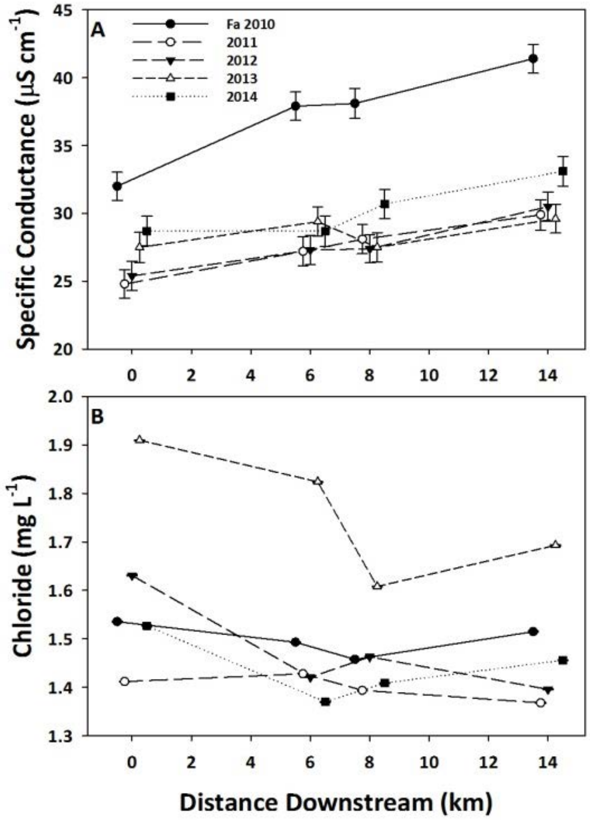

Figure 3. Annual geometric means (±standard error) for specific conductance **(A)** and chloride **(B)** at each of the four sampling sites along the SFLRR, relative to distance downstream.

measured in 2013 and the lowest in 2014 (Figure 3B). Chloride might be a good monitoring target because of its conservative nature and high concentrations in fracturing fluids. Fracturing flow back waters can range from 2,500–5,000 mg L^{-1} and produced waters can be greater than 20,000 mg L^{-1} (Kresse et al. 2012). Along with specific conductance, these values measured along the SFLRR represent near pristine conditions and provide an excellent baseline for future study, should the region be further developed for NG resources, or other changes in land use.

The major cations, calcium, magnesium, potassium and sodium showed similar trends as chloride, with concentrations ranging from

1.13-6.89 mg L^{-1}, 0.43-1.73 mg L^{-1}, 0.46-2.13 mg L^{-1}, and 0.77-3.33 mg L^{-1} respectively. With all four constituents there were no significant differences between sites (P>0.05); however, there was significant variability between years (P<0.0001 for all constituents). While chloride was the highest in 2013, all major cations were highest in 2010, and with the exception of magnesium, second highest in 2013 (Appendix C). As with specific conductance there was a statistically significant effect of the BA factor for magnesium, potassium and sodium. There was not a significant interaction effect between the BA and CI factors, indicating that changes measured in these variables were due to environmental changes upstream of our study area.

The SFLRR is a clear water stream draining a watershed that is minimally disturbed throughout much of its reach upstream of our study sites. Reflective of these clear water conditions, mean turbidity was very low across all sites (Appendix D; Figure 4A), and individual turbidity measurements ranged from 0.9–13.8 NTU, with the lowest value measured at site 1 in 2014 and the highest value at site 4 in 2011. Total suspended solids (TSS) were also relatively low, ranging from 0.1–17.8 mg L^{-1} (Appendix D; Figure 4B), with 97% of the measured values being less than 5.0 mg L^{-1}. These data are reflective of base flow conditions, not storm events when sediment is re-suspended from within the fluvial channel, eroded from stream banks, and transported from the landscape. All measured values greater than 5.0 mg L^{-1} were collected in the summer time when discharge was the lowest and stream productivity the highest which can result in increased phyto-plankton in the slow moving water.

The metals arsenic, lead, selenium, titanium and vanadium were consistently below the laboratory method detection limit (MDL); therefore, these variables were not included in

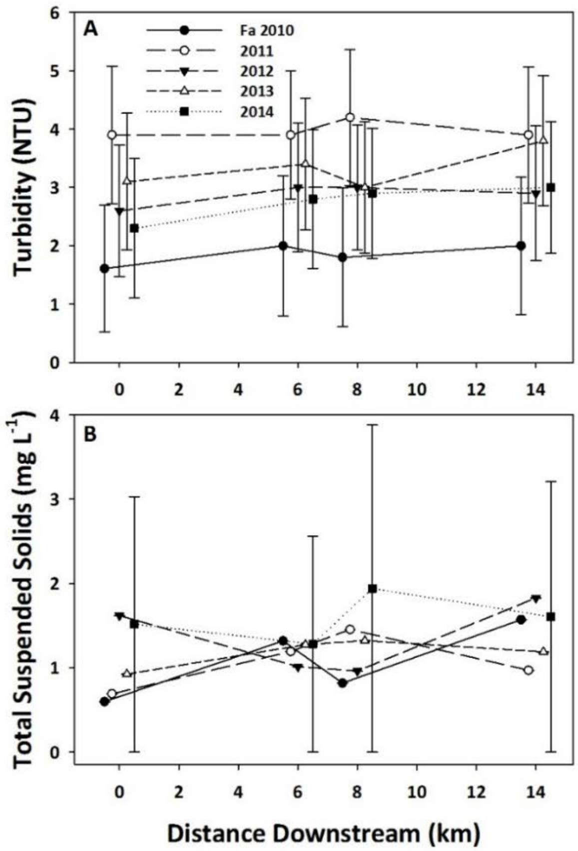

Figure 4. Annual geometric means (±standard error) for turbidity **(A)** and total suspended solids **(B)** at each of the four sampling sites along the SFLRR, relative to distance downstream.

further analyses. Basic summary statistics including geometric means and ranges of all other metals analyzed can be found in Appendix E. Trace metals aluminum, cadmium, chro-mium, cobalt, copper, molybdenum and nickel were also consistently below the MDL and only a few values exceeded the practical quantitation limit (PQL). However, aluminum was elevated across all sites during the February 26th, 2011 sample period and chromium and nickel were elevated at site 4 during the spring of 2013. These variables were not analyzed with LOESS procedures due to the reasoning that the outcome would be driven by only a few points.

All other metals (boron, iron, manganese, and zinc) were flow adjusted following LOESS procedures and scatter plots of the residuals were visually examined for any possible trends. With boron, there was an increase in annual geometric mean across all sites sampled following the logging and installation of the pipeline in the watershed (Appendix E; Figure 5). The BACI analysis of boron found no statistically significant interaction of the BA and CI terms, indicating that an effect of the landscape disturbance occurring within the GMWMA was not detected at the downstream sites. However, there was a highly significant BA effect ($P<0.0001$) for all comparisons of reference and downstream sites, which confirms the increasing trend found through the LOESS procedures. The gradual increase across all sites in the study indicates that the source of boron to the system was upstream of the study reach. While boron concentrations increased over the extent of this study, the maximum concentration measured of 0.146 mg L^{-1} at site 1, was well below the 5.0 mg L^{-1} set for livestock water.

In general manganese concentrations were below detection; however, during 5 sample

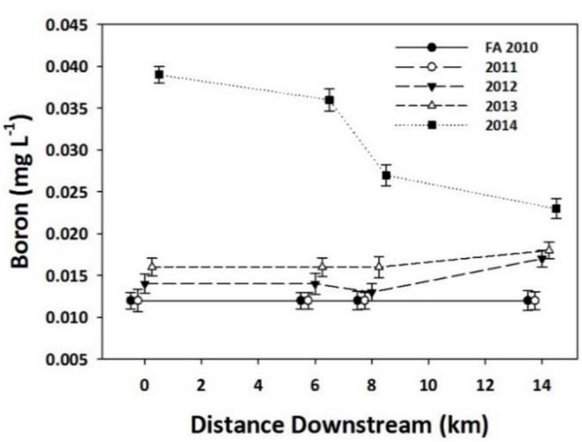

Figure 5. Annual geometric means (± standard error) for boron at each of the four sampling sites along the SFLRR, relative to distance downstream.

periods and a total of 6 samples collected (~3%) manganese concentrations were elevated above secondary drinking water standards (0.05 mg L^{-1}). These elevated concentrations gene-rally occurred at a single site within any given sample period, with the exception of October of 2011 where sites 3 and 4 were 0.121 and 0.081 mg L^{-1} respectively (Appendix E). The highest concentration measured was 0.275 mg L^{-1} collected from site 4 during June of 2012. Discharge reported by the USGS during this sample period was 0 CFS and water was only collected at site 4.

The concentration of zinc was elevated at site 1 during April of 2012 sample date (0.101 mg L^{-1}), while the downstream concentrations ranged between 0.010-0.018 mg L^{-1}. Unlike manganese, no samples collected had elevated zinc concentrations above secondary drinking water standards (5.0 mg L^{-1}).

Dissolved nutrient concentrations were low throughout the study at all sites, though concentrations were elevated on several occasions (Appendix F). Nitrate ranged from <0.005–0.268 mg L^{-1} across all sites and sample periods (Figure 6), while, soluble reactive phosphorus (SRP) ranged from <0.001–0.565 mg L^{-1} (Figure 6). These nitrate concentrations are well below nutrient supply concentrations generally required to saturate or increase primary production, based on nutrient thresholds compared with algal biomass in streams (0.270–1.500 mg L^{-1} total nitrogen; Evans-White et al. 2013). Soluble reactive phosphorus concentrations were elevated above nutrient supply concentrations required to saturate or increase primary production (0.007–0.100 mg L^{-1} total phosphorus; Evans-White et al. 2013) in 63% of the samples collected. This is not surprising as Ozark streams are generally labeled as nitrogen as opposed to phosphorus limited (Lohman et al. 1991; Austin et al. 2015). Additionally, these elevated values

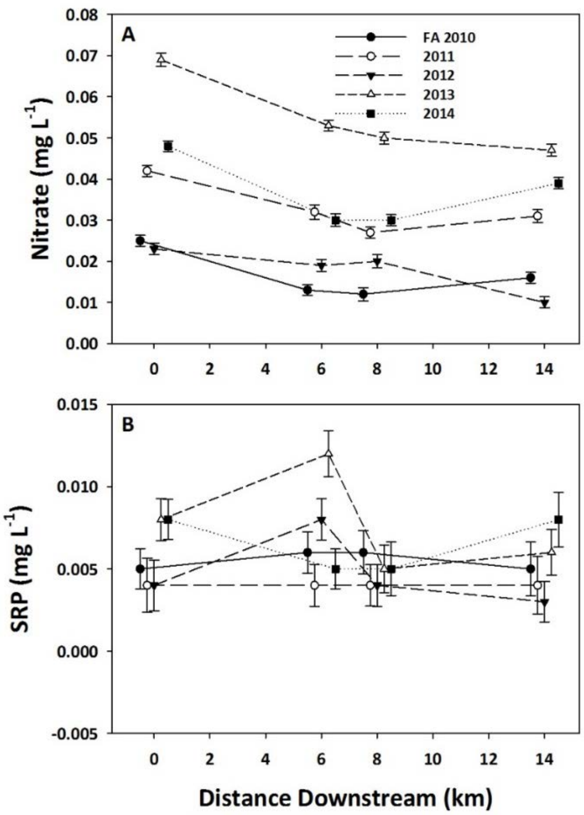

Figure 6. Annual geometric means (±standard error) for nitrate **(A)** and soluble reactive phosphorus (SRP) **(B)** at each of the four sampling sites along the SFLRR, relative to distance downstream.

represent sample maximums; annual geometric means for SRP were much lower ranging from 0.003–0.012 mg L^{-1}.

All constituents that were analyzed during this study had relatively low concentrations at all sites, with only a few exceptions (Appendices C, D, E, and F). The outlying concentrations for some metals might be the result of the hydrology of the system or possibly an error in sample collection or laboratory processing. The otherwise low concentrations of metals, particulates and nutrients are representative of nearly pristine stream conditions along the SFLRR driven by a watershed that is minimally disturbed. Because of this, the data over the past 4 years of study provide a good baseline for future study of the region should the land-scape be further altered by NG development, logging and other anthropogenic activities.

Benthic sediment

Fine benthic organic sediments across all sites ranged from (mean±1SE) 21.74±4.29 g m^{-2} at the reference site (site 1) to 39.46±10.18 g m^{-2} at site 2. Issues with sample processing resulted in the loss of data from the first two sample periods so pre-disturbance conditions are based off of only one sample period. While "Before" data consists of only one data point for each site, there were no statistically significant interactions between the BA and CI factors for any of the pairings between the reference and downstream sites (Table 2; Figure 7). Fine benthic inorganic sediments ranged from 303.40±82.44 g m^{-2} at the reference site to 558.48±168.20 g m^{-2} at site 2. Fine benthic inorganic sediments did not differ between the reference site and downstream sites prior to disturbance ($P>0.05$). Additionally, there were no significant interactions between the BA and CI factors for any of the pairings of reference and downstream sites (Table 2; Figure 8).

Fine inorganic sediments were fairly consistent across sample periods within each site and were relatively similar across sites (Figures 7 & 8). However, both fine benthic inorganic and organic sediments were elevated at site 2 in comparison to the reference site during the winter sample period following the disturbance (Figures 7A and 8A). This could be an indication of increased sediment erosion due to the NG transmission line and logging disturbances; although, this increase in fine benthic sediments was not long term. These trends suggest a pulse event as opposed to a step change in benthic fine organic and inorganic sediments. The high gradient nature of this system likely prevented long term storage of

Table 2. Two-way repeated measures analysis of variance output for each of the response variables for the pairings of contro (site 1) and impacted (sites 2-4) sites along the South Fork Little Red River within the Gulf Mountain Wildlife Management Area. Statistically significant P-values are bolded.

Variable	Factor	Site 1V2 F	Site 1V2 P	Site 1V3 F	Site 1V3 P	Site 1V4 F	Site 1V4 P
Fine Benthic Inorganic Sediment	BA	0.52	0.488	0.56	0.472	< 0.01	0.994
	CI	1.32	0.278	1.93	0.195	2.60	0.138
	BAxCI	0.04	0.838	2.19	0.170	0.66	0.434
Fine Benthic Organic Sediment	BA	1.54	0.261	0.40	0.549	0.62	0.462
	CI	0.80	0.406	1.37	0.287	2.38	0.174
	BAxCI	0.29	0.607	0.01	0.938	0.02	0.885
Algal Biomass	BA	0.03	0.876	< 0.01	0.993	0.57	0.471
	CI	0.14	0.715	1.23	0.297	4.84	0.055
	BAxCI	0.23	0.643	0.13	0.729	0.23	0.643
Gross Primary Production	BA	NA		NA		0.96	0.332
	CI					5.16	0.028
	BAxCI					0.47	0.498
Macroinvertebrate Density	BA	0.96	0.350	2.49	0.146	2.36	0.155
	CI	< 0.01	0.948	0.06	0.807	0.71	0.420
	BAxCI	1.70	0.221	0.82	0.386	1.42	0.261
EPT Taxa Density	BA	4.77	0.054	15.09	**0.003**	10.81	**0.008**
	CI	0.02	0.880	0.29	0.601	0.42	0.530
	BAxCI	4.74	0.054	2.29	0.162	7.17	**0.023**

sediments at the downstream sites following the logging of the watershed below site 1.

As with trace elements in the water column, there were no differences in trace element quantities in the benthic sediments collected between sites (P>0.05), with the exception of magnesium, which was greater at sites 3 and 4 than at sites 1 and 2 (P=0.006).

Algal biomass and gross primary production

Benthic chlorophyll *a* measured across all sample periods was least at site 3 (0.49±0.06 µg cm^{-2}) and greatest at site 4 (1.17±0.14 µg cm^{-2}). These measured concentrations of algal biomass across both sites and time fall within the oligotrophic or low productivity status for streams (Figure 10; Dodds et al. 1998). Further, the relatively low range of variability in Chl *a* across sites and time, likely resulted in no significant interaction terms between the BA and CI factors between any pairing of the control site and impacted sites (Table 2; Figure 9), indicating no detectable impact of NG activity or logging on algal biomass within the SFLRR during this study. Further, there were no

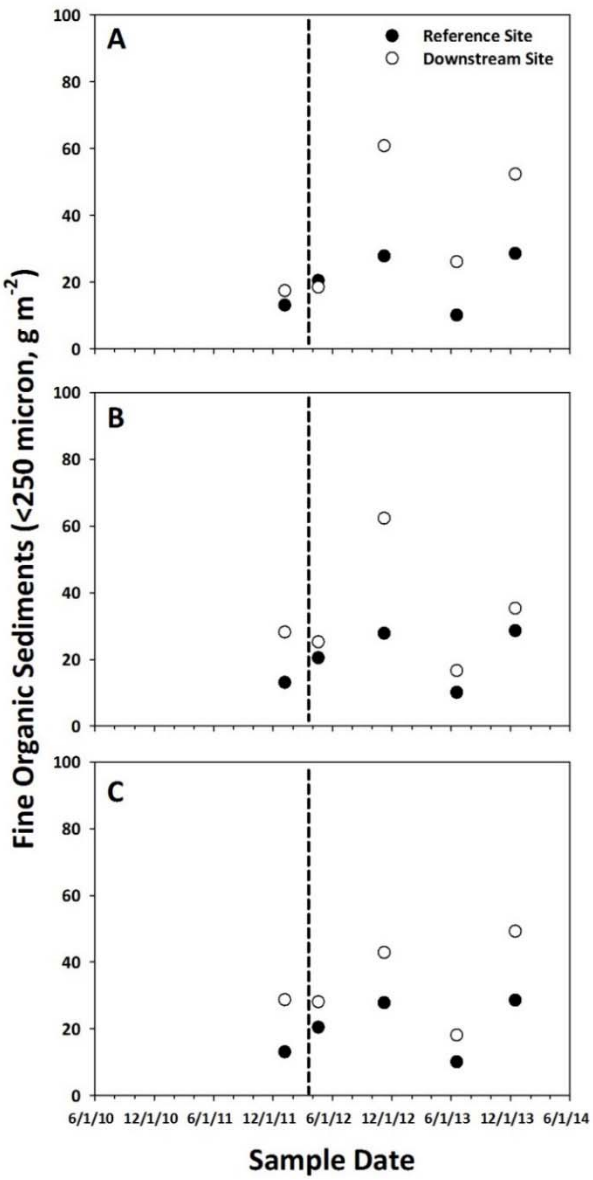

Figure 7. Comparison of mean fine organic sediments between control (●) and impacted (○) sites before and after the NG infrastructure development occurred within the Gulf Mtn. WMA along the SFLRR, which is depicted by the dotted line. The control site (site 1) is individually compared to each of the impacted sites (2-4) with 1V2 (A), 1V3 (B), and 1V4 (C). There were no significant interactions between the BA and CI factors within the 2-way rmANOVA.

differences between the reference site and downstream sites prior to the development of NG resources and logging of the SFLRR catchment (Table 2), indicating that the reference site provided a good reference for pre-disturbance conditions within the downstream sites.

Site 4 was the only downstream site to have increased Chl *a* following the disturbance with respect to the reference site. This increase in Chl *a* occurred during the fall/winter of 2012 and coincided with the end of a 2 yr drought. While this increase is suggestive of possible enrichment to the river reach sampled the measured algal biomass within this sample period fell within the low end of the range of values measured in other minimally impacted Ozark streams (1.03–5.98 μg cm^{-2}; Lohmann et al. 1992). Overall, the low measured Chl *a* for all sites and sample periods provides a good baseline of algal biomass within this minimally disturbed reach of the SFLRR drainage.

The mean monthly GPP estimated at site 1 (mean±1stdev; 1.995±2.916 g C m^{-2} d^{-1}) was on average higher than what was estimated at site 4 (0.679±0.740 g C m^{-2} d^{-1}). For both sites GPP was higher in spring and summer than fall and winter, as would be expected due to increased light availability. Gross primary production measured at site 4 consistently fell within the range of values measured at urban and agriculturally influenced streams in the LINX II (0.03 – 4.63 g C m^{-2} d^{-1}; Bernot et al. 2010). However, four monthly mean values for site 1 were more similar to values measured in row crop influenced streams in Illinois (0.03-≥15.00 g C m^{-2} d^{-1}), despite having relatively low nutrient concentrations. The BACI analysis examining GPP variability between sites 1 & 4 indicates that they are statistically significantly different (P=0.028; Table 2). However, there is not a statistically significant interaction term between the "Before-After" and "Control-Impact" factors (P=0.498; Figure 10, Table 2), indicating that the logging and NG disturbance to the landscape did not produce a detectable change in GPP at site 4. Due to less than ideal

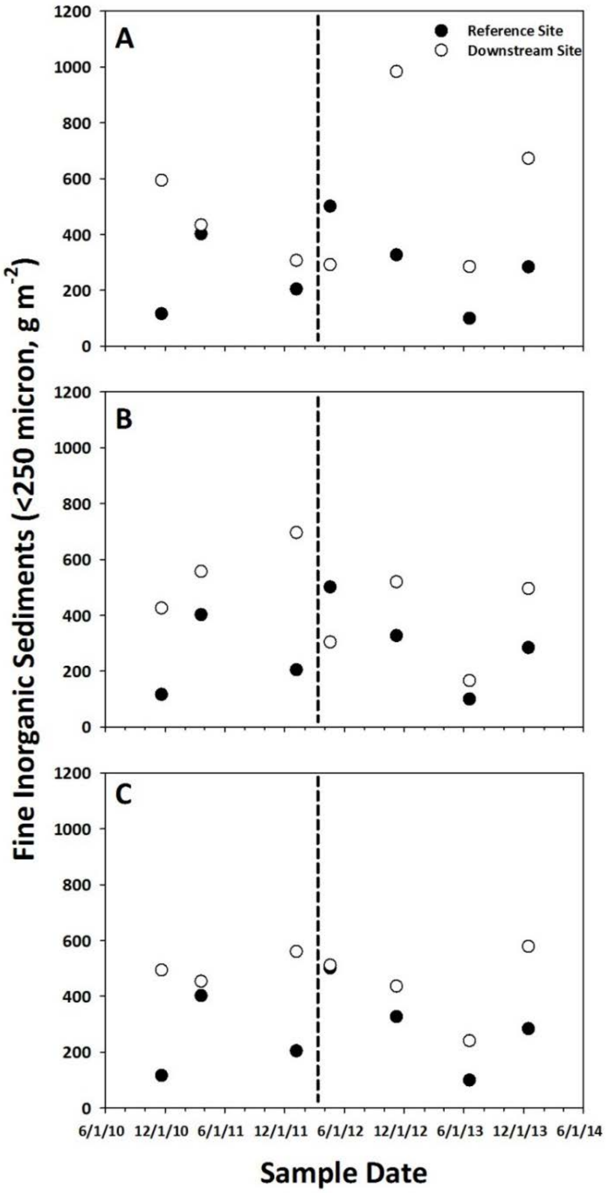

Figure 8. Comparison of mean fine inorganic sediments between control (●) and impacted (○) sites before and after the NG infrastructure development occurred within the Gulf Mtn. WMA along the SFLRR, which is depicted by the dotted line. The control site (site 1) is individually compared to each of the impacted sites (2-4) with 1V2 (A), 1V3 (B), and 1V4 (C). There were no significant interactions between the BA and CI factors within the 2-way rmANOVA.

conditions for collection of dissolved oxygen data (low precision data and no control over the placement of DO sensor), the GPP values reported within this report should be viewed as rough estimates.

Macroinvertebrate density

There were 58 distinct macroinvertebrate families collected from the four SFLRR sample reaches over the four years of study (Appendix H). Over the course of the study macro-invertebrate density was variable across sites, with site 4 having greater macroinvertebrate densities than sites 1–3 (P=0.006). While there was variability in total macroinvertebrate density across sites, there were no significant effects of logging and pipeline installation when comparing the reference site 1 to the downstream sites before and after the disturbance (Table 2; Figure 11). The orders Diptera, Ephemeroptera, Plecoptera, and Trichoptera were the most diverse, comprising 40 of the 58 families sampled. Densities of Diptera and Trichoptera were similar across all sites (P= 0.724 and 0.109 respectively); while, Ephemeroptera were highest at site 2 and

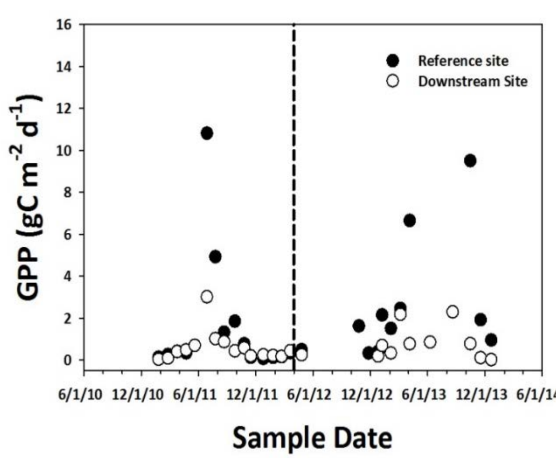

Figure 10**.** Comparison of mean GPP between site 1 control, (●) and site 4 impacted (○) sites before and after the NG infrastructure development and logging occurred within the Gulf Mtn. WMA along the SFLRR, which is depicted by the dotted line. There were no significant interactions between the BA and CI factors within the 2-way rmANOVA.

lowest at site 3 (P<0.001) and Plecoptera had the highest densities at site 4 and lowest at site 2 (P=0.002). Overall, Ephemeroptera, Plecoptera, and Trichoptera (EPT) combined densities were greatest at site 1 (P=0.007), and lowest at site 3. Unlike total macroinvertebrate density, we found a significant effect of logging and pipeline installation on EPT taxa when comparing the reference site 1 and downstream site 4 (P=0.023; Table 2; Figure 12C). The EPT density was greater in the reference site compared to site 4, which is interpreted as a decline in EPT taxa in the downstream reach. In particular, total and EPT density tended to be lower downstream compared to the reference the fall following NG and logging disturbance. There were no significant effects of logging and pipeline installation on a particular common family that included dipteran families: non-Tanypodinae Chironomids and Tanypodinae Chironomids; Ephemeropteran families: Baetidae, Caeniidae, Heptageniidae, and Leptophlebidae; Plecopteran families: Capniidae, Chloroperlidae, and Perlidae; and Trichopteran families: Hydrophilidae, and Polycentropodidae. While, no one family likely drove the EPT relationship, increasing densities of the Ephemeroptera family's Baetidae, Caeniidae, and Heptageniidae and Plecoptera family Capniidae were collectively driving the response.

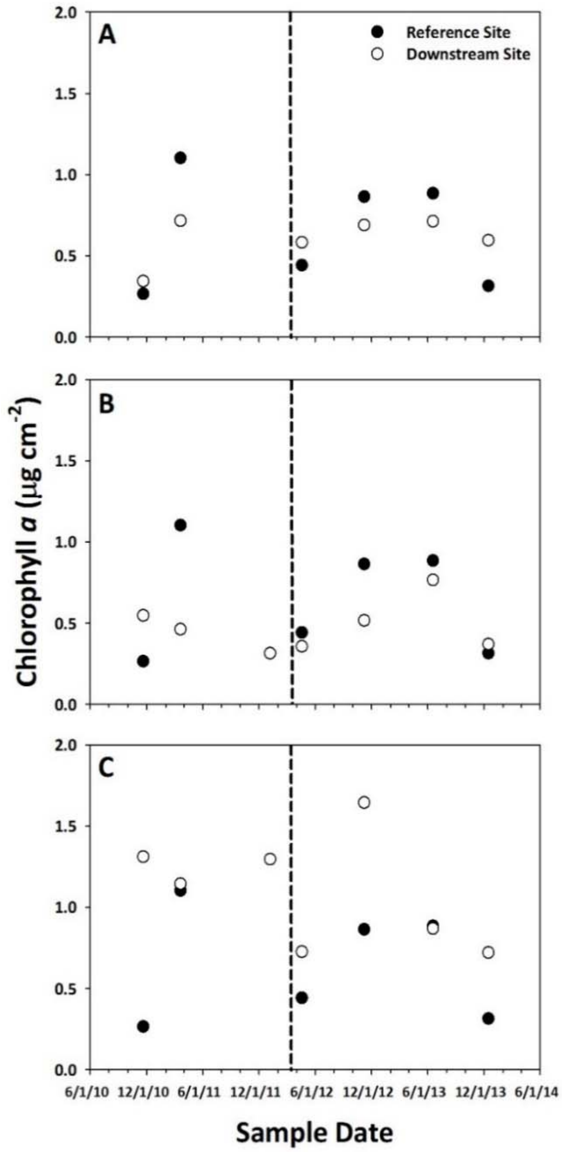

Figure 9. Comparison of mean Chl *a* between control (●) and impacted (○) sites before and after the NG infrastructure development and logging occurred within the Gulf Mtn. WMA along the SFLRR, which is depicted by the dotted line. The control site (site 1) is individually compared to each of the impacted sites (2-4) with 1V2 (A), 1V3 (B), and 1V4 (C). There were no significant interactions between the BA and CI factors within the 2-way rmANOVA.

Conclusions

Water quality within the ~14 km study reach of the SFLRR appeared to be minimally impacted by human activities, as demonstrated by low concentrations of all the physical and chemical parameters evaluated in the current study. The data obtained provide important information on the water quality representing baseline conditions throughout all of the sample periods. However, samples were collected during base flow conditions, and storm events may impact water quality via surface runoff of sediments and bound chemicals and potential overflow of polluted capture water.

Similar to the physico-chemical parameters, fine benthic sediments, as well as algal biomass and production, showed no long term changes as a result of NG development or logging practices. Both sediments and Chl *a* were elevated in the sample period following the disturbance (Fall 2012) at downstream sites, but these values all returned to normal the following sample period. This indicates that any disturbance that may have occurred resulted in a pulse response of the variables measured. Overall, when taxa were analyzed separately, macroinvertebrate densities were not affected by the NG development; however there was a significant effect on EPT taxa when analyzed as a group, which are commonly sensitive taxa. Small changes in the watershed (from logging or pipeline installation) often disturb the most sensitive aquatic organisms even when few abiotic changes are detected. However, the effect on EPT taxa was short lived and showed signs of returning to normal conditions during the last sample period.

The degree to which GMWMA watersheds were developed for NG activity was relatively low compared to development outside the GMWMA within the Fayetteville shale. This low level of NG activity might also explain the lack of detectable impact along the study reach of the SFLRR for most of the variables analyzed. Previous work within the Fayetteville shale region of north central Arkansas outside of the GMWMA found well pad densities ranging from 0.06 – 1.67 pads km^{-2} and pipeline densities as high as 1.44 km km^{-2} (Austin et al. 2015). Well pad density at the SFLRR sites ranged from 0.08–0.15 pads km^{-2} and pipeline density was low in comparison at 0.01 km km^{-2} (Table 1); additionally, as noted earlier, sites 2–4 of the SFLRR were impacted by logging which covered 0.40 km^2 or a percent catchment area cleared of 0.21–0.29%. The effectiveness of BMPs would be more appropriately tested in watersheds where NG development match the average pace within the shale play of interest.

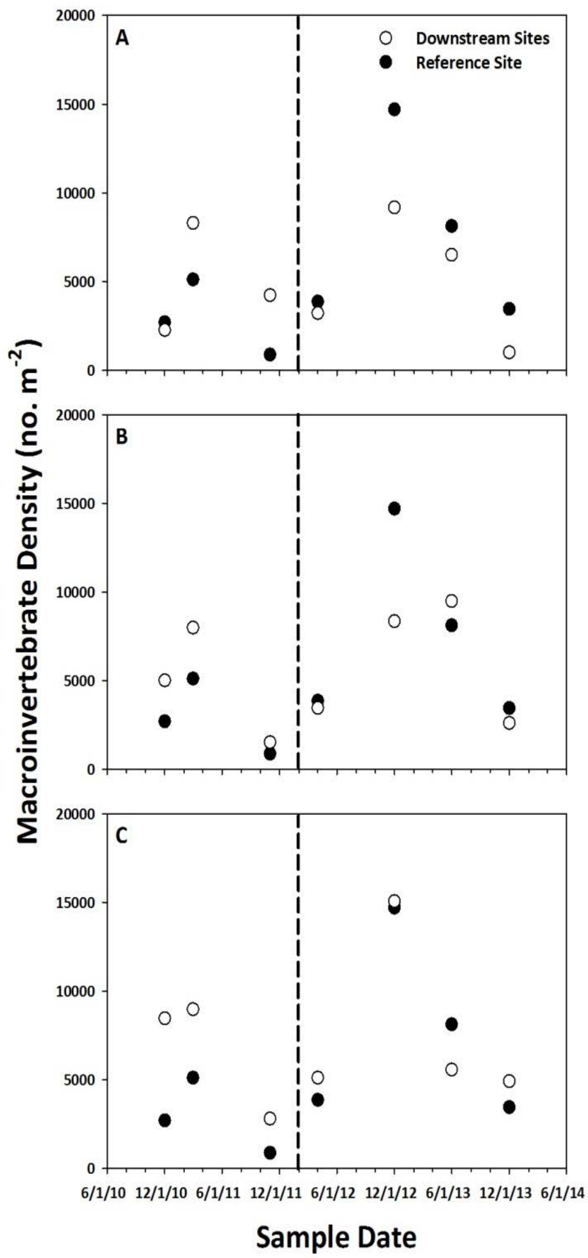

Figure 11. Comparison of mean macroinvertebrate densities between reference (●) and downstream (○) sites before and after the NG infrastructure development and logging occurred within the Gulf Mtn. WMA along the SFLRR, which is depicted by the dotted line. The reference site (site 1) is individually compared to each of the downstream sites (2-4) with 1V2 (A), 1V3 (B), and 1V4 (C). There were no significant interactions between the BA and CI factors within the 2-way rmANOVA.

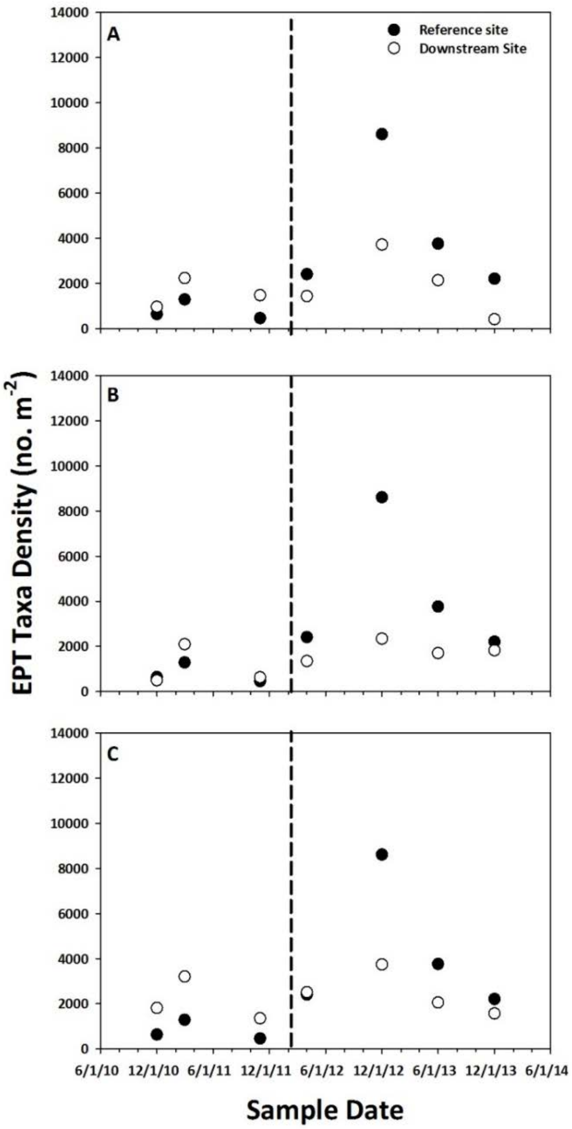

Figure 12. Comparison of mean EPT taxa densities between reference (●) and downstream (○) sites before and after the NG infrastructure development and logging occurred within the Gulf Mtn. WMA along the SFLRR, which is depicted by the dotted line. The reference site (site 1) is individually compared to each of the downstream sites (2-4) with 1V2 (A), 1V3 (B), and 1V4 (C). There were no significant interactions between the BA and CI factors within the 2-way rmANOVA.

Before-After Control-Impact designs are most effective at detecting disturbances that elicit a press or ramp response in the impacted site. A press change is one where the response variable changes quickly following a disturbance reaching a new constant level, whereas ramp responses changes steadily increasing or decreasing over time, eventually reaching a new constant level (Lake 2000). As the 2-Way rmANOVA is examining each point in time as an individual replicate before or after the disturbance, pulse events are lost among the mean measurement. Tailoring sampling events to catch elevated values physico-chemical parameters associated with this pulse type disturbance (for example, by sampling storm events) may result in detecting a significant change following the disturbances in future studies.

Unconventional NG development will likely continue to spread throughout out the major plays in the U.S. as NG has become the forefront of energy production in the U.S. (Malakoff 2014). In the future, as development continues across plays, more frequent water sampling, particularly during the first storm event after watershed development, is recommended. Additionally, sampling biological response variables, such as algal biomass and macroinvertebrates, should be planned to account for the pulse nature of this disturbance. This study provides results of one of the first reported BACI analyses of the potential effectiveness of BMPs at mitigating NG development impacts. At this current low density of NG activity, it appears that the BMPs implemented in the GMWMA were effective at preventing long term changes in water quality, algal biomass, GPP and sediments in the main stem of the SFLRR, though short term changes in these variables may be expressed in changes in EPT taxa densities at the downstream sites.

This project collected data on the physical, chemical and biological quality of the SFLRR, showing that water quality (based on the measured parameters) did not change over the four year study (2010 through 2014), with the exception of EPT taxa, in response to the low density of NG activities that occurred within the GMWMA. However, this study funded by the AGFC provided essential baseline information that can be used to evaluate water quality at the SFLRR in the future should NG activities expand within the GMWMA. The SFLRR flowing through the GMWMA is a unique water resource with chemical concentrations and biological diversity reflective high water quality.

Literature Cited

Allen, D.T., V.M. Torres, J. Thomas, D.W. Sullivan, M. Harrison, A. Hendler, S.C. Herndon, C.E. Kolb, M.P. Fraser, A.D. Hill, B.K. Lamb, J. Miskimins, R.F. Sawyer, and J.H. Seinfeld. 2013. Measurements of methane emissions at natural gas production sites in the United States. Proceedings of the National Academy of Science. 110: 17768-17773.

Alvarez, R.A., S.W. Pacala, J.J. Winebrake, W.L Chameides, and S.P. Hamburg. 2012. Greater focus needed on methane leakage from natural gas infrastructure. Proceedings of the National Academy of Science. 109: 6435-6440.

APHA (American Public Health Association). 2005. *Standard Methods for the Examination of Water and Wastewater*. (21st edn.). American Public Health Association: Washington D.C. 1368 pp.

Austin, B.J., N. Hardgrave, E. Inlander, C. Gallipeau, S. Entrekin, and M.A. Evans-White. 2015. Stream primary producers relate positively to watershed natural gas measures in north-central Arkansas. Science of the Total Environment. 529: 54-64.

Bailey, B.W., B.E. Haggard and L.B. Massey. 2012. Water Quality Trends Across Select 319 Monitoring Sites in Northwest Arkansas. AWRC MSC Publication 365, available at: http://www.uark.edu/depts/awrc/index.html.

Bernot, M.J., D.J. Sobota, R.O. Hall, JR., P.J. Mulholland, W.K. Dodds, J.R. Webster, J.L. Tank, L.R. Ashkenas, L.W. Cooper, C.N. Dahm, S.V. Gregory, N.B. Grimm, S.K. Hamilton, S.L. Johnson, W.H. McDowell, J.L. Meyer, B. Peterson, G.C. Poole, H.M. Valett, C. Arango, J.L. Beaulieu, A.J. Burgin, C. Crenshaw, A.M. Helton, L. Johnson, J. Merriam, B.R. Niederlehner, J.M. O'Brien, J.D. Potter, R.W. Sheibley, S.M. Thomas, K. Wilson. 2010. Inter-regional comparison of land-use effects on stream metabolism. Freshwater Biology 55:1874-1890.

Birdsong, B. 2011. Wildlife Management Area Details. Acessed February 2nd, 2012. http://www.agfc.com/hunting/Pages/wmaDetails.

Bott, T.L. 1996. Primary productivity and community respiration. Pages 533-556 *in* Methods in Stream Ecology, F. Richard Hauer and G.A. Lamberti (eds), Academic Press, New York, NY, USA.

Dodds, W.K., J.R. Jones, and E.B. Welch. 1998. Suggested classification of stream trophic state: distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. Water Resources. 32: 1455-1462.

EIA (Energy Information Administration). 2013. Annual Energy Outlook 2013: with projections to 2040. U.S. Department of Energy; Washington, D.C.

Entrekin, S., M. Evans-White, B. Johnson, and E. Hagenbuch. 2011. Rapid expansion of natural gas development poses a threat to surface waters. Frontiers in Ecology and the Environment. 9:503-511.

Evans-White, M.A., B.E. Haggard and J.T. Scott. 2013. A Review of Stream Nutrient Criteria Development in the United

States. J. Environ. Qual. 42: 1002-1014. doi:10.2134/jeq2012.0491

Green, R.H. 1979. *Sampling design and statistical methods for environmental biologists.* John Wiley and Sons, Inc. United States. 257pp.

Johnson, E., B.J. Austin, E. Inlander, C. Gallipeau, M.A. Evans-White, and S. Entrekin. 2015. Stream macroinvertebrate communities across a gradient of natural gas development in the Fayetteville Shale. Science of the Total Environment. 530-531: 323-332.

Kintisch, E. 2014. A bold baby step on emissions. Science. 344: 1070-1071.

Kresse, T., N. Warner, P. Hays, A. Down, A. Vengosh, and R. Jackson. 2012. Shallow groundwater quality and geochemistry in the Fayetteville Shale gas-production area, north-central Arkansas, 2011. U.S. Geological Survey Scientific Investigations Report 2012-5273.

Lake PS. 2000. Disturbance, patchiness, and diversity in streams. Journal of the North American Benthological Society 19*:* 573–592.

Lamberti, G.A., S.V. Gregory, L.R. Ashkenas, R.C. Wildman, and K.M.S. Moore. 1991. Stream ecosystem recovery following a catastrophic debris flow. Canadian Journal of Fisheries and Aquatic Sciences. 48:196-208. 116

Lohman, K., J.R. Jones and B.D. Perkins. 1992. Effects of nutrient enrichment and flood frequency on periphyton biomass in Northern Ozark streams. Canadian Journal of Fisheries and Aquatic Sciences. 49: 1198-1205.

Lohman, K., J.R. Jones, and C. Baysinger-Daniel. 1991. Experimental evidence for nitrogen limitation in a Northern Ozark stream. 1991. Journal of the North American Benthological Society. 10: 14-23.

Malakoff, D. 2014. The Gas Surge. Science. 344: 1464-1467.

Merritt, R., K.W. Cummins, and M. Berg. 2008. An Introduction to the Aquatic Insects of North America. 4th edition. Kendall Hunt, Dubuque, IA.

Miller, S.M., S.C. Wofsy, A.M. Michalak, E.A. Kort, A.E. Andrews, S.C. Biraud, E.J. Dlugokencky, J. Eluszkiewicz, M.L. Fischer, G. Janssens-Maenhout, B.R. Miller, J.B. Miller, S.A. Montzka, T. Nehrkorn, and C. Sweeney. 2013. Anthropogenic emissions of methane in the United States. Proceedings of the National Academy of Science. 110: 20018-20022.

Olmstead, S.M., L.A. Muehlenbachs, J.S. Shih, Z. Chu, and A.J. Krupnick. 2013. Shale gas development impacts on surface water quality in Pennsylvania. Proceedings of the National Academy of Science. 110: 4962-4967.

Owens, M. 1974. Measurements on non-isolated natural communities in running waters. Pages 111-119 *in* R.A. Vollenweider (editor). A manual on methods for measuring primary production in aquatic environments. Blackwell Scientific Publications, Oxford, UK.

Petersen, J.C., B.G. Justus., and B.J. Meredith. 2014. Effects of land use, stream habitat, and water quality on biological communities in wadeable streams in the Illinois River Basin of Arkansas, 2011 and 2012. U.S. Geological Survey Scientific Investigations Report 2014-5009, http://dx.doi.org/10.3133/sir-20145099.

Prud'Homme, B.A. and J.G. Greis. 2002. Best management practices in the South. Southern Forest Resource Assessment. 519-535.

Rahm, B.G. and S.J. Riha. 2014. Evolving shale gas management: Water resource risks, impacts, and lessons learned. Environmental Science: Processes Impacts. 16: 1400-1412. 117

Sartory, D.P. and J.U. Grobbelaar. 1984. Extraction of chlorophyll a from freshwater phytoplankton for spectrophotometric analysis. Hydrobiologia 114: 177-187.

Shahidehpour, M., Y. Fu, and T. Wiedman. 2005. Impact of natural gas infrastructure on electric power systems. Proceedings of the IEEE. 93:1042-1056.

Steinman, A. D. and G.A. Lamberti. 1996. Biomass and pigments of benthic algae. Pages 295-313 *in* Methods in Stream Ecology, F. Richard Hauer and G.A. Lamberti (eds), Academic Press, New York, NY, USA.

Stewart, K., B. Stark, and J. Stanger. 1993. Nymphs of North American stonefly Genera (Plecoptera). 2nd edition. University of North Texas Press, Denton, Texas.

U. S. Fish and Wildlife Service. 2009. Arkansas best management practices for natural gas pipeline construction and maintenance activities in the Fayetteville Shale area, upper Little Red River watershed. U. S. Fish and Wildlife Service, Arkansas Ecological Services Field Office, Conway, Arkansas. 42 pp. + appendices.

U.S. Fish and Wildlife Service. 2007. Best management practices for Fayetteville Shale natural gas activities. U.S. Fish and Wildlife Service. Conway, Arkansas. 30pp.

Waters, T., 1969. Subsampler for dividing large samples of stream invertebrate drift. Limnol. Oceanogr. 14, 813–815.

Wiggins, G.B., 1996. Larvae of the North American Caddisfly Genera (Trichoptera). 2nd edition. University of Toronto Press, Toronto, Canada.

Wiley, M.J., L.L Osbourne, and R.W. Larimore. 1990. Longitudinal structure of an agricultural prairie river system and its relationship to current stream ecosystem theory. Canadian Journal of Fisheries and Aquatic Sciences 47: 373-384.

Williams, H. F. L., D.L. Havens, K.E. Banks, and D.J. Wachal. 2008. Field-based monitoring of sediment runoff from natural gas well sites in Denton County, Texas, USA. Environmental Geology 55: 1463-1471.

Young, R.G., and A.D. Huryn. 1996. Interannual variation in discharge controls ecosystem metabolism along a grassland river continuum. Canadian Journal of Fisheries and Aquatic Sciences 53: 2199-2211.

Appendix A. Descriptive statistics for the mean, minimum and maximum monthly values of discharge, water temperature, specific conductance, dissolved oxygen, pH and turbidity at Site 1, USGS 07075250, along the South Fork of the Little Red River for project water years 1 (2010-2011), 2 (2011-2012), 3 (2012-2013) and 4 (2013-2014).

	Discharge (CFS)			Temperature (°C)			Specific Conductance (µS cm^{-1})			Dissolved Oxygen (mg L^{-1})			pH			Turbidity (FNU)		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
WY 1	34.3	0.1	541.7	14.3	1.3	26.9	30.7	17.8	81.2	8.6	1.4	13.3	6.6	6.1	6.9	5.6	0.7	133.3
SEP	23.7	0.4	186.2	21.5	18.2	24.2	29.9	25.3	32.5	7.6	5.0	8.8	6.4	6.1	6.6	3.5	1.0	18.2
OCT	1.6	1.4	2.0	15.4	11.5	18.1	31.3	29.6	33.4	8.0	5.7	9.8	6.5	6.3	6.7	1.0	0.7	1.5
NOV	8.0	3.2	14.2	10.2	6.8	12.9	31.7	30.0	33.0	8.7	7.5	11.1	6.6	6.4	6.9	1.2	0.8	2.4
DEC	10.2	3.8	51.6	4.9	3.1	9.1	28.0	24.0	29.5	10.8	9.9	11.7	6.9	6.8	6.9	3.3	1.7	14.4
JAN	10.0	4.4	40.3	4.1	1.3	8.0	24.8	24.0	25.2	11.9	10.3	13.3	6.9	6.8	6.9	4.4	2.4	12.6
FEB	103.6	24.2	541.7	6.1	1.4	9.9	22.1	20.9	23.6	11.5	10.3	13.0	6.8	6.6	6.8	7.8	4.2	20.5
MAR	71.4	23.2	195.7	10.3	8.1	14.5	21.6	20.9	23.1	10.5	9.3	11.0	6.6	6.6	6.7	5.0	2.9	10.3
APR	119.0	26.3	540.9	13.9	10.2	17.1	20.9	17.8	22.9	9.8	9.1	10.6	6.6	6.2	6.7	20.4	3.0	133.3
MAY	XX	XX	XX	15.3	11.9	18.4	21.9	21.9	21.9	9.7	9.0	10.7	6.5	6.4	6.6	24.7	16.2	33.3
JUN	1.4	0.8	2.0	25.9	25.5	26.3	33.7	31.2	37.4	5.4	4.3	6.3	6.3	6.2	6.5	2.1	1.5	4.2
JUL	0.3	0.1	0.9	26.2	25.4	26.9	51.4	34.9	64.9	2.8	1.4	4.4	6.2	6.1	6.3	4.2	1.3	7.7
UG	4.8	0.1	49.0	25.6	23.2	26.8	43.5	28.6	81.2	5.3	1.7	7.9	6.5	6.1	6.7	5.5	1.2	22.4
WY 2	76.9	0.0	1435.4	15.1	4.4	27.2	26.3	12.0	51.3	8.8	2.7	13.2	6.4	6.0	6.7	6.9	0.2	216.2
SEP	0.1	0.0	0.4	20.6	17.5	26.2	36.8	34.5	39.9	5.9	4.4	6.8	6.5	6.4	6.6	1.3	1.1	1.5
OCT	0.1	0.0	0.2	15.7	11.7	18.2	37.2	33.4	40.5	6.2	4.2	8.2	6.4	6.3	6.5	1.6	1.1	2.6
NOV	113.0	0.4	1137.7	12.2	9.0	15.0	25.8	20.0	33.5	9.6	7.8	10.9	6.4	6.1	6.6	2.0	2.0	2.0
DEC	97.4	2.2	687.0	8.3	6.7	10.8	16.2	12.0	21.0	11.6	10.8	12.1	6.3	6.2	6.4	14.5	2.8	36.7
JAN	144.5	47.6	659.9	6.8	4.8	8.9	18.8	18.0	20.0	12.3	11.6	13.0	6.5	6.4	6.6	3.5	2.5	10.3
FEB	147.6	51.0	762.1	7.7	4.4	11.4	18.1	16.9	20.1	12.1	11.0	13.2	6.5	6.4	6.6	2.5	2.2	3.4
MAR	380.4	23.9	1435.4	12.9	9.2	16.5	17.7	14.8	20.0	10.8	9.8	11.8	6.4	6.2	6.6	38.4	2.4	216.2
APR	35.7	4.3	115.2	16.2	14.1	19.6	20.8	19.1	24.3	9.4	8.6	10.0	6.6	6.2	6.7	3.3	2.6	10.2
MAY	2.0	0.9	3.9	21.6	18.4	24.0	29.8	25.4	33.4	6.5	2.7	8.9	6.3	6.1	6.5	2.1	1.5	2.9
JUN	0.1	0.1	0.1	23.6	21.4	26.2	38.1	32.9	46.6	4.9	3.1	6.0	6.2	6.0	6.4	2.0	1.5	5.5
JUL	0.1	0.0	0.2	26.2	24.5	27.2	XX	XX	XX	XX	XX	XX	6.4	6.4	6.4	1.8	0.2	5.2
AUG	0.0	0.0	0.4	24.3	24.0	24.5	48.2	42.2	51.3	XX	XX	XX	XX	XX	XX	2.5	1.2	4.7

Appendix A Con. Descriptive statistics for the mean, minimum and maximum monthly values of discharge, water temperature, specific conductance, dissolved oxygen, pH and turbidity at Site 1, USGS 07075250, along the South Fork of the Little Red River for project water years 1 (2010-2011), 2 (2011-2012), 3 (2012-2013) and 4 (2013-2014).

	Discharge (CFS)			Temperature (°C)			Specific Conductance ($\mu S\ cm^{-1}$)			Dissolved Oxygen ($mg\ L^{-1}$)			pH			Turbidity (FNU)		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
WY 3	64.4	0.2	709.2	14.6	5.2	27.7	24.9	17.9	43.7	9.6	6.9	12.3	6.0	5.4	6.6	4.8	0.2	190.3
SEP	4.5	0.2	57.5	22.1	18.5	26.7	35.3	27.0	43.7	XX	XX	XX	5.9	5.4	6.4	3.5	0.2	29.9
OCT	23.1	3.7	121.8	15.4	10.9	18.6	27.0	24.6	28.3	8.7	6.9	9.6	6.0	5.7	6.3	2.7	0.9	17.9
NOV	13.1	2.8	104.4	10.4	7.1	13.5	26.0	24.0	28.2	10.8	9.7	11.6	6.3	6.1	6.4	1.6	0.8	10.9
DEC	19.4	2.6	41.7	8.8	5.2	13.4	23.7	22.0	26.1	10.9	9.3	12.2	6.1	5.9	6.2	2.1	0.9	10.1
JAN	108.5	35.0	515.1	6.9	5.3	9.7	21.4	17.9	23.5	11.5	9.1	12.3	6.0	5.9	6.1	12.2	1.6	190.3
FEB	146.4	60.8	475.3	7.1	5.5	8.7	19.9	18.6	21.0	11.4	10.4	12.2	5.9	5.7	6.0	4.2	2.0	15.3
MAR	134.4	57.1	457.1	8.2	5.8	10.8	19.2	18.3	20.4	11.0	9.7	12.2	5.8	5.5	5.9	4.7	2.3	23.1
APR	156.9	68.8	599.4	12.3	8.7	14.8	19.2	18.2	20.3	9.7	8.3	11.0	5.8	5.7	6.0	14.4	2.0	61.5
MAY	89.1	30.3	341.8	14.9	11.0	17.5	20.9	18.1	23.0	8.3	7.2	10.5	5.7	5.4	6.1	3.6	2.3	14.6
JUN	70.4	1.5	709.2	21.4	16.8	27.7	24.9	21.2	29.1	7.6	6.9	8.3	5.9	5.5	6.4	3.5	1.5	31.3
JUL	0.6	0.4	1.3	25.0	22.6	26.8	32.1	28.3	35.1	7.6	7.0	8.1	6.4	6.2	6.6	1.9	1.1	14.6
AUG	16.0	0.7	85.0	22.8	19.1	26.1	30.2	27.5	32.4	7.8	7.3	8.1	5.8	5.4	6.2	4.0	1.3	21.9
WY 4	69.0	0.3	1161.6	14.2	4.0	27.3	25.2	18.0	35.4	9.5	6.9	12.4	5.9	5.4	6.7	4.5	0.7	59.9
SEP	0.4	0.3	0.8	22.4	18.7	25.8	33.0	31.2	35.4	7.7	7.1	8.3	6.2	6.1	6.4	1.6	1.2	2.5
OCT	0.8	0.4	4.8	16.7	11.0	23.2	31.1	29.1	33.8	8.5	7.1	10.1	6.1	5.7	6.3	1.4	0.7	2.4
NOV	17.1	4.7	156.3	10.6	6.1	14.5	28.8	26.3	32.0	9.9	7.9	11.4	5.8	5.6	6.1	7.9	0.7	38.4
DEC	117.2	6.4	1161.6	7.1	4.7	11.6	23.3	19.1	26.1	11.3	9.6	12.0	5.7	5.6	5.8	5.2	1.5	58.5
JAN	102.5	28.0	649.6	4.9	4.0	6.4	21.3	18.6	23.0	11.8	11.4	12.4	5.7	5.5	5.8	4.3	1.6	26.1
FEB	38.9	28.4	49.8	5.5	4.2	7.2	21.4	20.9	22.0	11.2	10.1	12.2	5.5	5.4	5.6	2.0	1.6	3.9
MAR	134.4	28.3	1050.0	7.6	4.3	9.4	20.1	18.0	21.5	10.9	9.9	12.0	5.6	5.4	5.9	4.5	1.3	50.8
APR	157.6	56.2	450.3	12.0	10.1	14.5	20.1	18.0	21.9	9.7	8.0	11.2	5.8	5.4	6.0	8.5	1.3	59.2
MAY	189.1	33.4	1159.1	15.5	12.4	18.0	20.8	18.7	22.5	9.2	8.1	11.0	5.8	5.5	6.0	10.7	2.7	59.9
JUN	59.9	17.2	207.2	19.7	17.4	22.5	23.1	21.7	24.1	8.2	7.6	9.1	6.0	5.5	6.4	4.0	2.4	10.1
JUL	8.9	2.7	30.1	22.8	20.3	25.3	26.5	24.4	28.5	7.8	7.5	8.6	6.2	6.0	6.4	3.0	1.0	18.5
AUG	0.9	0.4	2.2	25.1	21.4	27.3	32.3	29.1	35.1	7.6	6.9	8.0	6.5	6.1	6.7	1.2	0.7	5.5

Appendix B. Descriptive statistics for the mean, minimum and maximum monthly values of discharge, water temperature, specific conductance, dissolved oxygen, pH and turbidity at Site 2, USGS 07075270, along the South Fork of the Little Red River for project water years 1 (2010-2011), 2 (2011-2012), 3 (2012-2013) and 4 (2013-2014).

	Discharge (CFS)			**Temperature (°C)**			**Specific Conductance (µS cm^{-1})**			**Dissolved Oxygen (mg L^{-1})**			**pH**			**Turbidity (FNU)**		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
WY 1	117.1	0.1	7357.3	15.7	0.9	30.0	33.6	20.7	55.4	9.3	4.7	14.0	6.9	6.6	7.3	5.7	0.8	140.8
SEP	24.3	1.0	208.9	22.6	19.2	25.4	36.3	24.7	43.8	6.9	4.7	8.4	6.8	6.7	7.0	6.4	1.9	40.4
OCT	3.1	2.0	4.7	16.1	13.1	19.1	37.9	35.2	41.9	7.7	6.3	8.9	6.8	6.6	7.0	1.8	1.1	2.7
NOV	16.0	5.1	38.7	10.6	7.8	13.1	41.9	39.0	42.9	8.3	7.0	10.9	6.8	6.6	7.0	1.5	0.8	1.8
DEC	34.2	26.4	82.6	4.7	3.8	6.8	34.1	28.5	38.0	12.2	11.2	12.6	7.1	7.0	7.2	2.1	1.4	5.8
JAN	19.5	10.5	59.3	3.9	1.9	7.9	27.6	26.0	29.0	12.8	11.5	13.9	7.0	6.9	7.1	5.0	2.2	12.8
FEB	95.6	14.7	692.6	6.2	0.9	11.1	23.6	22.0	28.2	12.1	10.6	14.0	6.9	6.6	7.0	10.3	4.4	45.0
MAR	60.1	13.0	271.0	10.9	8.5	15.3	27.5	22.7	31.5	10.9	9.8	11.5	6.9	6.7	7.0	4.1	2.4	11.3
APR	656.0	13.4	7357.3	14.4	10.2	18.2	26.0	21.9	29.5	10.1	8.9	11.1	6.9	6.6	7.0	17.1	3.2	140.8
MAY	409.4	25.5	3939.8	16.8	11.9	21.4	25.5	20.7	29.9	9.9	9.1	11.1	7.0	6.8	7.3	9.8	5.0	39.1
JUN	13.8	5.9	49.0	25.9	22.0	28.0	34.7	27.0	41.3	7.4	5.2	9.3	6.9	6.7	6.9	2.6	0.9	5.8
JUL	3.5	0.1	12.5	29.3	28.0	30.0	46.6	41.1	52.6	5.7	5.3	6.2	6.8	6.8	6.9	1.4	0.8	2.2
AUG	14.4	0.1	142.0	27.2	23.7	30.0	40.7	29.5	55.4	6.9	5.4	8.5	6.8	6.7	7.0	5.8	1.0	36.6
WY 2	128.1	0.0	5170.2	17.1	4.5	29.9	36.0	15.7	72.7	9.1	4.8	13.0	6.5	6.1	6.9	4.5	0.8	63.9
SEP	0.2	0.0	1.1	21.2	18.2	27.2	41.9	38.1	44.0	6.3	5.9	6.9	6.7	6.6	6.8	1.3	0.8	1.7
OCT	0.1	0.0	0.6	15.4	11.9	17.9	45.8	44.0	48.1	7.0	6.0	7.8	6.7	6.7	6.9	1.8	1.0	2.4
NOV	377.3	0.6	4909.2	11.9	9.0	14.4	31.5	20.9	48.2	9.9	6.9	11.9	6.5	6.2	6.7	8.3	1.5	47.8
DEC	317.4	18.4	2190.2	8.3	6.7	10.8	22.5	19.4	25.0	11.9	11.0	12.5	6.3	6.2	6.5	5.6	3.0	23.3
JAN	115.0	7.5	855.4	6.7	4.7	8.9	23.7	21.3	25.4	12.3	11.5	13.0	6.5	6.3	6.6	4.4	2.6	22.0
FEB	105.0	9.6	1073.6	8.0	4.5	11.7	22.2	20.0	24.1	11.9	11.1	13.0	6.6	6.4	6.6	4.1	2.7	28.8
MAR	608.0	4.7	5170.2	13.2	9.6	17.0	19.0	15.7	22.0	9.9	9.4	10.4	6.4	6.1	6.6	10.3	2.9	63.9
APR	5.0	0.3	20.7	17.3	15.3	21.1	22.8	21.0	26.6	9.0	8.1	9.5	6.5	6.4	6.6	3.9	3.2	8.2
MAY	0.7	0.0	1.2	22.8	20.0	25.8	34.1	27.2	40.2	7.3	6.0	8.4	6.5	6.4	6.6	2.0	0.9	3.3
JUN	0.0	0.0	0.0	25.7	24.0	28.3	47.0	40.7	54.9	5.4	4.8	5.9	6.5	6.3	6.6	2.5	1.3	5.8
JUL	0.0	0.0	0.0	28.8	27.5	29.7	61.9	55.1	67.4	XX	XX	XX	6.6	6.5	6.7	5.0	4.3	5.5
AUG	0.0	0.0	0.0	26.8	24.4	29.9	70.1	65.7	72.7	XX	XX	XX	6.7	6.6	6.9	5.1	3.9	6.1

Appendix B Con. Descriptive statistics for the mean, minimum and maximum monthly values of discharge, water temperature, specific conductance, dissolved oxygen, pH and turbidity at Site 2, USGS 07075270, along the South Fork of the Little Red River for project water years 1 (2010-2011), 2 (2011-2012), 3 (2012-2013) and 4 (2013-2014).

	Discharge (CFS)			**Temperature (°C)**			**Specific Conductance ($\mu S\ cm^{-1}$)**			**Dissolved Oxygen ($mg\ L^{-1}$)**			**pH**			**Turbidity (FNU)**		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
WY 3	120.4	0.0	3304.5	15.3	3.7	29.3	29.8	19.0	66.7	9.8	4.4	13.6	6.7	6.3	7.0	5.0	1.0	173.1
SEP	1.0	0.0	8.5	23.1	20.0	27.3	56.9	31.3	66.7	XX	XX	XX	6.7	6.6	6.9	6.4	5.1	8.3
OCT	28.3	2.4	181.9	15.5	10.8	20.0	30.5	27.0	33.5	9.7	8.1	10.8	6.9	6.5	7.0	5.5	1.4	53.0
NOV	26.5	13.9	106.7	9.6	6.3	12.4	29.1	25.0	33.1	10.8	9.4	12.1	6.7	6.6	6.9	2.1	1.1	9.1
DEC	38.0	13.4	79.7	7.4	3.7	13.1	26.0	24.0	29.0	11.9	10.1	13.6	6.7	6.5	6.9	2.4	1.4	6.2
JAN	408.5	41.3	3304.5	6.2	4.5	9.8	22.8	19.3	25.0	12.9	11.7	13.6	6.7	6.3	6.8	14.2	2.0	173.1
FEB	328.8	88.8	1142.9	7.0	5.2	8.8	20.7	19.0	21.8	12.1	11.6	12.7	6.6	6.4	6.9	4.7	2.5	16.9
MAR	181.9	21.6	787.1	8.5	5.5	11.7	20.0	19.0	21.0	11.7	10.7	12.7	6.6	6.5	6.7	3.9	2.3	18.7
APR	216.8	27.7	1134.8	13.3	9.0	16.4	20.6	19.8	21.4	10.4	9.4	11.6	6.7	6.4	6.7	6.8	2.3	39.3
MAY	111.7	14.6	480.1	17.4	11.0	21.4	22.5	19.0	25.9	9.3	8.2	10.9	6.7	6.6	6.8	4.5	2.9	20.0
JUN	95.4	2.3	962.9	23.7	17.6	29.3	28.1	20.4	37.4	7.6	5.5	9.3	6.6	6.5	6.7	4.1	1.2	33.3
JUL	1.2	0.3	3.3	26.5	24.9	27.5	44.7	38.1	52.9	5.3	4.5	6.1	6.6	6.5	6.7	1.6	1.0	2.2
AUG	22.0	3.1	145.6	25.1	21.3	27.7	35.8	26.5	48.1	6.2	4.4	7.6	6.6	6.4	6.9	3.9	1.1	14.8
WY 4	116.4	0.0	2816.1	14.7	0.6	27.9	30.7	17.9	56.1	9.1	3.7	14.1	6.3	5.7	6.8	4.2	0.5	90.0
SEP	2.5	1.6	4.3	23.7	20.7	27.4	44.6	39.1	49.2	4.9	3.7	5.9	6.2	6.1	6.5	1.0	0.5	1.4
OCT	2.8	1.6	6.0	17.6	12.3	23.4	52.1	48.0	56.1	5.8	4.5	7.5	6.4	6.2	6.5	1.2	0.6	1.8
NOV	32.7	8.2	238.4	9.9	4.4	14.7	34.6	27.3	48.6	9.9	6.3	12.0	6.2	6.1	6.4	3.7	0.6	17.4
DEC	173.8	18.0	1631.6	5.9	2.7	9.7	25.9	20.5	31.5	11.9	10.2	13.0	6.1	5.7	6.3	5.1	1.3	43.2
JAN	138.6	22.2	1219.5	3.5	0.6	6.4	22.4	19.5	24.0	12.9	11.9	14.1	6.0	5.7	6.3	4.5	2.2	19.7
FEB	37.9	22.8	54.6	4.7	1.2	8.7	22.4	22.0	23.0	12.5	11.2	13.9	6.4	6.3	6.5	2.6	2.2	4.5
MAR	203.7	21.9	1427.6	8.0	2.2	11.5	21.5	19.0	23.0	11.5	10.5	13.3	6.3	5.8	6.6	5.5	2.0	46.7
APR	352.7	85.0	2816.1	13.5	10.6	16.3	20.4	17.9	22.0	9.5	8.3	10.7	6.4	6.0	6.5	9.2	3.2	90.0
MAY	336.1	57.9	2099.8	17.0	12.7	20.9	21.2	19.0	24.0	9.0	8.0	10.0	6.4	6.2	6.7	7.3	2.7	38.7
JUN	97.3	22.8	350.2	21.9	18.6	25.3	24.7	22.0	28.6	8.3	7.5	9.0	6.7	6.6	6.8	4.3	2.8	8.5
JUL	10.9	4.0	36.8	25.0	22.5	27.6	34.2	29.0	37.9	7.2	6.2	7.7	6.5	6.4	6.6	4.2	1.1	23.5
AUG	1.4	0.0	3.8	26.3	23.5	27.9	42.9	37.0	48.3	5.6	4.3	7.2	6.5	6.4	6.7	1.5	1.0	2.3

Appendix C. Annual geometric means for conductivity and ions measured at the four sites along the South Fork of the Little Red River during sample years of 2010 - 2014. Reported values from 2010 only reflect 4 sample periods collected in Nov and Dec.

	Conductivity ($\mu S\ cm^{-1}$)		**Barium ($mg\ L^{-1}$)**		**Calcium ($mg\ L^{-1}$)**		**Magnesium ($mg\ L^{-1}$)**	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
Site 1	26.8	17.0 - 53.0	0.007	0.002 - 0.024	2.020	1.260 - 5.472	0.748	0.430 - 1.614
2010	32.0	28.4 - 33.9	0.013	0.010 - 0.015	2.798	2.409 - 2.963	1.162	1.091 - 1.227
2011	24.8	17.0 - 36.8	0.011	0.002 - 0.024	1.996	1.391 - 3.619	0.784	0.533 - 1.293
2012	25.4	17.8 - 53.0	0.006	0.002 - 0.016	1.975	1.260 - 5.472	0.723	0.430 - 1.614
2013	27.5	20.8 - 40.7	0.004	0.002 - 0.017	1.844	1.436 - 2.773	0.639	0.515 - 0.948
2014	28.7	21.8 - 37.1	0.010	0.003 - 0.016	2.062	1.445 - 2.818	0.730	0.552 - 1.069
Site 2	28.7	18.4 - 54.3	0.008	0.002 - 0.018	2.166	1.130 - 4.452	0.798	0.482 - 1.518
2010	37.9	32.4 - 43.2	0.014	0.011 - 0.016	3.325	2.710 - 3.689	1.365	1.185 - 1.518
2011	27.2	19.0 - 44.3	0.011	0.002 - 0.018	2.081	1.130 - 4.015	0.829	0.553 - 1.480
2012	27.3	18.4 - 54.3	0.007	0.002 - 0.018	2.198	1.302 - 4.452	0.782	0.482 - 1.434
2013	29.4	21.0 - 42.5	0.004	0.002 - 0.016	1.960	1.481 - 3.332	0.675	0.561 - 1.067
2014	28.7	20.3 - 41.9	0.010	0.003 - 0.016	2.150	1.458 - 3.441	0.755	0.552 - 1.257
Site 3	29.0	18.5 - 48.6	0.008	0.002 - 0.020	2.286	1.339 -5.465	0.807	1.484 - 1.477
2010	38.1	33.7 -40.5	0.014	0.011 - 0.016	3.492	2.906 - 3.940	1.390	1.217 - 1.477
2011	28.1	19.0 - 43.2	0.011	0.002 - 0.019	2.248	1.433 - 3.980	0.842	0.554 - 1.442
2012	27.4	18.5 -48.6	0.007	0.002 - 0.018	2.312	1.339 - 5.465	0.775	0.484 - 1.256
2013	27.5	21.5 - 43.1	0.004	0.002 - 0.017	1.990	1.509 - 3.697	0.680	0.555 - 1.139
2014	30.7	22.9 - 46.0	0.011	0.003 - 0.020	2.312	1.463 - 4.052	0.774	0.559 - 1.275
Site 4	31.3	18.9 - 62.5	0.008	0.002 - 0.024	2.517	1.318 - 6.888	0.850	0.496 - 1.734
2010	41.4	36.1 - 45.7	0.014	0.011 - 0.016	3.828	3.163 - 4.269	1.414	1.268 - 1.564
2011	29.9	19.0 - 62.5	0.011	0.002 - 0.020	2.473	1.453 - 6.139	0.879	0.575 - 1.734
2012	30.5	18.9 - 62.3	0.007	0.002 - 0.024	2.624	1.318 - 6.888	0.835	0.496 - 1.530
2013	29.6	22.0 - 52.4	0.004	0.002 - 0.019	2.181	1.595 - 4.922	0.725	0.578 - 1.284
2014	33.1	23.9 - 49.9	0.010	0.002 - 0.018	2.475	1.390 - 4.412	0.810	0.549 - 1.409

Appendix C Con. Annual geometric means for conductivity and ions measured at the four sites along the South Fork of the Little Red River during sample years of 2010 - 2014. Reported values from 2010 only reflect 4 sample periods collected in Nov and Dec.

	Potassium (mg L^{-1})		Sodium (mg L^{-1})		Chloride (mg L^{-1})	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
Site 1	0.813	0.460 - 2.130	1.120	0.771 - 2.813	1.595	0.976 - 4.061
2010	0.897	0.620 - 1.140	1.232	1.706 - 1.381	1.536	1.379 - 1.689
2011	0.734	0.510 - 0.990	0.990	0.836 - 1.291	1.412	1.122 - 1.726
2012	0.744	0.460 - 1.270	1.063	0.771 - 1.335	1.631	0.976 - 2.659
2013	0.956	0.559 - 2.130	1.252	0.800 - 2.145	1.910	1.264 - 4.061
2014	0.819	0.460 - 1.899	1.205	0.936 - 2.813	1.527	1.298 - 2.636
Site 2	0.844	0.460 - 2.075	1.201	0.823 - 3.328	1.507	1.076 - 3.236
2010	1.068	0.670 - 1.490	1.374	1.140 - 1.657	1.493	1.355 - 1.698
2011	0.750	0.520 - 1.180	1.059	0.823 - 1.592	1.428	1.076 - 1.710
2012	0.887	0.550 - 1.580	1.416	0.885 - 3.328	1.421	1.113 - 1.842
2013	0.973	0.525 - 2.075	1.297	0.900 - 2.599	1.824	1.316 - 3.236
2014	0.723	0.460 - 1.208	1.051	0.911 - 1.535	1.370	1.210 - 1.665
Site 3	0.782	0.526 - 1.689	1.120	0.817 - 2.370	1.465	1.051 - 2.784
2010	1.067	0.680 - 1.460	1.402	1.192 - 1.773	1.458	1.341 - 1.617
2011	0.724	0.530 - 1.070	1.046	0.829 - 1.662	1.394	1.136 - 1.673
2012	0.790	0.530 - 1.150	1.165	0.837 - 1.469	1.463	1.051 - 2.770
2013	0.759	0.526 - 1.689	1.110	0.817 - 2.370	1.608	1.110 - 2.784
2014	0.795	0.527 - 1.151	1.102	0.958 - 1.461	1.409	1.258 - 1.630
Site 4	0.843	0.500 - 1.650	1.255	0.811 - 2.496	1.472	0.950 - 2.548
2010	1.222	0.740 - 1.650	1.735	1.339 - 2.183	1.515	1.355 - 1.700
2011	0.744	0.550 - 1.170	1.098	0.843 - 1.861	1.368	1.017 - 1.761
2012	0.859	0.500 - 1.650	1.371	0.811 - 2.073	1.396	0.950 - 1.915
2013	0.818	0.538 - 1.423	1.227	0.865 - 2.496	1.693	1.262 - 2.548
2014	0.893	0.725 - 1.176	1.256	1.044 - 1.891	1.456	1.170 - 1.732

Appendix D. Annual geometric means and ranges for measures of sediments and organic carbon in the four sites along the South Fork of the Little Red River during the sample years of 2010 - 2014. Reported values from 2010 only reflect 4 sample periods collected in Nov and Dec.

		Turbidity (NTU)		TSS (mg L^{-1})		TOC (mg L^{-1})	
		Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
Site 1		2.9	0.9 - 11.1	1.0	0.1 - 17.8	0.61	0.23 - 1.78
	2010	1.6	1.4 - 1.9	0.6	0.2 - 1.5	0.91	0.59 - 1.15
	2011	3.9	1.2 - 11.1	1.3	0.5 - 10.1	0.95	0.59 - 1.68
	2012	2.6	1.2 - 6.1	0.8	0.1 - 3.3	0.51	0.29 - 1.78
	2013	3.1	1.4 - 9.8	1.6	0.4 - 17.8	0.42	0.24 - 0.77
	2014	2.3	0.9 - 3.7	0.7	0.1 - 2.3	0.49	0.23 - 0.77
Site 2		3.2	1.5 - 12.1	1.3	0.1 - 3.5	0.68	0.24 - 2.43
	2010	2.0	1.7 - 2.4	1.2	0.8 - 2.1	1.03	0.57 - 2.01
	2011	3.9	1.5 - 12.1	1.5	0.6 - 2.9	0.90	0.51 - 1.94
	2012	3.0	1.6 - 7.7	1.0	0.1 - 2.6	0.57	0.24 - 2.43
	2013	3.4	1.9 - 7.1	1.6	0.3 - 3.5	0.48	0.25 - 0.83
	2014	2.8	1.8 - 4.3	1.0	0.3 - 1.7	0.69	0.40 - 1.23
Site 3		3.2	1.5 - 12.7	1.3	0.1 - 5.8	0.65	0.22 - 2.14
	2010	1.8	1.6 - 2.2	1.0	0.6 - 1.8	1.00	0.51 - 1.97
	2011	4.2	1.7 - 12.7	1.8	0.7 - 5.8	0.99	0.45 - 2.14
	2012	3.0	1.5 - 8.5	0.9	0.1 - 1.9	0.54	0.22 - 1.68
	2013	3.0	1.6 - 6.5	1.3	0.4 - 2.7	0.42	0.22 - 0.66
	2014	2.9	1.8 - 5.6	1.3	0.5 - 2.9	0.60	0.25 - 1.23
Site 4		3.3	1.2 - 13.8	1.5	0.3 - 7.9	0.75	0.27 - 2.08
	2010	2.0	1.5 - 2.4	1.2	0.4 - 4.0	1.19	0.81 - 2.08
	2011	3.9	1.2 - 13.8	1.5	0.7 - 2.9	0.97	0.57 - 2.04
	2012	2.9	1.3 - 7.8	1.3	0.4 - 2.5	0.62	0.29 - 1.20
	2013	3.8	2.1 - 6.7	1.9	0.8 - 6.6	0.54	0.27 - 0.97
	2014	3.0	1.5 - 5.3	1.6	0.3 - 7.9	0.84	0.54 - 1.22

Appendix E. Annual geometric mean and ranges for trace metals measured at the four sites along the South Fork of the Little Red river during the sample years of 2010 - 2014. Reported values from 2010 only reflect 4 sample periods collected in Nov and Dec.

	Aluminum (mg L^{-1})		Boron (mg L^{-1})		Cadmium (mg L^{-1})		Chromium (mg L^{-1})		Cobalt (mg L^{-1})		Copper (mg L^{-1})	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
Site 1	0.002	0.001 - 0.664	0.017	0.012 - 0.146	0.001	0.001 - 0.006	0.004	0.003 - 0.015	0.002	0.002 - 0.023	0.004	0.004 - 0.013
2010	0.001	0.001 - 0.001	0.012	0.012 - 0.012	0.001	0.001 - 0.001	0.006	0.006 - 0.007	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2011	0.006	0.001 - 0.664	0.012	0.012 - 0.012	0.001	0.001 - 0.002	0.006	0.003 - 0.015	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2012	0.001	0.001 - 0.004	0.014	0.012 - 0.028	0.001	0.001 - 0.003	0.003	0.003 - 0.003	0.003	0.002 - 0.023	0.004	0.004 - 0.008
2013	0.002	0.001 - 0.011	0.016	0.012 - 0.054	0.001	0.001 - 0.001	0.003	0.003 - 0.010	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2014	0.002	0.001 - 0.027	0.039	0.012 - 0.146	0.001	0.001 - 0.006	0.003	0.003 - 0.003	0.002	0.002 - 0.012	0.006	0.004 - 0.013
Site 2	0.003	0.001 - 0.753	0.016	0.012 - 0.092	0.001	0.001 - 0.006	0.004	0.003 - 0.041	0.002	0.002 - 0.025	0.004	0.004 - 0.010
2010	0.001	0.001 - 0.001	0.012	0.012 - 0.012	0.001	0.001 - 0.002	0.007	0.007 - 0.008	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2011	0.006	0.001 - 0.753	0.012	0.012 - 0.012	0.001	0.001 - 0.002	0.005	0.003 - 0.013	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2012	0.001	0.001 - 0.005	0.014	0.012 - 0.021	0.001	0.001 - 0.003	0.004	0.003 - 0.041	0.003	0.002 - 0.025	0.005	0.004 - 0.010
2013	0.002	0.001 - 0.012	0.016	0.012 - 0.042	0.001	0.001 - 0.004	0.004	0.003 - 0.017	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2014	0.003	0.001 - 0.017	0.036	0.012 - 0.092	0.001	0.001 - 0.006	0.003	0.003 - 0.003	0.003	0.002 - 0.011	0.005	0.004 - 0.010
Site 3	0.003	0.001 - 0.686	0.015	0.012 - 0.071	0.001	0.001 - 0.007	0.004	0.003 - 0.018	0.002	0.002 - 0.033	0.004	0.004 - 0.031
2010	0.001	0.001 - 0.001	0.012	0.012 - 0.014	0.001	0.001 - 0.002	0.007	0.005 - 0.008	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2011	0.006	0.001 - 0.686	0.012	0.012 - 0.012	0.001	0.001 - 0.002	0.006	0.003 - 0.018	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2012	0.001	0.001 - 0.004	0.013	0.012 - 0.019	0.001	0.001 - 0.004	0.003	0.003 - 0.007	0.003	0.002 - 0.033	0.005	0.004 - 0.031
2013	0.002	0.001 - 0.012	0.015	0.012 - 0.036	0.001	0.001 - 0.001	0.003	0.003 - 0.012	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2014	0.003	0.001 - 0.024	0.027	0.012 - 0.071	0.001	0.001 - 0.007	0.003	0.003 - 0.008	0.002	0.002 - 0.012	0.005	0.004 - 0.012
Site 4	0.003	0.001 - 0.858	0.016	0.012 - 0.263	0.001	0.001 - 0.007	0.005	0.001 - 0.256	0.002	0.002 - 0.024	0.004	0.004 - 0.029
2010	0.001	0.001 - 0.001	0.012	0.012 - 0.012	0.001	0.001 - 0.002	0.007	0.007 - 0.008	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2011	0.006	0.001 - 0.858	0.012	0.012 - 0.012	0.001	0.001 - 0.002	0.007	0.003 - 0.038	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2012	0.001	0.001 - 0.004	0.017	0.012 - 0.263	0.001	0.001 - 0.003	0.003	0.001 - 0.006	0.003	0.002 - 0.024	0.005	0.004 - 0.007
2013	0.002	0.001 - 0.012	0.018	0.012 - 0.194	0.001	0.001 - 0.001	0.007	0.003 - 0.256	0.002	0.002 - 0.002	0.004	0.004 - 0.004
2014	0.003	0.001 - 0.018	0.023	0.012 - 0.064	0.001	0.007 - 0.007	0.003	0.003 - 0.011	0.002	0.002 - 0.012	0.006	0.004 - 0.029

Appendix E Con. Annual geometric mean and ranges for trace metals measured at the four sites along the South Fork of the Little Red river during the sample years of 2010 - 2014. Reported values from 2010 only reflect 4 sample periods collected in Nov and Dec.

	Iron (mg L^{-1})		Manganese (mg L^{-1})		Molybdenum (mg L^{-1})		Nickel (mg L^{-1})		Zinc (mg L^{-1})	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
Site 1	0.028	0.007 - 0.386	0.002	0.001 - 0.014	0.005	0.003 - 0.056	0.003	0.002 - 0.026	0.005	0.002 - 0.101
2010	0.069	0.045 - 0.097	0.003	0.001 - 0.006	0.004	0.003 - 0.011	0.003	0.002 - 0.004	0.002	0.002 - 0.004
2011	0.034	0.013 - 0.386	0.001	0.001 - 0.001	0.006	0.003 - 0.056	0.004	0.002 - 0.026	0.003	0.002 - 0.051
2012	0.024	0.013 - 0.074	0.003	0.001 - 0.014	0.005	0.003 - 0.047	0.002	0.002 - 0.002	0.012	0.002 - 0.101
2013	0.025	0.013 - 0.178	0.002	0.001 - 0.009	0.004	0.003 - 0.010	0.002	0.002 - 0.002	0.005	0.002 - 0.023
2014	0.019	0.007 - 0.052	0.003	0.001 - 0.010	0.004	0.003 - 0.015	0.003	0.002 - 0.020	0.005	0.002 - 0.012
Site 2	0.040	0.009 - 0.471	0.003	0.001 - 0.067	0.004	0.003 - 0.016	0.003	0.002 - 0.030	0.003	0.002 - 0.044
2010	0.127	0.108 - 0.170	0.006	0.003 - 0.011	0.003	0.003 - 0.003	0.004	0.003 - 0.005	0.002	0.002 - 0.004
2011	0.039	0.013 - 0.471	0.001	0.001 - 0.001	0.004	0.003 - 0.007	0.003	0.002 - 0.011	0.002	0.002 - 0.044
2012	0.047	0.013 - 0.393	0.006	0.001 - 0.067	0.004	0.003 - 0.012	0.002	0.002 - 0.005	0.004	0.002 - 0.018
2013	0.031	0.013 - 0.235	0.003	0.001 - 0.019	0.003	0.003 - 0.008	0.002	0.002 - 0.002	0.003	0.002 - 0.018
2014	0.031	0.009 - 0.147	0.006	0.001 - 0.025	0.005	0.003 - 0.016	0.003	0.002 - 0.030	0.003	0.002 - 0.010
Site 3	0.046	0.013 - 0.455	0.003	0.001 - 0.121	0.004	0.003 - 0.014	0.002	0.002 - 0.039	0.003	0.002 - 0.037
2010	0.134	0.123 - 0.145	0.008	0.006 - 0.010	0.003	0.003 - 0.003	0.002	0.002 - 0.003	0.003	0.002 - 0.012
2011	0.044	0.013 - 0.430	0.001	0.001 - 0.121	0.004	0.003 - 0.012	0.003	0.002 - 0.011	0.002	0.002 - 0.037
2012	0.043	0.013 - 0.291	0.004	0.001 - 0.033	0.004	0.003 - 0.009	0.002	0.002 - 0.002	0.003	0.002 - 0.014
2013	0.039	0.013 - 0.216	0.003	0.001 - 0.016	0.003	0.003 - 0.007	0.002	0.002 - 0.002	0.003	0.002 - 0.014
2014	0.040	0.013 - 0.455	0.006	0.001 - 0.074	0.004	0.003 - 0.014	0.003	0.002 - 0.039	0.003	0.002 - 0.009
Site 4	0.059	0.013 - 1.033	0.004	0.001 - 0.275	0.004	0.003 - 0.018	0.003	0.002 - 0.135	0.003	0.002 - 0.027
2010	0.141	0.085 - 0.206	0.007	0.005 - 0.010	0.004	0.003 - 0.012	0.004	0.004 - 0.005	0.003	0.002 - 0.008
2011	0.060	0.013 - 0.548	0.002	0.001 - 0.081	0.003	0.003 - 0.005	0.003	0.002 - 0.041	0.002	0.002 - 0.023
2012	0.044	0.013 - 0.321	0.006	0.001 - 0.275	0.004	0.003 - 0.009	0.002	0.002 - 0.002	0.005	0.002 - 0.027
2013	0.068	0.013 - 1.033	0.004	0.001 - 0.022	0.004	0.003 - 0.008	0.004	0.002 - 0.135	0.004	0.002 - 0.016
2014	0.046	0.019 - 0.123	0.005	0.001 - 0.017	0.005	0.003 - 0.018	0.004	0.002 - 0.061	0.003	0.002 - 0.011

Appendix F. Annual geometric means and ranges for nutrients measured at the four sites along the South Fork of the Little Red River during the sample years of 2010 – 2014. Reported values from 2010 only reflect 4 sample periods collected in Nov and Dec.

	Nitrate (mg L^{1})		SRP (mg L^{-1})		Sulfate (mg L^{-1})	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
Site 1	0.041	0.004 - 0.255	0.005	0.001 - 0.302	2.348	1.692 - 6.097
2010	0.025	0.012 - 0.050	0.005	0.003 - 0.008	2.130	1.969 - 2.273
2011	0.042	0.005 - 0.216	0.004	0.001 - 0.017	2.295	1.855 - 6.097
2012	0.023	0.004 - 0.255	0.004	0.001 - 0.013	2.384	1.842 - 3.122
2013	0.069	0.005 - 0.202	0.008	0.001 - 0.180	2.534	1.844 - 4.478
2014	0.048	0.005 - 0.115	0.008	0.002 - 0.302	2.264	1.692 - 6.001
Site 2	0.030	0.005 - 0.268	0.006	0.001 - 0.565	2.043	0.760 - 6.790
2010	0.013	0.005 - 0.046	0.006	0.003 - 0.009	2.069	1.892 - 2.176
2011	0.032	0.005 - 0.129	0.004	0.001 - 0.010	1.915	1.402 - 2.122
2012	0.019	0.005 - 0.268	0.008	0.001 - 0.565	1.848	0.760 - 2.449
2013	0.053	0.005 - 0.206	0.012	0.001 - 0.096	2.568	1.854 - 6.790
2014	0.030	0.005 - 0.120	0.005	0.002 - 0.014	1.866	1.580 - 2.371
Site 3	0.028	0.005 - 0.257	0.005	0.001 - 0.052	2.011	0.847 - 4.257
2010	0.012	0.005 - 0.029	0.006	0.003 - 0.009	2.036	1.854 - 2.163
2011	0.027	0.005 - 0.120	0.004	0.001 - 0.009	1.895	1.320 - 2.245
2012	0.020	0.005 - 0.257	0.004	0.001 - 0.011	1.899	0.847 - 2.499
2013	0.050	0.005 - 0.187	0.005	0.001 - 0.020	2.260	1.757 - 4.257
2014	0.030	0.005 - 0.118	0.008	0.002 - 0.052	2.016	1.335 - 2.609
Site 4	0.026	0.001 - 0.232	0.005	0.001 - 0.247	1.997	1.302 - 4.263
2010	0.016	0.005 - 0.032	0.005	0.002 - 0.008	1.860	1.799 - 1.955
2011	0.031	0.005 - 0.117	0.004	0.001 - 0.012	1.888	1.347 - 2.139
2012	0.010	0.007 - 0.232	0.003	0.001 - 0.009	1.916	1.334 - 2.191
2013	0.047	0.005 - 0.185	0.006	0.001 - 0.183	2.326	1.903 - 4.263
2014	0.039	0.005 - 0.118	0.008	0.002 - 0.247	1.943	1.302 - 2.918

Appendix G. Mean and ranges of trace elements measured in benthic sediment sample at the SFLRR sites from the spring sample periods of 2011, 2012 and 2013.

Sample period	Site	P (mg kg^{-1})			K (mg kg^{-1})			Ca (mg kg^{-1})			Mg (mg kg^{-1})			S (mg kg^{-1})			Na (mg kg^{-1})		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Apr-11	1	4.7	4.3	5.2	25.8	24.7	26.9	283.6	279.6	287.7	51.1	50.1	52.2	7.9	7.6	8.1	3.5	3.2	3.8
	2	5.2	3.0	7.2	17.4	10.0	31.1	211.1	149.5	287.1	33.4	23.2	53.6	7.7	5.8	9.4	3.8	3.3	4.8
	3	9.3	4.7	20.4	39.7	22.4	52.8	480.8	182.5	724.4	95.8	36.2	165.2	12.2	5.7	25.8	5.9	3.7	7.6
	4	7.2	6.9	7.3	29.3	25.5	33.6	465.4	423.3	518.8	90.0	83.1	99.0	8.7	7.4	9.9	4.9	4.1	6.0
Apr-12	1	4.2	2.8	3.4	24.6	14.6	22.6	269.9	147.0	234.3	60.8	35.5	57.2	4.9	3.3	4.1	4.1	3.1	3.5
	2	5.4	2.7	9.8	17.8	8.3	31.4	265.1	96.5	551.4	47.9	22.1	85.6	6.7	3.3	13.2	3.5	2.4	5.1
	3	4.0	3.6	4.7	34.0	23.3	53.0	333.4	214.9	495.0	81.5	60.4	117.2	4.8	4.2	5.3	4.9	4.1	6.6
	4	4.6	3.3	5.5	27.4	18.5	38.0	284.7	207.1	394.2	66.0	46.3	92.0	4.6	3.5	5.3	4.4	3.6	4.9
Jun-13	1	3.5	1.8	2.2	20.8	21.2	24.1	354.0	282.9	350.5	62.6	56.2	59.4	4.5	3.9	4.4	3.1	2.9	3.2
	2	3.3	2.7	3.9	16.8	14.0	19.5	321.9	243.1	400.7	45.3	44.0	46.7	4.7	4.0	5.5	3.2	3.1	3.3
	3	3.7	1.7	5.7	21.3	21.0	21.6	278.7	201.8	355.6	63.3	49.5	77.1	4.5	4.0	4.9	2.8	2.6	3.0
	4	5.0	4.5	5.5	22.4	20.3	24.5	498.5	438.0	559.0	84.1	78.7	89.5	4.7	4.6	4.8	3.5	3.3	3.6

Appendix G con. Mean and ranges of trace elements measured in benthic sediment sample at the SFLRR sites from the spring sample periods of 2011, 2012 and 2013.

		Fe (mg kg^{-1})			Mn (mg kg^{-1})			Zn (mg kg^{-1})			Cu (mg kg^{-1})			B (mg kg^{-1})		
Sample period	Site	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Apr-11	1	151.4	147.0	155.9	165.9	165.5	166.3	1.5	1.5	1.6	0.3	0.2	0.3	0.1	0.1	0.1
	2	132.1	87.4	188.2	63.2	29.3	122.8	1.5	1.4	1.7	1.0	0.8	1.3	0.1	0.1	0.1
	3	213.1	86.5	408.6	93.2	73.9	119.2	1.8	1.1	2.5	1.2	0.8	1.4	0.1	0.0	0.3
	4	167.7	151.0	199.3	82.8	46.0	143.5	2.0	1.7	2.4	0.9	0.5	1.3	0.1	0.1	0.1
Apr-12	1	175.0	106.0	137.5	80.8	79.6	85.9	1.6	1.0	1.3	0.3	0.1	0.1	0.2	0.1	0.2
	2	190.6	128.4	258.4	97.4	41.4	185.7	1.9	0.9	2.8	0.3	0.0	0.6	0.4	0.2	0.7
	3	176.7	152.7	213.5	70.1	50.3	88.3	1.5	1.4	1.8	0.5	0.2	1.0	0.2	0.2	0.2
	4	212.8	167.6	258.2	73.1	38.8	98.6	1.9	1.5	2.5	0.3	0.2	0.3	0.2	0.2	0.2
Jun-13	1	269.4	119.7	258.6	99.8	162.4	190.1	2.1	1.9	2.2	1.1	0.7	2.5	0.5	0.4	0.5
	2	250.2	144.2	356.1	81.6	73.8	89.4	2.2	1.9	2.5	1.2	1.0	1.3	0.4	0.4	0.5
	3	269.6	146.6	392.7	59.1	41.7	76.5	1.7	1.3	2.0	0.9	0.7	1.1	0.4	0.4	0.5
	4	368.8	348.3	389.3	82.4	82.2	82.6	2.5	2.3	2.6	0.8	0.8	0.8	0.5	0.5	0.5

Appendix H. Average macroinvertebrate family densities in each stream reach from November 2010 through December 2013. Sample periods highlighted in grey occurred after logging and pipeline installation.

		Reference - Site 1							Downstream - Site 2							Downstream - Site 3							Downstream - Site 4						
		Before			After				Before			After				Before			After				Before			After			
Order	Family	12/10	3/11	11/11	4/12	12/12	6/13	12/13	12/10	3/11	11/11	4/12	12/12	6/13	12/13	12/10	3/11	11/11	4/12	12/12	6/13	12/13	12/10	3/11	11/11	4/12	12/12	6/13	12/13
Coleoptera	Curculionidae	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0
	Dryopidae	0	0	0	0	12	0	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dubiraphia	0	35	0	0	53	0	0	41	23	23	35	19	0	0	38	12	23	23	0	0	0	327	47	90	0	0	0	105
	Dytisicidae	0	0	0	58	0	12	12	0	0	0	35	0	0	23	0	0	0	0	0	105	12	0	0	0	0	94	0	0
	Elmidae	38	94	0	53	250	0	0	86	731	62	180	67	0	12	165	1310	47	234	273	0	0	819	3537	336	1704	79	0	343
	Hydrophilidae	0	0	0	0	0	23	0	0	0	0	0	0	0	0	19	0	0	0	0	0	0	0	12	0	12	0	0	29
	Psephenidae	12	29	0	0	19	23	12	47	74	31	23	23	12	12	105	43	58	23	0	16	0	35	35	58	26	0	0	23
	Scirtidae	0	0	0	0	0	0	0	0	0	0	0	0	0	96	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Staphylinidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0
Diptera	Ceratopogonidae	0	0	0	109	1076	47	99	0	0	47	199	175	94	79	0	0	35	142	0	129	23	105	0	23	23	94	114	304
	Dixella	0	0	0	0	0	0	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dolichopodidae	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0
	Empididae	0	0	0	35	0	0	94	0	0	47	12	0	0	0	0	0	12	31	0	0	0	0	0	12	12	0	0	0
	Ephydridae	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	12	0	0	0	0	0	0	187
	Limoniidae	35	18	0	12	12	12	246	0	47	0	0	23	0	16	21	44	152	41	15	47	35	0	19	35	16	0	44	29
	Non-Tanypodinae	1698	2830	325	1237	4765	3745	908	727	4556	2249	1018	4716	3399	332	2984	3415	699	1633	5298	6016	613	4746	1881	861	708	10409	2860	2568
	Phoridae	0	0	0	0	0	0	0	0	12	53	0	0	0	0	35	0	19	0	0	0	0	0	0	12	0	0	0	0
	Simuliidae	41	1246	140	0	0	94	94	0	511	901	0	0	1450	16	0	1032	12	0	0	1009	70	0	231	63	58	129	0	67
	Tabanidae	0	0	0	0	12	0	0	23	12	0	0	0	0	12	0	0	0	0	0	12	0	0	12	12	0	0	0	0
	Tanyderidae	0	0	0	0	0	936	0	152	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	125	0	0	0
	Tanypodinae	248	430	23	112	613	335	178	480	385	183	363	437	578	101	1142	225	61	88	897	732	123	713	82	105	89	727	540	211
	Tipulidae	0	0	12	12	23	0	58	0	58	31	0	0	0	58	0	12	47	48	0	12	35	0	35	23	12	0	0	35

Appendix H Con. Average macroinvertebrate family densities in each stream reach from November 2010 through December 2013. Sample periods highlighted in grey occurred after logging and pipeline installation.

		Reference - Site 1							Downstream - Site 2							Downstream - Site 3							Downstream - Site 4						
		Before			After				Before			After				Before			After				Before			After			
Order	Family	12/10	3/11	11/11	4/12	12/12	6/13	12/13	12/10	3/11	11/11	4/12	12/12	6/13	12/13	12/10	3/11	11/11	4/12	12/12	6/13	12/13	12/10	3/11	11/11	4/12	12/12	6/13	12/13
Ephemeroptera	Baetidae	58	94	41	746	392	374	31	23	520	35	231	94	977	16	0	530	97	389	0	498	0	53	216	103	487	234	716	55
	Caeniidae	91	278	70	133	6908	73	232	543	1318	338	1003	3055	389	126	222	363	204	297	784	507	12	1207	591	192	578	1223	621	296
	Ephemeraidae	0	0	0	0	0	0	0	0	12	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ephemerellidae	0	0	0	18	0	275	0	23	0	0	35	12	12	70	12	94	0	29	0	0	12	0	35	0	35	499	0	12
	Heptageniidae	304	239	63	137	632	2802	105	208	485	330	103	664	874	23	123	330	68	105	311	435	0	132	222	140	264	182	575	117
	Isonychiidae	0	86	0	111	0	0	0	0	35	175	0	23	0	0	47	51	0	23	12	29	0	0	140	58	35	23	0	97
	Leptophlebiidae	53	65	0	102	97	58	12	196	105	18	41	55	604	18	189	105	12	51	23	189	0	243	152	74	47	158	149	12
	Potamanthidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0
	Tricorythidae	0	0	0	0	0	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hemiptera	Corixidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0
	Veliidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Lepidoptera	Crambidae	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Megaloptera	Chauliodes	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0
	Corydalus	129	23	0	0	0	0	0	0	12	0	0	0	0	0	0	29	0	0	0	0	0	0	31	41	0	0	0	0
	Nigronia	0	0	0	0	0	66	0	0	12	0	0	0	121	0	0	0	0	0	0	28	0	0	12	0	0	0	58	0
	Sialis	12	12	23	0	12	0	0	18	0	0	31	12	0	23	23	12	0	0	0	0	0	12	0	0	0	0	0	0
Odonata	Coenagrionidae	56	246	0	23	119	12	47	86	12	0	18	88	0	0	143	70	0	0	0	12	187	88	12	58	0	94	23	31
	Gomphidae	23	23	0	12	18	23	0	47	12	12	12	12	0	0	31	35	70	23	41	105	0	23	20	12	23	0	23	0

Appendix H Con. Average macroinvertebrate family densities in each stream reach from November 2010 through December 2013. Sample periods highlighted in grey occurred after logging and pipeline installation.

		Reference - Site 1							Downstream - Site 2							Downstream - Site 3							Downstream - Site 4						
		Before			After				Before			After				Before			After				Before			After			
Order	Family	12/10	3/11	11/11	4/12	12/12	6/13	12/13	12/10	3/11	11/11	4/12	12/12	6/13	12/13	12/10	3/11	11/11	4/12	12/12	6/13	12/13	12/10	3/11	11/11	4/12	12/12	6/13	12/13
Plecoptera	Capniidae	0	0	189	0	647	47	1130	0	12	0	0	117	0	149	23	1404	140	608	1111	35	742	807	0	281	1010	1265	0	499
	Chloroperlidae	47	269	125	1041	550	12	720	0	53	631	44	47	0	122	0	240	117	422	593	12	611	0	901	332	157	240	0	396
	Leuctridae	0	0	111	133	0	0	74	0	0	0	269	94	0	23	12	0	39	70	0	187	101	35	12	12	47	0	0	43
	Nemouridae	0	0	170	12	0	0	0	0	0	0	0	0	47	0	0	0	0	94	0	0	0	0	0	0	117	0	0	0
	Perlidae	351	67	12	140	35	47	0	23	62	58	16	0	23	0	12	281	0	123	41	105	0	99	175	111	97	47	78	12
	Perlodidae	0	211	0	35	111	12	0	0	12	0	0	0	12	0	0	35	0	23	0	12	0	0	23	12	39	374	0	0
	Taeniopterygidae	0	0	0	23	0	749	0	12	0	199	0	12	0	12	12	0	0	0	70	0	0	0	0	211	23	216	0	45
Trichoptera	Glossosomatidae	0	132	0	35	94	0	39	0	129	12	0	0	0	31	0	53	23	23	0	0	1292	0	0	18	12	0	0	47
	Helicopsychidae	0	35	0	0	0	0	0	0	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0
	Hydropsychidae	152	35	18	12	0	70	12	0	105	82	0	0	464	0	12	190	0	35	12	79	12	0	143	76	12	47	124	67
	Hydroptilidae	0	0	12	0	0	53	0	0	281	0	0	0	0	0	0	0	0	47	0	0	0	0	94	0	23	0	0	0
	Lepidostomatidae	0	35	0	0	0	0	0	0	0	12	0	29	0	0	0	12	0	0	842	0	0	0	0	0	0	12	0	0
	Leptoceridae	0	0	0	0	0	0	0	0	0	0	0	0	47	0	0	0	0	0	0	12	0	12	0	0	0	0	83	0
	Limnephilidae	12	0	0	0	0	0	12	31	117	0	0	0	0	35	12	0	0	0	0	0	0	23	0	0	0	0	0	70
	Philopotamidae	0	76	23	158	0	0	0	0	82	0	0	0	234	16	0	0	0	117	0	292	35	0	0	0	82	41	35	228
	Phryganeidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0
	Polycentropodidae	109	324	0	187	0	602	113	0	78	68	12	0	380	41	39	474	23	23	12	353	0	29	2015	140	18	94	415	68
	Psychomyiidae	70	0	0	0	0	0	0	0	94	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0