

FINAL PERFORMANCE REPORT



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**Evaluation of Environmental Flow Requirements for Freshwater
Mussels of Greatest Conservation Need in the Mountain Fork,
Kiamichi and Little Rivers, Oklahoma**

Oklahoma Department of Wildlife Conservation

June 1, 2011 through May 30, 2014

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For Freshwater Mussels of Greatest Conservation Need
In the Mountain Fork, Kiamichi and Little Rivers, Oklahoma**

Submitted to:

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SUMMARY:

The Kiamichi and Little Rivers in southeastern Oklahoma are home to a rich aquatic fauna, including four federally listed endangered species. Mussel populations in these rivers have suffered in recent years due to a lack of instream flows caused by drought and water management. Mussel populations are further threatened by proposed plans to sell water from these rivers to metropolitan areas. Thus, there is a critical need to understand the environmental flow requirements of freshwater mussels so that policy makers and river managers can strive to protect mussel populations and still provide water from this region for human needs. This report (1) summarizes the literature on potential methods and models for estimating mussel environmental flow needs; (2) examines the relationship between historical and current flows in the Little and Kiamichi Rivers and mussel population success; (3) presents water depth and temperature data for 19 sites in the watersheds; (4) evaluates how invasive *Corbicula* may impact mussel flow needs; and (5) makes recommendations for mussel environmental flow methods and minimum instream flows.

We suggest that environmental flow models for mussels include habitat permanence for existing beds, optimal shear stress, water quality (temperature, dissolved oxygen, and ammonia), and promote overlap with host fish during appropriate seasons to ensure connectivity between mussel beds. The threat of extreme temperature exposure can be mitigated by focusing on water quality during the warmest and lowest flow months of the year and setting temperature and dissolved oxygen criteria for the most thermally sensitive mussel guild. To encourage successful reproduction and recruitment, mussels can be separated into guilds based on reproductive cycles that can be used to assess temporal flow needs. Hydraulic optima and existing mussel bed locations can be derived from previous mussel bed surveys in the region. New methodologies for estimating the thermal optima of unstudied species can be used to assess physiological tolerances of un-studied species. Biological rating methods should also be used for fish host species to encourage their presence near mussel beds during the appropriate time of the year. We further recommend monitoring existing mussel beds in the region while environmental flow criteria are being developed. Monitoring existing beds will reduce uncertainties regarding how mussels respond to changing flow conditions and will also allow for an adaptive management approach for managing the federally listed species.

Minimum instream flows can be based on discharge-rating temperature models developed for the Oklahoma Water Resources Research Institute by Vaughn and Julian. These models use air temperature and water depth to predict water temperature, which allows managers to determine

how much water to release to keep water temperatures below a certain threshold during summer low flow periods. 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. In the Kiamichi River, we recommend that during droughts, enough water should be released from Sardis Dam to maintain flow at both the Clayton and Antlers, as the reach between these two gages is critical mussel habitat with three federally listed endangered species.

A. NEED

Freshwater mussels are one of the most threatened faunas globally, largely because their life history traits make them highly vulnerable to environmental change such as habitat destruction and alteration, population fragmentation, and introduction of non-native species (Vaughn and Taylor 1999, Lydeard et al. 2004, Strayer et al. 2004). Freshwater mussels are a guild of filter feeding, burrowing bivalves that typically occur as dense, speciose aggregations (mussel beds) (Vaughn and Hakenkamp 2001, Strayer et al. 2004). Adult mussels are sedentary; movements are seasonal and on a scale of a few to an estimated maximum of 100 meters (Green et al. 1985, Waller et al. 1999, Allen and Vaughn 2009). Thus, unlike many stream organisms such as fish and aquatic insects (Townsend 1989, Matthews 1998, Matthews and Marsh-Matthews 2003), mussels have limited refugia from disturbances in streams (e.g. droughts, floods, sedimentation). Further, mussels are very long-lived (10 - > 100 yrs) with delayed reproduction (typically not reproducing until after age 7, depending on species), leading to long generation times (Anthony et al. 2001, McMahon and Bogan 2001, Barnhart et al. 2008). Thus, mussels cannot recover rapidly from disturbance. Finally, mussels are thermo-conformers whose physiological processes are constrained by water temperature within species-specific thermal preferences (McMahon and Bogan 2001, Spooner and Vaughn 2008b). Thus, changes in water temperature, including those caused by altered flow regimes, can lead to both shifts in community structure and changes in rates and magnitudes of ecological processes provided by mussel communities (Spooner and Vaughn 2008b, Vaughn et al. 2008, Vaughn 2010). The major cause of mussel decline in the U.S. is from the alteration of the natural flow regime of rivers (Watters 1999, Poff et al. 2007).

The Ouachita Region of southeastern Oklahoma, including the Ouachita Uplands and Gulf Coastal Plain, contains five small rivers identified by the Oklahoma Comprehensive Wildlife Conservation Strategy (OCWCS: ODWC 2005, p. 209) as a Very High Priority Conservation Landscape. These rivers are the Poteau River, the Kiamichi River, and the Little River with its major tributaries, the Mountain Fork River and the Glover River. The Upper Mountain Fork River is a state designated scenic river. These rivers contain a high proportion of species identified in the OCWCS as Species in Greatest Conservation Need (OCWCS, pp. 211-212), particularly freshwater mussels (Bivalvia: Unionoida). Of these rivers, the Kiamichi River and the Little River, with its major tributaries, contain the most abundant and diverse mussel populations (Vaughn and Pyron 1995, Vaughn et al. 1996, Vaughn 2000, 2003, Vaughn and Spooner 2004, Matthews et al. 2005, Spooner and Vaughn 2007, Galbraith et al. 2008). There are 19 mussel species identified as Species in Greatest Conservation Need that are known from the Kiamichi and Little River watersheds (ODWC 2005, Vaughn 2005, Galbraith et al. 2008), including four federally listed species (Ouachita Rock Pocketbook, *Arkansia wheeleri*; Scaleshell, *Leptodea leptodon*; Rabbitsfoot, *Quadrula cylindrica*; and Winged Mapleleaf (*Quadrula fragosa*).

Mussel populations in southeastern Oklahoma currently are threatened by human activities that alter natural flow patterns, in particular proposed plans to sell water from the Little and Kiamichi rivers. If these plans are carried out, water may be diverted from the Little River, its tributary the Mountain Fork River, and from the nearby Kiamichi River. These actions may impact the mussel populations in these rivers by (1) altering stream hydrology and the subsequent creation of new mussel habitat and (2) in particular by creating stressful low flow conditions during times of drought when water demand will be highest (Jones and Fisher 2005). Thus, there is a critical need to understand the environmental flow requirements of freshwater mussels so that policy makers and river managers can strive to protect mussel populations and still provide water from this region for human needs.

B. OBJECTIVES

1. Obtain information from the literature on potential methods and models for estimating mussel environmental flow needs and determine which model/method is most appropriate for the Kiamichi, Mountain Fork, and Little Rivers.
2. Gather and evaluate existing information on (a) historical and current flows in the Kiamichi, Mountain Fork and Little Rivers and (b) mussel population success under these flow regimes.
3. Collect data on the relationship between water level, discharge rate, and water temperature on an annual basis across a suite of sites in the Kiamichi, Mountain Fork and Little Rivers.
4. Evaluate how a co-occurring invasive species, *Corbicula*, may indirectly impact flow needs of native freshwater mussel species in southeastern Oklahoma rivers
5. Make recommendations regarding environmental flow requirements, minimum instream flows, and water management scenarios to maintain populations of mussel Species of Greatest Conservation Need in the Kiamichi, Mountain Fork and Little Rivers.

C. RESULTS

OBJECTIVE 1: Mussel E-flow Methods

Freshwater mussels are especially sensitive to changes in hydraulic conditions. Their complex lifecycle and sedentary adult life stage require adequate stream flows that permanently maintain wetted habitat, buffer water quality, and provide adequate food. In addition, the ectoparasitic juvenile life stage of mussels requires flows that support the presence of host fish species during the appropriate season. Previous attempts to develop environmental flows for mussels have not fully accommodated their unique habitat requirements or complex life history and have consequently not provided protective flow recommendations. We reviewed the unique requirements of mussels and how they influence the effectiveness of different environmental flow models.

E-flow needs of mussels

The freshwater mussels (Unionidae) of North America are a highly diverse and imperiled fauna (Bogan 1993, Strayer et al. 2004). A complex life history makes them reliant on natural flow regimes and especially susceptible to environmental changes including population fragmentation, habitat disturbance, and introduction of non-native species (Vaughn and Taylor 1999, Lydeard et al. 2004, Haag 2012). Over the past century, as the physical landscape of North America has changed, freshwater mussels have experienced significant declines in abundance and diversity (Neves et al. 1997, Ricciardi et al. 1998, Vaughn and Taylor 1999, McMahon and Bogan 2001, Strayer et al. 2004) largely due to alterations in the natural flow regime (Watters 1999, Poff et al. 2007). Understanding how to sustain remaining populations is vital to their long-term persistence.

Freshwater mussels have a two-stage lifecycle. Freshwater mussel larvae (glochidia) are ectoparasites, attaching to the gill or fin tissue of a host fish where they metamorphose and eventually release as juveniles into new habitat (McMahon and Bogan 2001, Haag 2012). The juvenile life stage is the most sensitive and least understood (Sparks and Strayer 1998, Beck and Neves 2003, Newton et al. 2003, Fisher and Dimock 2006, Hanlon and Neves 2006). Once established in a new location, adult mussels are sedentary filter feeders with a fixed retreat of 1-100 m (Green et al. 1985, Waller et al. 1999, Kappes and Haase 2012). The mixed sedentary and mobile life history is adapted to a flow regime that maintains wetted habitat for adults and host fish while also buffering water quality and providing adequate food replenishment.

Changes in flow regimes can be potentially catastrophic to population persistence because mussels are generally very slow to recover from population declines. Many mussel species are long-lived, 6-60 years, and do not become sexually mature until 6 years or later (Imlay 1982, McMahon and Bogan 2001). Fecundity rates are very high (200,000-17,000,000), but juvenile survival is very low (Yeager et al. 1994, Sparks and Strayer 1998, McMahon and Bogan 2001, Jones and Neves 2011). Disturbances that affect larvae may lead to the loss of entire year-classes (Payne and Miller 1989) or populations within river systems. Mussels are patchily distributed throughout rivers in diverse species beds (Strayer et al. 1994, Strayer et al. 2004). In this manner, beds serve as small populations within drainage meta-populations (Vaughn 1993). The significant loss of small populations can decrease the viability of a drainage metapopulation making it more difficult for existing populations to recover (Vaughn 2012).

Freshwater mussels are particularly sensitive to flow alterations created by impoundment releases that change the magnitude and timing of flows (Vaughn and Taylor 1999, Galbraith and Vaughn 2011, Allen et al. 2013). The success of mussel reproduction and the following larvae life stage are dependent on flows that mimic the flow regime under which mussels and their fish hosts co-evolved (Barnhart et al. 2008). Impoundment releases often produce large fluctuations in discharge that differ from those of a river's natural flow regime in their timing, magnitude, duration, and rate of change (Yeager 1993, Poff et al. 1997, Richter and Richter 2000). Increases in the magnitude of high flows may prevent juvenile mussels from settling in new habitat or dislodge newly settled adults (Neves and Widlak 1987, Holland-Bartels 1990, Layzer and Madison 1995, Hardison and Layzer 2001b, Daraio et al. 2010a, Daraio et al. 2010b). Increases in flow magnitude may also create sediment scour that physiologically interferes with mussel feeding, reproduction, and survival (Young and Williams 1983, Dennis 1984, Aldridge et al. 1987). In contrast, variation in the timing of high and low flows may cause mussel beds to be

exposed to altered temperature regimes (Galbraith and Vaughn 2011) or indirectly affect mussels by preventing host fish species from being present at the proper time to carry larvae (Freeman and Marcinek 2006, Gido et al. 2010).

Optimum flows for mussels maintain habitat continuously for adults and seasonally for host fish and for juveniles. The maintenance of habitat must encompass the abiotic and biotic factors that determine mussel distribution as well as incorporate the relationship between flow and water quality. Unfortunately, defining the characteristics that determine mussel distribution has been very challenging (Strayer 2008). The distribution of freshwater mussels is thought to be most strongly influenced by complex hydraulic parameters (Layzer and Madison 1995, Hardison and Layzer 2001, Gangloff and Feminella 2007, Steuer et al. 2008, Zigler et al. 2008, Allen and Vaughn 2010), followed by geomorphology (Gangloff and Feminella 2007, Atkinson et al. 2012), and substrate (Gangloff et al. 2004, Steuer et al. 2008, Allen and Vaughn 2010, Bodis et al. 2011). There is consensus that complex hydraulic conditions during extreme events (floods or droughts) have a stronger influence on the distribution of adult mussels than average hydraulic conditions (Gangloff and Feminella 2007, Zigler et al. 2008, Allen and Vaughn 2010). For example, extreme hydraulic events during glochidia release may be detrimental to settlement preventing the growth and formation of mussel beds (Neves and Widlak 1987, Holland-Bartels 1990, Layzer and Madison 1995, Hardison and Layzer 2001). Optimum flows need to be low enough to maintain hydrologic bed stability for deep pools while being high enough to prevent sedimentation and exposure to lethal water chemistry conditions (Vannote and Minshall 1982, Hartfield and Ebert 1986, Strayer 1993, 1999b).

Optimum flows for mussels also mimic the seasonal temperature regimes to which mussel and fish host life cycles are adapted. Mussels are thermo-conformers whose physiological processes are constrained by water temperature (Spooner and Vaughn 2008, Pandolfo et al. 2012). Flow alteration often causes changes in the thermal regime experienced by mussels. For example, decreases in water temperature below hypolimnetic release dams have been shown to reduce and even eliminate mussel populations for long distances (Ahlstedt 1983, Miller et al. 1984, Yeager 1993, Lydeard and Mayden 1995, Vaughn and Taylor 1999). Release of cold water during the summer when water temperatures should be warm suppresses mussel metabolic rates during a time of year when growth should be high (McMahon 1991) and inhibits reproduction (Layzer et al. 1993). Coldwater releases also may eliminate or inhibit reproduction of some species of warm water fishes (Layzer et al. 1993, Yeager 1993) and increase the success of introduced cold-water species such as trout. Therefore, abnormally cold discharge, particularly in summer, may act as a permanent colonization barrier to mussels (Vaughn and Taylor 1999).

Because mussels are dependent on fish hosts, any effects of hydrologic alterations on fish hosts also impacts mussel populations. Distribution, abundance, and movement patterns of fish hosts have been shown to be critical to the distribution and abundance of mussels (Watters 1993, Vaughn 1997, Haag and Warren 1998, Vaughn and Taylor 2000, Vaughn 2012). The disappearance of mussel species from several rivers has been linked to the disappearance of the appropriate fish host (Kat and Davis 1984), and mussels have re-colonized rivers after their fish hosts were re-introduced (Smith 1985). Low-head dams have been shown to block fish-host migration and lead to the extirpation of mussels in reaches above the dams (Watters 1996). Altered flow regimes can decrease both the species richness and abundance of fish communities

(Gore and Bryant 1986, Kinsolving and Bain 1993, Scheidegger and Bain 1995), potentially eliminating mussel hosts. Impacts likely vary both seasonally and with river microhabitat. For example, a high proportion of nest-building fish species, such as centrarchids, are common mussel hosts (Kat 1984, Vaughn 2012, Cummings and Watter 2014). Thus, altered hydrology that impacts or prevents nesting could result in mussel glochidia failing to attach to hosts, and reduced mussel recruitment.

E-flows for mussels under a changing climate

Changing climate conditions are elevating the negative impacts of flow alterations on mussels. While summer months are historically lower flow months in many regions of North America, drought conditions in the past decade have exacerbated the effects of low flows during the warmest months of the year for many mussel populations (Watters 1999, Golladay et al. 2004, Galbraith et al. 2010, Allen et al. 2013). Drought conditions across the southern U.S. have increased the occurrence and the magnitude of low flow conditions leading to temperature extremes and mass mussel die-offs (Gagnon et al. 2004, Haag and Warren 2008, Gough et al. 2012, Randklev et al. 2013, Shea et al. 2013). Pre and post drought mussel surveys in the Kiamichi River of SE Oklahoma over a 20 year period that included two extreme droughts revealed widespread declines in mussel abundances and localized losses in species richness that favored species with higher thermal optima (Galbraith et al. 2010). Such changes in mussel bed species composition can have cascading effects on the remaining mussel community and ecosystem processes (Vaughn et al. 2014).

Discharge that is too low, especially when combined with high temperatures, negatively impacts mussels (Gagnon et al. 2004, Golladay et al. 2004, Haag and Warren 2008). Decreases in river discharge can affect benthic organisms by decreasing water velocity, water depth, and wetted channel width, increasing sedimentation, and changing the thermal regime and water chemistry (Dewson et al. 2007). Adult mussels are fixed-retreat organisms precluding relocation when environmental conditions become sub-optimal. What is considered sub-optimal varies by species and is heavily influenced by temperature (Spooner and Vaughn 2008, Spooner and Vaughn 2009, Gough et al. 2012). Confounding the effects of high temperatures, mussels are thermo-conformers and lack the ability to regulate their own temperature further increasing mortality rates during extreme temperature exposures (McMahon 1991, Pandolfo et al. 2012).

The varying temperature sensitivities of mussel species can lead to feedback cycles that increase mortality during low flow and high temperature extremes. Extended periods of exposure to high temperatures, low dissolved oxygen, and high ammonia levels are lethal for mussels (Gagnon et al. 2004, Golladay et al. 2004, Cherry et al. 2005, Haag and Warren 2008, Strayer and Malcom 2012); however, there is often a range of physiological tolerances among species within a mussel bed (Spooner and Vaughn 2008, Spooner and Vaughn 2009). The least temperature tolerant species are the first to experience mortality during high temperature events and their decay can further decrease habitat suitability for the remaining mussels. For example, *Corbicula fluminea* is a widespread invasive bivalve with a relatively low anaerobic capacity compared to most mussel species that can lead to mass die-offs under sub-optimal conditions (White and White 1977, Milton and McMahon 1999, Haag and Warren 2008, Weitere et al. 2009). Known for reaching high abundances, *Corbicula* is common in many mussel beds and is often the most sensitive species present. Low flow summer conditions combined with extreme temperatures and low

dissolved oxygen levels have caused massive *Corbicula* die-offs in recent years. Die-off events have negative cascading impacts on other mussel bed inhabitants by decreasing dissolved oxygen and increasing ammonia to potentially toxic levels (Cherry et al. 2005, Cooper et al. 2005). Indirectly, ammonia released by decaying *Corbicula* can fertilize algae, leading to large algal blooms, which further decrease dissolved oxygen and habitat suitability for other mussel bed inhabitants (Sousa et al. 2012).

Environmental flow recommendations for mussels need to address the biotic and abiotic feedbacks of invasive species and climate change in addition to their unique life history. Incorporating the complex requirements of mussels is vital to developing flow recommendations that increase population biomass and promote persistence.

E-flow methods for mussels

There are many methods available for determining environmental flows, which have been extensively reviewed by other authors (Jowett 1997, Arthington and Zalucki 1998, Gore et al. 2001, Tharme 2003, Acreman and Dunbar 2004, Annear et al. 2004, Anders et al. 2006, Caissie et al. 2007, Petts 2009). Methods can be grouped into categories by methodology (Tharme 2003, Acreman and Dunbar 2004) or resource objective (Annear et al. 2004, Annear et al. 2009). The methodology classification is generally accepted and includes the categories of hydrological, hydraulic rating, habitat rating, and holistic methods (Tharme 2003)(Table 1). While there is some overlap among methods, each offers varying advantages and disadvantages (Jowett 1997, Tharme 2003, Acreman and Dunbar 2004, Petts 2009). For the purposes of this review, we focus on the specific models and methodologies that either have or have the potential to successfully model the unique environmental flow needs of mussels.

Hydrological environmental flow methods focus on hydraulic characteristics making them potentially useful for defining mussel habitat, yet their simplistic ecological assumptions have many drawbacks. Hydrological models assume that as the wetted area of a river is increased, biological productivity increases (Jowett 1997, Caissie et al. 2007). These models do not incorporate seasonal or life history changes in habitat requirements, but consider biological activity as a byproduct of flow. Also called ‘fixed percentage’ or ‘look-up tables’, hydrological models use historic discharge records to establish minimum and optimal flow recommendations (Tharme 2003, Caissie et al. 2007). They have often been used as a starting point for environmental flow recommendations because they are relatively easy to assemble (Tharme 2003, Caissie et al. 2007). While hydrological methods have been applied to help protect mussels indirectly (Orth and Maughn 1982 (Tennant); (Jones and Fisher 2005) (IHA); Li et al. 2009 (Tennant); (Turton et al. 2009) (HIT and HIP)), they cannot specifically address their varying life history needs or the effects of climate change and invasive species.

Hydraulic and biological rating models offer a direct connection between flow and measurable habitat parameters (Tharme 2003). These models focus on the effect various flows will have on measures of available habitat as a result of river morphology. Hydraulic and biological rating methods are typically employed when environmental flows are designed specifically for biota; however, many of these methods were originally developed for fish (Jowett 1997, Tharme 2003, Annear et al. 2009) limiting their applicability to other organisms (Layzer and Madison 1995, Gore et al. 2001). Rating methods define habitat by taking cross-sections of a river and

measuring the change in habitat as a function of flow. The primary assumption is that habitat determines the distribution of biota within a river and that as habitat changes the distribution of biota will change in a predictable manner determined by habitat suitability criteria (Layzer and Madison 1995, Jowett 1997). Freshwater mussels challenge this assumption because adult mussels require benthic habitat that is persistent under all flow conditions and their distribution is best predicted by complex hydraulic variables, which readily change with changing flows (Gore et al. 2001). Further, evidence suggests that hydraulic preferences of adult mussels may vary with flow conditions (Layzer and Madison 1995, Layzer and Scott 2006). Despite these limitations, rating models can be designed to incorporate habitat permanence for adult mussels (Layzer and Madison 1995, Maloney et al. 2012) and may provide better predictive results for mussel habitat than any other currently available option (Layzer and Madison 1995, Gore et al. 2001).

Perhaps the greatest challenge of using rating models for mussels is measuring the habitat variables that are most influential in determining species presence and abundance (habitat suitability criteria). Difficulty defining mussel habitat is a common theme in environmental flow modeling that creates a tendency to over-estimate the availability of habitat (Gore et al. 2001). Previous researchers have advocated carefully addressing site-specific mussel bed conditions when selecting habitat suitability criteria and defining habitat for rating models (Layzer and Madison 1995). Site-specific information is important because mussel beds tend to be in stable locations where they likely serve as centers for dispersal and subsequent recruitment of new beds (Vannote and Minshall 1982). Mussel relocation projects have even relied on relocations into existing beds for a higher probability of success without a full grasp of the conditions that make existing beds optimal (Layzer and Scott 2006). Layzer and Madison (1995) conducted one of the first attempts to model the specific variables associated with individual mussels and mussel beds to develop environmental flow recommendations for mussels in Horse Lick Creek, Kentucky, U.S. The authors found that when complex hydraulic variables were used to develop habitat suitability curves under all flow conditions, the suitability of habitat varied with flow (Layzer and Madison 1995). The correlation between mussel abundance and complex hydraulic parameters was much stronger at lower flows suggesting that extreme shear stress conditions were the limiting factor for mussel populations (Layzer and Madison 1995). The authors also used a habitat-rating model (PHABSIM) to model host fish species presence at existing beds, but found no correlation between the number of known suitable host fish species and mussel abundance (Layzer and Madison 1995). The authors stressed the need for site-specific assignment of environmental flows that are designed to maintain habitat for existing mussel beds (Layzer and Madison 1995). The popularity of such site and species-specific environmental flow recommendations has generally declined in recent years in favor of more holistic river management approaches (Tharme 2003, Anderson et al. 2006, Poff et al. 2010b). Unfortunately, there is little evidence that habitat models for benthic organisms can be successfully used to make generalized predictions among locations even when rivers are similar (Jowett 2003).

Recent regionally specific work with endangered mussel species has provided novel applications of rating models to address the unique habitat requirements of mussels. Maloney and colleagues (2012) applied a two-dimensional hydrodynamic flow model to measure habitat availability at varying flows for the endangered dwarf wedgemussel (*Alasmidonta heterodon*) in the Upper Delaware River. Using simple and complex hydraulic variables, the researchers controlled for

permanently available adult mussel habitat at low and high flows (Maloney et al. 2012). Results suggested that existing mussel beds were located in refuge areas of lower shear stress and velocity, but ground truthing revealed that existing mussel beds only occupied a fraction of persistently available habitat predicted by the model (Maloney et al. 2012). Also working with *A. heterodon*, Castelli and colleagues (2012) applied a novel use of time series analysis to develop temperature ratings based on historic records and knowledge of temperature thresholds. By rating past extreme temperature events, they were able to develop flow recommendations to decrease thermal stress for *A. heterodon* in the Delaware River without prior knowledge of the thermal optima for the species (Castelli et al. 2012).

Rating models have also been successfully used to address the juvenile habitat needs of mussels. Daraio and colleagues (Daraio et al. 2010a, Daraio et al. 2010b) applied a hydrodynamic model to simulate juvenile mussel dispersal in large rivers. Model simulations indicated that dam operations likely affected juvenile settling by altering complex hydraulic parameters during periods of glochidia release (Daraio et al. 2010b). Similarly, Morales and colleagues (Morales et al. 2006b) used a hydrodynamic model to simulate dispersal of juvenile mussels in the Upper Mississippi River and found shear stress and substrate type combined could accurately predict settling into locations where current mussel beds existed. While only a portion of the life history of mussels, juvenile settling work is providing crucial information about how flow alterations can directly and indirectly optimize mussel bed formation and persistence (Daraio et al. 2010a, Daraio et al. 2012b). Juvenile settling work is also being used to inform models that simulate mussel population dynamics incorporating biotic interactions and abiotic conditions (Morales et al. 2006a).

Despite such recent advances, mussel environmental flow modeling has yet to be combined into a framework that can be applied to entire mussel assemblages. The community modeling approach has been used successfully to develop flow recommendations for other benthic assemblages where species in a community can be assumed to require similar habitat (Dunbar et al. 2010); however, this method is not well suited for mussels due to varying species requirements (Gore et al. 2001, Hardison and Layzer 2001, Jowett 2003). Alternatively, the guild approach allows flow recommendations to be made for clusters of species based on species traits (Aadland 1993) (fish); (Merritt et al. 2010, Poff et al. 2010a, Merritt et al. 2010 (plants); Poff et al. 2010b (macroinvertebrates)) or habitat associations (Leonard and Orth 1988, Jowett and Richardson 1995)(fish- habitat); Brunke et al. 2001 (benthic invertebrates including mussels-habitat)). The guild approach to developing environmental flows may be especially suitable for taxa with poorly defined habitat requirements (Souchon et al. 2008) and has been suggested as a potential approach for mussels (Gore et al. 2001).

OBJECTIVE 2: Current and Historical Flows and Mussel Success in the Kiamichi, Mountain Fork and Little Rivers

The Kiamichi and Little Rivers are adjacent, similar in size, and have similar mussel faunas. These rivers are predominantly rain fed with groundwater inputs that create a hydrograph of flashy flow events in early spring, low flows in summer, and lower magnitude flashy flows in fall and winter. Flows in these rivers have been managed differently during recent droughts, and this has affected mussel faunas differently.

Kiamichi River

The Kiamichi River has been strongly impacted by release patterns from a tributary reservoir (Sardis Lake) that provides ~ 25 % of flows to the lower river (Figure 1)(Vaughn et al. 2014). Daily discharge data (1972-2012) for the river below the confluence with Jackfork Creek were collected and analyzed from USGS gage 07336200 (Kiamichi River near Antlers, OK). Daily discharge data (1972-2012) from USGS gage 07335700 (Kiamichi River near Big Cedar, OK) were used to characterize the upper section of the river above the Sardis Dam confluence (Figure 1). “Severe hydrologic drought” was defined as flows below the 10th percentile of flow frequency (*sensu* Svoboda et al. 2002). Downstream portions of the river have a larger watershed, so should be less susceptible to drought than upstream reaches, which is what hydrographs show for 1973 – 2004 (Figure 2). However, beginning in 2005, the upstream and downstream reaches exhibit the same drought behavior, which we attribute to the lack of releases from Sardis Lake. That is, the lack of releases from Sardis Lake during drought periods increased the magnitude and frequency of hydrologic drought in downstream reaches. This more intensive hydrologic drought in hot, summer months led to drying of the lower river, and high water temperatures (in some cases exceeding 40°C because of the extremely shallow water). Essentially, since Sardis Lake was constructed in 1982, the lower reaches of the river behave like upper reaches in terms of hydrologic drought because water is being captured by Sardis Dam and typically not flowing downstream, causing the river to act as a losing stream (Vaughn et al. 2014).

These changes in the flow regime have impacted mussel populations in the Kiamichi River. In 1991, Vaughn established long-term mussel monitoring sites on the Kiamichi River (Vaughn and Pyron 1995). Sites with major mussel beds were chosen that were located both upstream and downstream of the confluence with the Sardis Lake outflow. Four of these sites, two above and two below the Sardis Lake confluence (Figure 1) were sampled across three periods: 1991, 2003 and 2011. At each site for each sampling period, we excavated 15, 0.25 m² quadrats to a depth of approximately 15 cm following Vaughn et al. (1997). Mussels were brought to shore, their length measured, and returned to the mussel bed alive. We used ANOVA (SPSS ver. 19) to compare mussel densities at the four sites over time.

Additionally, we conducted more intensive sampling at site 4 in 2011. When we arrived at this site on July 31, 2011, we discovered that approximately the lower one third of the mussel bed (87 m in length) was completely dry with many freshly dead (tissue still attached) mussels (Figure 3). We divided the site into three sections: the upstream pool, the downstream riffle that still had some water (hereafter “wet riffle”), and the most downstream riffle that was completely dry (hereafter “dry riffle”). In the pool and wet riffle sections, we excavated 15, 0.25 m² quadrats and identified and measured mussels as described above. In the wet riffle section, there were many freshly dead mussels, 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. 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 ANOVA (SPSS ver. 19) to compare mussel densities in the pool vs. wet riffle and live vs. dead mussels in the wet riffle.

Mussel densities declined over time across all sites and periods ($F_{(2,11)} = 7.43$, $P = 0.012$), except at site 2 between 2003 and 2011 (Figure 4). Declines were much steeper between 1991 and 2003 than between 2003 and 2011. In past surveys of site 4, mussel densities in the pool and riffle portion of the bed have been approximately equal (Vaughn and Pyron 1995); however in 2011, mussel densities in the pool were approximately 12 times higher than in the shallower wet riffle (Figure 5A, $F_{(1,24)} = 37.04$, $P < 0.001$). On July 31, 2011 the pool was covered by water depths of 30-to-100 cm, with midday water temperatures $< 30^{\circ}\text{C}$. In contrast, the portion of the riffle that still had water covering it was extremely shallow (average depth 10 cm) and the midday water temperature was 40°C . In the wet riffle, freshly dead mussels (tissue still attached) were twice as abundant in quadrats as live mussels (Figure 5B, $F_{(1,19)} = 6.137$, $P = 0.023$). In the completely dry lower riffle, we found 19 species of freshly dead mussels (Table 2).

Little River

The Little River is influenced by mainstem Pine Creek Lake in the middle reaches and by a tributary impoundment, Broken Bow Lake, further down. Studies on how flows from these rivers affect mussels have already been published (Vaughn and Taylor 1999, Galbraith and Vaughn 2011, Allen et al. 2013), and thus are only briefly summarized here.

In recent drought years managed releases from Pine Creek Lake have been maintained to meet water quality criteria in the middle Little River; as a consequence mussel populations in this section of the river have not declined (Allen et al. 2013).

Broken Bow Lake is a hypolimnetic release reservoir. Cold water is released to the Mountain Fork River and then flows into the lower Little River. Releases are maintained in the summer for hydropower and to supply cold water and flow for a stocked brown trout fishery. These summer flows are higher in magnitude and colder than the natural flow regime (Galbraith and Vaughn 2011). Mussel populations in the Little River below the confluence of the Mountain Fork River have suffered massive declines in abundance and species richness (Vaughn and Taylor 1999), likely because of these abnormally cold summer flows.

OBJECTIVE 3: Relationship between water level, discharge rate, and water temperature on an annual basis across a suite of sites in the Kiamichi, Mountain Fork and Little Rivers.

We installed submerged data loggers (HOBO model U20 water level data loggers) at 9 sites in the Kiamichi River network, 6 sites on the Little River, and 4 on the Mountain Fork River (Figure 6). These loggers automatically record water level (via air and water pressure) and water temperature at preset intervals. These sites were strategically selected to capture influences from reservoirs and tributaries. We installed additional non-submerged (atmospheric) HOBOS within the study area to calibrate the submerged HOBOS with atmospheric pressure. The non-submerged HOBOS also record air temperature at the same preset intervals. Depth and flow data from these loggers are given in Appendix 1.

OBJECTIVE 4: Potential flow-related *Corbicula* impacts on native mussels

Invasive *Corbicula* now co-occur with native freshwater mussels in most mussel beds in southeastern Oklahoma (Vaughn and Spooner 2006), and this will likely to continue into the

future. There is continued debate about whether native freshwater mussels and *Corbicula* compete for space and food, and whether *Corbicula* may be displacing natives via competition (Strayer 1999a, Vaughn and Spooner 2006). However, a larger issue is that *Corbicula* are more sensitive than native mussels to many environmental stressors including high water temperature and lowered dissolved oxygen (Weitere et al. 2009). *Corbicula* populations are notorious for undergoing rapid die-offs in response to summer low flows (McMahon 1979, McMahon and Williams 1986). This has important implications for native mussels, because when *Corbicula* die and decay, the subsequent build up of ammonia is toxic to native mussel juveniles (Cherry et al. 2005, Cooper et al. 2005) and even adults (Galbraith et al. 2010, Sousa et al. 2012). Further, the ammonia provided by the *Corbicula* decay fertilizes algae, leading to algal blooms, oxygen depletion, and further *Corbicula* death and decay in a feedback loop that leads to massive mortality of both juvenile and adult native mussels. Thus, although *Corbicula* are considered a nuisance species, it is important to quantify their sensitivity to high temperatures associated with low flows to protect native freshwater mussels.

We used methods developed by Spooner and Vaughn (2008) for native mussels to estimate thermal tolerance and nutrients released by *Corbicula* across a range of temperatures, 15, 25, and 35 °C, occurring in the Little and Kiamichi Rivers. For each temperature we measured respiration rates and ammonia and phosphorus excretion rates. We also measured these rates for a suite of native unionid (*Lampsilis teres*, *Plectomerus dombeyanus*, *Potamilus purpuratus*, *Pyganodon grandis* and *Quadrula verrucosa*) mussels for comparison.

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 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.

Corbicula and native mussels were acclimated to experimental temperatures for two weeks in 500-L Frigid Unit Living Streams®. Animals were fed cultured algae during acclimation, and then starved for 24 hours before conducting the experiments (Vaughn et al. 2004).

Measurements on individual animals were conducted in continuously stirred, covered glass beakers (500 ml or 1500 ml, depending on animal size) housed in 1.8 m³ temperature-controlled chambers. Following Spooner and Vaughn (2008) we placed animals in pre-filtered water 1.5 hours, measured respiration rate as the change in oxygen concentration, then collected 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.

Corbicula respiration (Figure 7) and nutrient excretion rates increased with temperature. Nutrient excretion rates were an order of magnitude higher than native mussels for both ammonia (Figure

8) and phosphorus (Figure 9) at 25°C. We were unable to measure nutrient rates for *Corbicula* at 35 °C, because all *Corbicula* died shortly after being exposed to this temperature. Since this is a common summer temperature at many Kiamichi and Little River sites (Appendix 1), this result demonstrates that *Corbicula* die offs and subsequent nutrient pulses could be a significant risk to native mussel populations in these rivers during low summer flows.

OBJECTIVE 5: Make recommendations regarding environmental flow requirements, minimum instream flows, and water management scenarios to maintain populations of mussel Species of Greatest Conservation Need in the Kiamichi, Mountain Fork and Little Rivers.

The documented and potential future losses of mussel biodiversity from SE Oklahoma make it a very high priority for development of mussel specific environmental flows (Master et al. 1998). Oklahoma is facing growing water demands from its major metropolitan cities and neighboring states (OWRB 2008, 2012). In addition, climate projections for the south-central U.S. forecast more extreme temperature events and flashier precipitation events (IPCC, 2013). These forecasts necessitate the use of impoundments for flood control and increase the need for environmental flows that protect freshwater ecosystems (Ostfeld et al. 2012). While instream flow laws for Oklahoma are being re-assessed to better protect aquatic life (OCWP, 2011), it has never been more urgent to establish flow recommendations that protect the remaining freshwater mussel diversity.

Prior environmental flow models have been used to draft flow recommendations for mussels in SE Oklahoma, but they have not addressed the distinct threats to mussels in the region. Many of the flow recommendations have been made for fish and do not meet the habitat needs of mussels for reasons described previously. A Hydroecological Integrity assessment Process (HIP) was recently designed for Oklahoma to identify hydrologic indices that are ecologically relevant for maintenance of the natural flow regime and protection of aquatic species of conservation concern (Turton et al. 2009). While this effort can provide flow recommendations based on historic discharge and thermal regimes, designation of only hydrologic indices will not address the habitat needs of mussel juveniles, mussel adults, and host fish species. An Instream Flow Incremental Methodology (IFIM) and Physical Habitat Simulation Model (PHABSIM) have also been used to model habitat permanence at existing mussel beds in the Kiamichi River providing flow specific depths for mussel bed maintenance (Jones and Fisher 2005). This model provided valuable information about flow and depth relationships for existing beds, but did not incorporate temperature thresholds to address climate change, water management practices, and the presence of temperature sensitive invasive species; or the seasonal habitat requirements of fish hosts.

An e-flow approach for SE Oklahoma

Environmental flow recommendations for mussels in SE Oklahoma will better address population viability if they are based on mussel life history and thermal optima of species guilds and mimic the natural flow regime whenever possible. We suggest that environmental flow models for mussels include habitat permanence for existing beds (Layzer and Madison 1995, Maloney et al. 2012), optimal shear stress (Maloney et al. 2012) water quality (temperature, dissolved oxygen, and ammonia) (Orth 1987, Jowett 1997, Spooner and Vaughn 2008, Olden and Naiman 2010, Spooner and Vaughn 2012, Spooner et al. 2012) and promote overlap with

host fish during appropriate seasons and ensure connectivity between mussel beds (Vaughn 2012). The threat of extreme temperature exposure can be mitigated by focusing on water quality during the warmest and lowest flow months of the year (as in the middle Little River, described above) and setting temperature and dissolved oxygen criteria for the thermally sensitive guild (Spooner and Vaughn 2008)(Figure 10). This is particularly important because climate models predict that droughts in this region will become more frequent and severe in the future (Mellilo et al. 2013, Seager and Vecchi 2010). To ensure that thermal stress does not decrease reproduction or health, water quality criteria must also accommodate optimal thermal ranges for other mussel species (Galbraith and Vaughn 2009, Spooner and Vaughn 2009). To encourage successful reproduction and recruitment, mussels can be separated into guilds based on reproductive cycles that can be used to assess temporal flow needs (Cummins et al. 2011)(Figure 10). Hydraulic optima and existing mussel bed locations can be derived from previous mussel bed surveys in the region. New methodologies for estimating the thermal optima of unstudied species can be used to assess physiological tolerances of un-studied species (Castelli et al. 2012). Biological rating methods should also be used for fish host species to encourage their presence near mussel beds during the appropriate time of the year (Layzer and Madison 1995).

We further recommend monitoring existing mussel beds in the region while environmental flow criteria are being developed. Monitoring existing beds will reduce uncertainties regarding how mussels respond to changing flow conditions and will also allow for an adaptive management approach for managing the federally listed species (Runge 2011). The effectiveness of environmental flows can be gauged by comparing new mussel recruitment with historic mussel recruitment and flow data (Gore et al. 2001). There is much effort required for this type of modeling; yet, we feel this approach will provide flow recommendations that holistically support the complex life history of mussels while addressing regionally specific threats.

Minimum instream flows for SE Oklahoma mussels

Vaughn and Julian (2013) developed 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 target water temperatures that ensure mussel survival (Figures 11 & 12). Using water temperature and depth data from the HOBO data loggers (Appendix 1), Vaughn and Julian (2013) developed multivariate regression models that use air temperature and water depth to predict water temperature. These models were then used to determine how much water should to be released from Sardis Dam to maintain healthy mussel communities downstream (Vaughn and Julian 2013).

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 a discharge of 1.8 cms at the Clayton gage and prevent mussel mortality. 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 as the reach between these two gages is critical mussel habitat with three federally listed endangered species.

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E. TABLES AND FIGURES

Table 1. Environmental flow methods by methodology (Tharme 2003) and objective (Annear et al. 2009). Methods listed represent the fourteen most commonly used methods in North American (Annear et al. 2009). An asterisk indicates that the model was not specifically mentioned in the publication. Acronyms include PHABSIM (Physical HABitat SIMulation Model), IFIM (Instream Flow Incremental Methodology), DFA (Demonstration Flow Assessment), SNTEMP (Stream Network Temperature modeling), HEC-RAS (Hydrologic Engineering Centers River Analysis System), IHA (Indicators of Hydrologic Alteration), and RVA (Range of Variability Approach).

Method	Methodology	Objective
PHABSIM	Biological rating	Habitat
2-D hydraulic	Biological rating	Habitat
Target fish community	Biological rating	Habitat
IFIM	Biological rating	Holistic
DFA	Biological rating*	Holistic
Wetted perimeter	Hydraulic rating	Habitat
SNTEMP	Hydraulic rating*	Water quality
HEC-RAS	Hydraulic rating*	Geomorphology
Tennant	Hydrological	Habitat
Flow duration curve	Hydrological	Habitat
Geomorphic stream classification	Hydrological*	Geomorphology
Channel maintenance flow	Hydrological*	Geomorphology
IHA	Hydrological	Hydrology
RVA	Hydrological	Hydrology

Table 2. Species of freshly dead unionid mussel individuals found at the dry riffle at Site 4 on July 31, 2011. We also encountered many freshly dead Asian clams, *Corbicula fluminea*.

Actinonaias ligamentina
Amblema plicata
Ellipsaria lineolata
Fusconaia flava
Lampsilis cardium
Lampsilis siliquoidea
Leptodea fragilis
Megalonaias nervosa
Obliquaria reflexa
Obovaria jacksoniana
Potamilus purpuratus
Ptychobranhus occidentalis
Quadrula pustulosa
Quadrula quadrula
Strophitus undulatus
Tritogonia verrucosa
Truncilla donaciformis
Truncilla truncata
Villosa iris

Figure 1. Map of the Kiamichi River showing sample sites, gage locations and reservoirs. The Upper River segment extends from the town of Whitesboro to immediately above the Sardis Lake confluence, and the Lower River segment is from just below the Sardis Lake confluence to where the river flows into Hugo Lake. The town of Whitesboro is located north-adjacent to sampling site 1, and the town of Antlers is located south-adjacent to the Antlers USGS gage.

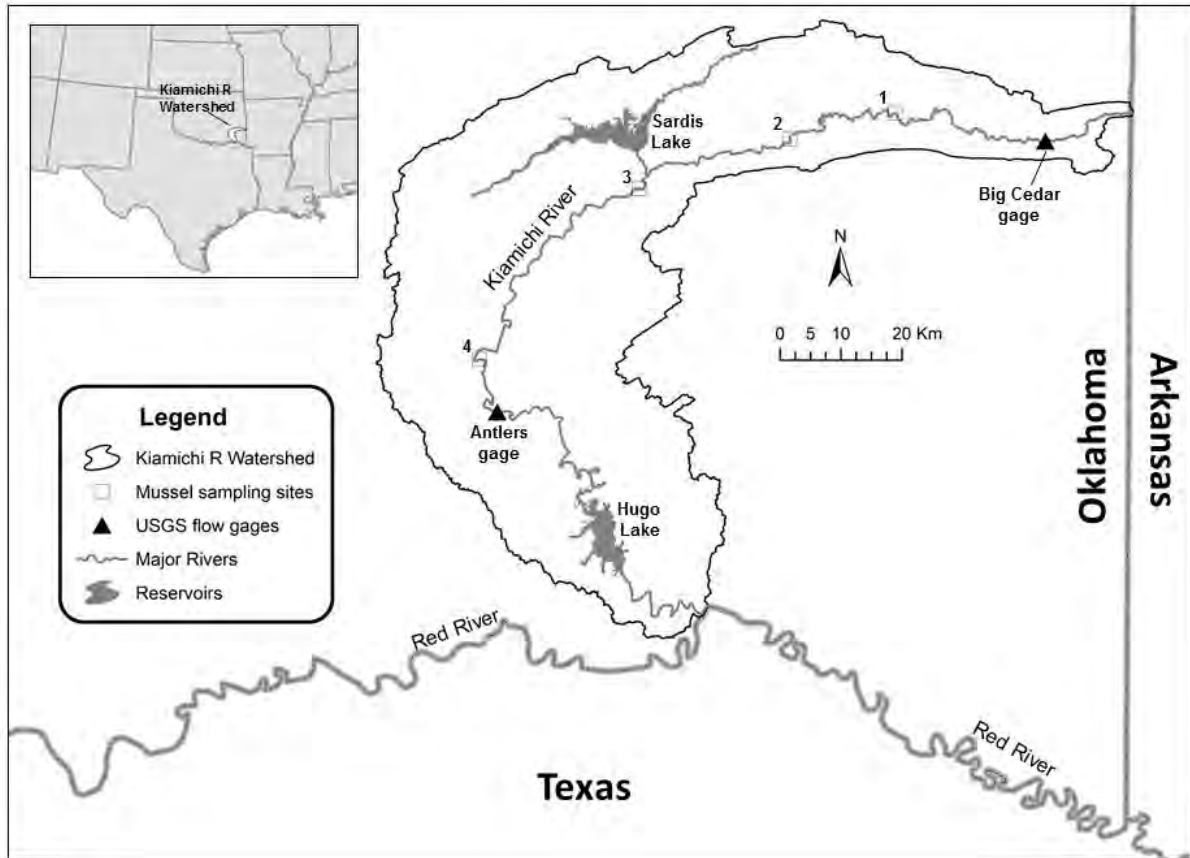


Figure 2. Severe hydrologic drought time-series for Kiamichi River at Big Cedar (upper river above Sardis Lake confluence) and at Antlers (downstream below Sardis Lake confluence). Daily discharge data were obtained from the Big Cedar (USGS 07335700) and Antlers (USGS 07336200) gages. From Vaughn and Julian (2013) and Vaughn et al. (2014).

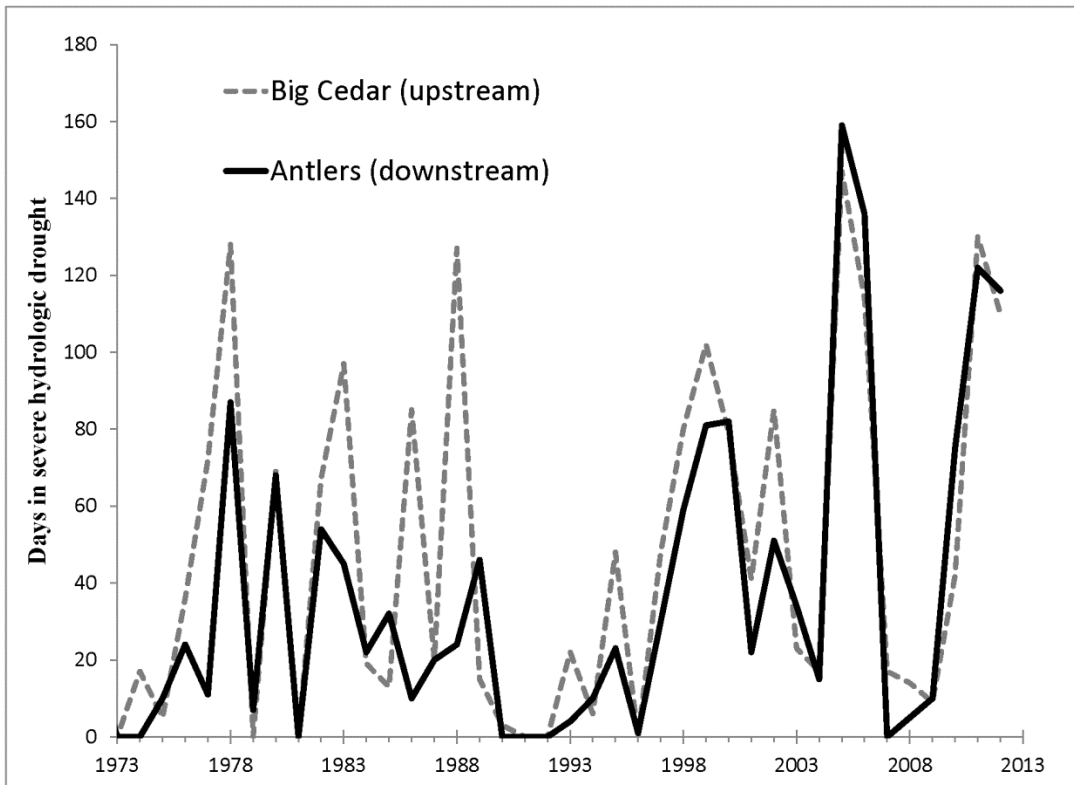


Figure 3. Photographs of Site 4 on July 31, 2011 showing dry riverbed and freshly dead mussels.



Figure 4. Mean mussel densities (all species combined, ± 1 S.E.) for the four sampling sites over the three time periods. Filled circles 1991, open triangles 2003, filled squares 2011.

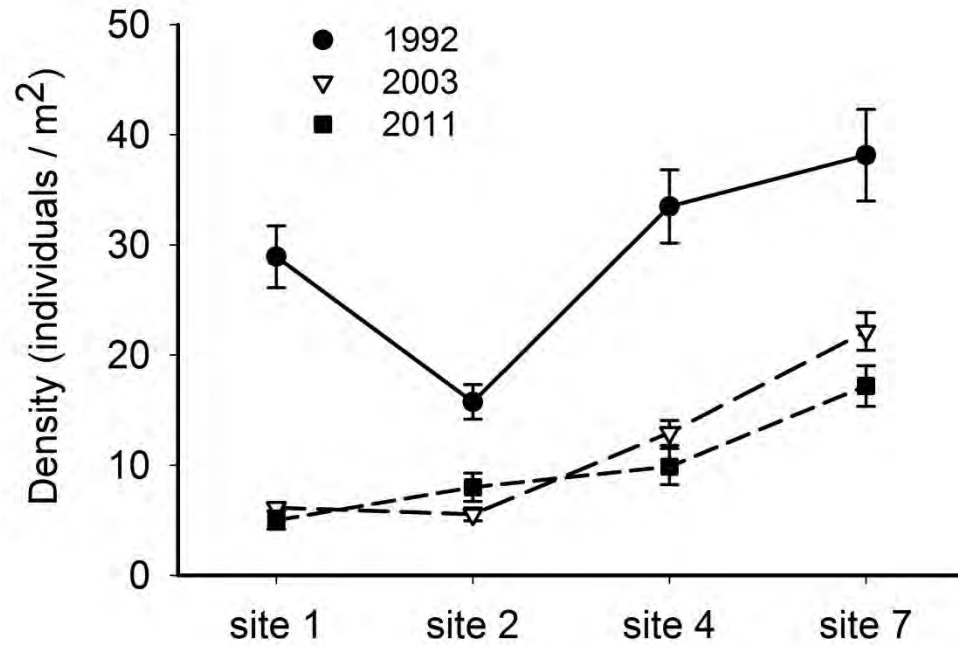


Figure 5. Mean mussel density (± 1 S.E.) at Site 4 in 2011. (A) Live mussels in upstream pool vs. downstream riffle. (B) Live vs. dead mussels in the downstream riffle.

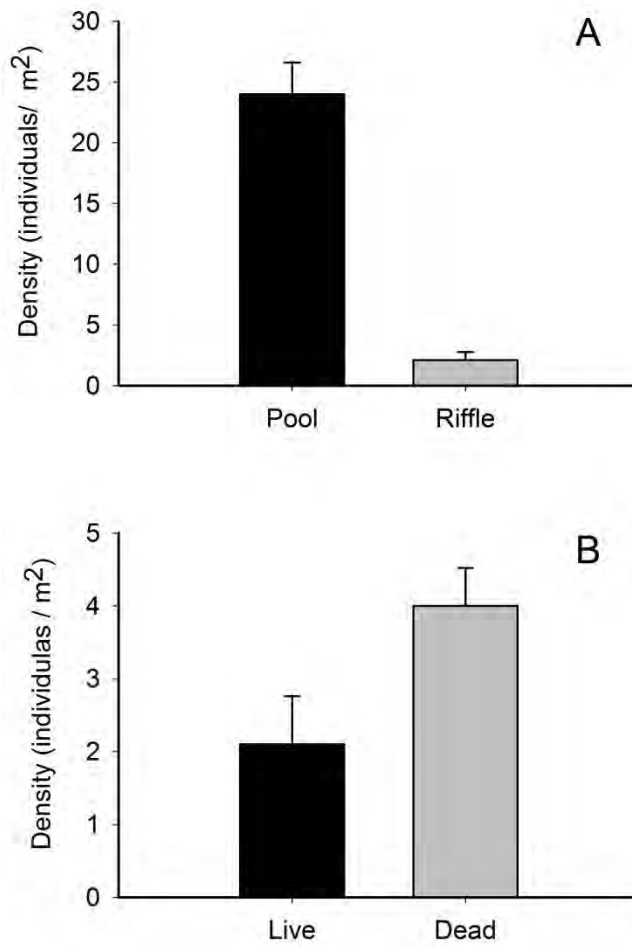


Figure 6. Hobo logger locations.



Figure 7. *Corbicula* and native mussel respiration rates across three temperatures.

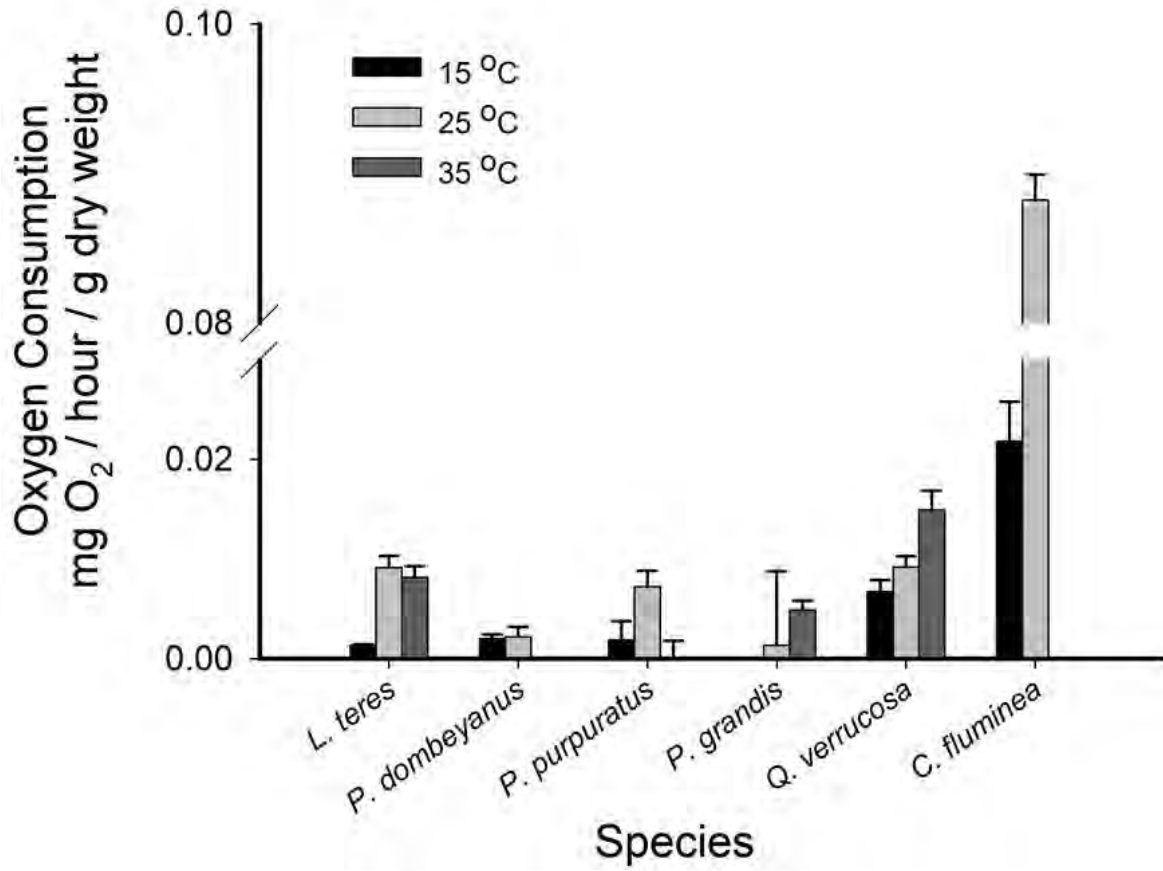


Figure 8. *Corbicula* and native mussel ammonia excretion rates across three temperatures.

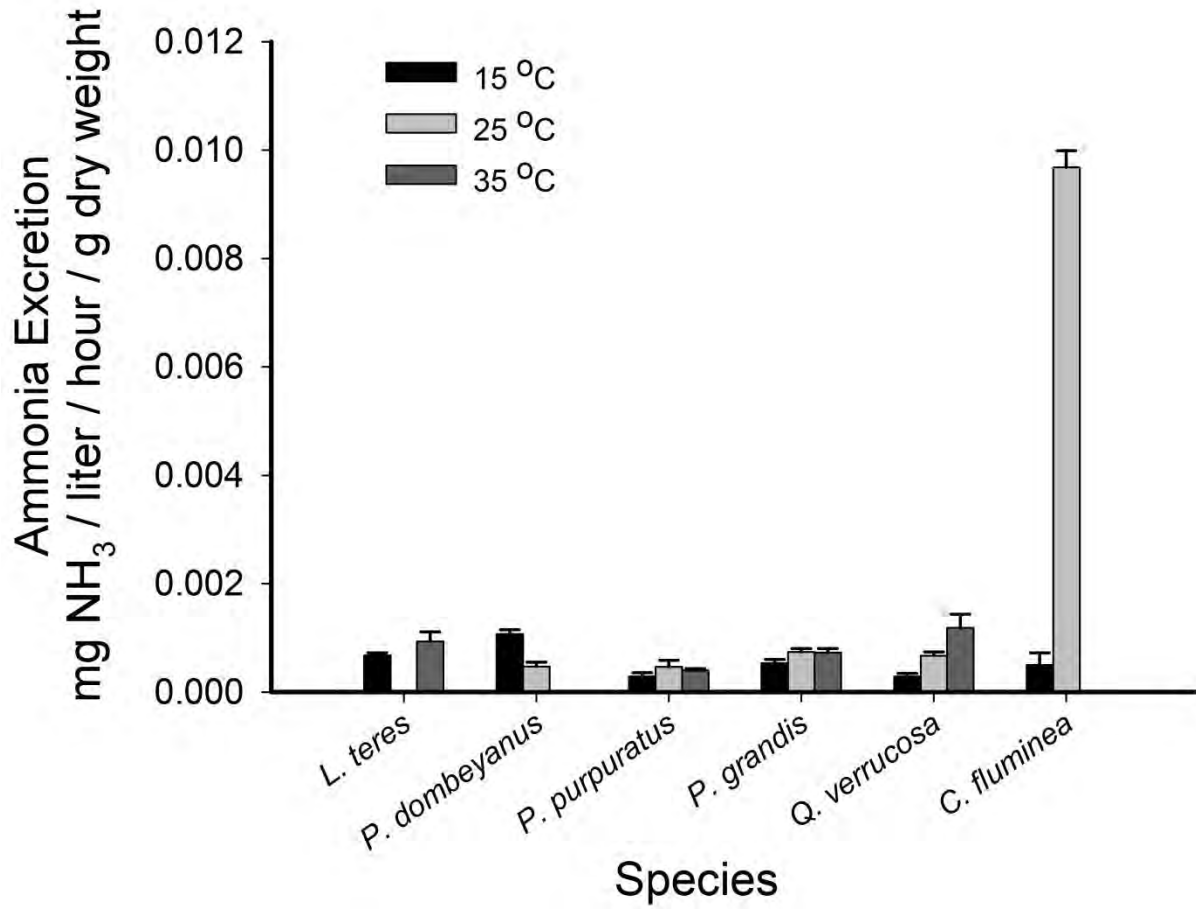


Figure 9. *Corbicula* and native mussel phosphorus excretion rates across three temperatures.

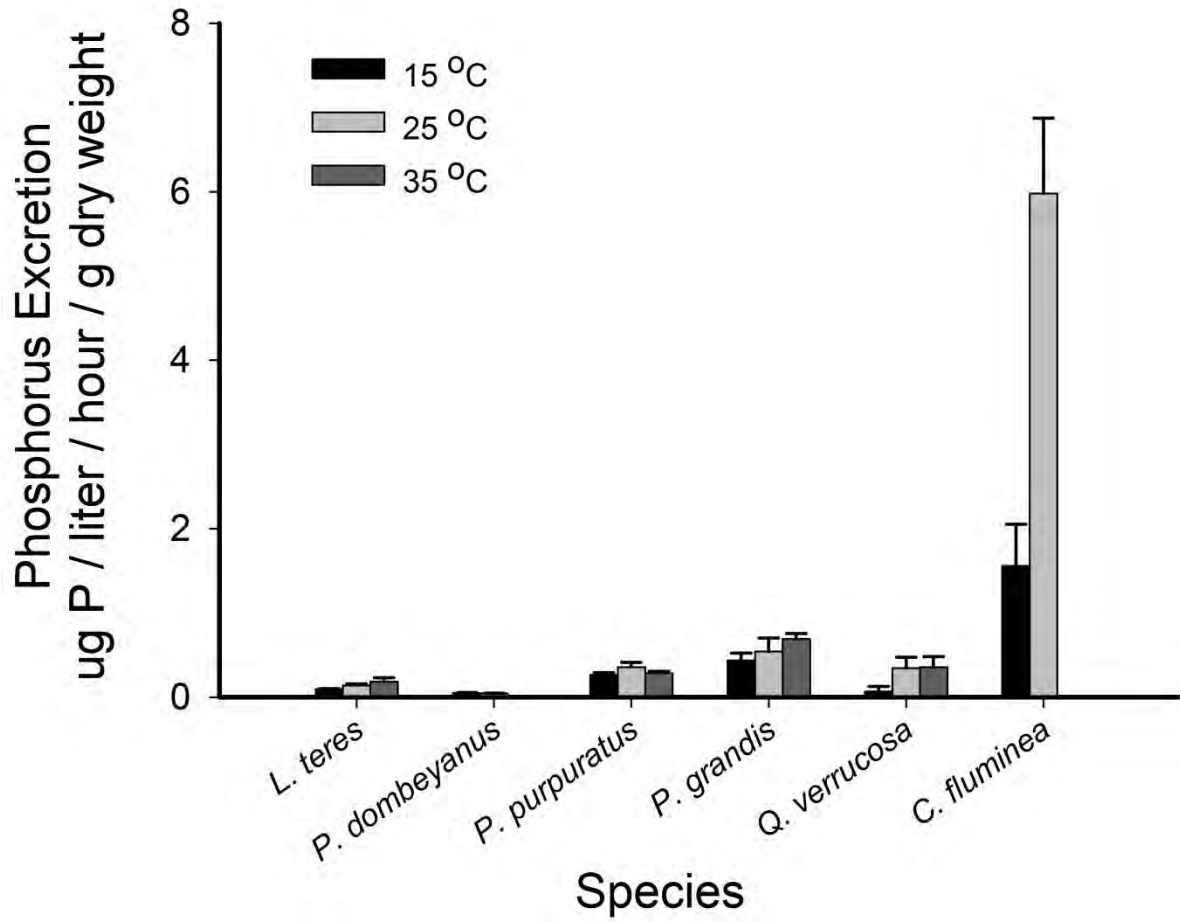


Figure 10. Kiamichi River discharge over time below Sardis Lake near Clayton, Oklahoma with mussel life history guilds and thermal stress potential over time.

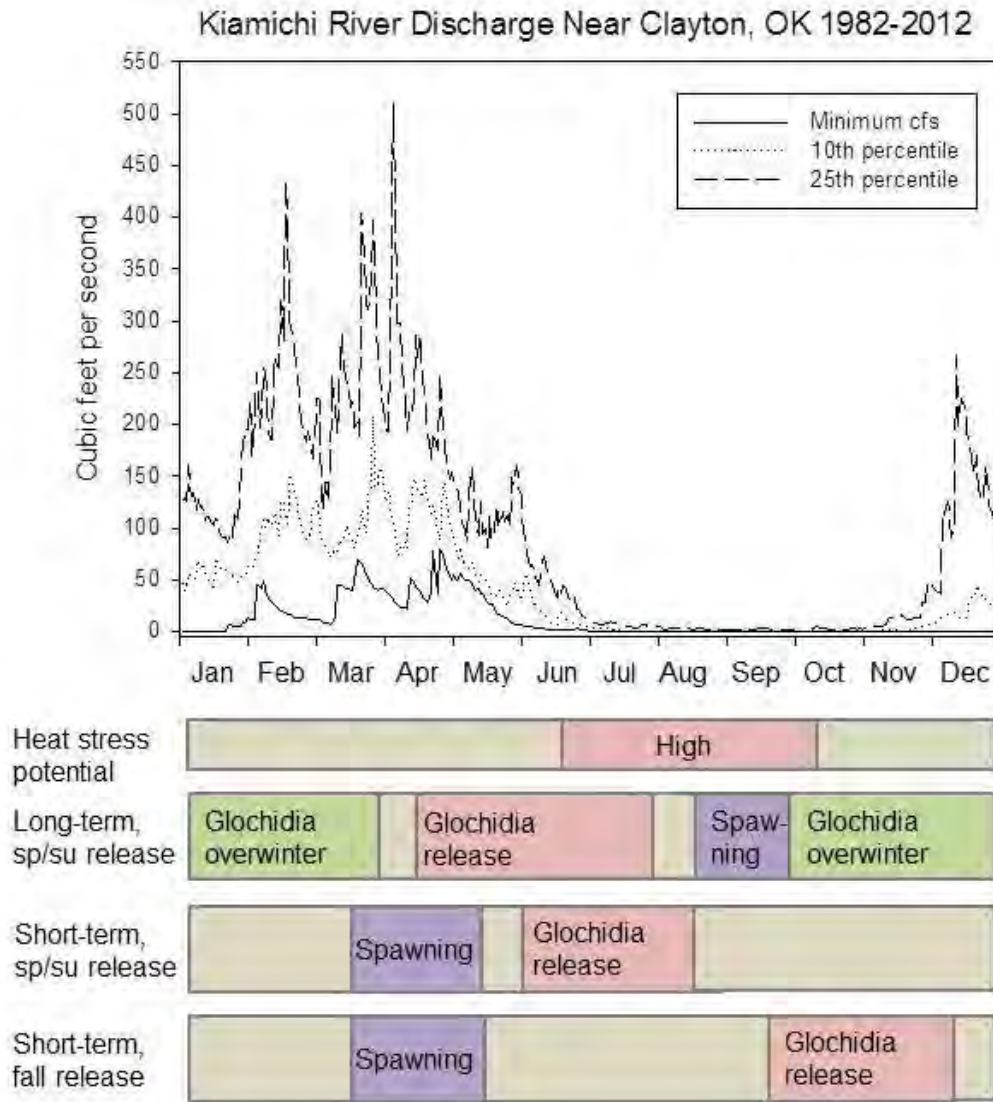


Figure 11. Discharges required for Kiamichi River near Clayton (USGS 07335790) to reduce maximum water temperature below target water temperatures. From Vaughn and Julian (2013).

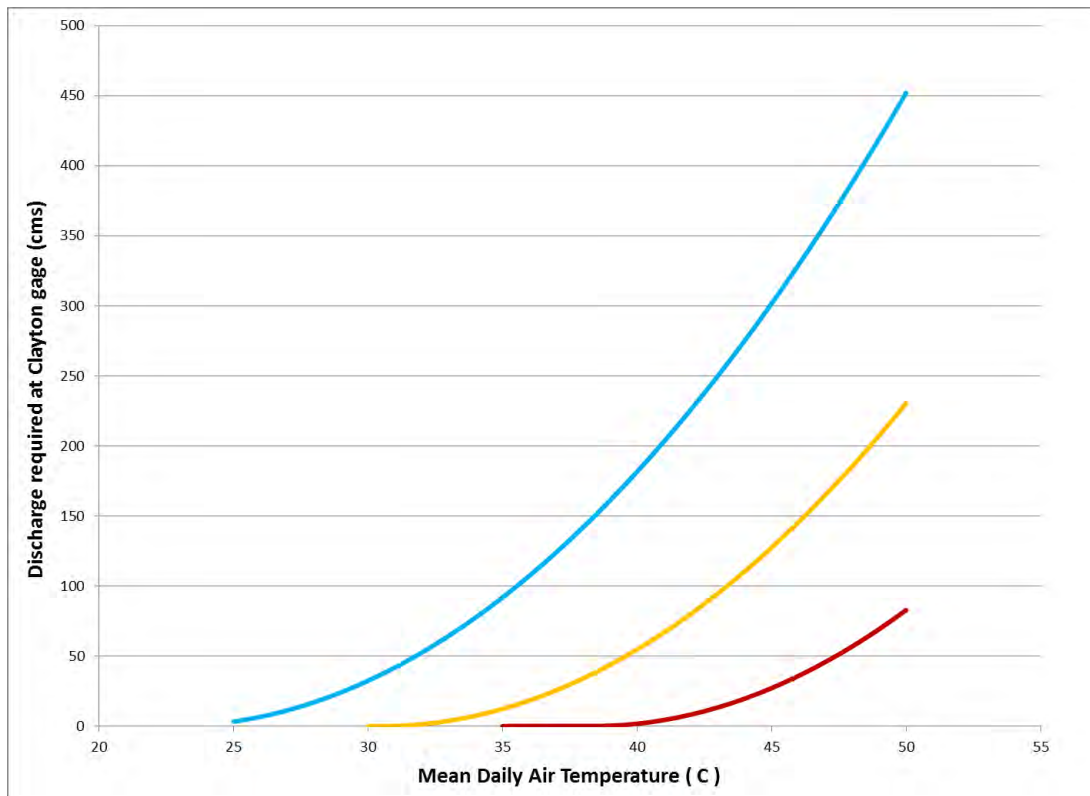
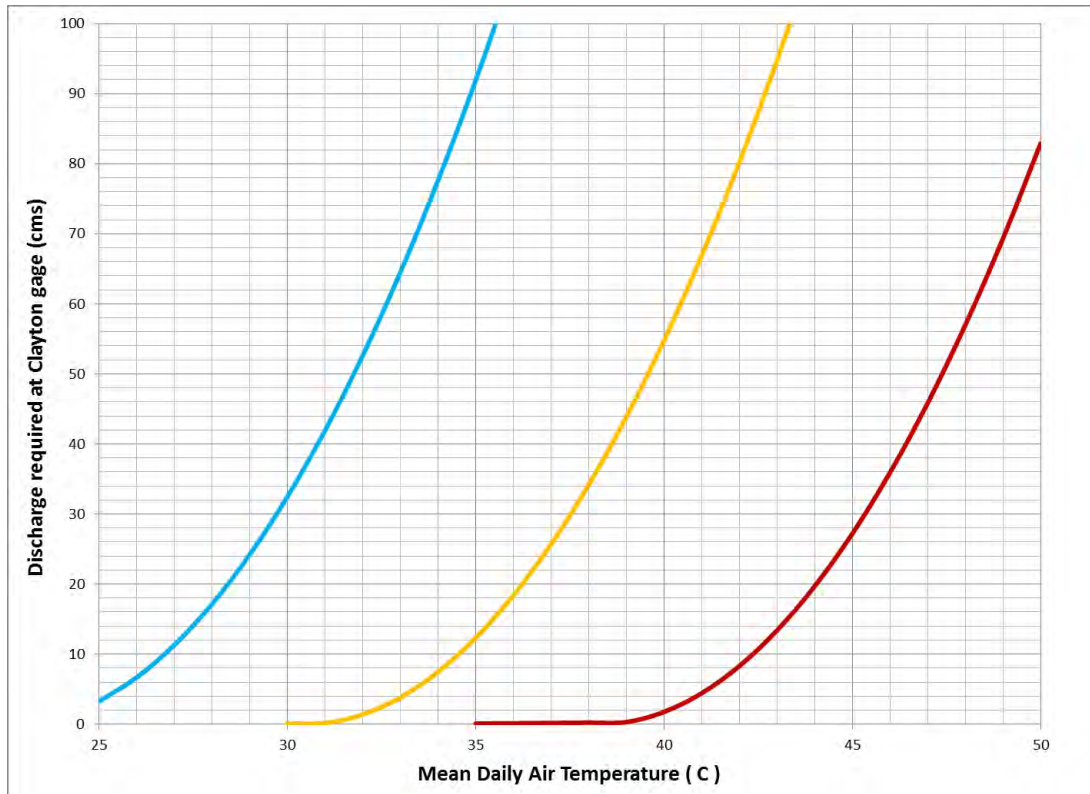


Figure 12. Discharges (under 100 cms) required for Kiamichi River near Clayton (USGS 07335790) to reduce maximum water temperature below target water temperatures. This is the same figure as Figure 11, just with shorter ranges for visual simplicity. From Vaughn and Julian (2013).

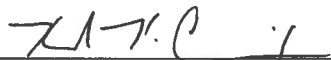



F.

Prepared by:

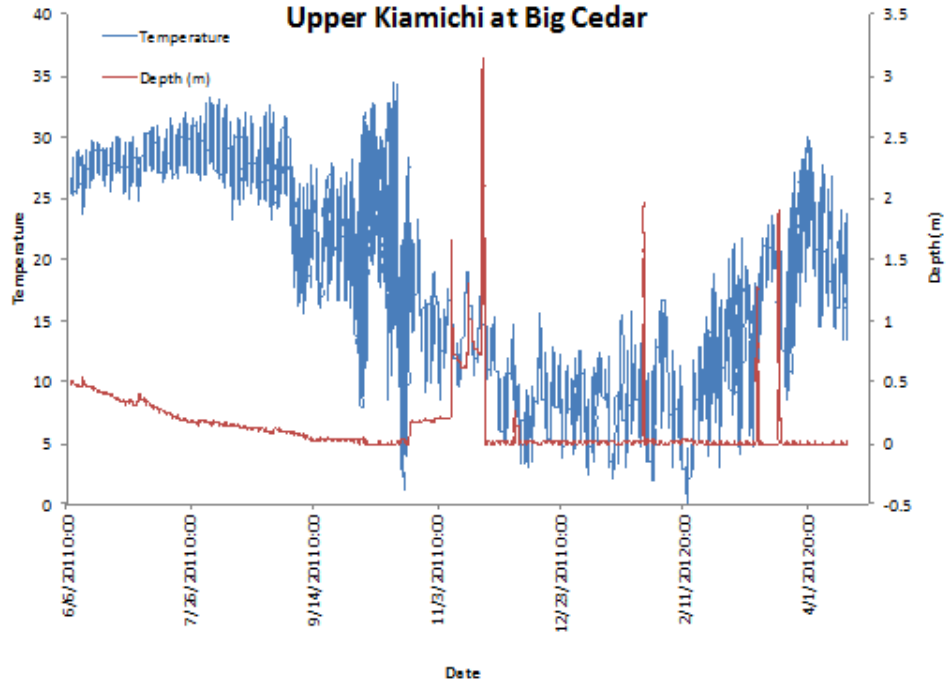
Dr. Caryn C. Vaughn

Date: 28 February 2014

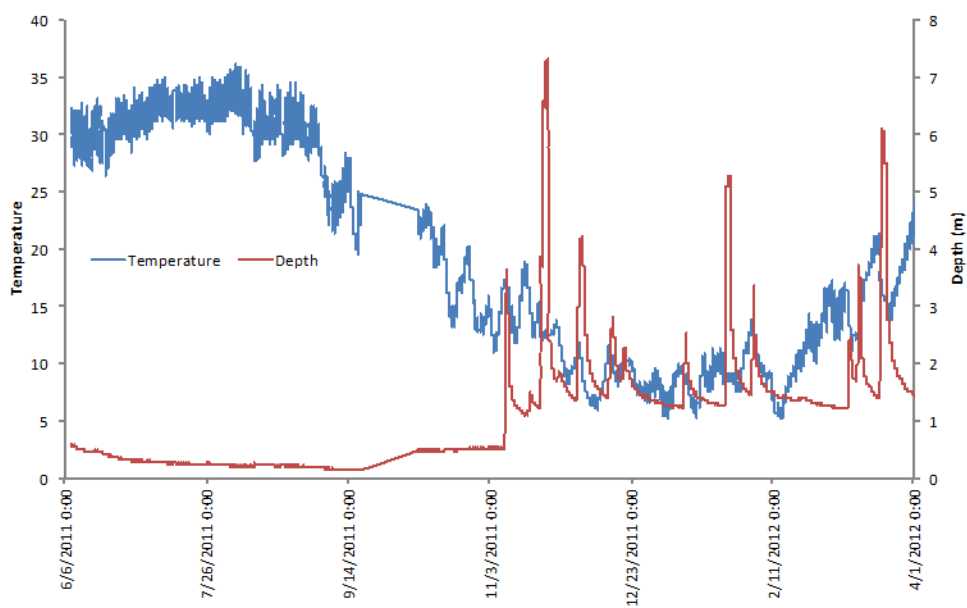
Approved by: 
Fisheries Division Administration
Oklahoma Department of Wildlife Conservation


Andrea K. Crews, Federal Aid Coordinator
Oklahoma Department of Wildlife Conservation

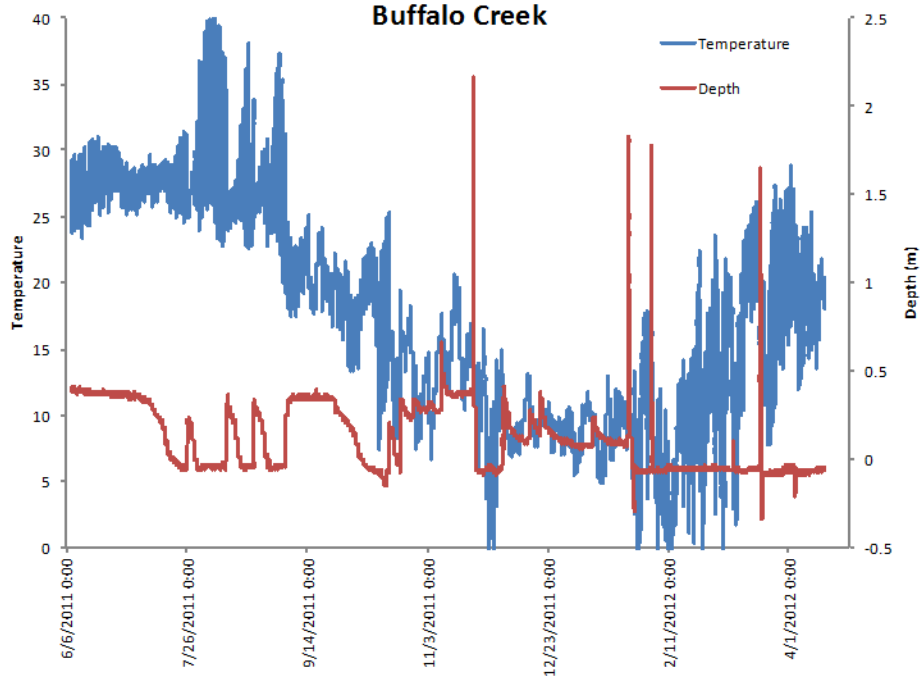
APPENDIX 1. Water depth and temperature for sites in Figure 6 from summer 2011 through spring 2012. If no data are reported, that logger was not recovered.

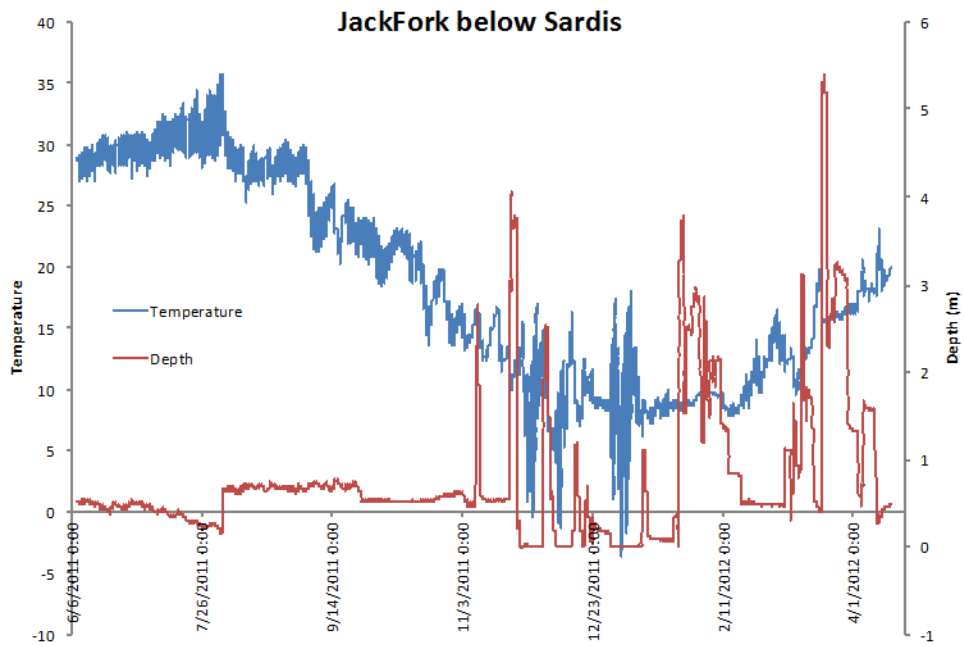
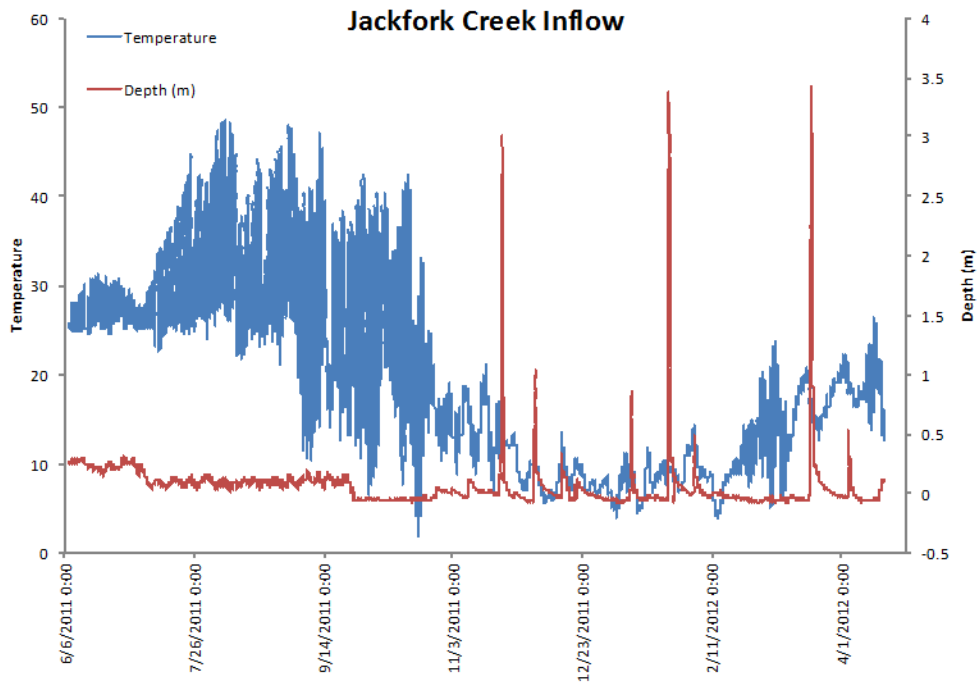


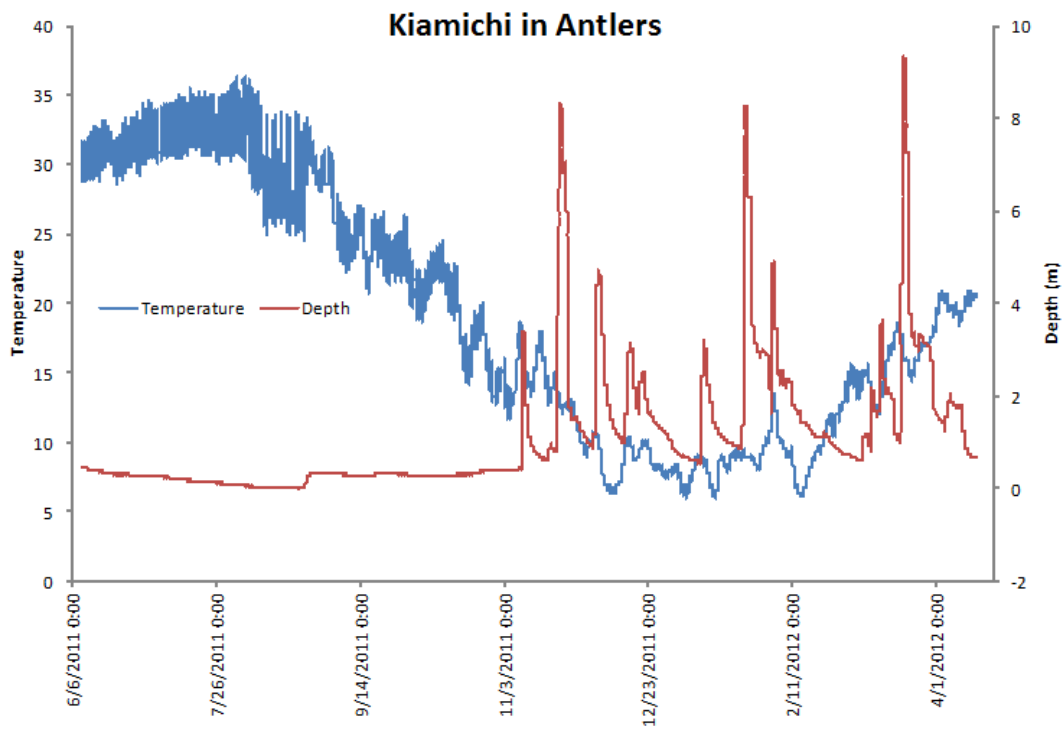
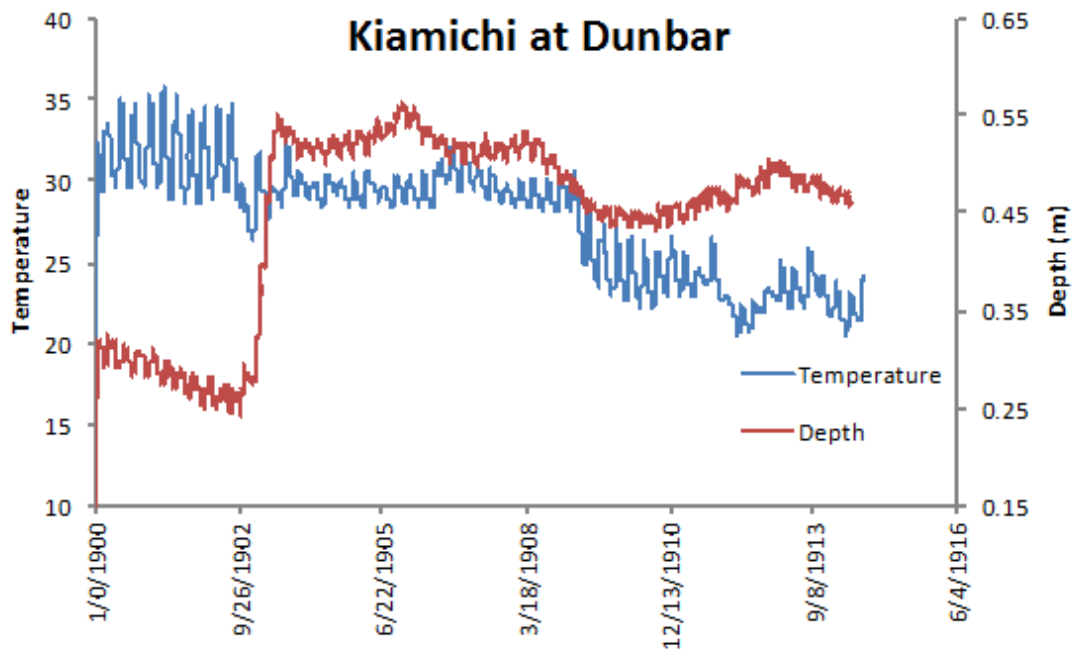
Kiamichi at Tuskahoma

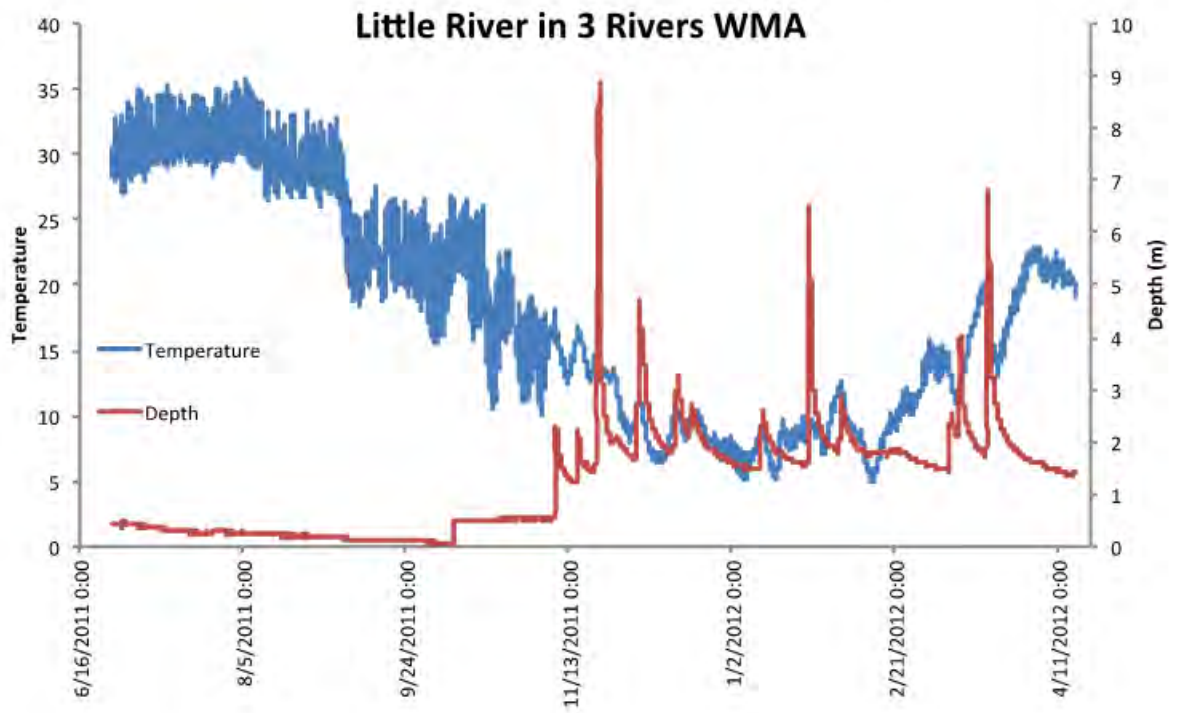


Buffalo Creek

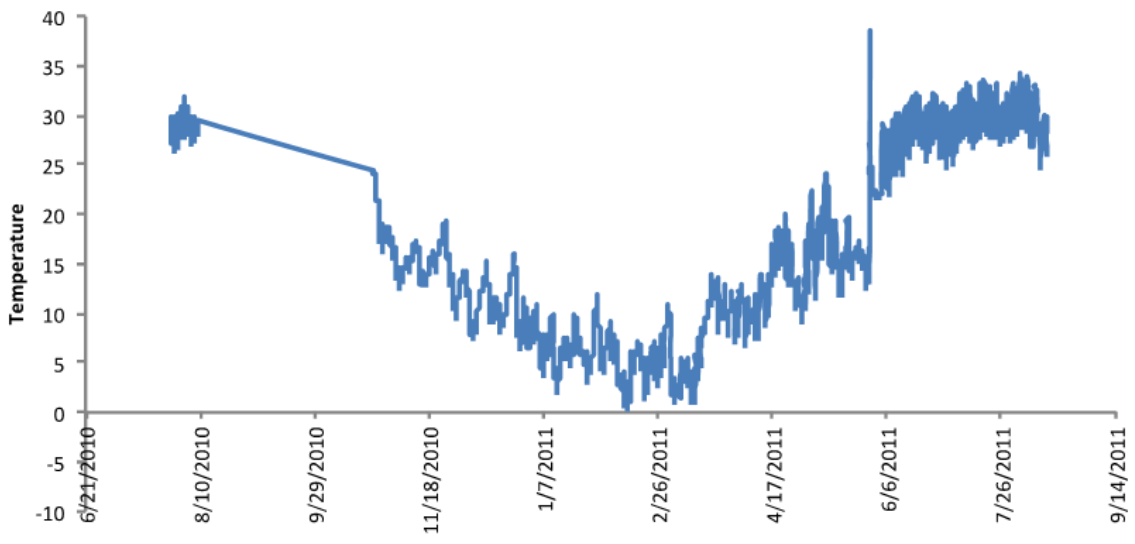


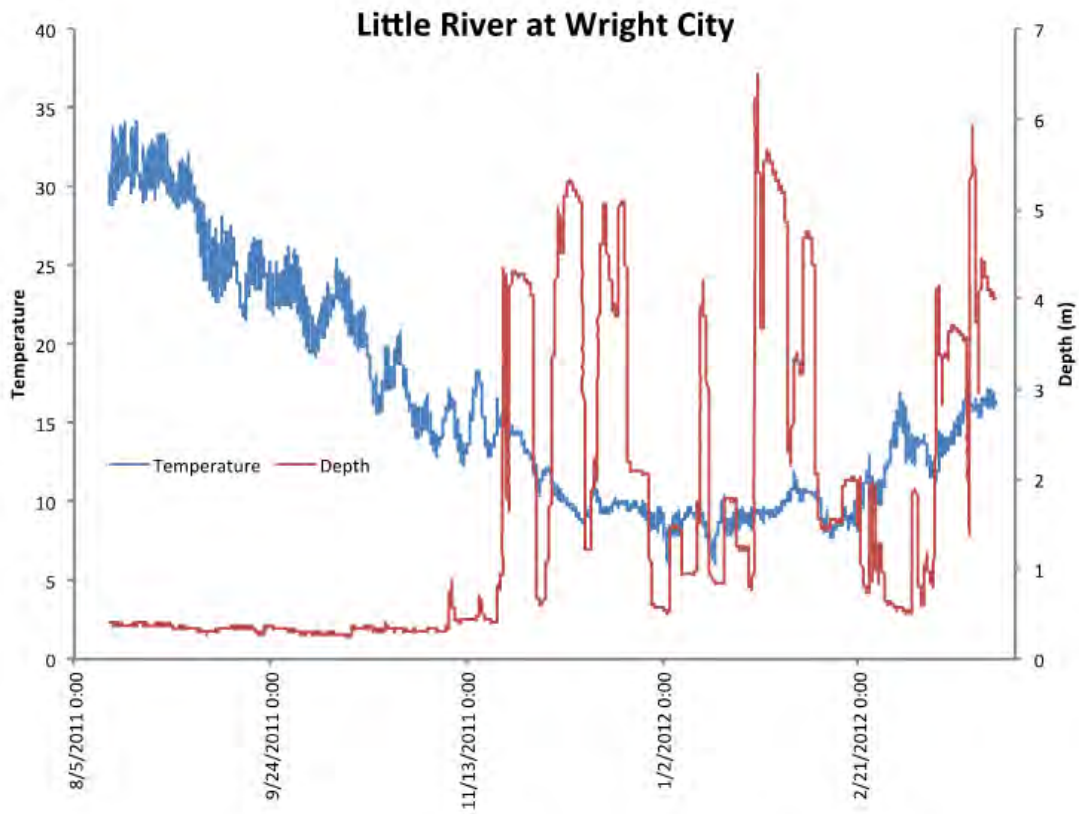
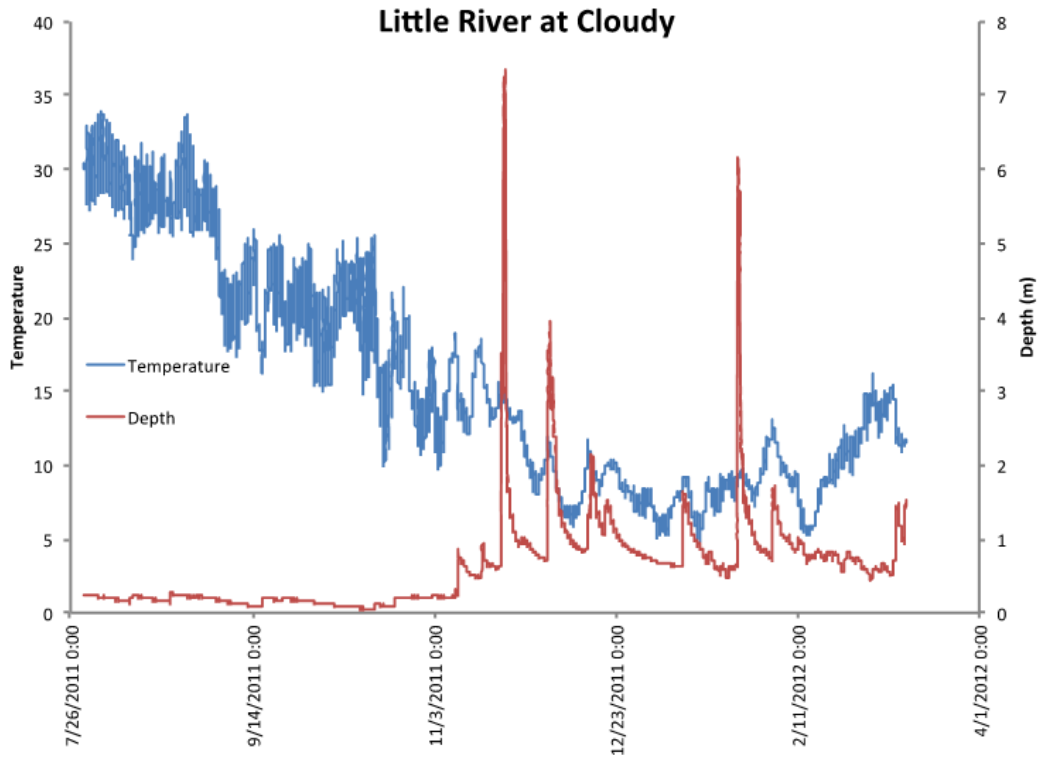


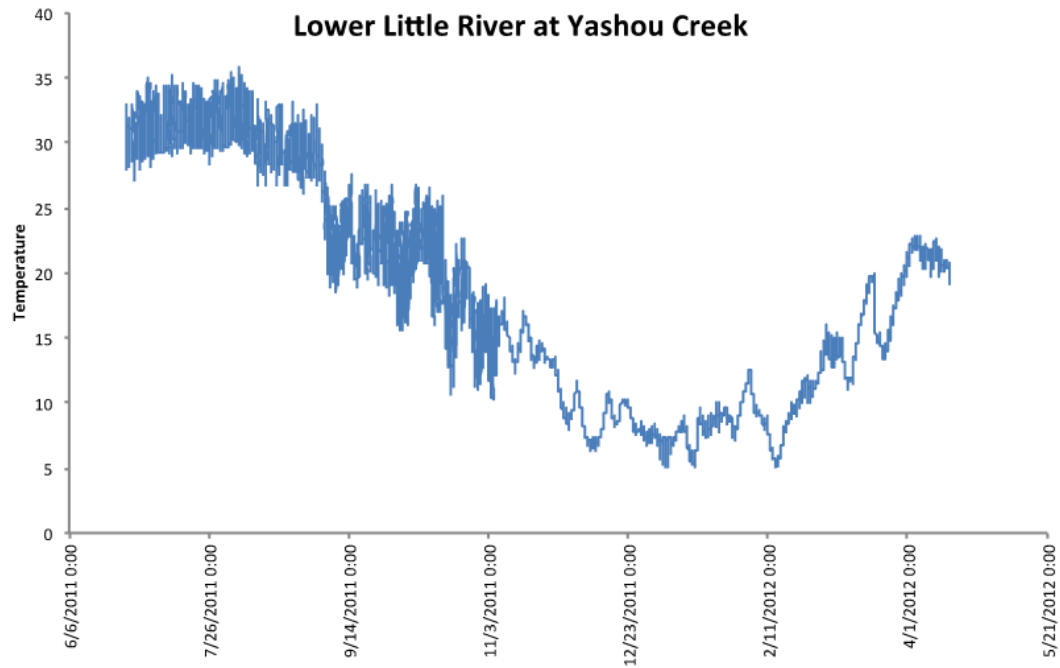




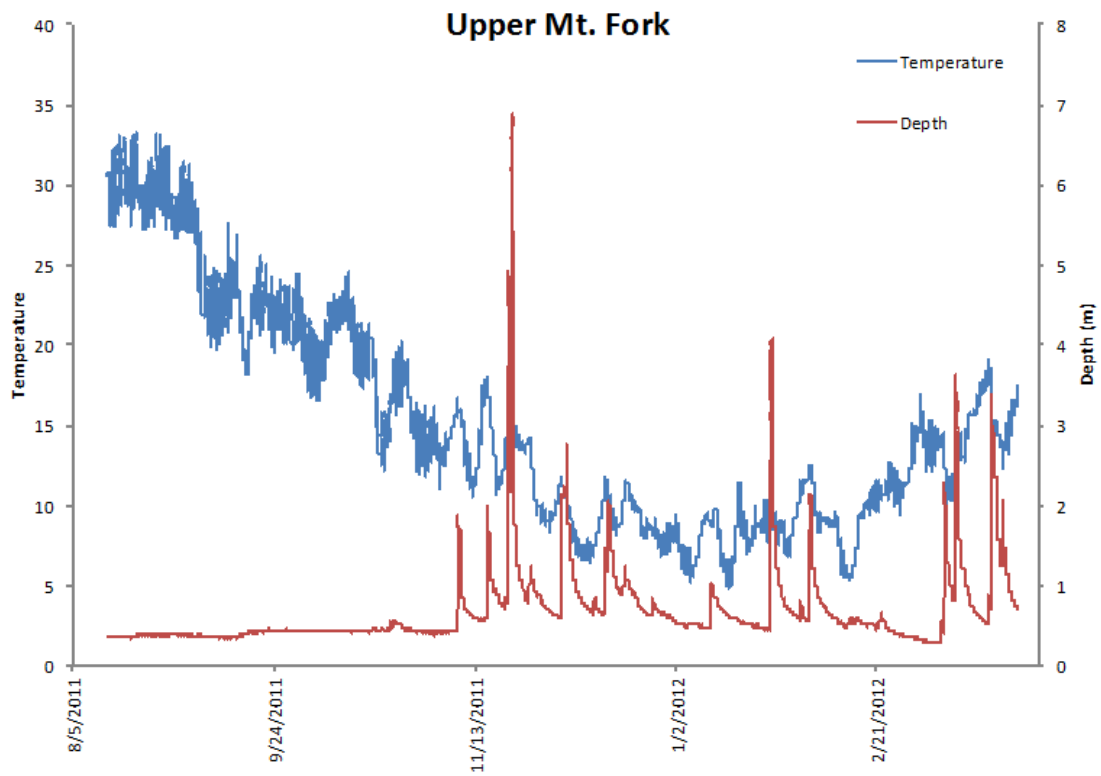
Upper Little River

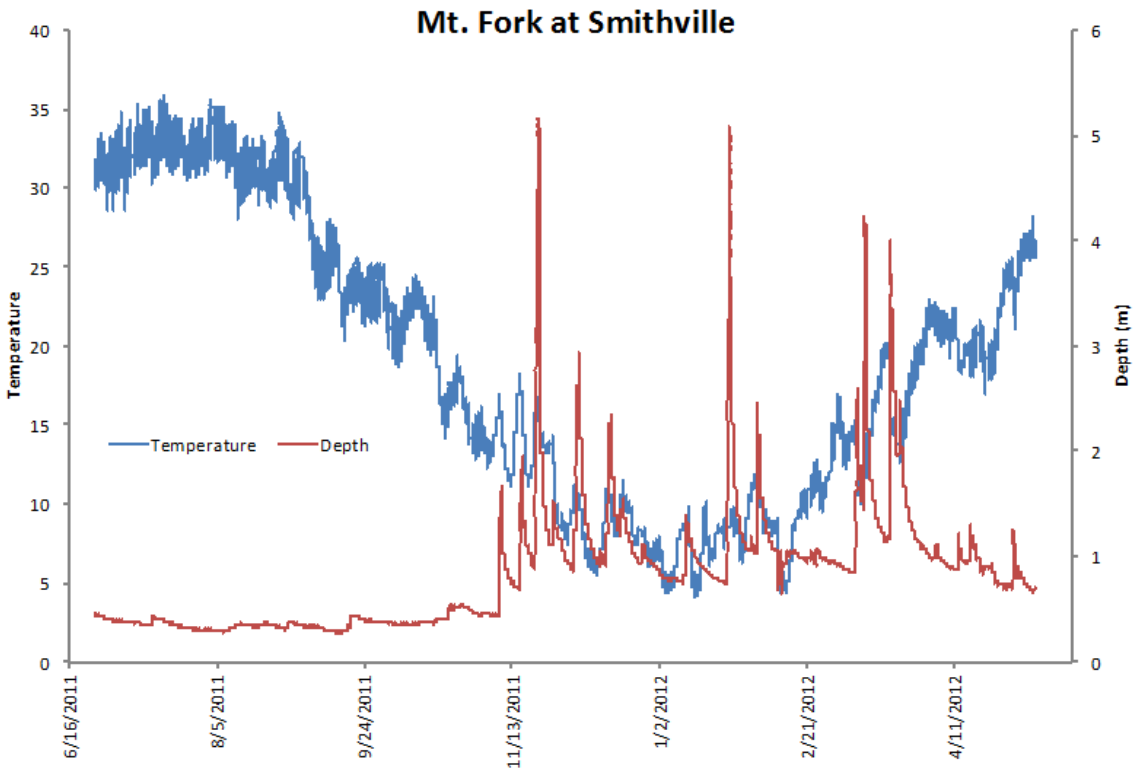
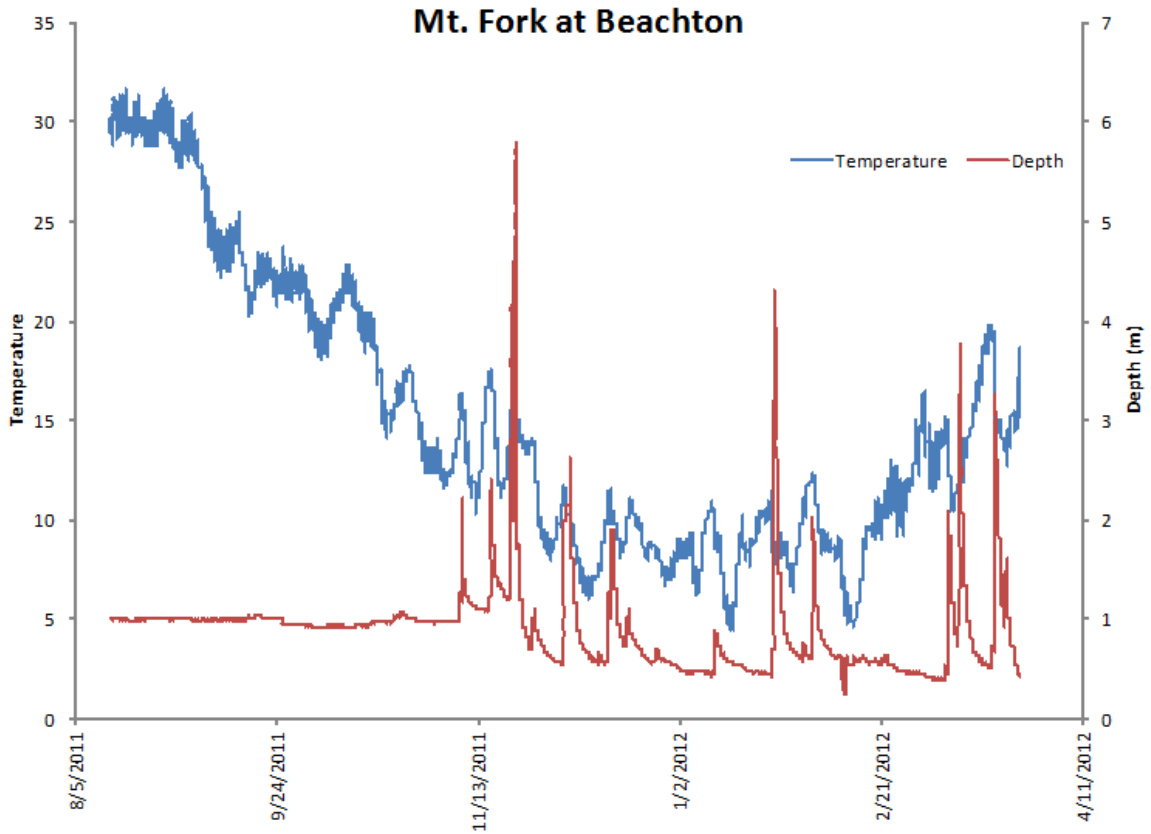






Sensor got buried in trees and sand – don't trust the depth data.





Mt. Fork above Broken Bow

