

Title: Incorporating Ecological Costs and Benefits into Environmental Flow Recommendations For Oklahoma Rivers: Phase 1, Southeastern Oklahoma.

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Problem and Research Objectives:

Providing a safe and sustainable water supply to the growing Oklahoma population while also providing for economic growth and maintaining natural ecosystems is the most serious challenge facing Oklahoma policy makers in the coming decades. Accomplishing this will require consideration of both the economic and ecological costs and benefits of different water allocation and management strategies (Arthington et al. 2006, Richter 2010). Multiple approaches have been used to attempt to quantify the amount of water needed by natural water bodies in Oklahoma. In-stream flows (ISFs) quantify the amount of water that needs to be left in a stream to maintain non-consumptive uses such as fisheries or riparian areas (OWRB 2009). Currently, there are over 200 methods for determining ISFs, ranging from designation of minimum flows to those that mimic natural flow regimes (Turton et al. 2009).

Rivers in the Ouachita and Gulf Coastal Plains ecoregions of southeastern Oklahoma provide an excellent test system for examining the ecological costs and benefits of different environmental flows/in-stream flow recommendations. These rivers are known for their relatively abundant and pristine water and harbor the highest aquatic biological diversity in the state (Matthews et al. 2005). However, the water in these rivers also is in high demand to meet regional, human water needs (<http://www.owrb.ok.gov/supply/ocwp/ocwp.php>). In particular, the Kiamichi River is at the center of intense conflict over water use and governance between Oklahoma City, the State of Oklahoma, the Tarrant County Water District (Fort Worth, TX), and the Choctaw and Chickasaw nations. The source of conflict is over who gets to use water from a storage reservoir. Sardis Lake is an impoundment on a tributary to the Kiamichi. The Corps of Engineers built this reservoir in 1982 for flood control, water supply and recreation. However, Oklahoma owed money to the federal government for constructing the reservoir, and in 2011 90% of the water storage rights to Sardis Lake were sold to Oklahoma City. The Tarrant County Water District disputes this ownership. Under the 1978 Red River Compact (<http://www.oscn.net/applications/oscn/deliverdocument.asp?id=97778&hits=>), they claim to have rights to 25% of the water from Sardis Lake, and they want Oklahoma to sell it to them.

They have sued the state to get access to the water and the U.S. Supreme Court is reviewing this case this spring (US Supreme Court 2013). Finally, both the Choctaw and Chickasaw nations also claim to own the water in the Kiamichi watershed, including that in Sardis Lake. The river flows through the jurisdictional Choctaw Nation in southeastern Oklahoma, and the historical Choctaw Nation capital abuts the banks of the Kiamichi in the town of Tuskahoma. Together, Sardis and Hugo (a reservoir at the most downstream end of the Kiamichi) lakes are the water supply for people in 29 Oklahoma counties. Current and planned inter-basin water transfers will extract hundreds of thousands of acre-feet of freshwater per year out of southeastern Oklahoma, with 220,000 acre-feet/year going to Oklahoma City alone by 2050 via the Atoka Pipeline (OWRB 2008). In addition to the Supreme Court case, there are multiple, ongoing and pending lawsuits over who gets to use and sell the water from Sardis Lake.

Missing from the above dispute are the needs of the fish and wildlife that live in and around the Kiamichi River. The Kiamichi River is known for its high aquatic biodiversity (Vaughn 2000, Matthews et al. 2005). It is home to over 86 species of fish and 30 species of freshwater mussels, including 3 federally listed endangered mussel species (Vaughn et al. 1996, Pyron et al. 1998, Matthews et al. 2005, Galbraith et al. 2008). In 1998 the river was selected by The Nature Conservancy, arguably the most influential conservation organization globally, as one of the most critical rivers in the U.S. for preserving biodiversity (Master et al. 1998). The water now impounded by Sardis Lake historically provided 30% of the water flowing into the lower Kiamichi River. However, in recent drought years the organisms in the lower river have suffered because water has been held in Sardis Lake rather than being released to flow down stream. This has occurred during hot summer months and has led to drying of the lower river (Figure 1), high water temperatures (in some cases exceeding 100° F because of the extremely shallow water), massive mussel and fish mortality (Galbraith et al. 2010; W.J. Matthews personal communication), and record low lake levels downstream in Hugo Reservoir (USACE 2012). This has occurred because Sardis Lake has no designated “non-consumptive” uses and Oklahoma has no in-stream flow regulations, which means that water managers are not required to release water for mussels, fish and other river organisms during droughts. While periodic heat waves and drought are normal in this region (Stambaugh et al. 2011), the last two summers have been the hottest on record and most of this area is entering an unprecedented 3rd year of extreme to exceptional drought that is predicted to persist for the foreseeable future.

Freshwater mussels are large, long-lived bivalve mollusks. Mussels are very sensitive to changes in flow regimes and temperature (Strayer et al. 2004, Pandolfo et al. 2010, 2012, Galbraith et al. 2012). Adult mussels are highly sedentary; they move very slowly and only short distances if they move at all (Allen and Vaughn 2009). Thus, unlike fish, mussels cannot move to new habitat, such as the bottom of a pool, when flows are inappropriate, and in-stream flow models developed for fish and other mobile organisms typically do not work well for mussel populations (Layzer and Madison 1995, Gore et al. 2001). Establishing environmental flows that safeguard mussel populations will protect the three endangered mussel species and hopefully prevent future litigation related to these species. In addition, because mussels provided important habitat and other services for other river organisms such as insects and fish, protecting mussels also protects these other groups (Vaughn and Spooner 2006, Aldridge et al. 2007).

Ecosystem services describe the benefits that humans derive from natural ecosystems. These include *provisioning services* obtained directly from the ecosystem such as water, food and timber, *regulating services* such as water purification, climate control, carbon storage and

pollination, and *cultural services*, which are the benefits that people obtain through tourism, aesthetic experiences or spiritual enrichment (Daily and Matson 2008, Perrings et al. 2011, Wainger and Mazzotta 2011). Rivers and the organisms that inhabit them provide many important ecosystem services to people such as provisioning of freshwater, nutrient processing and water filtration, and recreation and ecotourism (Brauman et al. 2007). Freshwater mussels are filter feeders that move large amounts of water over their gills (Vaughn et al. 2004) resulting in multiple ecosystem services including biofiltration, nutrient cycling and storage (Vaughn and Hakenkamp 2001, Vaughn 2010). This “pre-filtration” or biofiltration by mussels means that water extracted for human uses from rivers with healthy mussel populations should require less treatment than water from rivers without mussels, saving money (Kreeger and Bushek 2008).

Like most invertebrates, mussels are ectotherms whose physiological processes are governed by external, environmental temperatures. Vaughn’s laboratory has discovered that different mussel species prefer different environmental temperatures and perform ecosystem services differently at these different temperatures (Spooner and Vaughn 2008). Because of these differences in thermal preferences and performance, the amount of water filtered by mussels and nutrient cycling rates differ with the species makeup of mussel communities, water volume, and water temperature (Vaughn et al. 2008, Vaughn 2010).

Water temperatures in rivers are influenced by numerous factors, including quantity of groundwater inputs, volume of surface water, watershed snow coverage, incoming solar radiation, air temperature, and wind speed (Allan and Castillo 2007). The direct absorption of solar radiation is the main heat input into large rivers, while convective warming by the air is more influential in small streams. Indeed, many stream studies have found strong linear relationships between air and water temperature (Wetzel 2001). Anthropogenic inputs/outputs can also affect water temperatures in rivers. Man-made reservoirs, in particular, have the potential to warm downstream waters (via greater absorption of solar radiation from increased water surface area, and longer water residence times) or cool downstream waters (via cool-water releases from the bottom of the reservoir) (Stanford et al. 1996, Allan and Castillo 2007). Because of the various unobservable pathways and interactions of water throughout a watershed, it is practically impossible to derive a numerical model that accounts for all water-heat fluxes. A much more practical strategy of predicting river water temperatures is the use of an empirical model, one that takes into account the dominant control on water temperature for that size of stream.

We need to determine the appropriate volume and timing of water diversions from the Kiamichi and other rivers to meet human needs while maintaining natural ecological function. In this project we combined information on discharge and water temperature under various stream flows with information on how mussel communities perform the ecosystem services of water filtration, nutrient cycling and nutrient storage under those conditions to determine how different stream flows influence the ecosystem services provided by mussels. We focused on the Kiamichi River because we already have rigorous data on mussel communities (Galbraith et al. 2005) and the physical characteristics of river reaches where these communities occur (Jones and Fisher 2005), and because this river is under the most pressure for regional water diversions as described above. From previous work by Vaughn’s laboratory, we already had strong data on the ecosystem services performed by various mussel species under different temperature regimes (Vaughn and Spooner 2008). We added to this dataset by obtaining additional thermal preference/performance data for a wider variety of mussel species. We also gathered data on

how water temperature in the Kiamichi River is dictated by atmospheric and flow (regulated vs. unregulated) conditions. Finally, we used these data to produce multivariate models that predict water temperature from air temperature and water depth, and in turn allow us to determine the amount of water required to be released from Sardis Reservoir to maintain target stream temperatures. We then compare these targeted stream temperatures with mussel success and ecosystem services.

Objectives:

1. Conduct laboratory experiments to measure mussel thermal preference and performance (respiration rates, filtration rate, and nitrogen and phosphorus recycling rates and storage) for species of freshwater mussels from southeastern Oklahoma. Combine these data with mussel community biomass data to estimate ecosystem services.
2. Place automatic recording level loggers in river reaches/mussel beds in the Kiamichi River to obtain daily information on flow discharge and water temperature across seasons.
3. Create a GIS-based model that quantifies (i) incoming solar radiation to the Kiamichi watershed (using Oklahoma Mesonet data); (ii) water-surface reflection and topographic and riparian shading (using methods from Julian et al. 2008b); and (iii) water budgets (using flow and hydrographic data). This GIS-based model will be combined with empirical data from Objective 2 to develop predictive relationships of water temperature based on variable flow and atmospheric conditions.
4. Compare model results with various in-stream flow scenarios to make environmental flow recommendations that protect mussel populations and system-wide ecological function.

METHODS

Objective 1: *Conduct laboratory experiments to measure mussel thermal preference and performance (respiration rates, filtration rate, and nitrogen and phosphorus recycling rates and storage) for species of freshwater mussels from southeastern Oklahoma. Combine these data with mussel community biomass data to estimate ecosystem services.*

Spooner and Vaughn (2008) measured respiration rates, algal clearance rates, and nitrogen and phosphorus recycling rates for eight species of mussels from southeastern Oklahoma at 15, 25, and 35 °C. We added to this dataset by measuring the above rates for six additional species of mussels across the three temperatures. Mussels were acclimated to experimental temperatures for two weeks in 500-L Frigid Unit Living Streams®. Mussels were fed cultured algae during acclimation, and then starved for 24 hours before conducting the experiments (Vaughn et al. 2004). Measurements on individual mussels were conducted in continuously stirred, covered glass beakers (500 ml or 1500 ml, depending on mussel size) housed in 1.8 m³ temperature-controlled chambers. Following Spooner and Vaughn (2008) we added an aliquot of cultured algae to each beaker, allowed mussels to filter for 1.5 hours, and measure filtration rate as the mass-specific change in chlorophyll concentration. Each mussel was then placed in a second beaker with pre-filtered water for an additional 1.5 hours where we measured respiration rate as the change in oxygen concentration and collect water samples to determine excretion (NH₃, PO₄) rates. At the end of the experiment, mussels were measured for shell dimensions and weighed. All rate were expressed on a gram dry weight basis.

On July 31, 2011 and June 10, 2012, we quantitatively sampled mussels at the Paine's site on the Kiamichi River. This is a long-term mussel-monitoring site established in 1991 (Site 7 from Vaughn and Pyron 1995; Site KM11 Hobo logger). We divided the site into three sections; the upstream pool, the downstream riffle that had water (hereafter "riffle"), and the most downstream riffle that was completely dry (hereafter "dry riffle") (Figure 1). In the pool and riffle sections, we excavated 15, 0.25 m² quadrats following Vaughn et al. (1997). Mussels were identified, measured for length, and returned to the stream. In the riffle there were many freshly dead mussels (tissue still attached), so we separately tallied densities and sizes for live and dead mussels. In the dry riffle we established eight transects across the riverbed spaced 10 meters apart. Then, at each one meter interval across each transect we counted freshly dead mussel individuals that could be observed from the surface for one meter to either side of the transect line.

We used length-dry weight regressions to estimate mean mussel biomass for each species. We combined this information with our measured densities to estimate the total biomass of each species in the pool and riffle. We multiplied the dry-weight corrected nitrogen and phosphorus excretion rates and algal clearance rates from our laboratory experiment by mussel biomass from our field survey to get areal rates (rates per g dry weight per square meter of riverbed), and summed across species to get community wide ecosystem service rates (N recycling, P recycling and biofiltration) based on the species actually present in the pool and riffle. We did not use the dry riffle in our ecosystem services estimates because we did not have mussel length data for that area and thus could not estimate biomass. We used mussel biomass and stoichiometric data to estimate the amount of nitrogen, phosphorus and carbon stored in mussel soft tissue and shell (Christian et al. 2008, Atkinson et al. 2010).

Objective 2: *Place automatic recording level loggers in ten river reaches/mussel beds in the Kiamichi River to obtain daily information on flow discharge and water temperature across seasons.*

We installed 8 Onset[®] HOBO[®] data loggers (model U20-001-01) that measured water depth and water temperature across the Kiamichi River watershed (Figure 2; Table 1). These sites were strategically selected to capture influences from Sardis Reservoir and tributaries. We also installed 3 Onset[®] HOBO[®] data loggers (model U20-001-01) that measured atmospheric pressure and air temperature across the watershed. These data were used to calibrate and compare the water temperature and depth data. Daily solar radiation data was collected from OK Mesonet stations distributed across the Kiamichi watershed. The Mesonet is a network of 120 environmental monitoring stations distributed across Oklahoma (<http://www.mesonet.org/index.php/site/about>). All of these stations collect air temperature (°C) and solar radiation (400-1100 nm; W/m²) in 5-minute intervals.

Objective 3: *Create a GIS-based model that quantifies (i) incoming solar radiation to the Kiamichi watershed (using Oklahoma Mesonet data); (ii) water-surface reflection and topographic and riparian shading (using methods from Julian et al. 2008b); and (iii) water budgets (using flow and hydrographic data). This GIS-based model will be combined with empirical data from Objective 2 to develop predictive relationships of water temperature based on variable flow and atmospheric conditions.*

With the intention of developing a GIS-based model that estimates water temperatures using solar radiation budgets (BLAM; Julian et al. 2008a), we collected 22 hemispherical canopy photographs throughout the watershed (Figure 2). We analyzed these canopy photos with Gap Light Analyzer (GLA) software and derived canopy shading and the percentage of incoming solar radiation that reached the stream surface on an average summer day. We then used these values to calibrate a canopy-shading map for the entire watershed based on an Enhanced Vegetation Index (EVI) derived from Landsat imagery taken close to the same period as the canopy photos. This canopy-shading map can be used to calculate daily solar radiation budgets at the ground/stream surface, which can then be used to develop empirical mechanistic models for river water temperature.

Objective 4: *Compare model results with various in-stream flow scenarios to make environmental flow recommendations that protect mussel populations and system-wide ecological function.*

Using data from Objective 2, we developed multivariate regression models for each monitoring station (Figure 2, Table 1) that uses air temperature and water depth to predict water temperature. These models were then used to (1) develop an historical timeline of water temperatures in the Kiamichi River; and (2) determine what flows need to be released from Sardis Dam to maintain healthy mussel communities downstream and/or maximize the ecosystem services they provide.

PRINCIPAL FINDINGS AND SIGNIFICANCE

Objective 1: *Mussel thermal preference and performance and estimated ecosystem services.*

We measured respiration (Figure 3), nitrogen excretion (Figure 4) and phosphorus excretion rates (Figure 5) and clearance (filtration) rates (Figure 6) for five unionid mussel species (*Lampsilis teres*, *Plectomerus dombeyanus*, *Potamilus purpuratus*, *Pyganodon grandis* and *Quadrula verrucosa*) and the invasive clam *Corbicula fluminea*.

Mussel densities at the Paine's site mussel bed (Vaughn site 7) were strongly associated with water depth and temperature. In late July 2011-12, the upper pool portion of this mussel bed was covered by water depths of 30-to-100 cm, with midday water temperatures < 30°C. In contrast the portion of the riffle that still had water covering it was extremely shallow with hot water temperatures. On July 31, 2011 the average depth in the riffle was 10 cm and the midday temperature was 40°C, well above the thermal tolerances for both juvenile and adult mussels (Pandolfo et al. 2010, Galbraith et al. 2012). In past surveys mussel densities in the pool and riffle/run portion of this site have been approximately equal (Vaughn and Pyron 1995), however in 2011-12 mussel densities in the pool were approximately 12 times higher than in the shallower riffle (Figure 7A). In the riffle freshly dead mussels (tissue still attached) were twice as abundant in quadrats as live mussels (Figure 7B). In the completely dry lower riffle we found 19 species of freshly dead mussels.

We estimated ecosystem services for the Paine's site mussel bed based on the actual community composition, densities and rates for species we found in quadrats at the site in 2011-12: *Actinonaias ligamentina*, *Amblema plicata*, *Ellipsaria lineolata*, *Fusconaia flava*, *Lampsilis cardium*, *Obliquaria reflexa*, *Potamilus purpuratus*, *Quadrula pustulosa*, *Quadrula verrucosa* and *Truncilla truncata*. Rates for *P. purpuratus* and *Q. verrucosa* were estimated from data

collected in this study. Rates for the other species are from Spooner and Vaughn (2008). We estimated ecosystem services separately for the pool, live mussels in the riffle, and lost services due to mussel death (the freshly dead mussels in the riffle). Community nitrogen and phosphorus recycling rates were highest in the pool and lowest in the riffle and increased with temperature (Figure 8). This is because mussel metabolic rates rise with temperature and they excrete at higher rates because they are stressed (Spooner and Vaughn 2008). What is interesting is that the N and P recycling capability lost through mussel death in the riffle was much higher than that provided by surviving, live mussels in the riffle (Figure 9). The same pattern can be seen for biofiltration (Figure 9) and nutrient storage (Figure 10).

Objective 2: Discharge and water temperature time-series.

Because of the extremely low flows to no flows in the watershed during the summers of 2011 and 2012, we were not able to construct stage-discharge rating curves for each monitoring station. Instead, we relied on water discharge data from four federal monitoring stations located within our study area (Table 2). We obtained daily precipitation, air temperature (for verification of HOBO data), and solar radiation data from three Oklahoma Mesonet stations located around the watershed (Table 3). All of these data were used to create time-series for each station that displayed mean water temperatures (Appendix 1) and maximum water temperatures (Appendix 2). During our study period (June 8, 2011 – September 30, 2012), there were 4 days at the Kiamichi River station @ Clayton in which water temperatures exceeded 35 C – the temperature at which adult mussels begin to die. Kiamichi River @ Antlers had 21 days where water temperature exceeded 35 C. During these days, there were no releases from Sardis Dam or in the case of Antlers, releases did not convey all the way to Antlers due to the lower Kiamichi River being a losing stream during extended droughts in the post-Sardis Dam hydrologic regime. The effect of lack of releases from Sardis Dam on downstream reaches during droughts is illustrated in Figure 11. Sardis Dam captures approximately 25% of the Kiamichi River watershed above the Antlers gage. When none of this runoff is released during extended droughts, the lower reaches behave like the upper reaches in terms of hydrologic drought. Before Sardis Dam (1982) downstream reaches such as Antlers were not as susceptible to hydrologic drought as the upper reaches on account of a larger contributing watershed.

In addition to numerous days of lethal water temperatures, there were also long periods of no flow days at many of the stations (Table 4) that also led to mass mortality of mussels (USFWS, unpublished data; C.L. Atkinson, unpublished data).

Objective 3: Predictive relationships of water temperature based on variable flow and atmospheric conditions.

We analyzed the canopy photos with Gap Light Analyzer (GLA) software and derived canopy shading and the percentage of incoming solar radiation that reached the stream surface on an average summer day (Table 5). We then used these values to calibrate a canopy-shading map for the entire watershed based on an Enhanced Vegetation Index (EVI) derived from Landsat imagery taken close to the same period as the canopy photos (Figure 12).

Solar radiation at the stream surface was not a good predictor of water temperatures (Figure 13), which we attribute to the extremely low flow volumes of the Kiamichi streams during the drought of 2011-12. Under these flow conditions, water temperature is more influenced by heat

diffusion at the air-water interface than by solar radiation heating. That is, the air temperature is the dominant control on water temperature for low flow conditions. Thus, we changed our strategy to model water temperatures using a multivariate regression model that incorporates air temperature and flow depth. These multivariate regression models predicted mean daily water temperatures (Appendix 3) and maximum daily water temperatures (Appendix 4) accurately. The coefficient of determination (r^2) for mean daily water temperature ranged from 0.77 to 0.85 for all the stations except Antlers (K9), which had an $r^2 = 0.64$ (Appendix 3). We attribute the lower predictability for K9 to the extreme variability in groundwater-surface water exchanges over our study period. Similarly, r^2 for maximum daily water temperature ranged from 0.62 to 0.83 (Appendix 4). For all models, water temperature increased predictably with increasing air temperature, and decreased predictably with increasing water depth. These models were used to determine how different water releases from Sardis Dam affect downstream water temperatures (Figure 14; Objective 4).

Objective 4: Compare model results with various in-stream flow scenarios to make environmental flow recommendations that protect mussel populations and system-wide ecological function.

The managed daily water releases of 0.59 cms (21 cfs) from Sardis Dam beginning on August 2, 2011 did not increase discharge at the Antlers site until August 27, 2011 (25 days later). The likely reason for this lack of conveyance is that the water table was considerably lower than the stream bed at the end of July 2011, and thus all water released by Sardis Dam was quickly lost to the subsurface until the local water table rose high enough to intersect the channel bed, which occurred on August 27, 2011. Note that there were three small rainfall events (> 1 cm) during this period that also helped to raise the water table. What all of these data mean is that the Kiamichi River is a losing stream (i.e. discharge is lost to the subsurface due to the water table being lower than the stream bed) during extended periods of drought, particularly when 25% of its watershed runoff is held behind Sardis Dam without daily releases.

Figures 15 and 16 show the discharge-temperature rating curves that can be used to determine the required discharge for the Kiamichi River near Clayton (USGS 07335790) in order to reduce maximum water temperature to the target water temperatures that ensure mussel survival and allow them to provide ecosystem services. At the bare minimum, we recommend that maximum water temperatures be kept below 35°C, which is the temperature at which almost all juvenile mussels and many adult mussels start to die (Pandolfo et al 2010, 2012; Galbraith et al. 2010, 2012). For example, on a day with a mean daily air temperature of 40°C, enough water needs to be released from Sardis Dam to ensure 1.8 cms at the Clayton gage and prevent mussel mortality (Table 6). Note that these recommendations are based on empirical data and do not directly take into account the water temperature of Sardis Reservoir. Even more important than regulating water temperature, we recommend that during droughts, enough water should be released from Sardis Dam to maintain flow at both the Clayton and Antlers gages (> 0.01 cms) as the reach between these two gages is critical mussel habitat with 3 federally listed endangered species.

Adult freshwater mussels are sedentary and dispersal is via their larvae (glochidia) that are obligate parasites on fish (Strayer et al. 2004). While no flow days have occurred in the river in the past, in pre-reservoir construction droughts the river would have been recolonized by fish hosts moving up from the Red River (Vaughn 2012). The presence of Hugo Dam downstream prevents recolonization from the Red River and its tributaries and creates an isolated mussel

community above Hugo Lake. Vaughn has been monitoring mussels in the Kiamichi River since 1990 and has found that mussel populations have declined following the drought in the early 2000s (Galbraith et al. 2010) and the 2011-12 drought. As an example, at Paine's site mussel abundance has decreased 50 % since 1991 (Figure 17). The occurrence of the endangered mussel species have also decreased throughout the river (Galbraith et al. 2008), including the abundance of *Arkansia wheeleri*. The Kiamichi River contains the only viable population in the world of *A. wheeleri* (Vaughn and Pyron 1995). Thus, it is imperative that we manage releases from Sardis Dam to maintain flows in the river between Sardis Lake and Hugo Lake.

Freshwater mussels provide important ecosystem services to humans, including pre-filtration of water and nutrient recycling and storage. Different mussel species perform these services differently at various temperatures, but when the contributions of whole mussel communities are considered biofiltration and nutrient recycling generally increase with temperature up to a point because mussel metabolic rates increase with temperature. However, when water temperatures become so warm that mussels can no longer filter or excrete nutrients in a normal manner or actually die, these ecosystem services are lost. For the Kiamichi River, the maximum temperature that mussel communities can continue to perform normally is 35°C, although some species begin to decrease their performance at temperatures above 25 or 30°C (for example, *Actinonaias ligamentina*, see Vaughn et al. 2008). In addition, once mussels die it may take decades for populations to recover and provide lost ecosystem services, assuming flows are maintained in the river. Mussels have very long life spans (30 to 50 years), don't reach reproductive maturity until around age 6, and often don't reproduce every year. In mussel beds hard hit by the 2011-12 drought, such as the riffle at Paine's site, it will likely take approximately 30 years to achieve enough mussel biomass to restore ecosystem services.

REFERENCES:

- Aldridge, D. C., T. M. Fayle, and N. Jackson. 2007. Freshwater mussel abundance predicts biodiversity in UK lowland rivers. *Aquatic Conservation-Marine and Freshwater Ecosystems* **17**:554-564.
- Allan, D. J. and M. M. Castillo. 2007. *Stream ecology: Structure and Function of Running Waters*. Springer, Dordrecht.
- Allen, D. C. and C. C. Vaughn. 2009. Burrowing behavior of freshwater mussels in experimentally manipulated communities. *Journal of the North American Benthological Society* **28**:93-100.
- Arthington, A. H., S. E. Bunn, N. L. Poff, and R. J. Naiman. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* **16**:1311-1318.
- Atkinson, C. L., S. P. Opsahl, A. P. Covich, S. W. Golladay, and L. M. Conner. 2010. Stable isotopic signatures, tissue stoichiometry, and nutrient cycling (C and N) of native and invasive freshwater bivalves. *Journal of the North American Benthological Society* **29**:496-505.
- Berg, D. J., W. R. Haag, S. I. Guttman, and J. B. Sickel. 1995. Mantle biopsy: a technique for nondestructive tissue-sampling of freshwater mussels. *Journal of the North American Benthological Society* **14**:577-581.
- Bogan, A. E. and K. Roe. 2008. Freshwater bivalve (Unioniformes) diversity, systematics, and evolution: status and future directions. *Journal of the North American Benthological Society* **27**:349-369.
- Bovee, K. D. 1994. Data collection procedures for the Physical Habitat Simulation system. U.S. Geological Survey, Biological Resources Division, Fort Collins, CO.
- Brauman, K. A., G. C. Daily, T. K. Duarte, and H. A. Mooney. 2007. The nature and value of ecosystem services: An overview highlighting hydrologic services. Pages 67-98 *Annual Review of Environment and Resources*.
- Christian, A. D., B. G. Crump, and D. J. Berg. 2008. Nutrient release and ecological stoichiometry of freshwater mussels (Mollusca : Unionidae) in 2 small, regionally distinct streams. *Journal of the North American Benthological Society* **27**:440-450.
- Daily, G. C. and P. A. Matson. 2008. Ecosystem services: From theory to implementation. *Proceedings of the National Academy of Sciences of the United States of America* **105**:9455-9456.
- Durham, B. W. and G. R. Wilde. 2006. Influence of stream discharge on reproductive success of a prairie stream fish assemblage. *Transactions of the American Fisheries Society* **135**:1644-1653.
- Frazer, G. W., C. D. Canham, and K. P. Lertzman. 1999. Gap Light Analyzer (GLA), version 2.0: Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs. Users Manual and Program Documentation. Simon Fraser University and Institute of Ecosystem Studies, Burnaby, B.C. and Millbrook, NY.
- Galbraith, H. S., D. E. Spooner, and C. C. Vaughn. 2005. *Arkansia wheeleri* monitoring in the Kiamichi River. Final report to Oklahoma Department of Wildlife Conservation.
- Galbraith, H. S., D. E. Spooner, and C. C. Vaughn. 2008. Status of rare and endangered freshwater mussels in southeastern Oklahoma rivers. *Southwestern Naturalist* **53**:45-50.

- Galbraith, H. S., D. E. Spooner, and C. C. Vaughn. 2010. Synergistic effects of regional climate patterns and local water management on freshwater mussel communities. *Biological Conservation* **143**:1175-1183. .
- Galbraith, H. S., C. J. Blakeslee, and W. A. Lellis. 2012. Recent thermal history influences thermal tolerance in freshwater mussel species (Bivalvia: Unionoida). *Freshwater Science* **31**:83-92
- Gore, J. A., J. B. Layzer, and J. Mead. 2001. Macroinvertebrate instream flow studies after 20 years: a role in stream management and restoration. *Regulated Rivers: Research & Management* **17**:527-542.
- Graf, D. L. and K. S. Cummings. 2007. Review of the systematics and global diversity of freshwater mussel species (Bivalvia : Unionoida). *Journal of Molluscan Studies* **73**:291-314.
- Jones, C. and W. L. Fisher. 2005. Final report for project T-8-P. Instream flow modeling for mussels and fishes in southeastern Oklahoma. Oklahoma Department of Wildlife Conservation.
- Julian, J., M. W. Doyle, and E. H. Stanley. 2008a. Empirical modeling of light availability in rivers. *Journal of Geophysical Research*. DOI: 10.1029,2007JG000601. 16 pp.
- Julian, J., E. H. Stanley, and M. W. Doyle. 2008b. Basin-scale consequences of agricultural land use on benthic light availability and primary production along a sixth-order temperate river. *Ecosystems* **11**:1091-1105.
- Kehmeier, J. W., R. A. Valdez, C. N. Medley, and O. B. Myers. 2007. Relationship of fish mesohabitat to flow in a sand-bed southwestern river. *North American Journal of Fisheries Management* **27**:750-764.
- Kreeger, D. and D. Bushek. 2008. From the headwaters to the coast: A watershed-based perspective on bivalve shellfish restoration. *Journal of Shellfish Research* **27**:1022-1022.
- Labbe, T. R. and K. D. Fausch. 2000. Dynamics of intermittent stream habitat regulate persistence of a threatened fish at multiple scales. *Ecological Applications* **10**:1774-1791.
- Layzer, J. B. and L. M. Madison. 1995. Microhabitat use by freshwater mussels and recommendations for determining their instream flow needs. *Regulated Rivers: Research & Management* **10**:329-345.
- Master, L. M., S. R. Flack, and B. A. Stein. 1998. Rivers of life: critical watersheds for protecting freshwater diversity. The Nature Conservancy, Arlington, VA.
- Matthews, W. J., C. C. Vaughn, K. B. Gido, and E. Marsh-Matthews. 2005. Southern plains rivers. In, A. Benke and C. E. Cushing, editors. *Rivers of North America*. Academic Press.
- Naimo, T. J., E. D. Damschen, R. G. Rada, and E. M. Monroe. 1998. Nonlethal evaluation of the physiological health of unionid mussels: methods for biopsy and glycogen analysis. *Journal of the North American Benthological Society* **17**:121-128.
- OWRB (Oklahoma Water Resources Board). 2009. Oklahoma Comprehensive Water Plan 2011 Update: Technical Memorandum, Instream Flows in Oklahoma and the West.
- Pandolfo, T. J., W. G. Cope, C. Arellano, R. B. Bringolf, M. C. Barnhart, and E. Hammer. 2010. Upper thermal tolerances of early life stages of freshwater mussels. *Journal of the North American Benthological Society* **29**:959-969.
- Pandolfo, T. J., T. J. Kwak, and W. G. Cope. 2012. Thermal tolerances of freshwater mussels and their host fish: species interactions in a changing climate. *Walkerana* **15**:69-82.
- Perrings, C., S. Naeem, F. S. Ahrestani, D. E. Bunker, P. Burkill, G. Canziani, T. Elmqvist, J. A. Fuhrman, F. M. Jaksic, Z. Kawabata, A. Kinzig, G. M. Mace, H. Mooney, A. H. Prieur-

- Richard, J. Tschirhart, and W. Weisser. 2011. Ecosystem services, targets, and indicators for the conservation and sustainable use of biodiversity. *Frontiers in Ecology and the Environment* **9**:512-520.
- Poff, N. L., B. D. Richter, A. H. Arthington, S. E. Bunn, R. J. Naiman, E. Kendy, M. Acreman, C. Apse, B. P. Bledsoe, M. C. Freeman, J. Henriksen, R. B. Jacobson, J. G. Kennen, D. M. Merritt, J. H. O'Keeffe, J. D. Olden, K. Rogers, R. E. Tharme, and A. Warner. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* **55**:147-170.
- Richter, B. D. 2010. Re-thinking environmental flows: from allocations and reserves to sustainability boundaries. *River Research and Applications* **26**:1052-1063.
- Spooner, D. E. and C. C. Vaughn. 2008. A trait-based approach to species' roles in stream ecosystems: climate change, community structure, and material cycling. *Oecologia* **158**:307-317.
- Stanford, J. A., J. V. Ward, W. J. Liss, C. A. Frissell, R. N. Williams, J. A. Lichatowich, and C. C. Coutant. 1996. A general protocol for restoration of regulated rivers. *Regulated Rivers-Research & Management* **12**:391-413.
- Strayer, D. L., J. A. Downing, W. R. Haag, T. L. King, J. B. Layzer, T. J. Newton, and S. Nichols. 2004. Changing perspectives on pearly mussels, North America's most imperiled animals. *BioScience* **54**:429-439.
- Turton, D., W. L. Fisher, T. Seilheimer, and R. Esralew. 2009. An assessment of environmental flows for Oklahoma. Oklahoma Water Resources Board.
- United States Supreme Court. 2013.
<http://www.supremecourt.gov/Search.aspx?FileName=/docketfiles/11-889.htm>
- Vaughn, C. C. 2000. Changes in the mussel fauna of the Red River drainage: 1910 - present. Pages 225-232 in R. A. Tankersley, D. I. Warmolts, G. T. Watters, B. J. Armitage, P. D. Johnson, and R. S. Butler, editors. *Proceedings of the First Freshwater Mussel Symposium*. Ohio Biological Survey, Columbus, Ohio.
- Vaughn, C. C. 2010. Biodiversity losses and ecosystem function in freshwaters: emerging conclusions and research directions. *BioScience* **60**:25-35.
- Vaughn, C. C. 2012. Life history traits and abundance can predict local colonisation and extinction rates of freshwater mussels. *Freshwater Biology* **57**:982-992.
- Vaughn, C. C., C. M. Mather, M. Pyron, P. Mehlhop, and E. K. Miller. 1996. The current and historical mussel fauna of the Kiamichi River, Oklahoma. *Southwestern Naturalist* **41**:325-328.
- Vaughn, C. C., C. M. Taylor, and K. J. Eberhard. 1997. A comparison of the effectiveness of timed searches vs. quadrat sampling in mussel surveys. Pages 157-162 in K. S. Cummings, A. C. Buchanan, and L. M. Koch, editors. *Conservation and Management of Freshwater Mussels II: Initiatives for the Future*.
- Vaughn, C. C. and C. C. Hakenkamp. 2001. The functional role of burrowing bivalves in freshwater ecosystems. *Freshwater Biology* **46**:1431-1446.
- Vaughn, C. C. and M. Pyron. 1995. Population ecology of the endangered Ouachita Rock Pocketbook mussel, *Arkansia wheeleri* (Bivalvia: Unionidae), in the Kiamichi River, Oklahoma. *American Malacological Bulletin* **11**:145-151.
- Vaughn, C. C. and D. E. Spooner. 2006. Unionid mussels influence macroinvertebrate assemblage structure in streams. *Journal of the North American Benthological Society* **25**:691-700.

- Vaughn, C. C. and C. M. Taylor. 1999. Impoundments and the decline of freshwater mussels: a case study of an extinction gradient. *Conservation Biology* **13**:912-920.
- Vaughn, C. C., K. B. Gido, and D. E. Spooner. 2004. Ecosystem processes performed by unionid mussels in stream mesocosms: species roles and effects of abundance. *Hydrobiologia* **527**:35-47.
- Vaughn, C. C., S. J. Nichols, and D. E. Spooner. 2008. Community and foodweb ecology of freshwater mussels. *Journal of the North American Benthological Society* **27**:41-55.
- Wainger, L. and M. Mazzotta. 2011. Realizing the Potential of Ecosystem Services: A Framework for Relating Ecological Changes to Economic Benefits. *Environmental Management* **48**:710-733.
- Wetzel, R. G. 2001. *Limnology: Lake and River Ecosystems*. Academic Press.

Table 1. Locations of HOBO data loggers that measure water depth and water temperature. Period of data collection may not be continuous due to logger displacements (flood or anthropogenic) and to days with no flow.

ID	Description	Location (WGS 84)	Elevation (m)	Period of Data (MM/DD/YYYY)
K1	Atmosphere, Upper watershed	N34 38.359 W94 36.733	280	06/08/2011 – 09/30/2012
K2	Kiamichi River @ Big Cedar	N34 38.351 W94 36.724	279	06/08/2011 – 09/30/2012
K3	Buffalo Creek	N34 43.711 W95 14.141	203	06/08/2011 – 09/30/2012
K4	Jackfork Creek above Sardis Reservoir	N34 36.063 W95 33.956	193	06/08/2011 – 07/19/2011
K5	Atmosphere, Middle watershed	N34 34.428 W95 21.435	164	06/08/2011 – 09/30/2012
K6	Kiamichi River @ Tuskahoma	N34 36.715 W95 16.640	155	06/08/2011 – 09/30/2012
K7	Jackfork Creek below Sardis Dam	N34 36.377 W95 20.091	160	06/08/2011 – 09/30/2012
K8	Kiamichi River @ Clayton	N34 34.531 W95 20.406	154	06/08/2011 – 09/30/2012
K9	Kiamichi River @ Antlers	N34 14.933 W95 36.317	126	06/08/2011 – 09/30/2012
K10	Atmosphere, Lower watershed	N34 14.846 W95 36.451	141	06/08/2011 – 09/30/2012
K11	Kiamichi River @ Paine's	N34.42720 W95.58134	139	8/01/2011 – 09/24/2011

Table 2. Water discharge gages in the watershed. The Sardis Lake gage is maintained by USACE (USACE station ID: CYD02).

ID	Name	Location (NAD27)	Elevation (m)	Watershed area (km²)	Period of Data (MM/YYYY)
USGS 07335700	Kiamichi River near Big Cedar, OK	N34 38.300 W94 36.750	270	102.6	10/1965 – current ¹
USGS 07335790	Kiamichi River near Clayton, OK	N34 34.483 W95 20.433	158	1810	11/1980 – current
USGS 07336200	Kiamichi River near Antlers, OK	N34 14.917 W95 36.300	128	2924	10/1972 – current
USGS 07335775	Sardis Lake near Clayton, OK	N34 37.750 W95 21.050	161	712	11/1994 – current

¹USGS began recording water temperature at this site 2/2012.

Table 3. Oklahoma mesonet stations in the watershed used to characterize and verify air temperature and precipitation.

ID (number)	Name	Location (NAD27)	Elevation (m)	Period of Data (MM/YYYY)
TALI (93)	Talihina	N34.71070 W95.01152	204	03/1997 – present
CLAY (29)	Clayton	N34.65657 W95.32596	186	03/1997 – present
ANTL (4)	Antlers	N34.22438 W95.70059	179	03/1997 – present

Table 4. No flow days at each of the four discharge monitoring stations for Summer 2011 (June 8 – September 30) and Summer 2012 (June 1 – September 30). Except during large floods, discharge on Jackfork Creek below Sardis Dam is set by controlled releases from the dam.

ID	Name	Watershed area (km²)	No Flow Days	
			Summer 2011	Summer 2012
USGS 07335700	Kiamichi River near Big Cedar, OK	102.6	95	112
USGS 07335790	Kiamichi River near Clayton, OK	1810	13	32
USGS 07336200	Kiamichi River near Antlers, OK	2924	52	31
USGS 07335775	Jackfork Creek below Sardis Dam	712	55	67

Table 5. Locations and data from canopy photographs that measure stream shading.

ID	Date (MM/DD/YYYY)	Location (WGS 84)	Elevation (m)	Width (m)	Canopy shading (%)	Stream surface solar radiation (%)
CP1	06/7/2011	N34 38.244 W94 39.153	264	8.8	64.0	54.4
CP2	06/7/2011	N34 38.396 W94 36.669	267	14.6	59.2	60.1
CP3	06/7/2011	N34 38.411 W94 36.620	280	4.5	88.4	18.2
CP4	06/7/2011	N34 38.448 W94 37.304	285	5.9	86.5	26.9
CP5	06/7/2011	N34 40.942 W94 53.174	210	30.1	51.2	72.0
CP6	06/7/2011	N34 39.463 W95 02.522	187	30	46.4	84.5
CP7	06/7/2011	N34 43.717 W95 14.151	201	14	68.8	66.6
CP8	06/7/2011	N34 36.068 W95 33.953	197	15	65.0	63.2
CP9	06/8/2011	N34 36.715 W95 16.640	155	36	45.8	86.8
CP10	06/8/2011	N34 36.850 W95 17.969	154	14.7	47.5	82.9
CP11	06/8/2011	N34 36.826 W95 17.850	171	10	84.8	28.3
CP12	06/8/2011	N34 36.375 W95 20.096	171	11.3	66.9	55.9
CP13	07/14/2011	N34 40.863 W94 55.682	183	25	61.6	65.7
CP14	07/14/2011	N34 40.790 W94 56.538	192	28	49.0	64.3
CP15	07/14/2011	N34 40.812 W94 56.543	188	37.5	40.9	89.0
CP16	07/14/2011	N34 40.375 W94 56.275	198	4.5	86.7	21.6
CP17	07/14/2011	N34 40.385 W94 56.285	200	3.9	82.6	26.1
CP18	07/14/2011	N34 40.361 W94 56.269	198	4.9	79.8	33.7
CP19	07/14/2011	N34 40.018 W94 57.585	200	10	80.5	38.4
CP20	07/14/2011	N34 34.500 W95 21.263	182	40	44.4	87.2
CP21	07/14/2011	N34 34.389 W95 21.425	157	37.5	46.8	84.3
CP22	07/14/2011	N34 14.953 W95 36.428	130	42	41.1	89.7

Table 6. Required discharge (in mean daily cubic meters per second) for Kiamichi River near Clayton (USGS 07335790) to prevent maximum water temperatures from exceeding 35°C, and thus preventing mussel mortality. Releases from Sardis Dam can be used to supplement discharge at the Clayton gage.

Mean daily air temperature (C)	Required discharge at Clayton gage (cms)
36	0.1
37	0.2
38	0.2
39	0.3
40	1.8
41	4.4
42	8.3
43	13.4
44	19.7
45	27.2
46	35.9
47	45.8

Figure 1. Google image of Paine's site showing the areas sampled for mussels (pool, riffle and dry lower riffle).



Figure 2. Study area and environmental variables monitoring network.

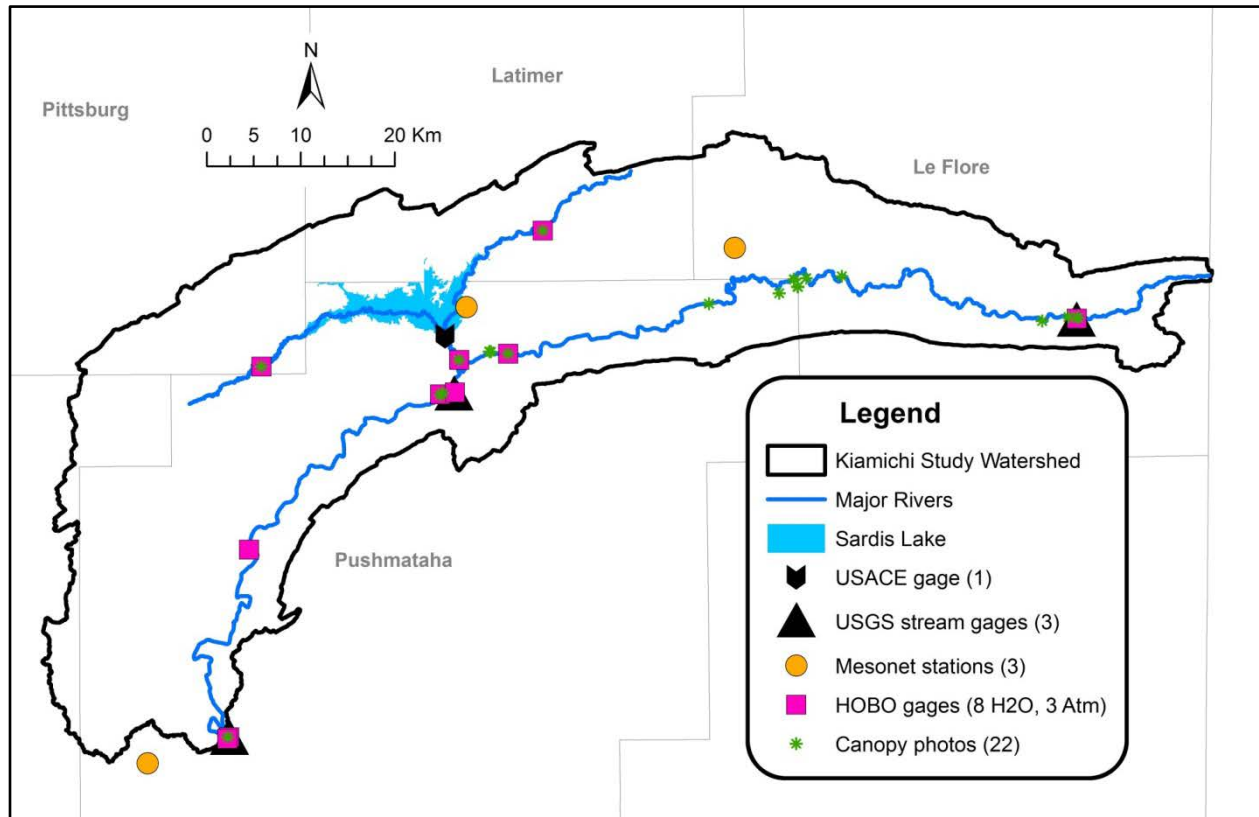


Figure 3. Mussel respiration rates.

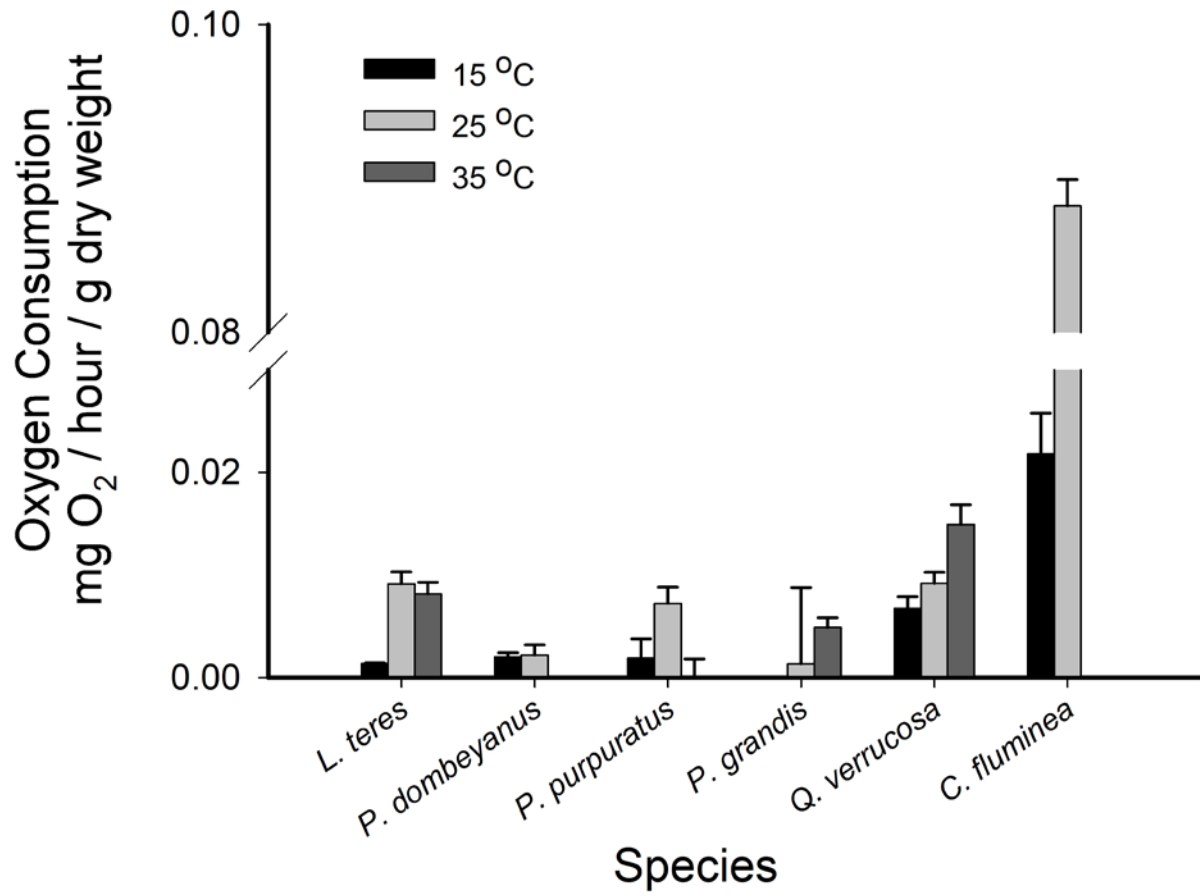


Figure 4. Mussel nitrogen excretion rates.

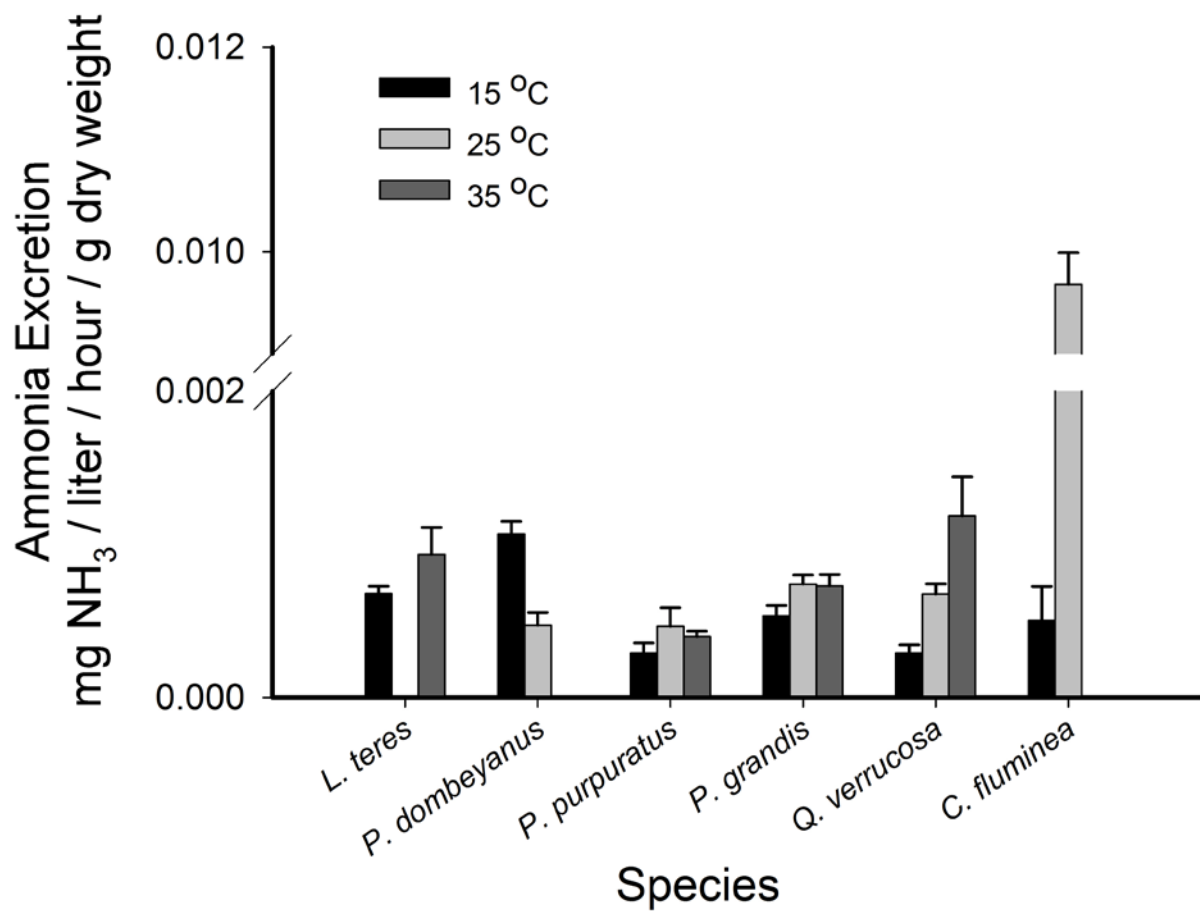


Figure 5. Mussel phosphorus excretion rates.

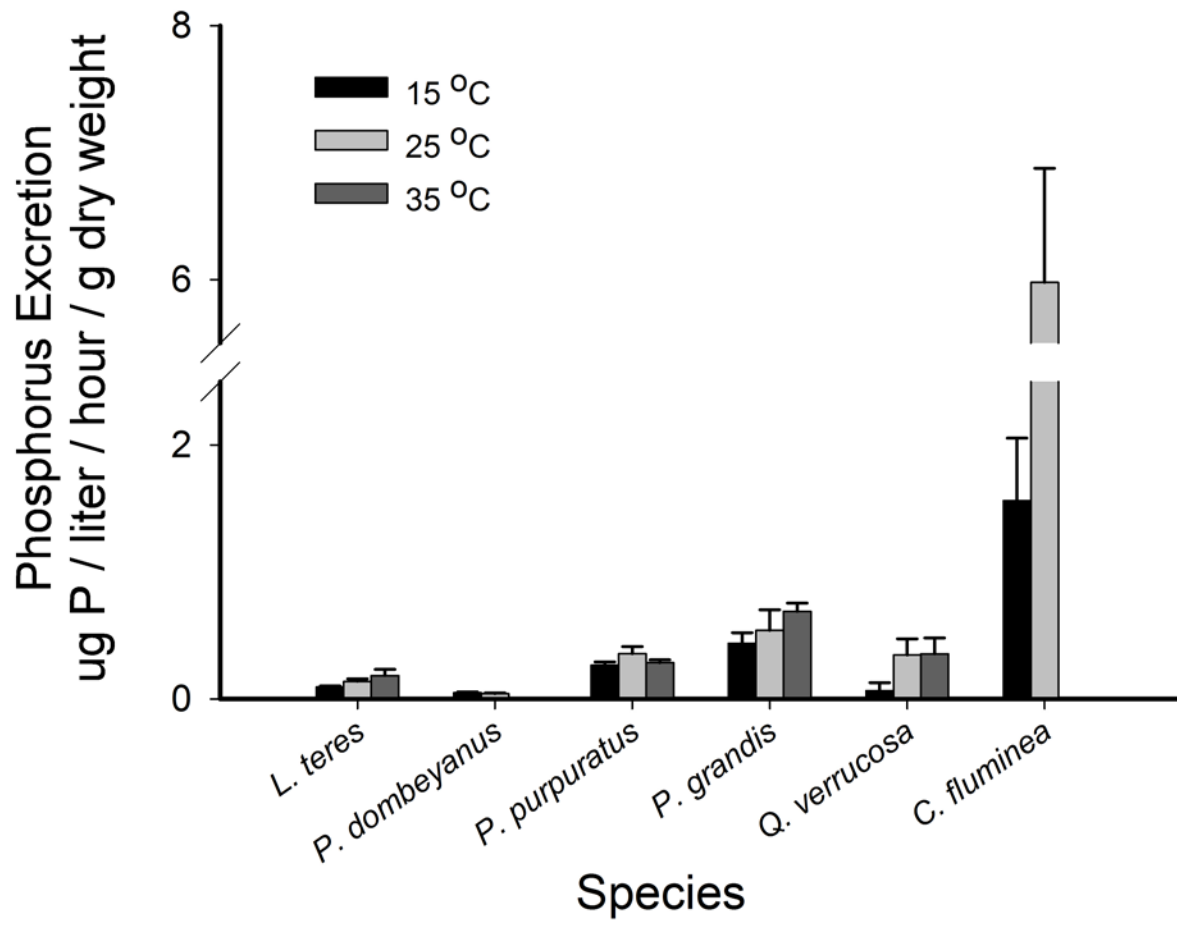


Figure 6. Mussel filtration rates.

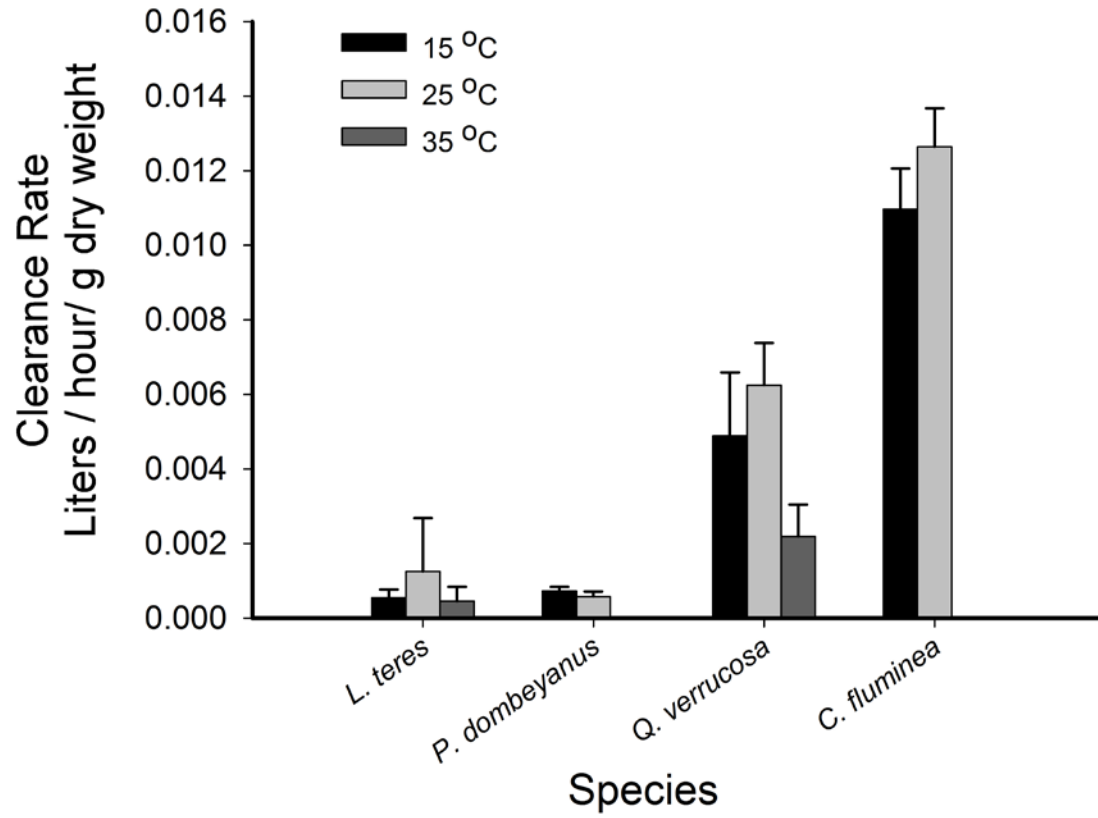


Figure 7. Mussel densities (± 1 S.E.) at Paine's site (Vaughn site 7 from Vaughn and Pyron (1995). A: Comparison of pool and riffle densities. B: Comparison of live and dead mussels in the riffle.

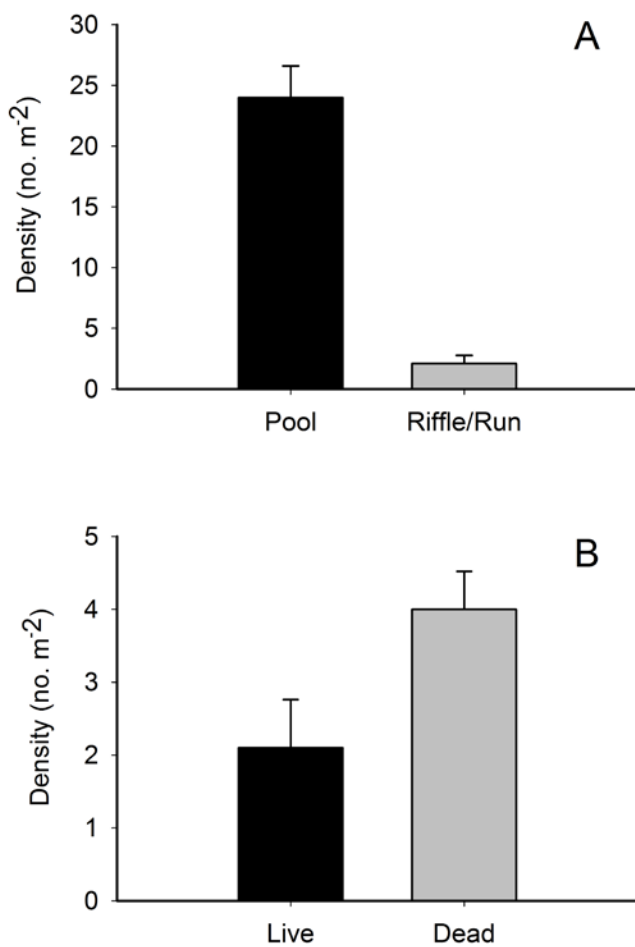


Figure 8. Mussel nitrogen and phosphorus recycling at Paine's site.

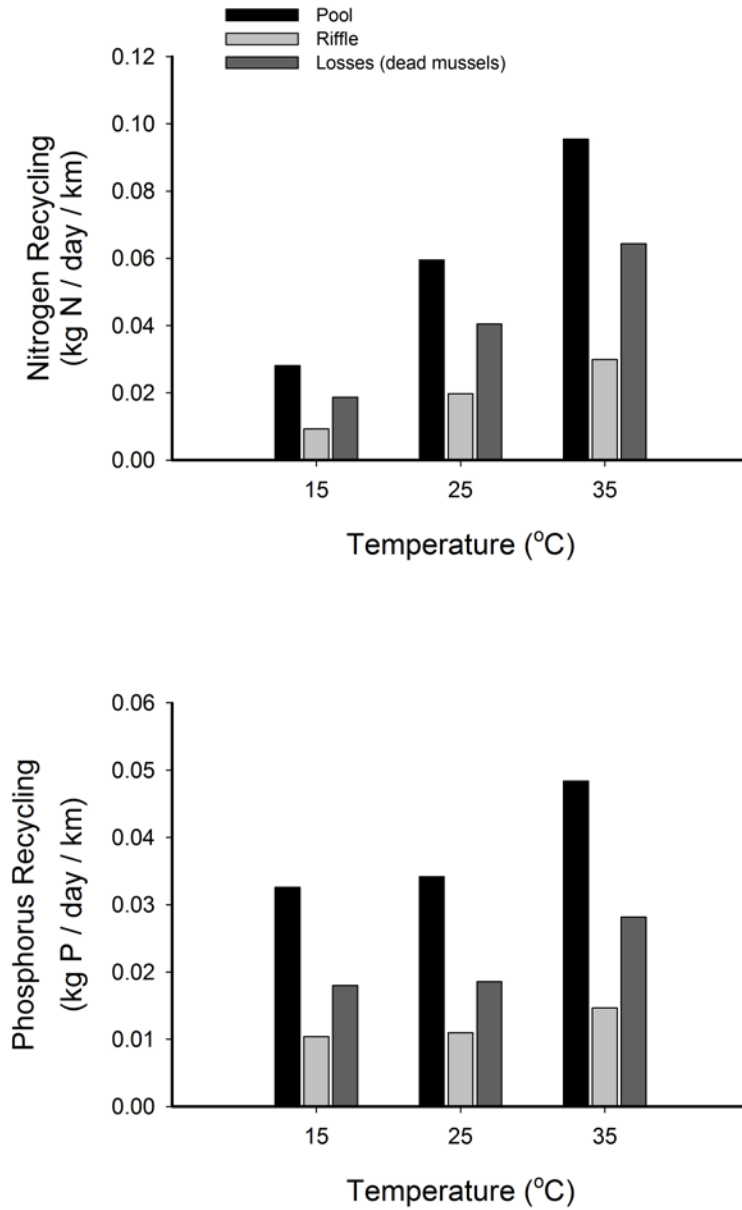


Figure 9. Mussel biofiltration at Paine's site.

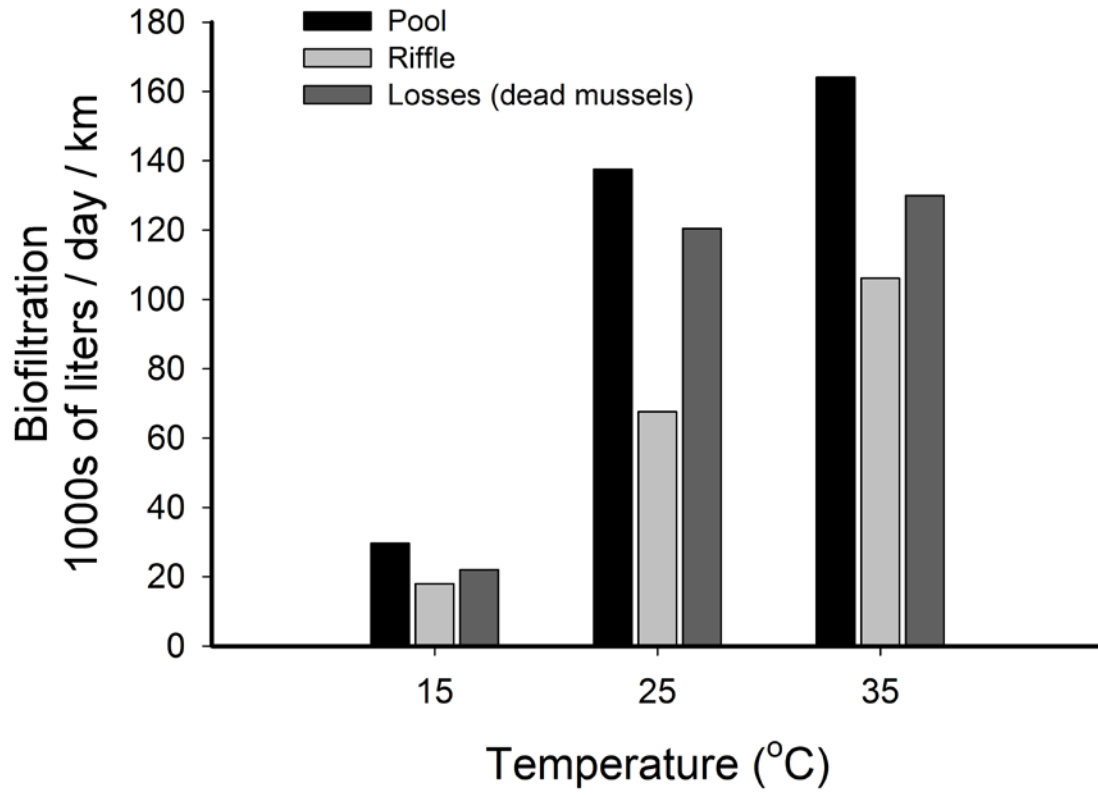


Figure 10. Mussel nutrient storage at Paine's site.

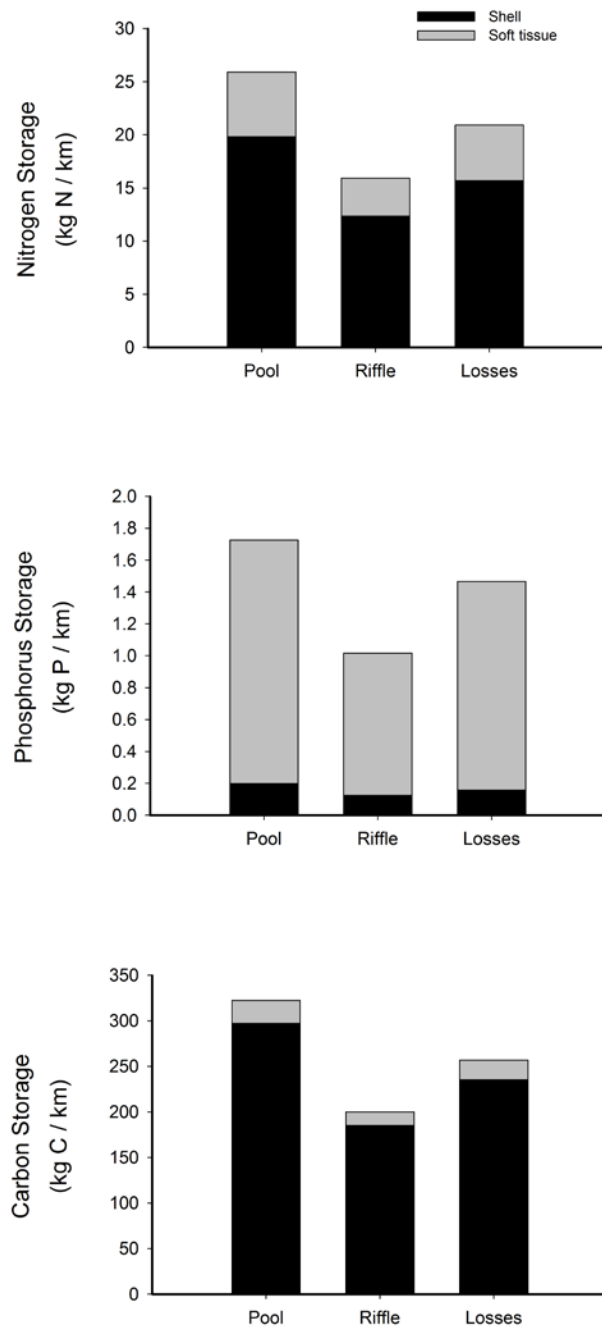


Figure 11. Severe hydrologic drought frequency for Kiamichi River at Big Cedar (upper watershed) and at Antlers (downstream extent of study area). Discharge data were obtained from the USGS gages listed in Table 2. The Kiamichi River at Antlers should be less susceptible to drought given it has a much larger watershed, which the displayed trends show from 1973 to 2004. Beginning in 2005, the two locations along the river exhibit the same drought behavior, which we attribute to the lack of releases from Sardis Dam (which captures approximately 25% of the total watershed's runoff). That is, the lack of releases from Sardis Dam during drought periods increases the magnitude and frequency of hydrologic drought in downstream reaches.

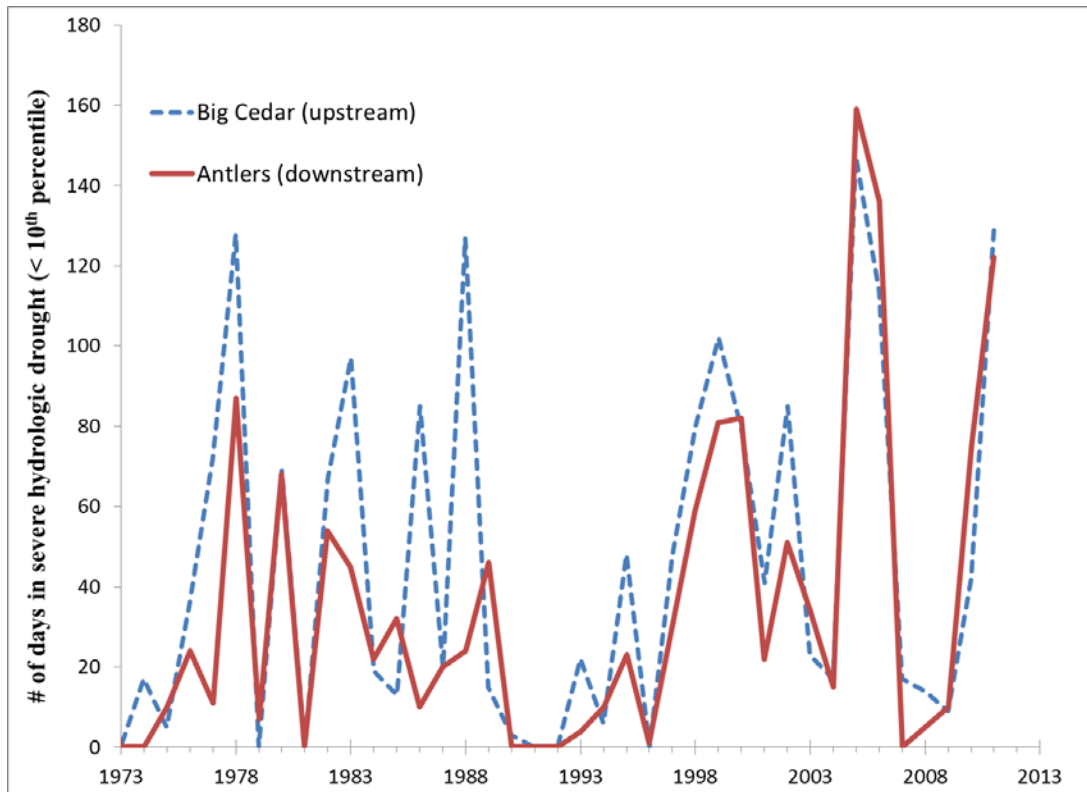


Figure 12. Map of canopy shading across the Kiamichi River watershed, derived using canopy photograph analyses in combination with subpixel mapping of Landsat imagery.

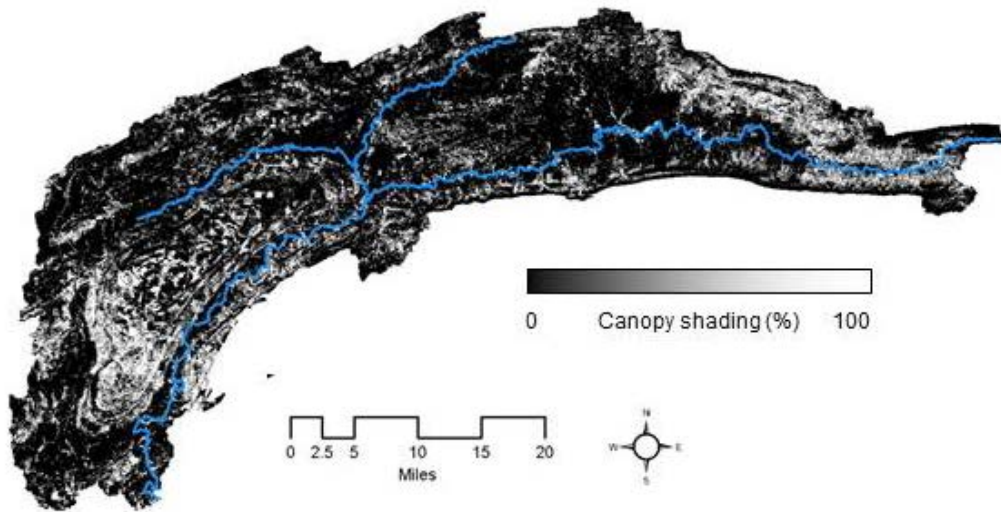


Figure 13. Relationship between mean daily water temperature of Kiamichi River @ Clayton and total daily solar radiation reaching watershed stream surface for the summer of 2011 (6/8/2011 – 9/30/2011). There was not a strong relationship between these two variables ($r^2 = 0.23$), and thus the GIS model based on solar radiation budgets was not pursued. Note that prior to Sardis Dam releases on August 2, 2011, water temperature remained above 29 C.

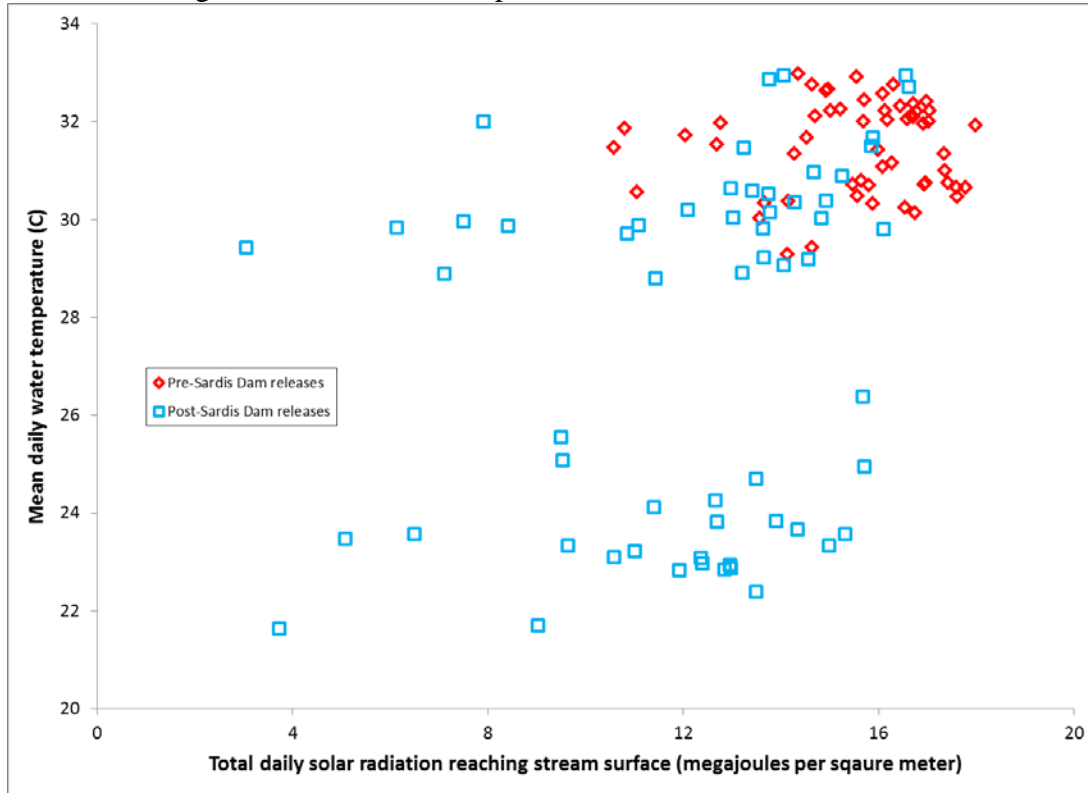


Figure 14. The effect of different water releases from Sardis Dam on downstream water temperatures in the Kiamichi River, at Clayton in this case during Summer 2011. Water temperatures were calculated using actual air temperatures with modeled water depths (Appendix 5E). Refer to Appendix 3F for the multivariate regression model used.

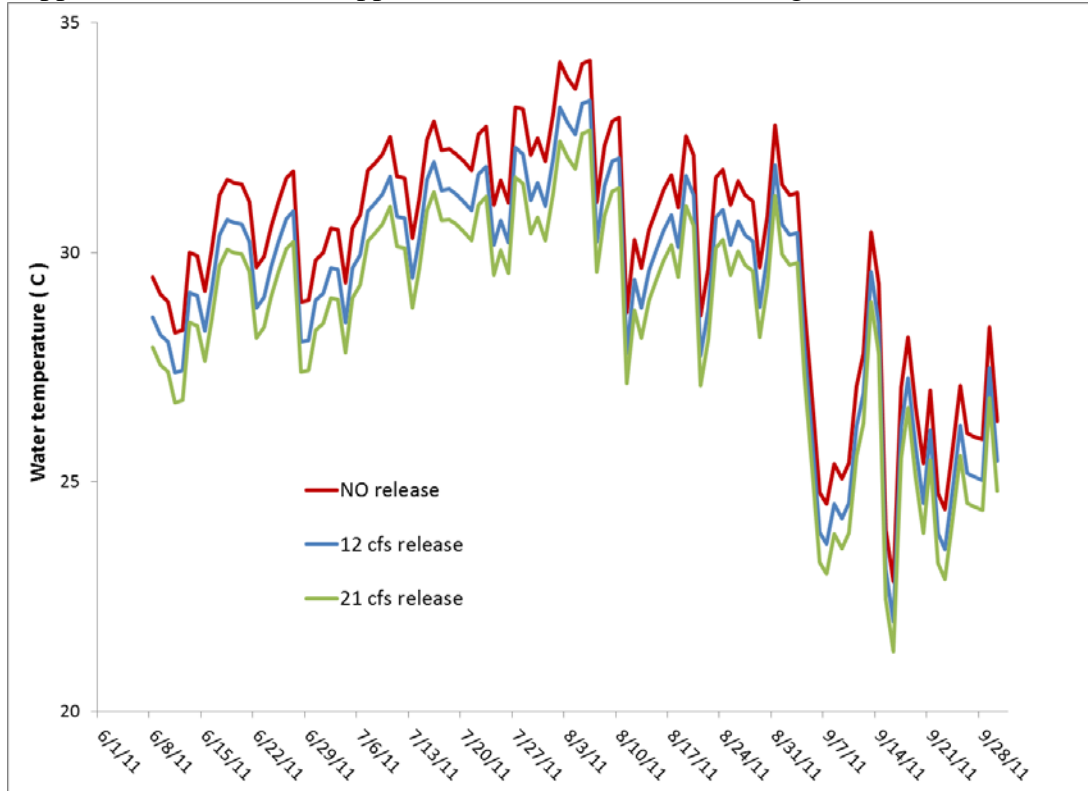


Figure 15. Discharges required for Kiamichi River near Clayton (USGS 07335790) to reduce maximum water temperature below target water temperatures assessed in Objective 1. Empirical rating curves were developed using Appendix 4F in combination with Appendix 5C.

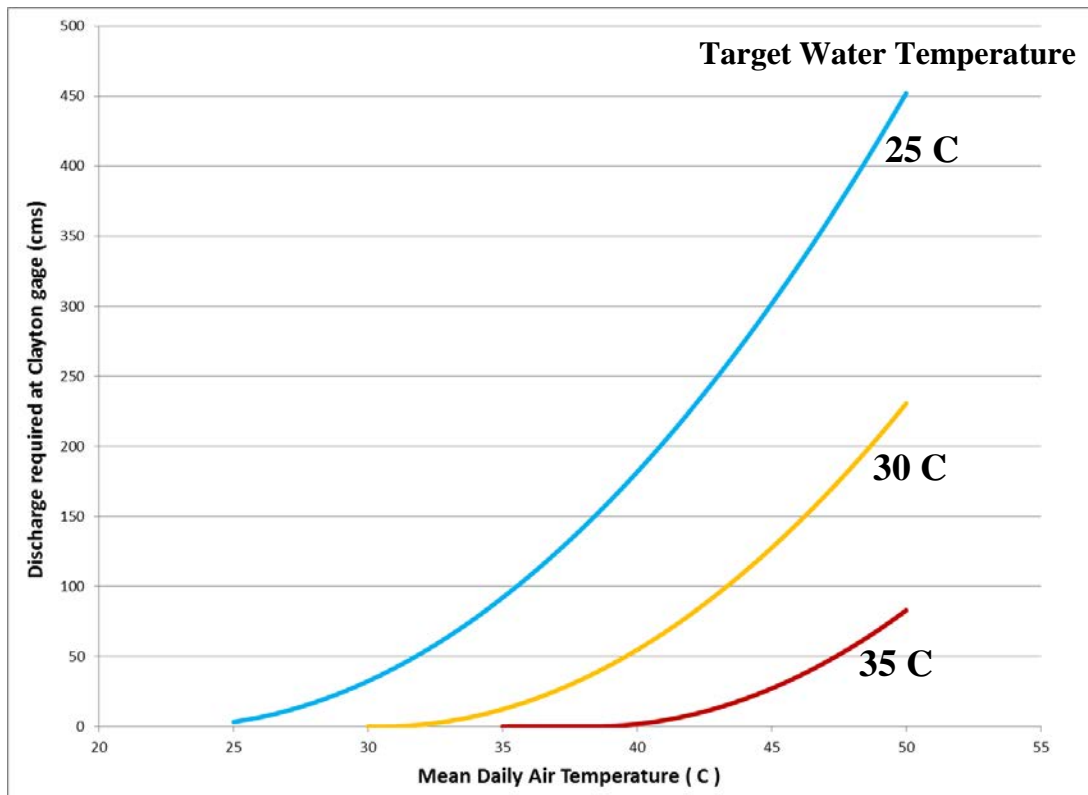


Figure 16. Discharges (under 100 cms) required for Kiamichi River near Clayton (USGS 07335790) to reduce maximum water temperature below target water temperatures assessed in Objective 1. Empirical rating curves were developed using Appendix 4F in combination with Appendix 5C. This is the same figure as Figure 15, just with shorter ranges for visual simplicity.

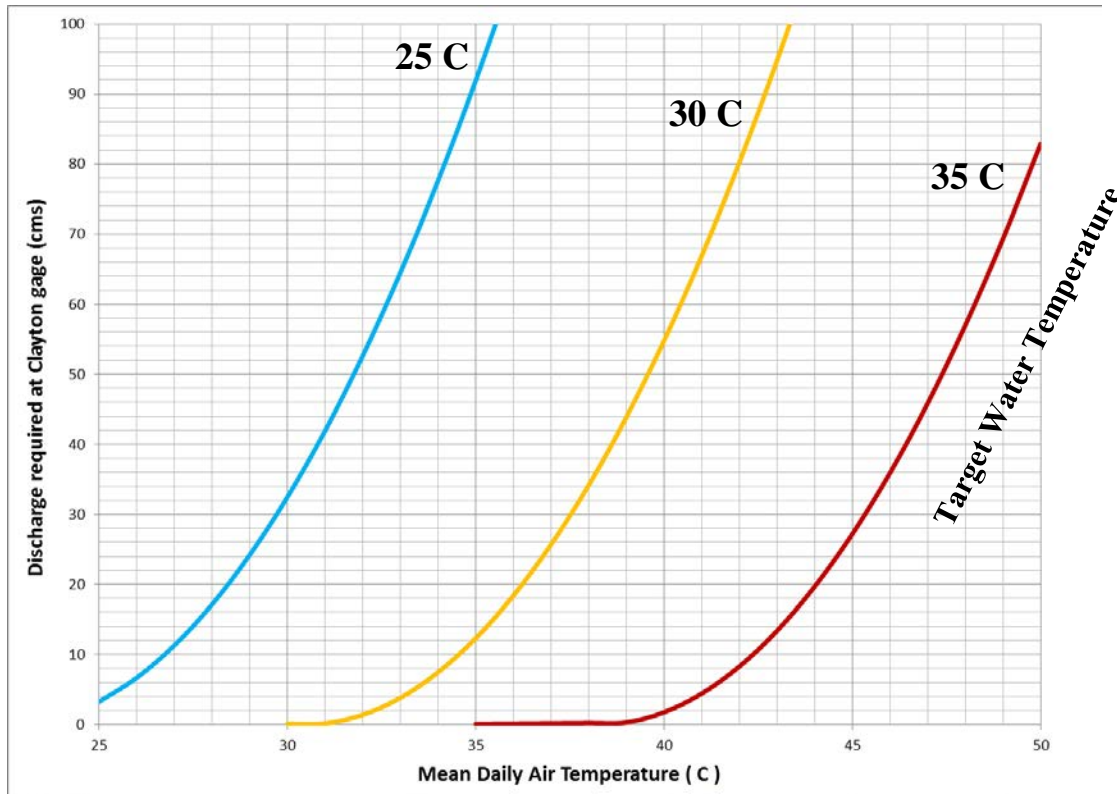
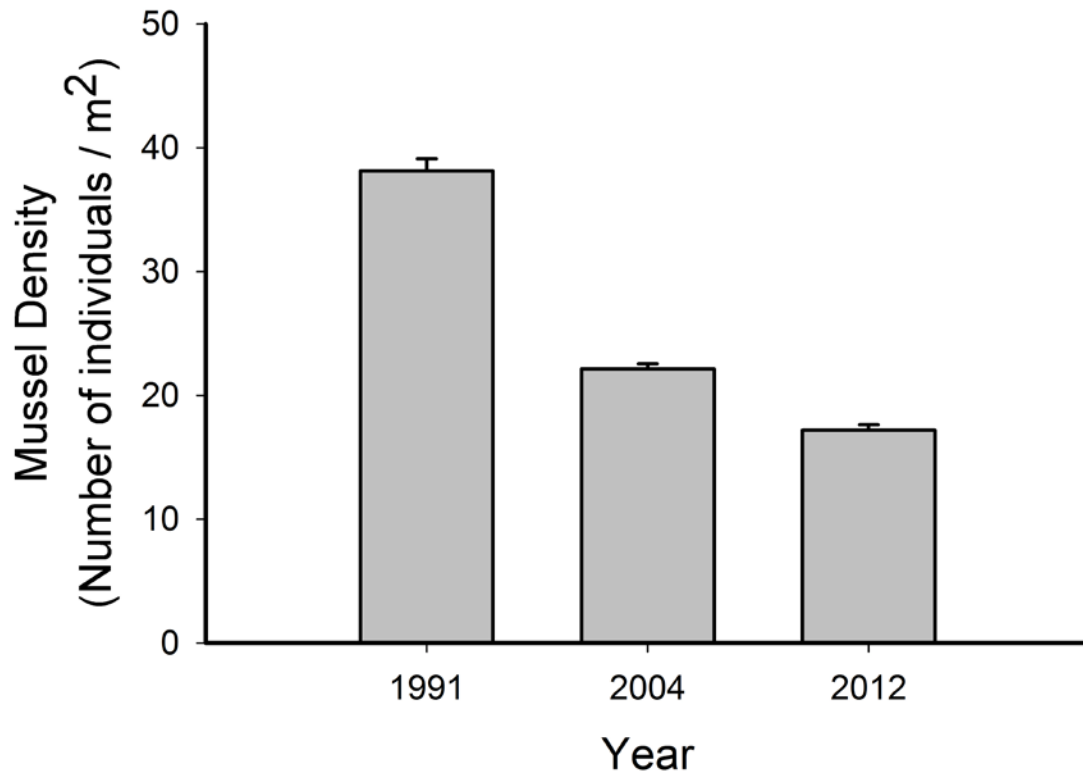
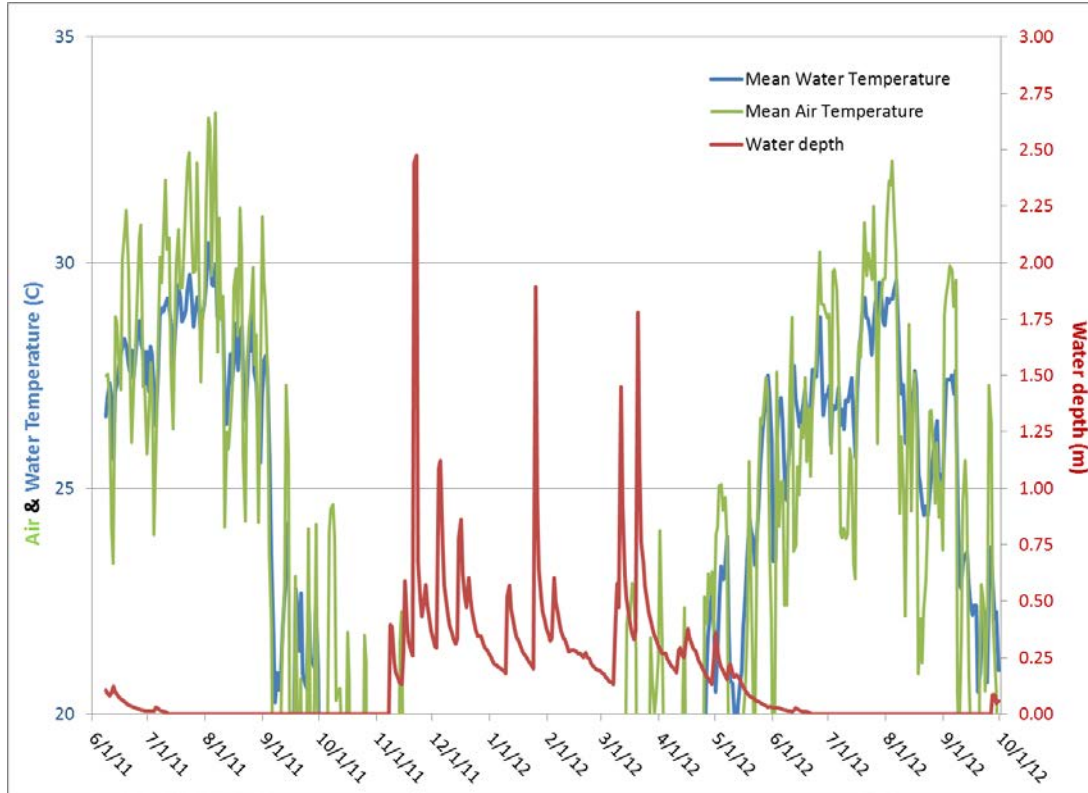


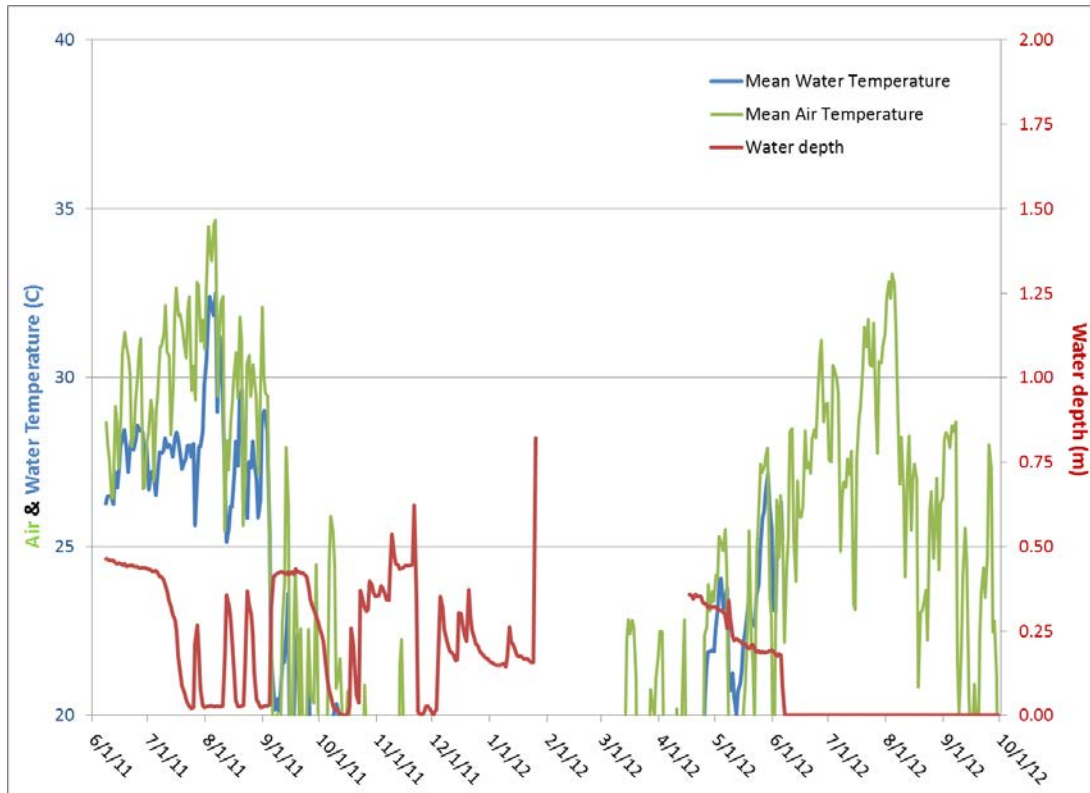
Figure 17. Average mussel densities at Paine's site (Vaughn site 7, Hobo logger site K11 across three decades – 1991, 2004 and 2012. From Vaughn and Pyron (1995), Galbraith et al. (2010) and Vaughn unpublished.



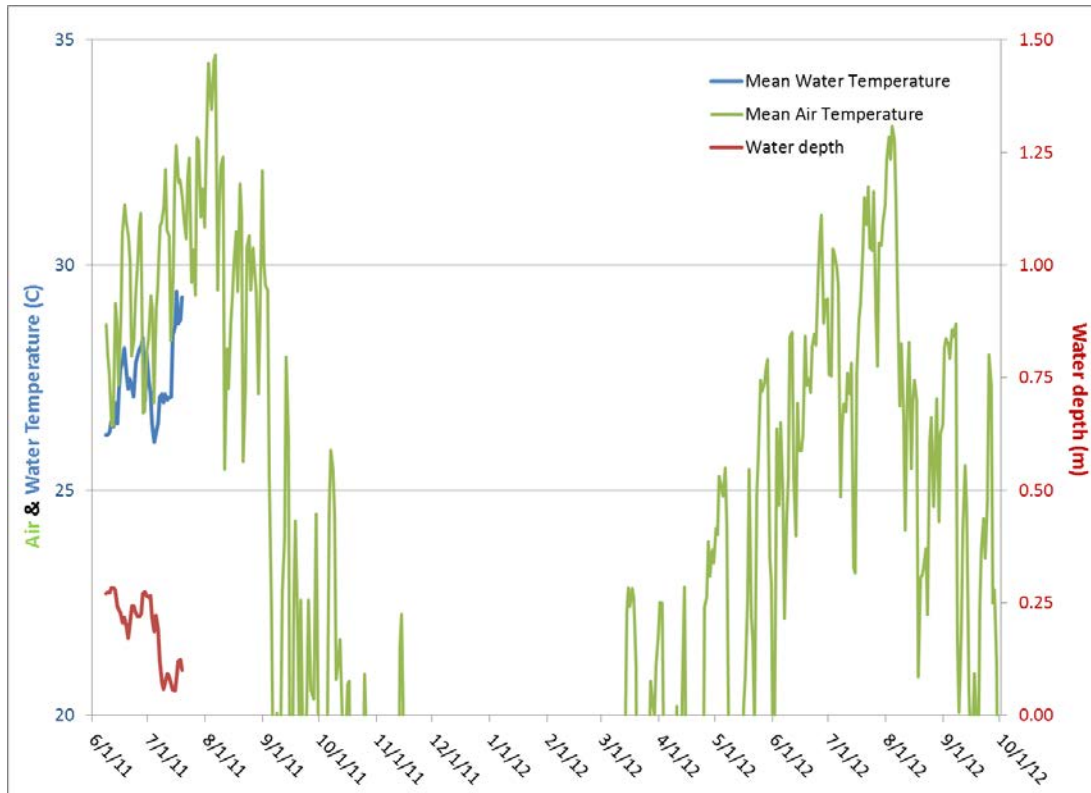
Appendix 1 – Mean water temperature time-series



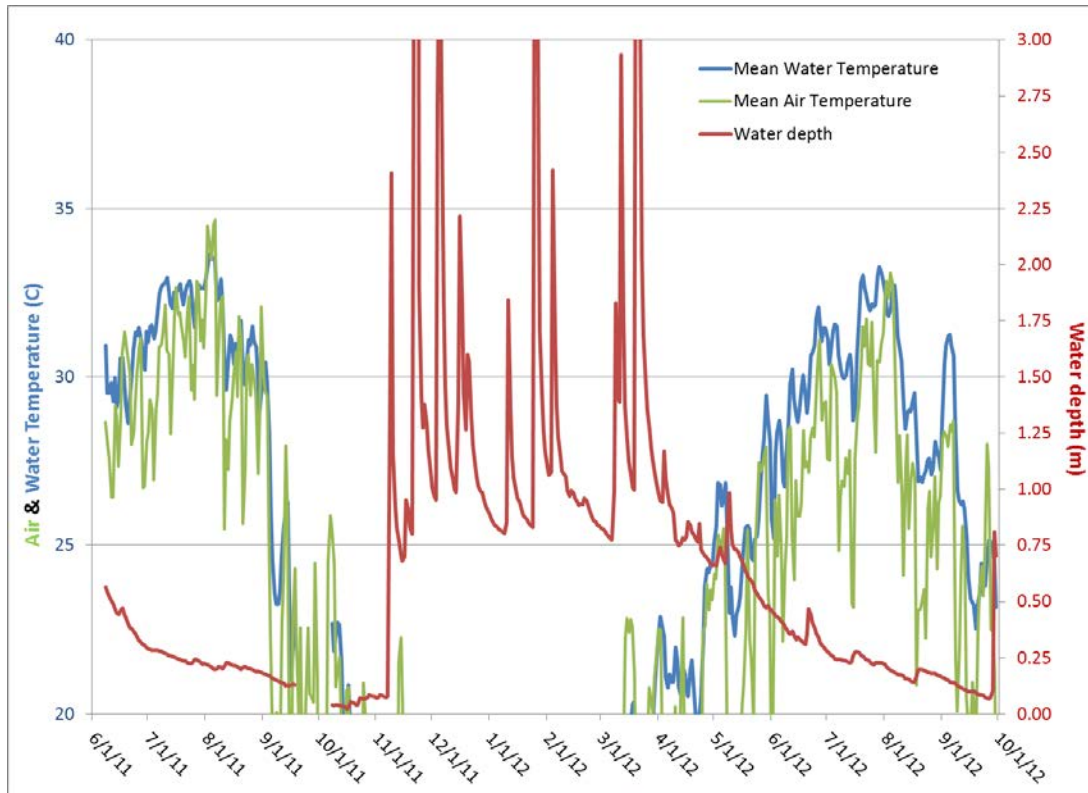
Appendix 1A. Water depth and mean daily air & water temperature for Kiamichi River station at Big Cedar (K2), the most upstream station of the study area. Because our HOB0 gage was displaced on several occasions, water depth was obtained from the USGS gage at the same site. Water temperature for 2012 was also obtained from the USGS gage due to our HOB0 gage being out of water during most of this period.



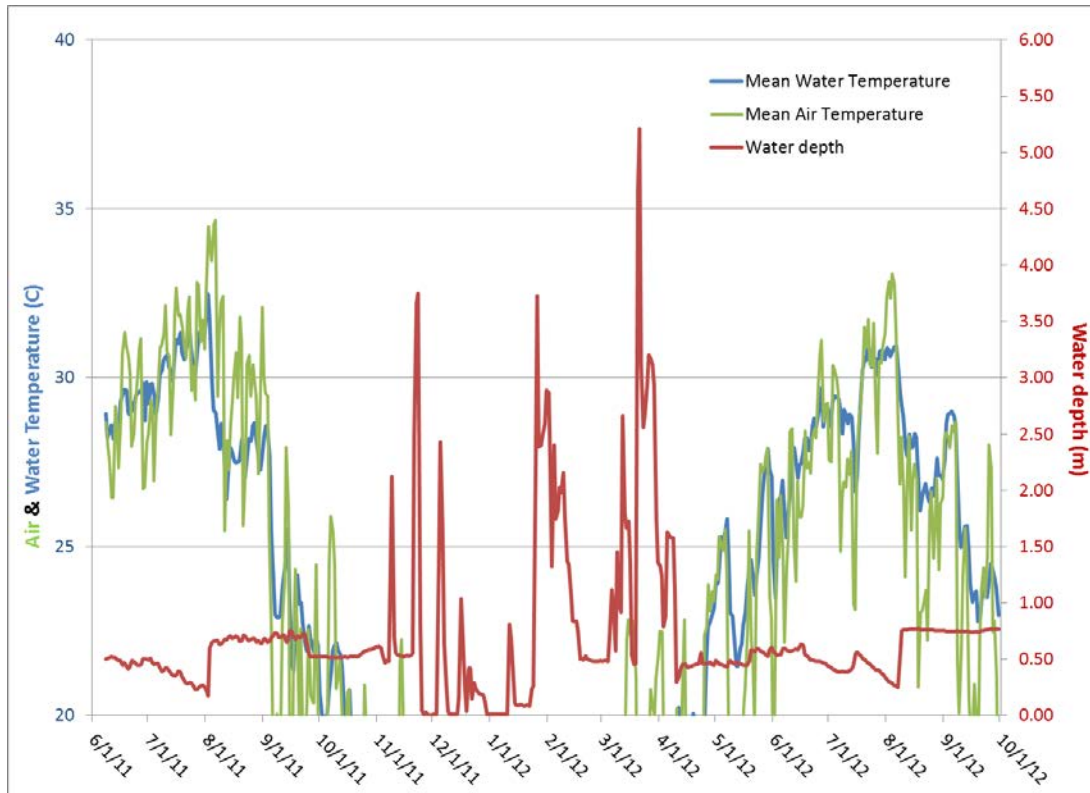
Appendix 1B. Water depth and mean daily air & water temperature for Buffalo Creek station (K3), one of the two main inputs to Sardis Lake. The HOBO gage was displaced by a flood on January 25, 2012 and was not replaced until April 17, 2012. The creek was dry from June 7 to September 30, 2012 and thus no water temperature data for this period.



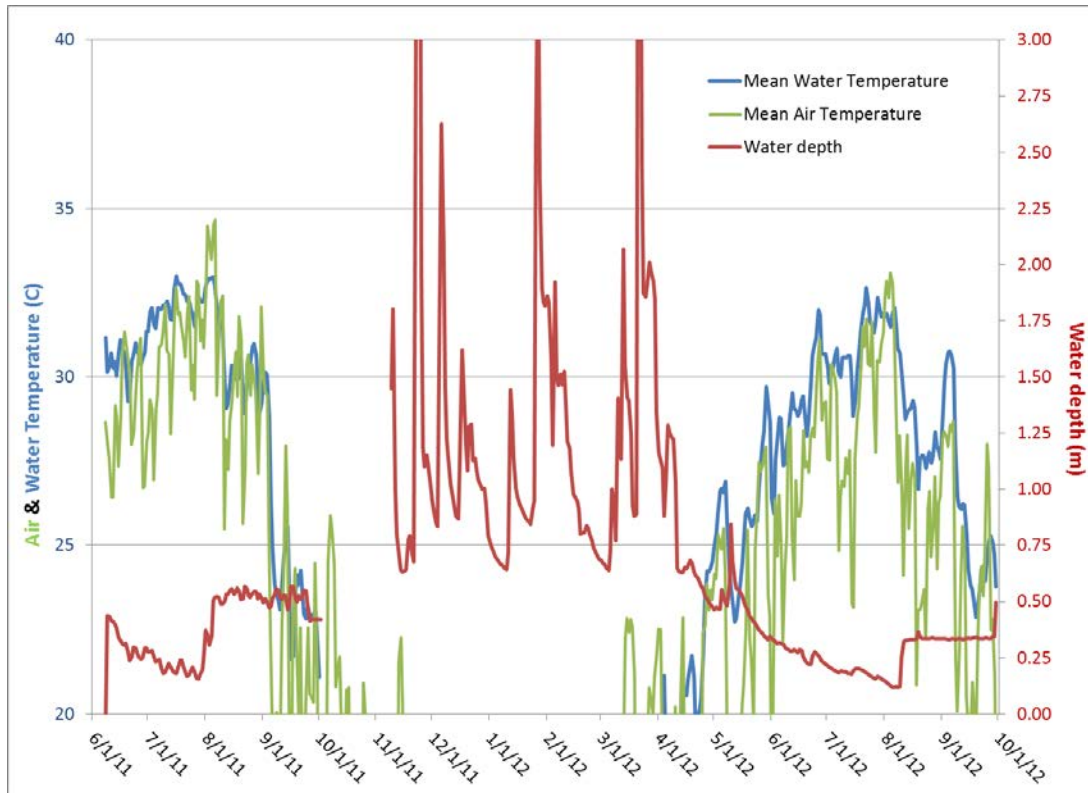
Appendix 1C. Water depth and mean daily air & water temperature for Jackfork Creek station above Sardis Reservoir (K4), one of the two main inputs to Sardis Lake. The logger malfunctioned on July 19, 2011, with no usable data after this date.



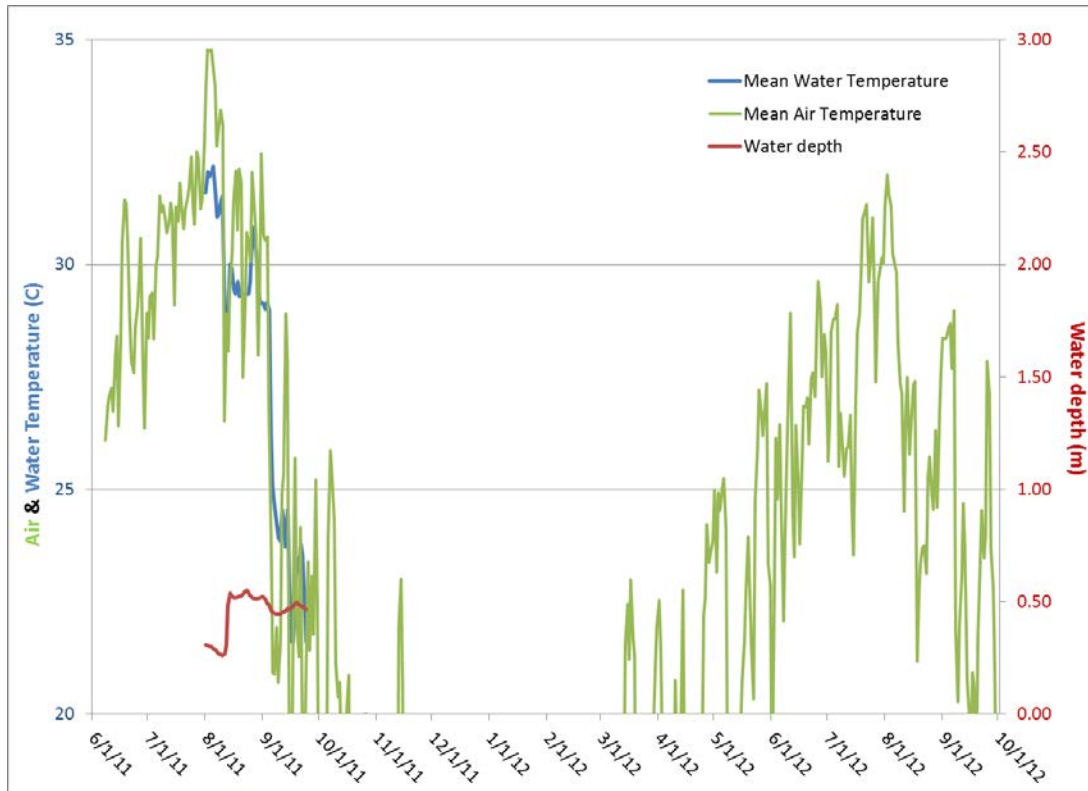
Appendix 1D. Water depth and mean daily air & water temperature for Kiamichi River station at Tuskahoma (K6), upstream of the Jackfork Creek confluence.



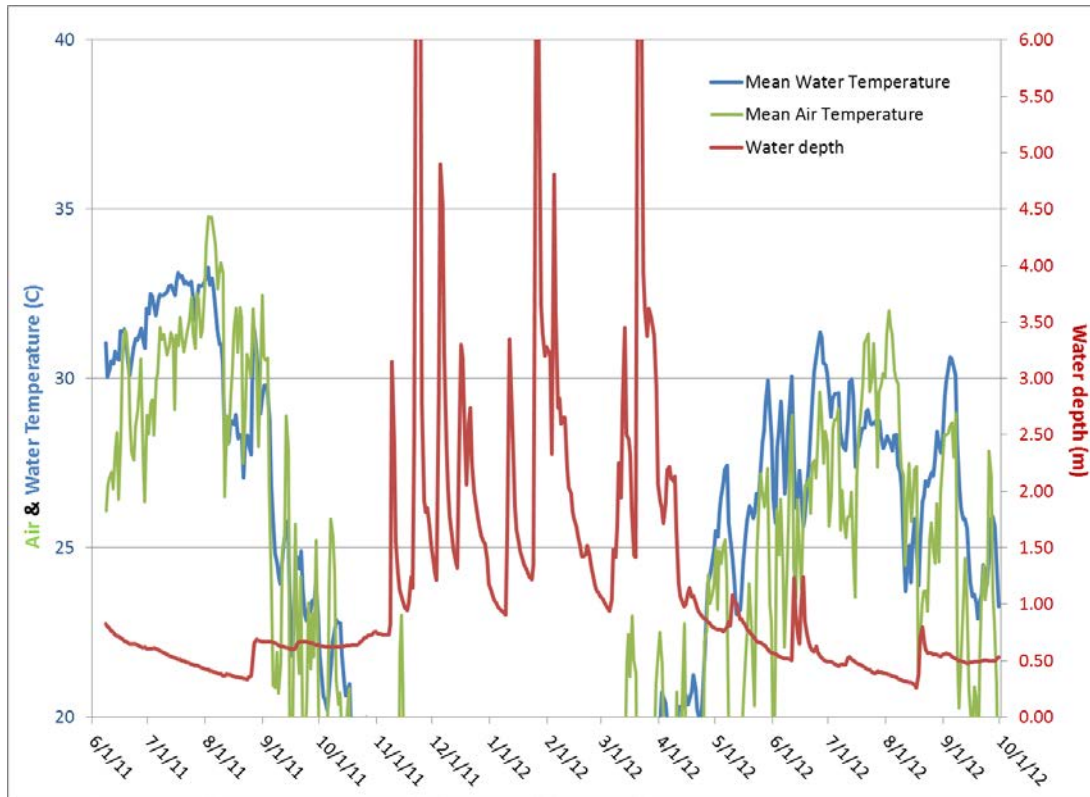
Appendix 1E. Water depth and mean daily air & water temperature for Jackfork Creek station below Sardis Dam (K7). This station measures releases from Sardis Dam. Note the spikes in water depth on August 3, 2011 and August 8, 2012 from managed Sardis Dam releases of 21 cfs and 12 cfs, respectively.



Appendix 1F. Water depth and mean daily air & water temperature for Kiamichi River station at Clayton (K8), downstream of the Jackfork Creek confluence. Note the spikes in water depth on August 3, 2011 and August 8, 2012 from managed Sardis Dam releases of 21 cfs and 12 cfs, respectively.

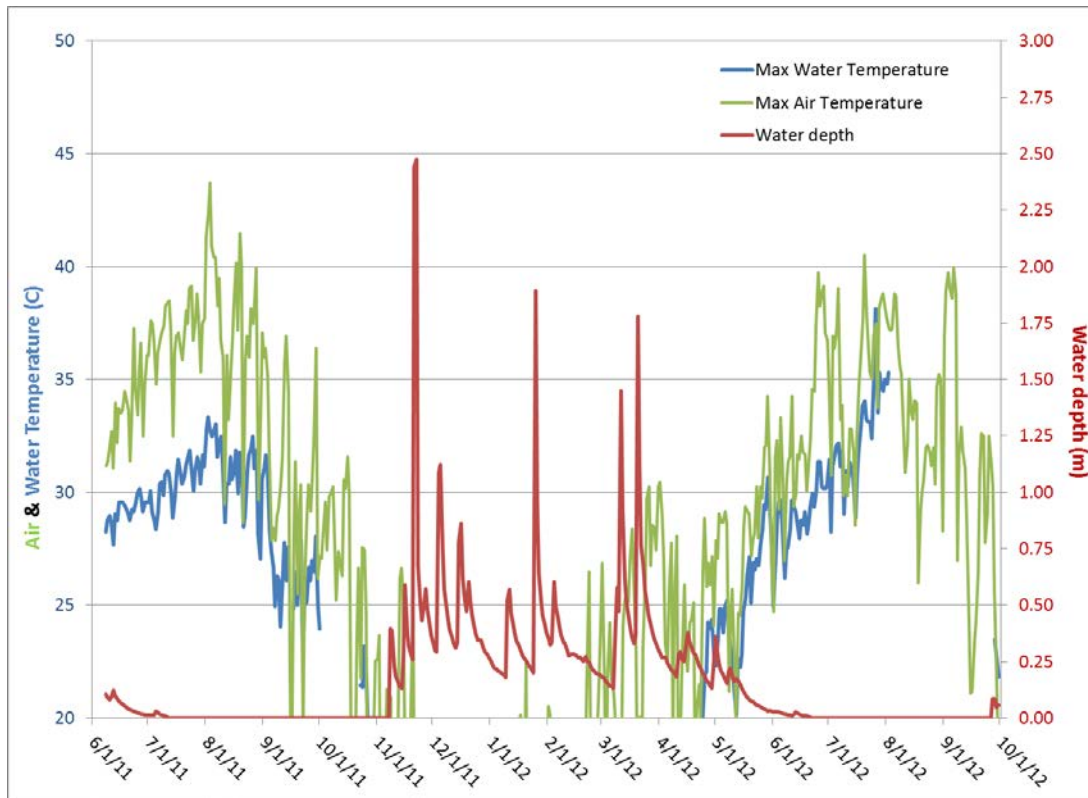


Appendix 1G. Water depth and mean daily air & water temperature for Kiamichi River station at Paine's (K11). Note the spike in water depth on August 13, 2011 from managed Sardis Dam releases of 21 cfs. Due to access issues, logger was not installed until July 31, 2011. After September 24, 2011, logger was buried under large debris jam and was not accessible. With such little data from this site, it was not modeled for water temperature changes. These data are useful, however, to show the flow timing and magnitude effects from Sardis Dam releases on downstream reaches.

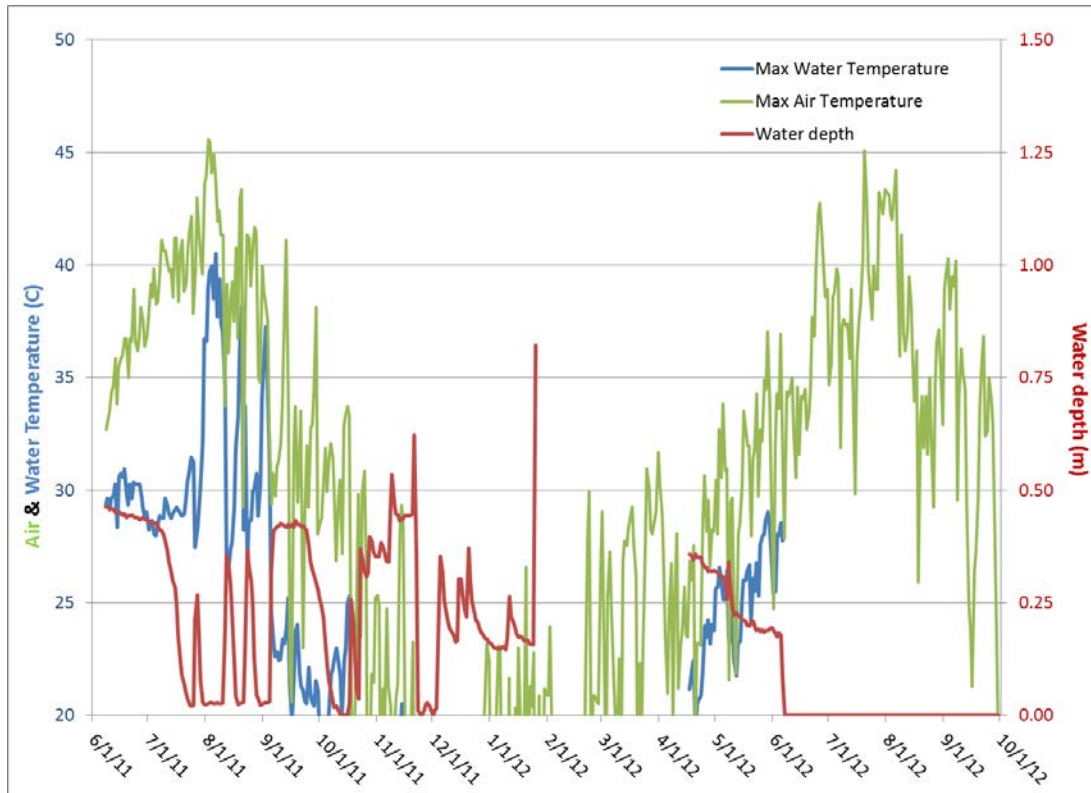


Appendix 1H. Water depth and mean daily air & water temperature for Kiamichi River station at Antlers (K9), downstream extent of study area. Note the spikes in water depth on August 27, 2011 and August 19, 2012 from managed Sardis Dam releases of 21 cfs and 12 cfs, respectively.

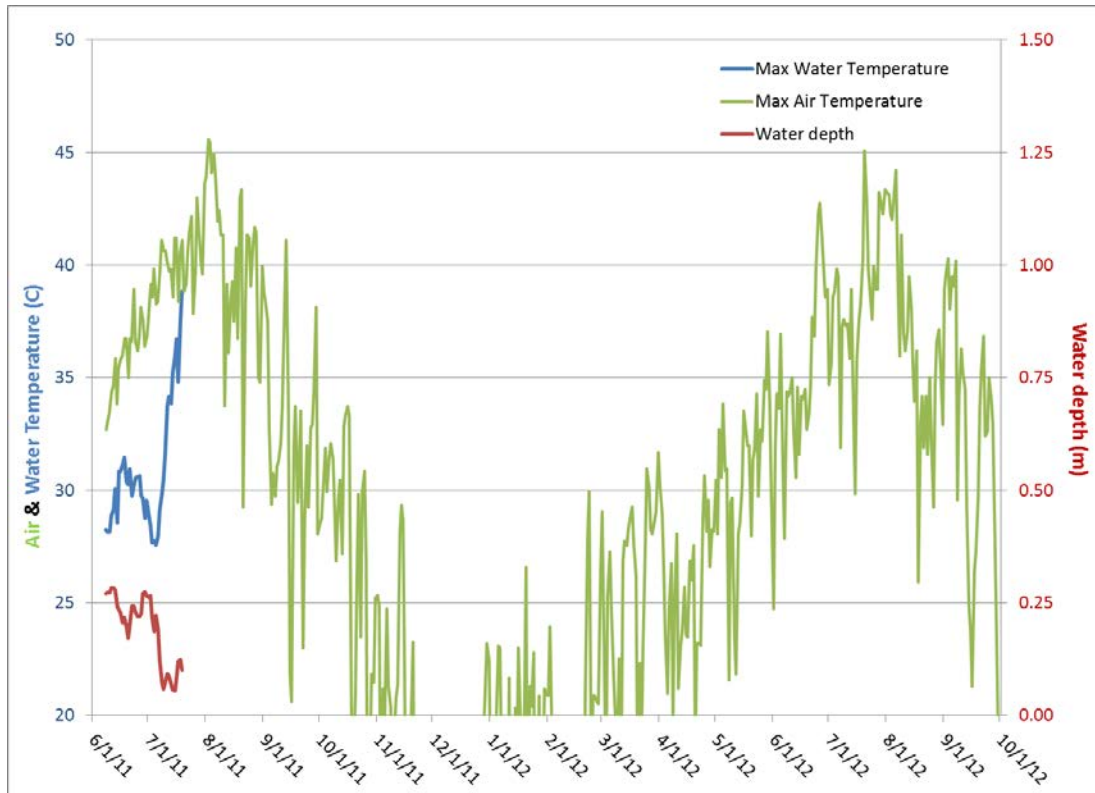
Appendix 2 – Maximum water temperature time-series



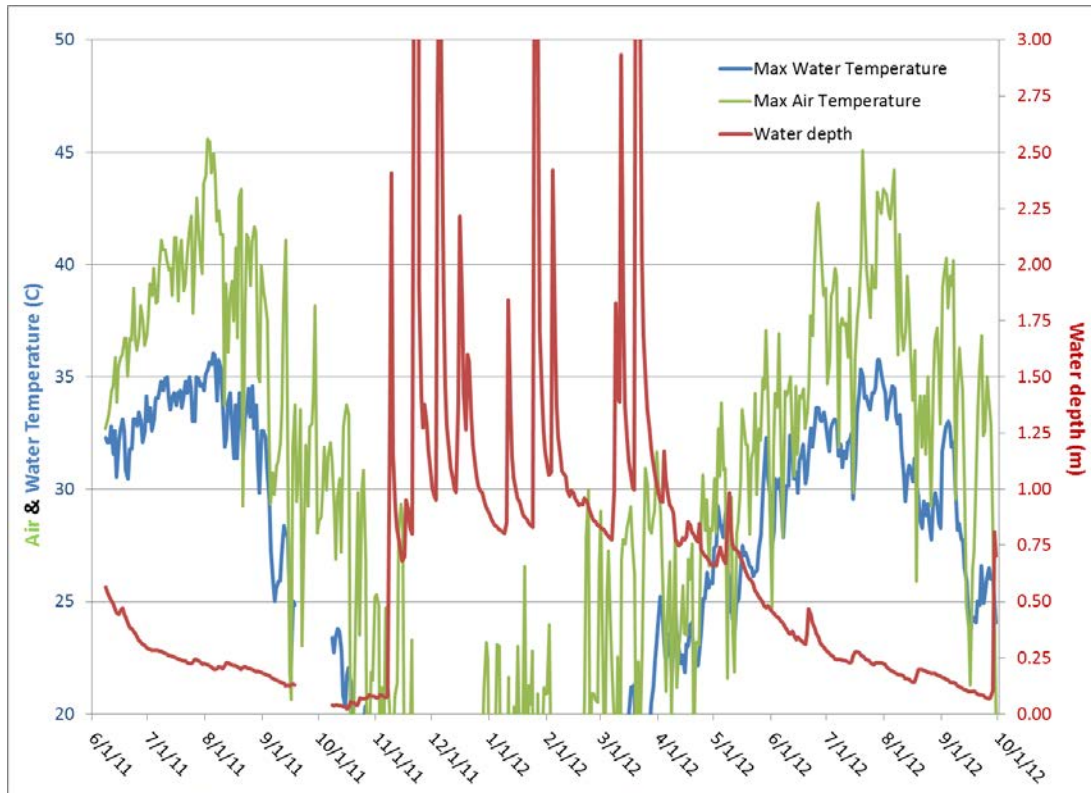
Appendix 2A. Water depth and maximum daily air & water temperature for Kiamichi River station at Big Cedar (K2), the most upstream station of the study area. Because our HOBO gage was displaced on several occasions, water depth was obtained from the USGS gage at the same site. Maximum water temperature is not reported for most of 2012 because our HOBO gage was out of water during most of this period.



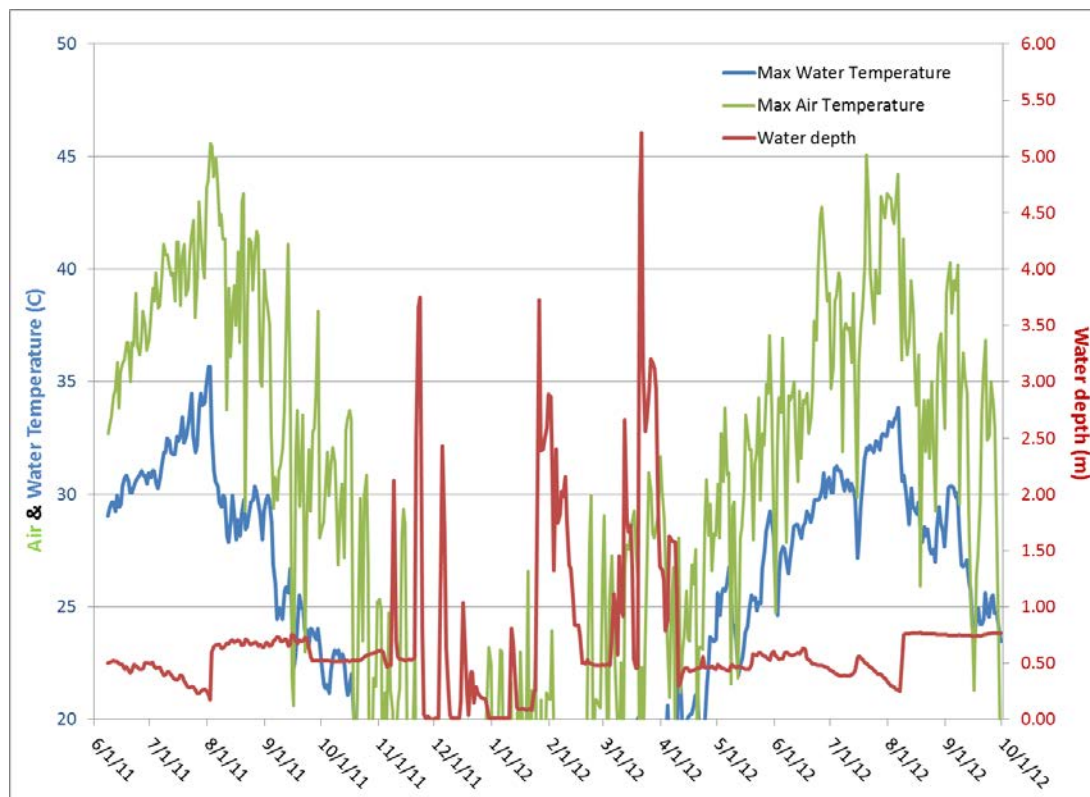
Appendix 2B. Water depth and maximum daily air & water temperature for Buffalo Creek station (K3), one of the two main inputs to Sardis Lake. The HOBO gage was displaced by a flood on January 25, 2012 and was not replaced until April 17, 2012. The creek was dry from June 7 to September 30, 2012 and thus no water temperature data for this period.



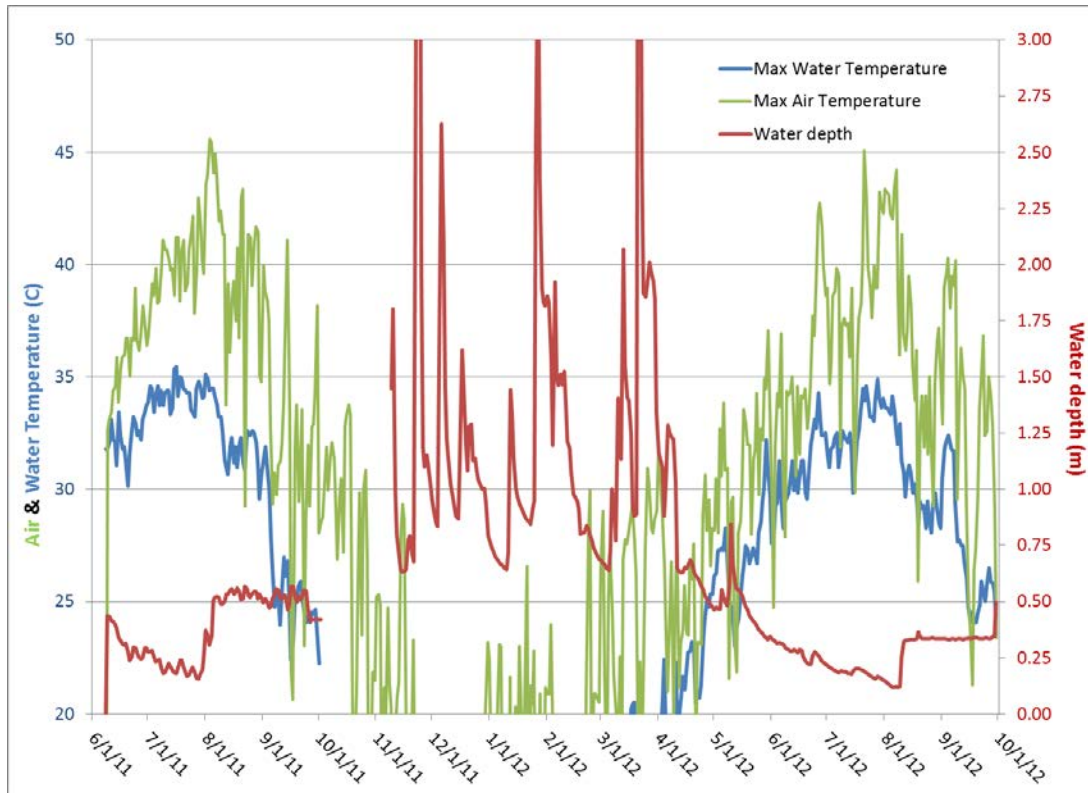
Appendix 2C. Water depth and maximum daily air & water temperature for Jackfork Creek station above Sardis Reservoir (K4), one of the two main inputs to Sardis Lake. The logger malfunctioned on July 19, 2011, with no usable data after this date.



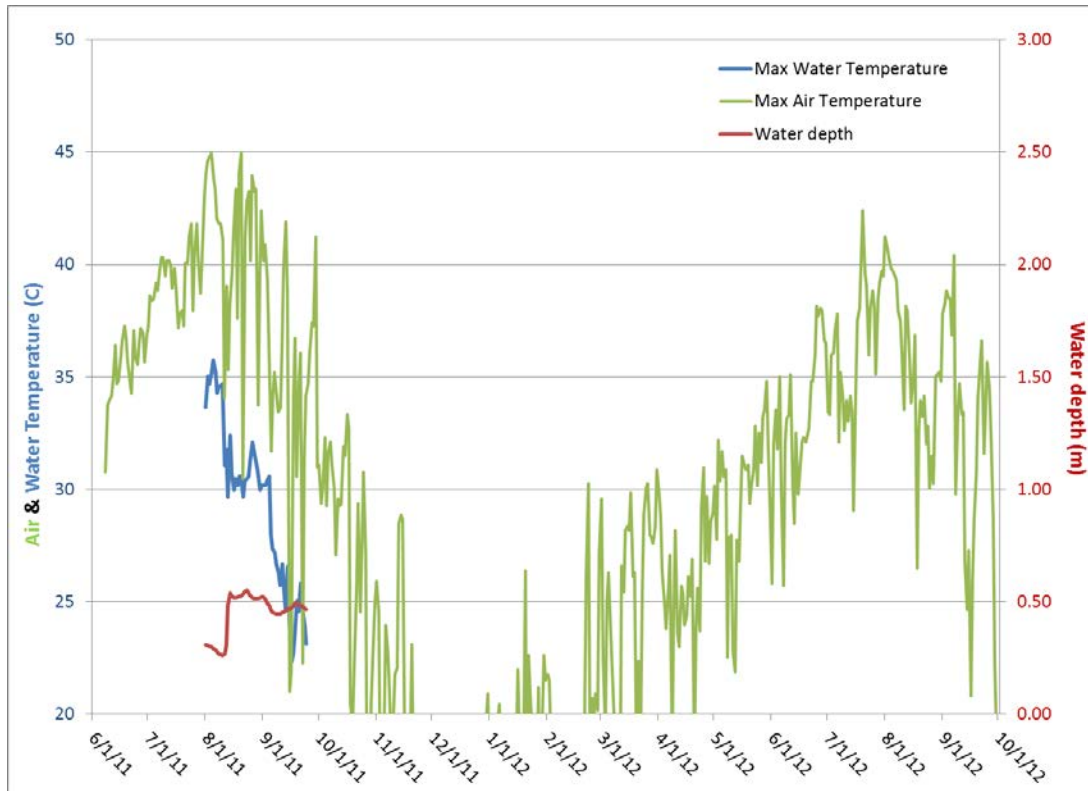
Appendix 2D. Water depth and maximum daily air & water temperature for Kiamichi River station at Tuskahoma (K6), upstream of the Jackfork Creek confluence.



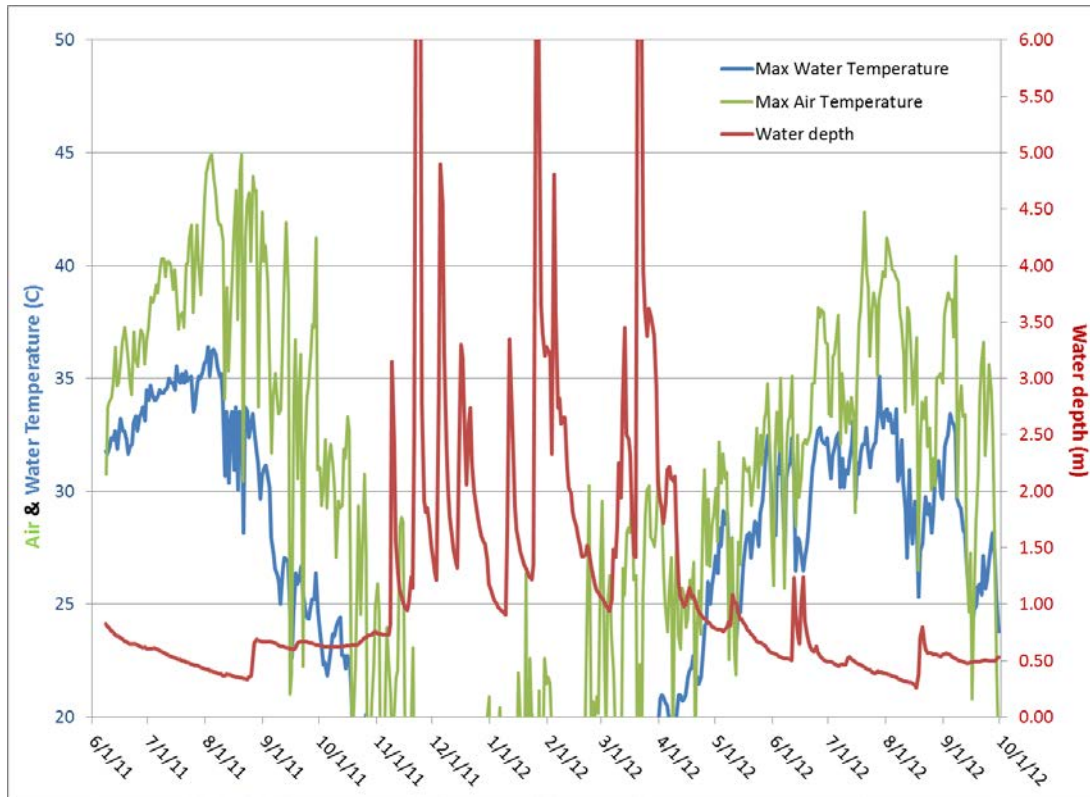
Appendix 2E. Water depth and maximum daily air & water temperature for Jackfork Creek station below Sardis Dam (K7). This station measures releases from Sardis Dam. Because Sardis Reservoir is such a large body of water, its water temperatures will be considerably lower than air temperatures during the summer. Note the spikes in water depth on August 3, 2011 and August 8, 2012 from managed Sardis Dam releases of 21 cfs and 12 cfs, respectively.



Appendix 2F. Water depth and maximum daily air & water temperature for Kiamichi River station at Clayton (K8), downstream of the Jackfork Creek confluence. Note the spikes in water depth on August 2, 2011 and August 8, 2012 from managed Sardis Dam releases of 21 cfs and 12 cfs, respectively.

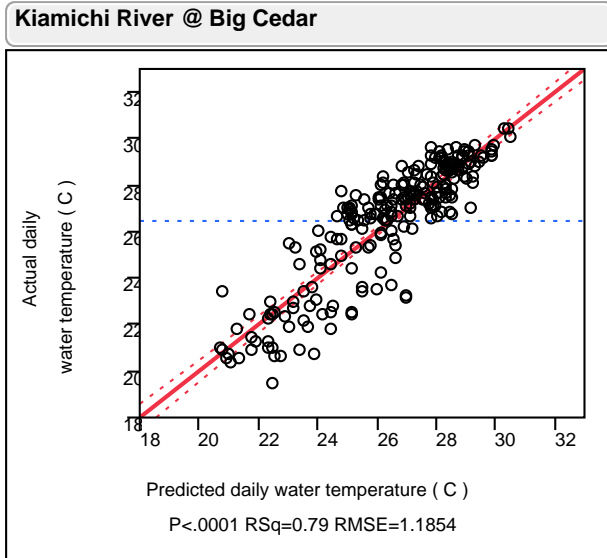


Appendix 2G. Water depth and maximum daily air & water temperature for Kiamichi River station at Paine's (K11). Note the spike in water depth on August 13, 2011 from managed Sardis Dam releases of 21 cfs. Due to access issues, logger was not installed until July 31, 2011. After September 24, 2011, logger was buried under large debris jam and was not accessible. With such little data from this site, it was not modeled for water temperature changes. These data are useful, however, to show the flow timing and magnitude effects from Sardis Dam releases on downstream reaches.

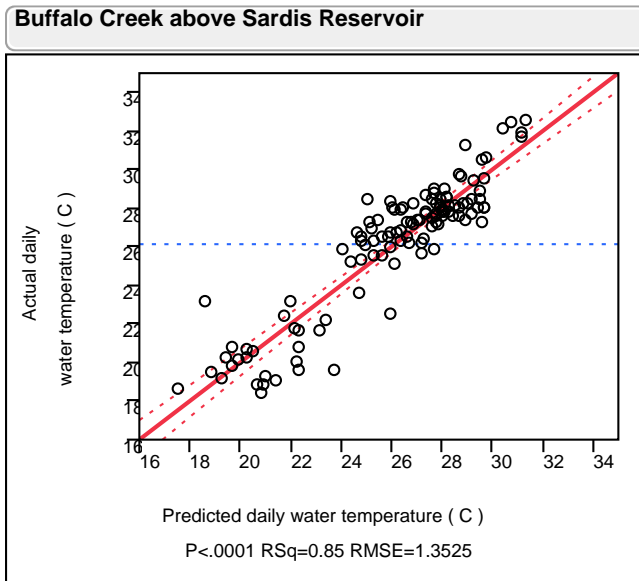


Appendix 2H. Water depth and maximum daily air & water temperature for Kiamichi River station at Antlers (K9), downstream extent of study area. Note the spikes in water depth on August 27, 2011 and August 19, 2012 from managed Sardis Dam releases of 21 cfs and 12 cfs, respectively.

Appendix 3 – Mean daily water temperature regression models



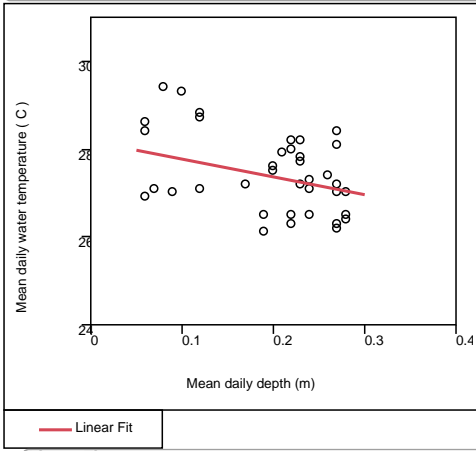
Appendix 3A. Actual vs. predicted mean daily water temperature (T_w) for Kiamichi River at Big Cedar (K2) using a bivariate model with mean daily air temperature (T_{air}). Water depth (D) was not used for this station because of its narrow range (0 – 0.12 cm). Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w = 0.58T_{air} + 11.09$.



Appendix 3B. Actual vs. predicted mean daily water temperature (T_w) for Buffalo Creek above Sardis Reservoir (K3) using a multivariate model that includes mean daily air temperature (T_{air}) and mean daily water depth (D) at the station. Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w = 0.69T_{air} - 1.69D + 7.26$.

Jackfork Creek above Sardis Reservoir

Bivariate Fit of Tw and D



Linear Fit

$$T_w = 28.176366 - 4.0509241 \cdot D$$

Summary of Fit

RSquare	0.129377
RSquare Adj	0.107612
Root Mean Square Error	0.81769
Mean of Response	27.40476
Observations (or Sum Wgts)	42

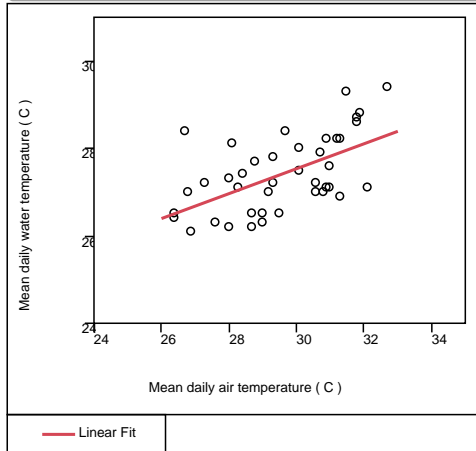
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	3.974342	3.97434	5.9441
Error	40	26.744705	0.66862	Prob > F
C. Total	41	30.719048		0.0193

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	28.176366	0.340707	82.70	<.0001
Average of Depth_m	-4.050924	1.661538	-2.44	0.0193

Bivariate Fit of Tw and Tair



Linear Fit

$$T_w = 18.982302 + 0.2851159 \cdot T_{air}$$

Summary of Fit

RSquare	0.32793
RSquare Adj	0.311128
Root Mean Square Error	0.718425
Mean of Response	27.40476
Observations (or Sum Wgts)	42

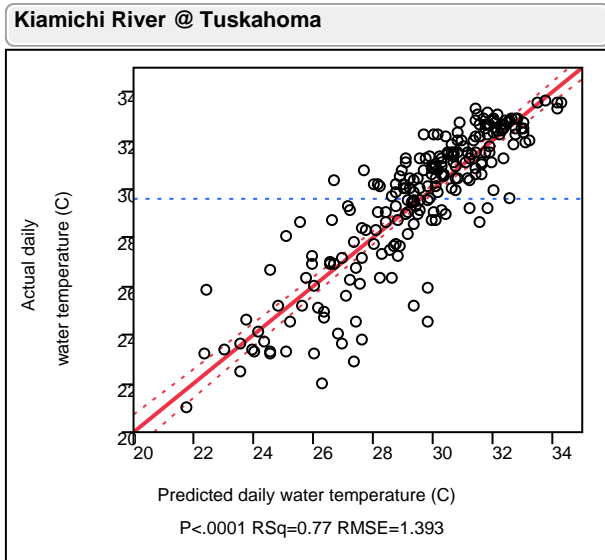
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	10.073689	10.0737	19.5176
Error	40	20.645359	0.5161	Prob > F
C. Total	41	30.719048		<.0001

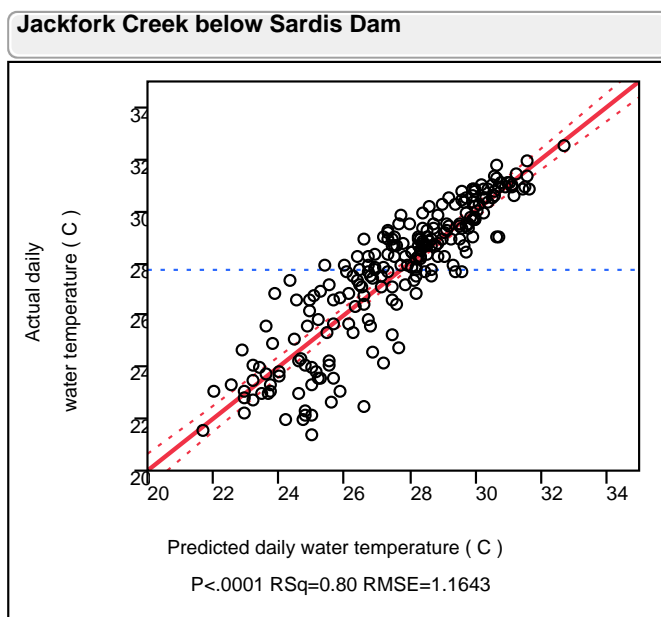
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob
Intercept	18.982302	1.909672	9.94	<.000
Mean_Air_Temp_C	0.2851159	0.064537	4.42	<.000

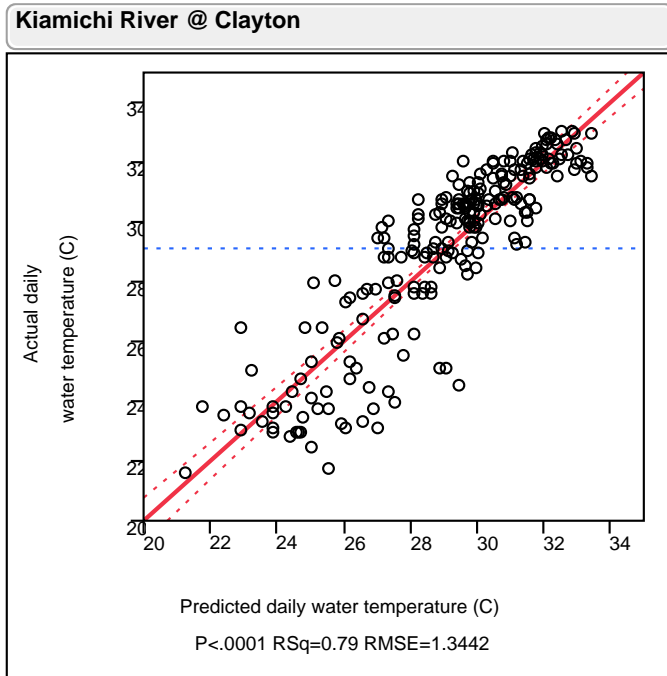
Appendix 3C. Bivariate plots of mean daily water temperature (T_w) vs. water depth (D) and mean daily air temperature (T_{air}) for Jackfork Creek station above Sardis Reservoir (K4). The plots show that T_w has a significant negative correlation with D and a significant positive correlation with T_{air} . There were not enough measurements to derive a robust model for T_w .



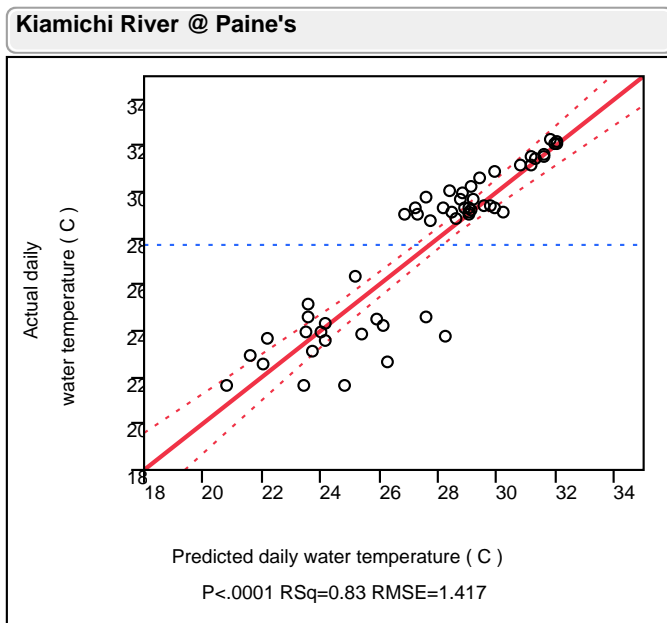
Appendix 3D. Actual vs. predicted mean daily water temperature (T_w) for Kiamichi River at Tuskahoma (K6) using a bivariate model with mean daily air temperature (T_{air}). Mean daily water depth (D) could not be included in the multivariate model for this station because it had a nonlinear relationship with water temperature. Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w = 0.66T_{air} + 11.26$.



Appendix 3E. Actual vs. predicted mean daily water temperature (T_w) for Jackfork Creek below Sardis Dam (K7) using a multivariate model that includes mean daily air temperature (T_{air}) and mean daily water depth (D) at the station. Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w = 0.46T_{air} - 4.23D + 17.54$.

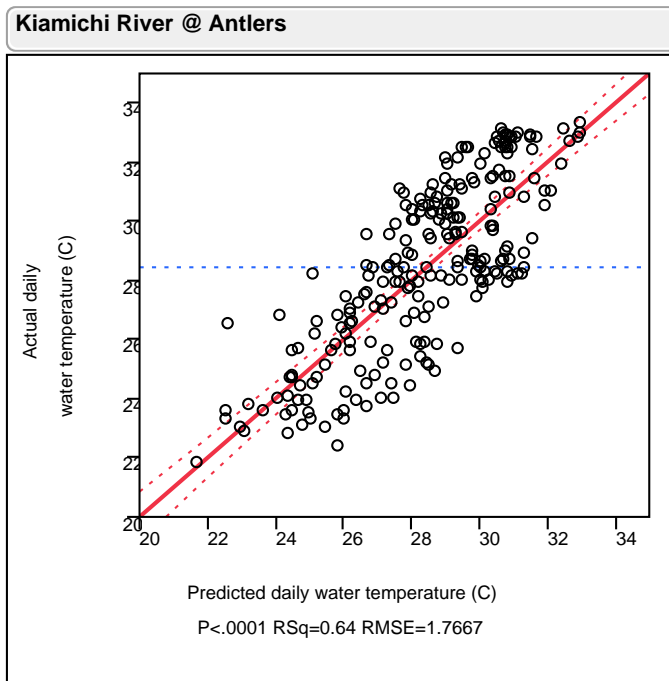


Appendix 3F. Actual vs. predicted mean daily water temperature (T_w) for Kiamichi River at Clayton (K8) using a multivariate model that includes mean daily air temperature (T_{air}) and mean daily water depth (D) at the station. Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w = 0.59T_{air} - 4.37D + 14.36$.



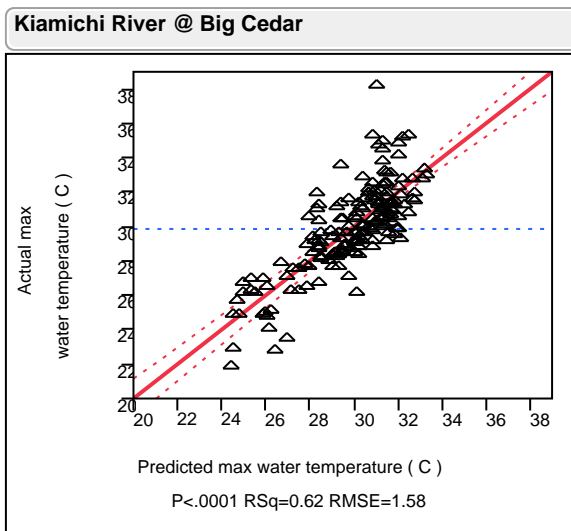
Appendix 3G. Actual vs. predicted mean daily water temperature (T_w) for Kiamichi River at Paine's (K11) using a multivariate model that includes mean daily air temperature (T_{air}) and mean daily water depth (D) at the station. Horizontal blue dotted line represents the mean value.

Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w = 0.58T_{air} - 2.47D + 12.52$.

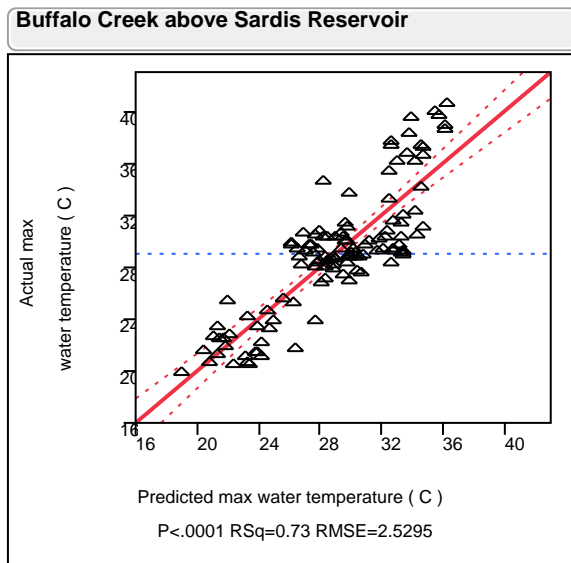


Appendix 3H. Actual vs. predicted mean daily water temperature (T_w) for Kiamichi River at Antlers (K9) using a bivariate model with mean daily air temperature (T_{air}). Water depth (D) was not used for this station because of collinearity with air temperature (i.e. lower flow occurred on warmer days). Model equation: $T_w = 0.61T_{air} + 11.83$.

Appendix 4 – Maximum daily water temperature regression models



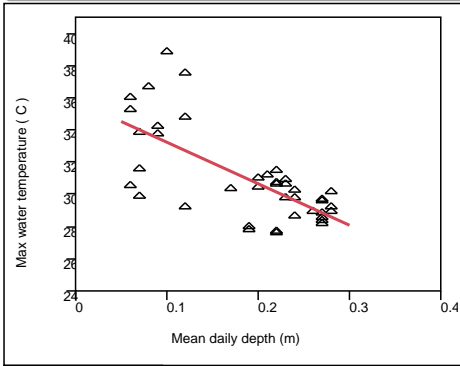
Appendix 4A. Actual vs. predicted maximum daily water temperature (T_w) for Kiamichi River at Big Cedar (K2) using a bivariate model with mean daily air temperature (T_{air}). Water depth (D) was not used for this station because of its narrow range (0 – 0.12 cm). Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w(\text{max}) = 0.53T_{air} + 15.75$.



Appendix 4B. Actual vs. predicted maximum daily water temperature (T_w) for Buffalo Creek above Sardis Reservoir (K3) using a multivariate model that includes mean daily air temperature (T_{air}) and mean daily water depth (D) at the station. Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w(\text{max}) = 0.71T_{air} - 9.82D + 11.85$.

Jackfork Creek above Sardis Reservoir

Bivariate Fit of Max Tw and D



— Linear Fit

Linear Fit

$$T_w(\max) = 35.810794 - 25.76917 \cdot D$$

Summary of Fit

RSquare	0.493621
RSquare Adj	0.480962
Root Mean Square Error	2.030906
Mean of Response	30.90238
Observations (or Sum Wgts)	42

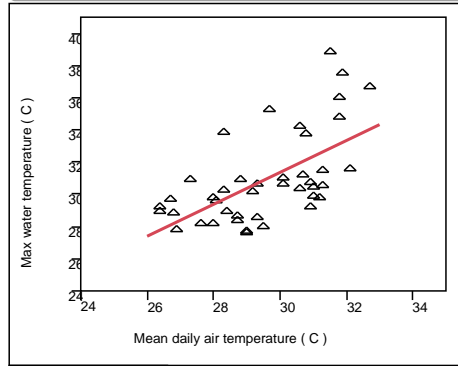
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	160.82662	160.827	38.9923
Error	40	164.98314	4.125	Prob > F
C. Total	41	325.80976		≈.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	35.810794	0.846217	42.32	≈.0001
Average of Depth_m	-25.76917	4.126779	-6.24	≈.0001

Bivariate Fit of Max Tw and Tair



— Linear Fit

Linear Fit

$$T_w(\max) = 1.646827 + 0.9903549 \cdot T_{air}$$

Summary of Fit

RSquare	0.373047
RSquare Adj	0.357373
Root Mean Square Error	2.259798
Mean of Response	30.90238
Observations (or Sum Wgts)	42

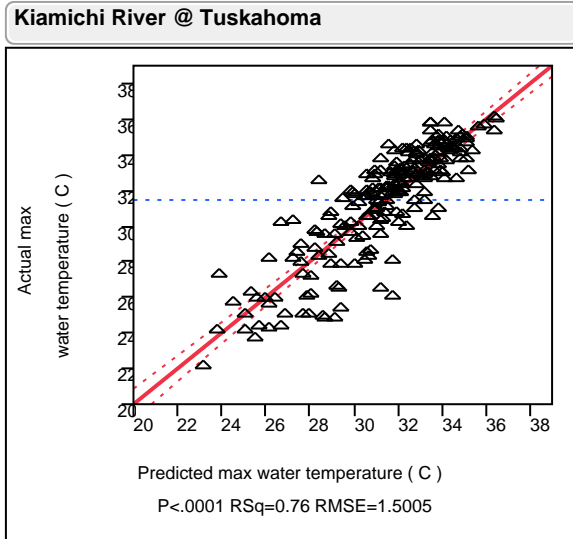
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	121.54224	121.542	23.8006
Error	40	204.26752	5.107	Prob > F
C. Total	41	325.80976		≈.0001

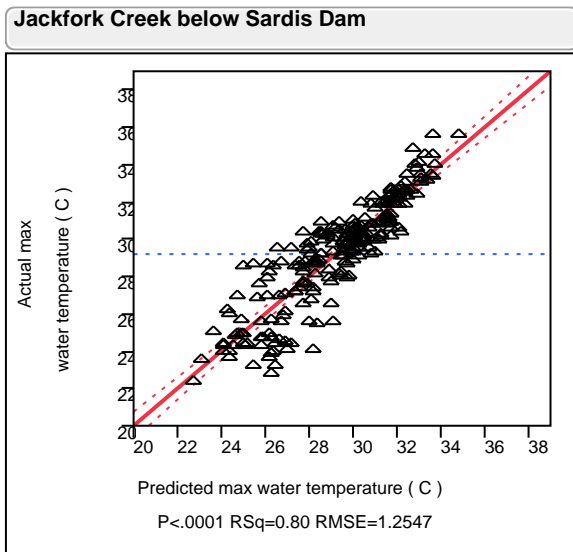
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob
Intercept	1.646827	6.006857	0.27	0.785
Mean_Air_Temp_C	0.9903549	0.203	4.88	≈.000

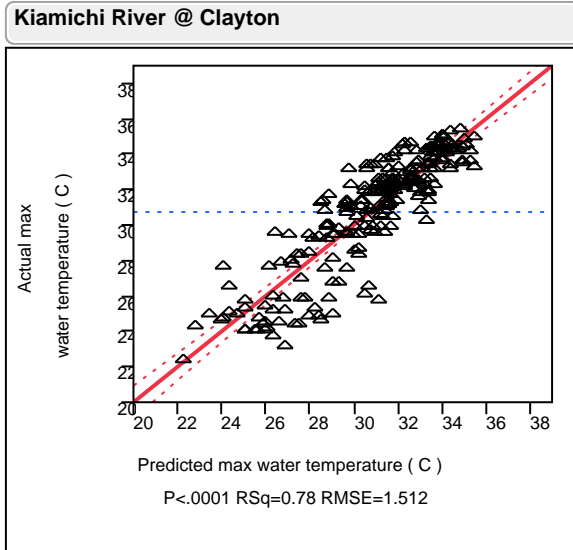
Appendix 4C. Bivariate plots of maximum daily water temperature (T_w) vs. water depth (D) and mean daily air temperature (T_{air}) for Jackfork Creek station above Sardis Reservoir (K4). The plots show that $T_w(\max)$ has a significant negative correlation with D and a significant positive correlation with T_{air} . There were not enough measurements to derive a robust model for $T_w(\max)$.



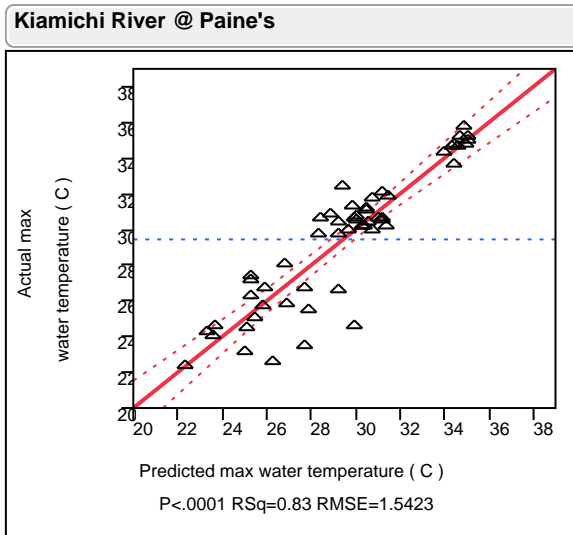
Appendix 4D. Actual vs. predicted maximum daily water temperature (T_w) for Kiamichi River at Tuskahoma (K6) using a bivariate model with mean daily air temperature (T_{air}). Mean daily water depth (D) could not be included in the multivariate model for this station because it had a nonlinear relationship with water temperature. Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w(\max) = 0.71T_{air} + 11.89$.



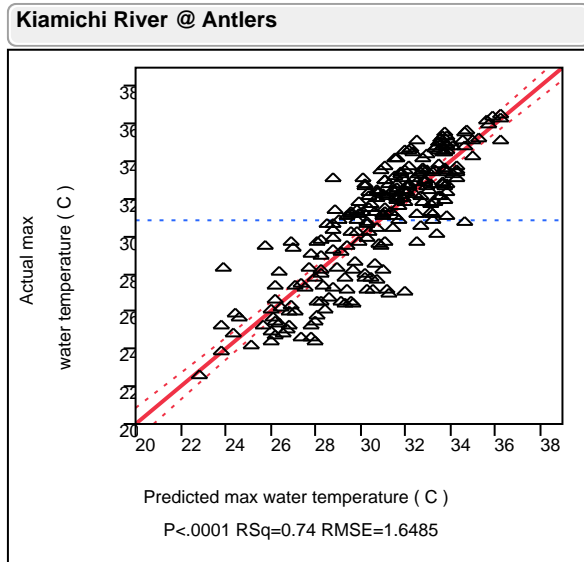
Appendix 4E. Actual vs. predicted maximum daily water temperature (T_w) for Jackfork Creek below Sardis Dam (K7) using a multivariate model that includes mean daily air temperature (T_{air}) and mean daily water depth (D) at the station. Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w(\max) = 0.47T_{air} - 5.78D + 19.58$.



Appendix 4F. Actual vs. predicted maximum daily water temperature (T_w) for Kiamichi River at Clayton (K8) using a multivariate model that includes mean daily air temperature (T_{air}) and mean daily water depth (D) at the station. Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w(\max) = 0.64T_{air} - 4.84D + 14.75$.

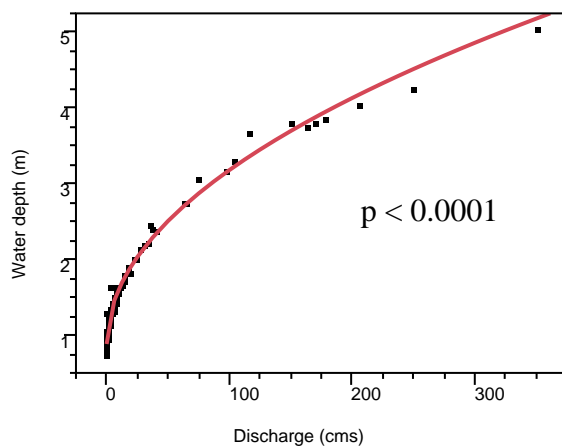


Appendix 4G. Actual vs. predicted maximum daily water temperature (T_w) for Kiamichi River at Paine's (K11) using a multivariate model that includes mean daily air temperature (T_{air}) and mean daily water depth (D) at the station. Horizontal blue dotted line represents the mean value. Diagonal solid red line represents $y=x$, and diagonal red dashed lines are 95% confidence intervals. Model equation: $T_w(\max) = 0.59T_{air} - 10.41D + 17.73$.

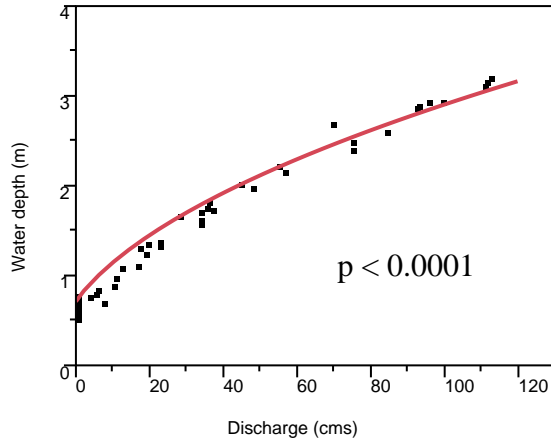


Appendix 4H. Actual vs. predicted maximum daily water temperature (T_w) for Kiamichi River at Antlers (K9) using a bivariate model with mean daily air temperature (T_{air}). Water depth (D) was not used for this station because of collinearity with air temperature (i.e. lower flow occurred on warmer days). Model equation: $T_w(\max) = 0.72T_{air} + 11.08$.

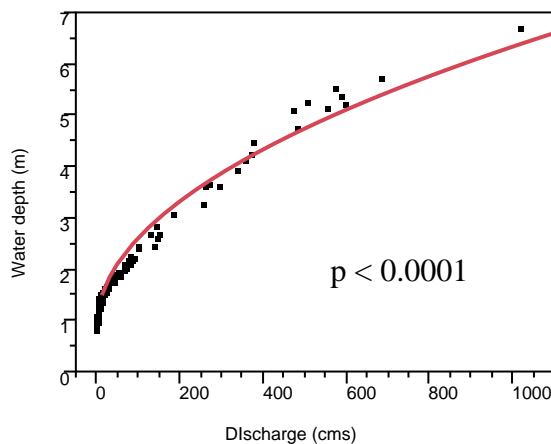
Appendix 5 – Hydrology data



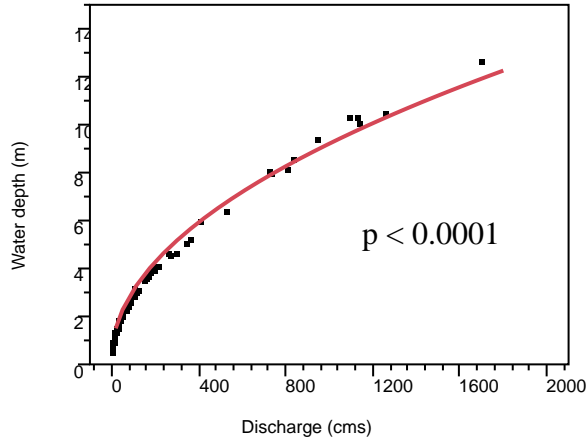
Appendix 5A. Depth-Discharge rating curve for Kiamichi River near Big Cedar (USGS 07335700). Use the following equation to calculate water depth at Big Cedar gage (D_{BIGC}) using the discharge reported on the USGS waterdata site (Q_{BIGC}): $D_{BIGC} = 0.88 + 0.23(Q_{BIGC})^{0.5}$



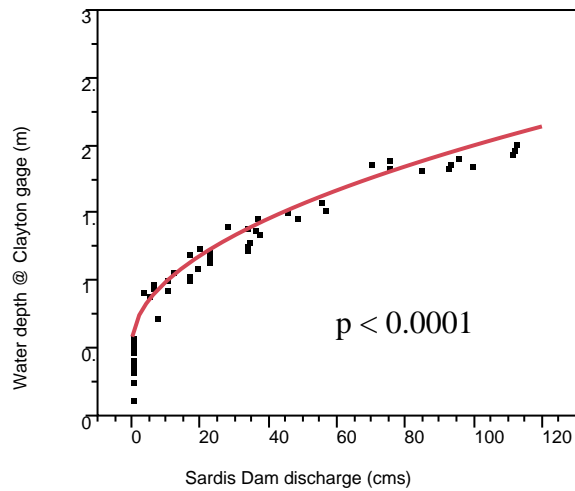
Appendix 5B. Depth-Discharge rating curve for Jackfork Creek below Sardis Dam using releases from Sardis Lake near Clayton (USGS 07335775) for discharge. Use the following equation to calculate water depth below Sardis Dam (D_{SARD}) using the discharge reported on the USGS waterdata site (Q_{SARD}): $D_{SARD} = (0.52 + 0.08 * Q_{SARD})^{0.5}$



Appendix 5C. Depth-Discharge rating curve for Kiamichi River near Clayton (USGS 07335790). Use the following equation to calculate water depth at Clayton gage (D_{CLAY}) using the discharge reported on the USGS waterdata site (Q_{CLAY}): $D_{CLAY} = 0.88 + 0.17(Q_{CLAY})^{0.5}$



Appendix 5D. Depth-Discharge rating curve for Kiamichi River near Antlers (USGS 07336200). Use the following equation to calculate water depth at Clayton gage (D_{ANTL}) using the discharge reported on the USGS waterdata site (Q_{ANTL}): $D_{ANTL} = 0.28 + 0.28(Q_{ANTL})^{0.5}$



Appendix 5E. Relationship between Sardis Dam releases (Q_{SARD}) and water depth of Kiamichi River @ Clayton (D_{CLAY}): $D_{CLAY} = 0.525 + 0.147(Q_{SARD})^{0.5}$. This equation was used to determine the necessary releases from Sardis Dam to prevent maximum water temperatures (via Appendix 4F) from exceeding target temperatures identified in Objective 1.