MILL DAM EFFECTS ON FRESHWATER MUSSEL GROWTH IN AN ALABAMA STREAM

A Thesis
by
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ABSTRACT

MILL DAM EFFECTS ON FRESHWATER MUSSEL GROWTH IN AN ALABAMA STREAM
(May 2010)

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Small dams are common in the southeastern U.S., yet few studies have quantified their effects on the region's aquatic biota such as imperiled freshwater mussels. I investigated why freshwater mussels are more abundant and larger immediately downstream from a small dam than conspecifics in up- or downstream reaches. I attempted to answer 2 questions. First, is the larger size of mussels immediately below mill dams attributable to faster growth or greater age? Second, do sites up-and downstream from dams differ in mussel food quantity or quality? I thin-sectioned shells to age mussels and compare growth rates between populations. Additionally, I measured total suspended solids (TSS) from filtered water samples seasonally. I analyzed length-at-age data using multiple growth models and found that mill reach mussels grew faster than up- and downstream populations. TSS quantity varied seasonally but was generally highest in the impoundment and mill reach from spring-fall. TSS organic-to-inorganic ratios were highest in the upstream reach from spring-fall but highest in the impoundment and mill reach during winter. Temperature was consistently higher in all seasons in the impoundment and mill reach. My data suggest that some small impoundments enhance mussel food resources and growth conditions in downstream reaches. Increased food quantity and quality combined with elevated temperatures are the likely mechanisms responsible for promoting rapid shell growth downstream from some impoundments. These heretofore undocumented positive effects of small dams suggest that some older, more stable dams may actually benefit or promote the persistence of imperiled mussel populations. Positive effects of small dams and the degree of imperilment of mollusk populations should be factored into cost-benefit analyses when prioritizing sites for dam removal projects.

DEDICATION

I would like to dedicate this thesis to my family.

ACKNOWLEDGEMENTS

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INTRODUCTION

Large dam effects on lotic organisms and habitat are well documented and include restricted organism passage, altered temperature, chemistry, and sediment regimes, and macroinvertebrate community changes (Fraley 1979, Holden 1979, Armitage 1984, Ward and Stanford 1987, Jensen 1987, Lessard 2000, Lessard and Hayes 2003). Effects of more ubiquitous small dams are more poorly understood because > 90% are privately owned and undergo less regulatory scrutiny than large government-owned dams (Shuman 1995, Dean et al. 2002). The peak of large dam building in the U.S. occurred in the 1st half of the 20th century. The average age of large dams is ~40 y, and many dams are in need of rehabilitation (Shuman 1995). With 75,000 dams in the U.S. facing rehabilitation, removal, or failure a more quantitative understanding of their effects of aquatic biota is needed for effective management (FEMA 1993).

Dams directly affect stream community and habitat structure by altering substrate composition and water flow. Changes to flow and substrate have dramatic effects on food webs, water chemistry and temperature in downstream reaches (Downward and Skinner 2005, Maxted et al. 2005, Haxton and Findlay 2008). Dams slow water flow and fluvial sediment transport resulting in stream bank incision, substrate armoring, and geomorphic changes (Ligon et al. 1995). The impoundment formed upstream of a small dam represents a significant alteration of habitat parameters essential to the survival of many lotic organisms. Dam failure can also alter stream morphology and destabilize streambeds which may contribute to declines in freshwater mussels and other stream macroinvertebrates (Dean et al. 2002, Lessard and Hayes 2003, Sethi et al. 2004, Downward and Skinner 2005).

Freshwater pearly mussels (Bivalvia: Unioniformes) are imperiled globally (Riaccardi and Rasmussen 1999, Lydeard et al. 2004, Poole and Downing 2004). Freshwater mussel declines are linked to anthropogenically-mediated changes to aquatic environments (Bauer 1988, Poole and Downing 2004, Brainwood et al. 2006). Cold, hypolimnetic (bottom of reservoir) releases dramatically reduce downstream temperature and peaking operations alter flow regimes and lead to substantial changes in mussel and macroinvertebrate assemblages (Parmalee and Bogan 1998, Rehn 2009). In the Little River (Oklahoma) dam-mediated flow changes (unseasonable extreme highs and lows) and unnaturally cold temperatures caused freshwater mussel die-offs up to ~20 km downstream (Vaughn and Taylor 1999). Dams also limit the passage and distribution of host fish necessary for mussels to complete their life cycle and therefore limit mussel distribution (Bogan 1993, Watters 1996). Impoundments harbor few mussels because of unsuitable habitat (Bogan 1993, Dean et al. 2002).

Filter feeders process large quantities of particulate organic matter (POM) in freshwater systems (Monaghan et al. 2001). Dams alter sediment movement and POM concentrations in downstream reaches (Nichols and Garling 2000, Christian et al. 2008, Lydeard et al. 2004). Although POM typically decreases downstream in general, surface water quality typically increases downstream from reservoirs (Webster et al. 1979, Zdislaw 1984). Surface-release (epilimnetic) dams yield rich supplies of plankton compared to bottom (hypolimnetic) release dams (Hartman and Himes 1961, Ward 1975, Petts 1984). Nitrogen, phosphate, and silica are frequently limiting nutrients for plankton growth (Whitely and Campbell 1974). Nutrient availability in the impoundment and downstream is largely dependent upon reservoir retention time (Petts 1984). Surface-discharges contain elevated plankton concentrations that may promote growth and survival of filter-feeding macroinvertebrates (Cushing 1963, Simmons and Voshell 1978, Merkley 1978, Webster et al. 1979, Zdislaw 1984).

Mussels, like all mollusks, accrete shell layers sequentially during growth. Shell formation is seasonal and typically slows during winter (Negus 1966). Shell growth patterns reflect environmental

conditions including seasonal and yearly climactic variation (Clark 1974, Soldati et al. 2009). Because freshwater mussels are long-lived (100+ y), growth rates may reveal subtle differences in water temperature, chemistry, or food availability (Helama and Valovirta 2008, Soldati et al. 2009). Growth ring production in freshwater mussels has long been assumed to be annular (Isley 1914, Coker et al. 1921). Several techniques are routinely used to obtain age data from mussel shells, including external ring counts, acetate peels, shell ashing, and shell thin-sectioning. Most studies suggest that thin-sections provide the most accurate age estimates (Clark 1980, Neves and Moyer 1988).

Use of shell thin sections to estimate age is impeded by incomplete rings (false annuli) that occur intermittently between complete annular rings (Negus 1966, Neves and Moyer 1988). Day (1984) suggested false annuli were due to a brief stop in growth following disturbances (e.g., predator attacks, temperature fluxes). Factors responsible for false annuli production remain poorly understood. Annular ring validation is important to accurately age populations (Beamish and McFarlane 1983, Anthony et al. 2001). Annular ring validation studies of freshwater mussel populations in the southeastern U.S. (Alabama and Mississippi) have shown that freshwater mussels form annual rings (Haag and Commens-Carson 2008, Rypel et al. 2008).

Mussels in Sandy Creek are larger and more abundant directly downstream of the mill dam (Jones Mill Dam) compared to populations up- and downstream of the impoundment. *Elliptio arca* (the numerically dominant unionid in this reach) densities immediately downstream of the mill dam averaged $8/m^2$ (range 0-$64/m^2$) compared to $0.1/m^2$ and $0.2/m^2$ in the up- and downstream reaches, respectively (Gangloff et al. 2009a). Moreover, in Sandy Creek, *E. arca* (and other unionids) are significantly larger in the mill reach than individuals collected up- or downstream. Similar patterns are seen in *E. arctata* in Loblockee Creek (Tallapoosa Drainage) and *E. fumata* in Halawakee Creek (Chattahoochee Drainage) (Gangloff et al. 2009a).

Growth curves can reveal important parameters of freshwater mussel populations. Surprisingly, few studies have attempted to utilize freshwater mussel population growth data to

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address ecological questions. Here I estimate age at length for mussels at 3 locations in a small

Alabama stream (Sandy Creek) to discern the effects of a small dam on growth rates. I am attempting

to understand if the Jones Mill Dam affects mussel growth rates or lifespan and what factors may

drive increases in growth or lifespan.

METHODS

Study sites

I studied in Sandy Creek, a 3rd order stream in east-central Alabama near the town of Waverly in Chambers County. Sandy Creek is above the fall line in the Tallapoosa River Drainage of the Mobile River Basin in the piedmont physiographic region. Land use in the Sandy Creek catchment is mainly row planted loblolly pine (*Pinus taeda*), but was historically row crop agriculture (primarily cotton). Bottomlands along Sandy Creek are broad and typically well-forested with hardwoods.

I established 4 study sites on Sandy Creek; (1) upstream (~2 km) from the impoundment formed by Jones' (Stephen's) Mill Dam (32.74327°, -85.54998°), (2) within the impoundment formed by Jones' (Stephen's) Mill Dam (32.75079°, -85.55959°), (3) mill reach 0-150 m downstream from Jones' (Stephen's) Mill Dam (32.75079°, -85.55959°), and (4) downstream (~5 km) from Jones' (Stephen's) Mill Dam (32.50774°, -85.57854°; Fig. 1).

Study species

Elliptio arca is endemic to the Mobile Basin and occurs both above and below the fall line (Williams et al. 2008). Stansberry (1976) classified *E. arca* as endangered, while Williams et al. (1993) listed it as threatened. Lydeard et al. (1999) designated *E. arca* as imperiled across its range, and Garner et al. (2004) considered it a species of highest conservation concern. NatureServe ranks *E. arca* as G2G3Q, imperiled/vulnerable with questionable taxonomy (www.natureserve.org). *Elliptio arca* lives in medium to large streams in a range of habitats, however it does not occur in lentic habitats (Williams et al. 2008). *Elliptio arca* is sexually mature at 2 y and uses *Etheostomoa artesiae*, the Redspot darter, *Percina nigrofasciata*, the Blackbanded darter, and *Ammocrypta*

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meridiana, the Southern Sand darter, as glochidial hosts (Haag and Staton 2003, Haag and Warren 2003).

Mussel shell collection and thin sectioning

I collected fresh dead shell material opportunistically from the upstream, mill, and downstream reaches for thin sectioning and analysis. *Elliptio arca* does not occur in Jones Mill Pond. Jones Mill Pond mussel assemblages are dominated by *Pyganodon grandis* and *Utterbackia imbecilis* (Gangloff et al. 2009a). For sectioning, I selected the least eroded valve and cut from the shell umbo to margin along the longest part of the valve (Fig. 2). I smoothed the cut valve with 240 grit, dipped it in Buehler™ epoxy resin, then placed it on a petrographic slide and allowed it to dry for 24 h. Next, I sectioned prepared specimens with a saw chuck on a Hillquist™ saw/grinder removing all but ~ 2 mm of material. Finally, I polished specimens with 400 and 600 grit silicon carbide paper to achieve an even reflection across the entire specimen. I counted shell growth rings under a 10x compound microscope. A growth line is a continuous band from the periostracum (shell margin) to the umbo region (Neves and Moyer 1988, Haag and Commens-Carson 2008).

Cage experiment

I collected ~30 *Elliptio arca* from 3 sites (upstream, mill, and downstream reaches) using visual and tactile searches. Mussel shell length was measured along the greatest anterior-posterior dimension with digital calipers (Mitutoyo, ±0.01 mm) 5 times. Each mussel was cleaned and dried before adhering a numbered bee-tag (The Bee Works, Canada) to the umbo region of each valve with Zap-a-Gap™, a cyanoacrylate adhesive. To facilitate cage relocation, I used underwater epoxy (JB Weld™) to adhere Passive Integrated Transponders (PIT, Biomark™) tags to 1 mussel per cage. I made a 1-2 mm notch in the ventral margin of both valves with a Dremel™ drill to physically mark a reference point.

I placed 3 mussels into plastic mesh cages anchored to the stream bed using rebar and photo-resistant cable ties. Each cage was filled with ~6 cm of gravel and sand collected at each location. I constructed the mussel cages (190 x 90 x 160 cm) using 2 layers of plastic mesh and photo-resistant cable ties to retain mussels yet allow water circulation (Gangloff et al. 2009b). Ten cages (N=30 mussels per site) were placed in the upstream, mill, and downstream reaches. At the upstream site, I marked 16 mussels using notches and PIT tags and returned them to the reach without a cage. Cages were monitored seasonally. Mussels were removed from cages after 1 y, measured, and sectioned to examine growth differences between sites.

Growth curves and statistical analyses

A common equation used to create growth curves for freshwater mussels is the von Bertalanffy equation (von Bertalanffy 1938, Kesler and Downing 1997, Anthony et al. 2001). Growth rate and size of freshwater mussels is an often overlooked component of population viability and the von Bertalanffy equation is a useful tool to compare growth rates between populations (Hastie et al. 2000). However, Haag (2009) has suggested the von Bertalanffy equation may overestimate mussel age; therefore I included alternate equations to examine growth.

The von Bertalanffy growth equation is $L_t = L_\infty(1 - e^{-K(t-t_0)})$ where L_t is the shell at a given age (*t*), L_∞ is the theoretical shell length-at-age infinity, K is a fitted constant showing the rate of L_t approaching L_∞ over time, and t_o is the theoretical age when the shell length is 0 (Ricker 1975, Kesler and Downing 1997). I used Fishery Analysis and Simulation Tools (FAST) (Version 2.0, Auburn, AL) to apply the von Bertalanffy equation. The Morgan-Mercer-Flodin (MMF) equation, also used for growth curve construction, is $Y = \frac{(a \cdot b + c \cdot X^d)}{(b + X^d)}$ where a, b, c, and d are fitted constants, Y is cumulative shell length, and X is age (Morgan et al. 1975, Soldati et al. 2009). I used CurveExpert 1.4 (Microsoft Corporation, USA) to apply the MMF equation.

Site-scale length-at-age data were normally distributed with equal variances (Shapiro-Wilk and Levene's tests $P > 0.05$) so I used a parametric ANCOVA with site as the covariate to assess growth differences. I computed growth curve residual scores and then used ANOVA (and LSD post-hoc tests) to assess growth differences between site residual scores. All total suspended solids (TSS), water chemistry, and temperature data were also normally distributed with equal variances (Shapiro-Wilk and Levene's tests $P > 0.05$) so I performed ANOVAs to assess differences across sites and LSD post-hoc analyses to asses between site differences. I used SPSS software (Version 17, SPSS Inc., Chicago, IL) for ANOVA, ANCOVA, and curve fitting procedures.

Total suspended solids and water chemistry

I adapted my TSS sampling protocol from the 19th edition of Standard Methods 2540 D-E. I collected water samples seasonally (March, June, and November 2009, and February 2010) from the mill, upstream, and downstream reaches as well as from the impoundment at Jones' (Stephen's) Mill Pond. I collected water samples from mid water column and transferred samples to an acid washed 1 L HDPE bottle through 250 μm mesh. Samples were then vacuum filtered with a microfiltration unit using a pre-ashed and pre-weighed 47 mm Gelman™ type A/E 1.0 μm pore glass fiber filter (GFF). At least three replicate subsamples were filtered from each site. TSS dry mass was determined by drying GFFs at 103-105˚C for 1 h, cooling to room temperature in a desiccator, and weighing on an analytical balance (Ohaus Analytical PLUS™ ±0.00001g). Next, GFFs were ashed in a muffle furnace at 550˚C for 1 h and cooled in a desiccator. GFFs were weighed again to determine the organic matter fraction (dry mass - ash mass) and inorganic matter fraction (ash mass).

Additional water samples (250 mL) were collected for water chemistry analysis. Routine elements (Ca, K, Mg, Al, As, Ba, B, B, Cd, Cr, Cu, Fe, Pb, Mn, Ni, P, Na, Zn, No_3-N, electrical conductivity, and pH) were quantified by the Alabama Cooperative Extension Soil and Water Testing lab in Auburn, AL. I focused on P and No_3-N as these can limit phytoplankton production to test if

phytoplankton were a major component of increased organic material downstream. Temperature was measured with iButton (Maxim Integrated Products) temperature loggers.

<center>RESULTS</center>

Thin sectioning and growth curves

The cage experiment did not successfully examine annular growth during the 2009-2010 growing season due to high mortality from sediment covering cages. All mussels from the cages were able to be used in analysis of overall length-at-age analysis between sites.

Residuals from a linear regression of freshwater mussel length-at-age data showed mill reach mussels were growing faster than mussels upstream or downstream (Fig. 3). ANOVA revealed significant between site differences in mean length-at-ages 4 ($F_{2,20} = 4.335$, $p = 0.029$), 5 ($F_{2,30} = 41.491$, $p < 0.0001$), 6 ($F_{2,37} = 63.753$, $p < 0.0001$), and 7 ($F_{2,21} = 50.512$, $p > 0.0001$; Fig. 4). Mussels at ages 5, 6, and 7 y were significantly larger in the mill reach compared to up-and downstream reaches. ANCOVA revealed a significant interaction between age and site ($F_{11,120} = 347.74$, $p < 0.0001$) and LSD post hoc tests showed mussels in the mill reach are growing faster than mussels upstream or downstream of Jones (Stephen's) Mill Dam. Separate curves applied the mussels at each reach show the growth rate is highest in the mill reach (Fig. 5).

The von Bertalanffy growth equation describing length-at-age for *Elliptio arca* in the mill reach of Sandy Creek was $L_t = 86.297(1 - e^{-0.737(t-2.206)})$ with an $r^2 = 0.948$ and $p > 0.001$ when solving for all variables. When L_∞ was held constant using the largest individual found in the mill reach the von Bertalanffy equation was $L_t = 109\left(1 - e^{-0.137(t-3.304)}\right)$ with $r^2 = 0.803$ and $p > 0.0156$. The von Bertalanffy growth equation describing length-at-age for *E. arca* in the downstream reach of Sandy Creek was $L_t = 61.228(1 - e^{-1.167(t-2.702)})$ with $r^2 = 0.998$ and $p > 0.0006$ when solving for all variables. When L_∞ was held constant using the largest individual found in the

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downstream reach the von Bertalanffy equation was $L_t = 68.1\left(1 - e^{-0..416(t-0.992)}\right)$ with $r^2 =$

0.938 and $p > 0.0311$. No significant von Bertalanffy model was established for the mussels in the

upstream reach (Table 1). I applied the Mercer Morgan Flodin (MMF) equation to the length-at-age

data for each site. The equation did not converge for the length-at-age data from any reach. I used a

curve fit program in SPSS to determine whether a suite of alternate models would characterize growth

better. Many models were significant, however none of the r^2 values fit as well as the von

Bertalanffy equation (Table 1).

Total suspended solids

I found a significant interaction between site and season for organic, inorganic, and total

suspended solids (TSS), so the data were analyzed separately by season. ANOVAs revealed

significant TSS differences between sites in spring ($F_{3,16}=25.885$, $p < 0.0001$), fall ($F_{3,16}=5.131$, $p =$

0.016) and winter ($F_{3,16}=57.839$, $p < 0.0001$), but not summer (Fig. 6). Post-hoc tests showed TSS

were highest in the mill followed by the impoundment, and up- and downstream reaches in the spring.

In fall, TSS were lowest in the downstream reach compared to all other reaches. In winter, the

downstream reach had the highest TSS, followed by both the impoundment and upstream reaches,

and the mill reach had the lowest TSS.

Organic to inorganic ratio

I measured significant differences in the water column organic to inorganic ratio (O:I)

between sites in spring ($F_{3,16}= 20.929$, $p < 0.0001$) and winter ($F_{3,16}= 6.058$, $p = 0.009$; Fig. 7). Post-

hoc tests revealed in spring, O:I was higher in the upstream reach compared to all other sites. In

winter, O:I was higher in the mill reach than all other sites.

Organic material

Organic matter (OM) was significantly different between sites in spring ($F_{3,16}$ =27.112, $p <$ 0.0001), fall ($F_{3,16}$ = 3.686, p = 0.043), and winter ($F_{3,16}$ = 7.615, p = 0.004), but not summer (Fig. 8). Post-hoc tests revealed OM was higher in the impoundment and mill reaches compared to up- or downstream in the spring. In fall, the mill reach had more OM than in the downstream and impounded reach, while OM in the upstream reach was not different from any other sites. In winter, OM was lowest in the mill reach compared to the other reaches.

Inorganic material

I observed significant differences between sites in inorganic material (IM) in the spring ($F_{3,16}$ = 22.511, $p < 0.0001$) and winter ($F_{3,16}$ = 56.973, $p < 0.0001$; Fig. 9). Post-hoc tests showed that IM differed between all sites during spring. Spring IM concentrations were greatest at the mill and lowest in the upstream reach. In winter, IM concentrations were highest in the downstream reach and lowest in the mill reach.

Water chemistry and temperature

There were no significant differences between sites in any routine elements (Ca, K, Mg, Al, As, Ba, B, B, Cd, Cr, Cu, Fe, Pb, Mn, Ni, P, Na, Zn, No$_3$-N, electrical conductivity, and pH; Table 2). ANOVA revealed temperature was significantly different between sites ($F_{2,7997}$ = 183.88, $p < 0.0001$) and LSD post-hoc analysis revealed the highest temperature was in the impoundment directly above the mill dam ($\bar{x} = 20.1$ ℃), followed by immediately below the mill dam ($\bar{x} = 18.7$ ℃), and the lowest temperature was upstream ($\bar{x} = 16.2$ ℃). Downstream temperature data are unavailable. ANOVA also revealed significant temperature differences between sites in each month (all $F > 11.0$, $p < 0.0001$) from April 2007 to April 2008 (Fig. 10). The upstream reach was colder than the mill reach and the impoundment in all months except January.

DISCUSSION

Freshwater mussels in Sandy Creek immediately downstream of Jones Mill Dam appear to be growing faster than individuals upstream or farther downstream. One or more environmental differences associated with the dam is enhancing conditions for mussel growth. Residuals from the growth data suggest that mussels in the mill reach are indeed growing faster than up-and downstream populations and that they are considerably larger at ages 5-7 y. The mill reach supports the largest individuals ever measured of 4 freshwater mussel taxa (*Elliptio arca*, *Hamiota altilis*, *Villosa vibex*, and *Villosa lienosa*) (Singer and Gangloff 2009). Jones Mill Pond is increasing mussel food quality, quantity, and downstream water temperature. Changes in stream physicochemical parameters are a direct result of the impoundment and are consistent with conditions that likely result in more rapid shell accretion and possibly greater life spans.

I hypothesize that warmer spring and fall temperatures in conjunction with higher food levels are the primary mechanism responsible for dramatic size differences between Sandy Creek *E. arca* populations. Elevated temperatures resulting from the sun warming the surface of this small, shallow impoundment simply allow mill reach mussels to have a longer window for growth than up- or downstream populations. Freshwater mussel lifespan and maximum size are limited by colder temperatures (Bauer 1992) which may partially explain why *E. arca* in the up-and downstream populations do not grow as large as mill reach conspecifics.

Mill ponds and other small impoundments are productive environments for algae and bacterial growth and spring and fall blooms may play an important role in improving mussel food quality (organic matter concentration) during these critical growth periods. Elevated spring OM concentrations give mill reach mussels a head start on growth. In fall, OM remains elevated in the impoundment and mill reach but declines in the up-and downstream reaches. Enhanced food

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quality and production during cooler months may further extend the growing season. For example, I found that even when organic levels are lowest in the mill reach (winter), food quality remains high which should be an additional benefit to mussels experiencing elevated temperatures. Elevated winter food quality and water temperature may thus be complementarily beneficial to mill reach mussels.

I measured water chemistry data to test whether phosphorus or nitrate increases in the impoundment were tracking TSS and OM concentrations. However, no statistically significant patterns were observed. Water samples were collected during a relatively wet period. Samples collected during drought years when impoundment retention times are elevated could reveal a pattern of increased OM (from algae) when more phosphorus is available from bottom sediments.

Other studies have shown that freshwater mussels in high nutrient streams grow more than mussels in low nutrient streams with temperature also affecting growth (Kesler and Van Tol 2000, Kesler et al. 2007). Anthony and others (2001) argue for plasticity of growth rates of mussel populations in varying habitats and my von Bertalanffy equations demonstrate that mussel growth rates differ across habitats. Even though handling has been suggested as a hindrance to mussel shell accretion, handling likely did not play a major role in this study because individuals were not handled over several years (Haag 2009).

The von Bertalanffy equation fit successfully to length-at-age data for freshwater mussels in the mill and downstream reaches; however, a curve could not be derived for the mussels from the upstream reach. This lack of convergence may be due to the limited number of small size classes. The equation consistently underestimated the maximum size, or L_∞, especially at the mill reach, but holding L_∞ constant and solving for the other variables controls for the underestimation. I also applied linear, logarithmic, quadratic, compound, growth, exponential, logistic, and Mercer Morgan Flodin (MMF) equations to the data. However, these models failed to provide a better fit to the data. The widespread use of the von Bertalanffy equation for freshwater mussel growth rates allows comparison of growth between species and populations (Bauer 1992, Kesler and Downing 1997,

Hastie et al. 2000, Anthony et al. 2001). Better model fit using the von Bertalanffy equation might be possible if I had sectioned more small mussels. However, because *E. arca* is already a species of conservation concern, it would have been imprudent to sacrifice additional animals. Haag (2009) found that the von Bertalanffy equation functioned best when a wide range of mussel size classes was used (Haag 2009). More recent studies have found that utilizing cross-dating and other dendrochronological methods may increase reliability and validation of mussel ages (Rypel et al. 2008, Helama and Valovirta 2008).

It is possible that mill dams could have detrimental effects on mussel populations if the associated temperature increases reach extremes and inhibit mussel metabolism. Further, increased temperatures and algal blooms may reduce downstream dissolved oxygen levels and impact mussel metabolism, growth, and survivorship in the mill reach. Removal of older structures like Jones Mill Dam would result in severe mortality for mill reach mussels and recovery of the population would likely be slow (Wallace 1990, Poff and Hart 2002). Following other dam removals, large quantities of sediment have been reported to smother downstream mussels (Sethi et al. 2004). Moreover, mussels that survived the dam removal would experience decreased growth rates as food and temperature conditions became more uniform along the stream gradient.

Jones Mill Dam has been in its current position for ~175 years (Gangloff et al. 2009a). During this period, it is possible that population genetics in the three reaches are influencing mussel response to local environmental conditions. It would be interesting to perform a reciprocal transplant experiment using juvenile mussels cultured from each reach to determine whether each population has a similar response to the impoundment. Use of juveniles would allow examination of growth differences between sites at early life stage. Most authors consider the early life stage to be a major limiting factor in mussel population dynamics and persistence because the smaller, or younger, a mussel the higher the chance of mortality (Villella et al. 2004, Strayer 2008). Juvenile and adult mussels do not acquire food in the same ways as adults, so it is important to determinehow the dam affects all life stages (Vaughn and Hakenkamp 2001).

My data suggest that some dams may have heretofore undocumented benefits for freshwater mussels immediately downstream of the mill pond. Positive effects of small dams should be thoroughly explored during the process of evaluating their suitability for removal projects. Restoration of a deteriorating mill dam may, in some cases, be a better management option for some taxa when deciding between removal or restoration, especially if large aggregations of imperiled mussels are present immediately downstream. Although dam removals will always offer the benefits of increased ecosystem connectivity and function for some groups of organisms, these benefits are not universal. Careful vetting of both positive and negative impacts of removal projects is critical to effective management of imperiled aquatic taxa.

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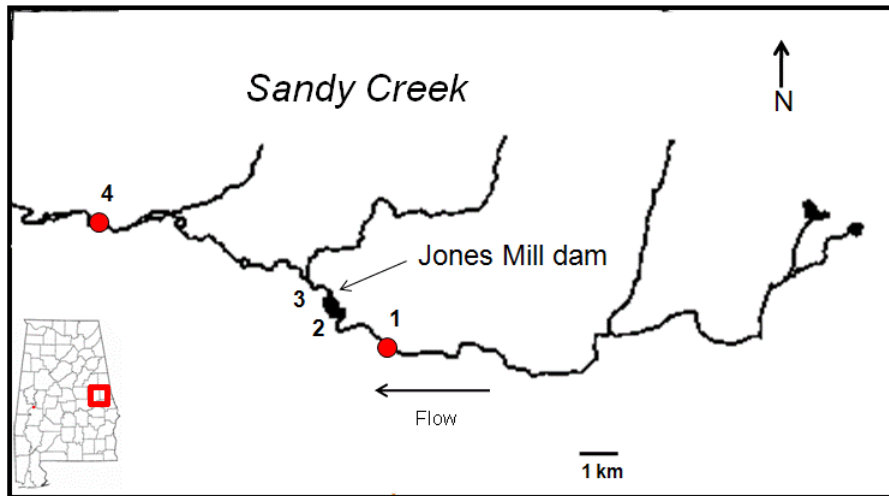
Figure 1. Location of (1) upstream, (2) impoundment, (3) mill, and (4) downstream study reaches in relation to Jones' (Stephen's) Mill Dam, Chambers County, Alabama. Inset map shows area of detail in East-central Alabama.

Figure 2. Drawing of *Elliptio arca* by Erin E. Singer. The white line depicts where the initial cut is made for thin section preparation (axis of maximum growth).
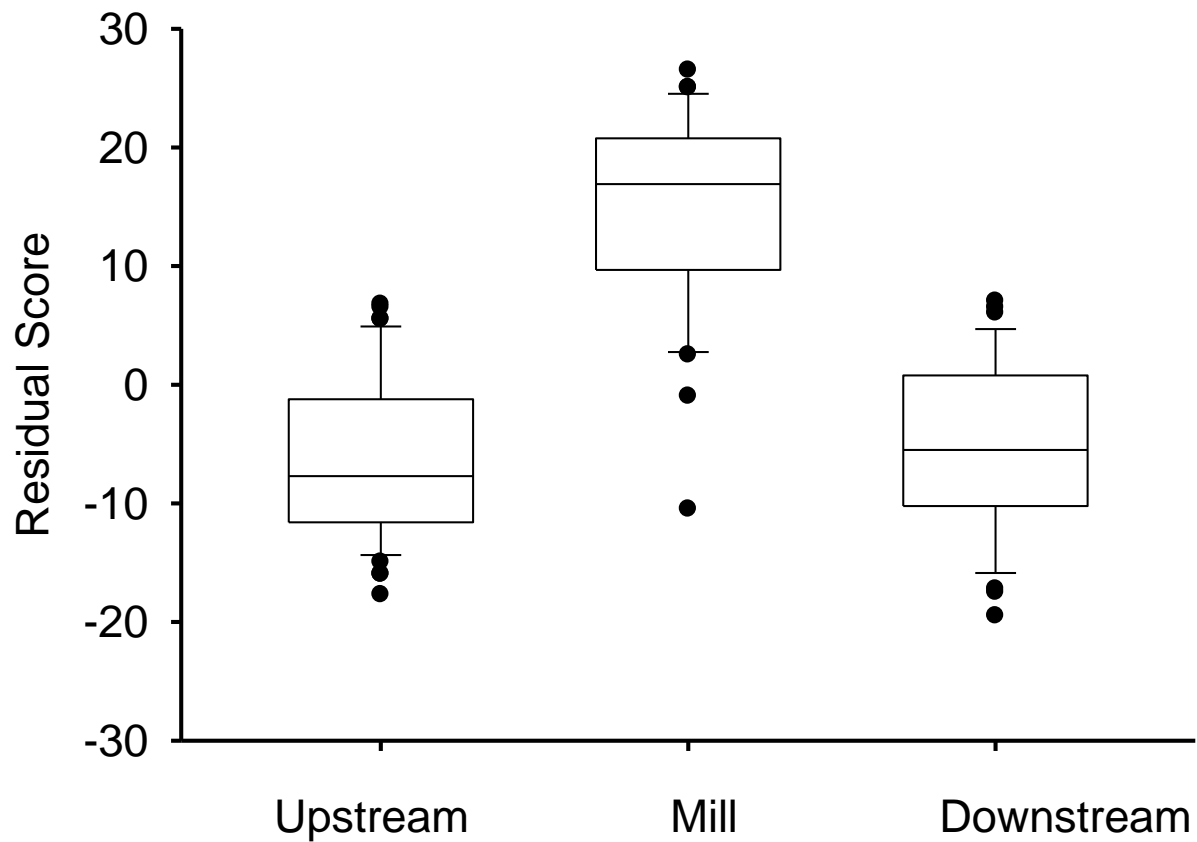
Figure 3. Residuals from a linear regression of length-at-age data from *Elliptio arca* from the upstream, mill, and downstream reaches of Sandy Creek, Chambers Co., AL. The line within the box marks the median, the boundaries of the boxes indicate the 25th and 75th percentiles, respectively, and the error bars above and below the boxes indicate the 90th and 10th percentiles.

Figure 4. Observed mean length-at-ages between 4 and 7 (a-d, respectively) of *Elliptio arca* from the upstream, mill, and downstream reaches of Sandy Creek, Chambers Co., AL. Computed ANOVA values for ages 4-7 are ($F_{2,20} = 4.335$, $p = 0.029$), ($F_{2,30} = 41.491$, $p < 0.0001$), ($F_{2,37} = 63.753$, $p < 0.0001$), and ($F_{2,21} = 50.512$, $p > 0.0001$), respectively. The line within the box marks the median, the boundaries of the boxes indicate the 25th and 75th percentiles, respectively, and the error bars above and below the boxes indicate the 90th and 10th percentiles.
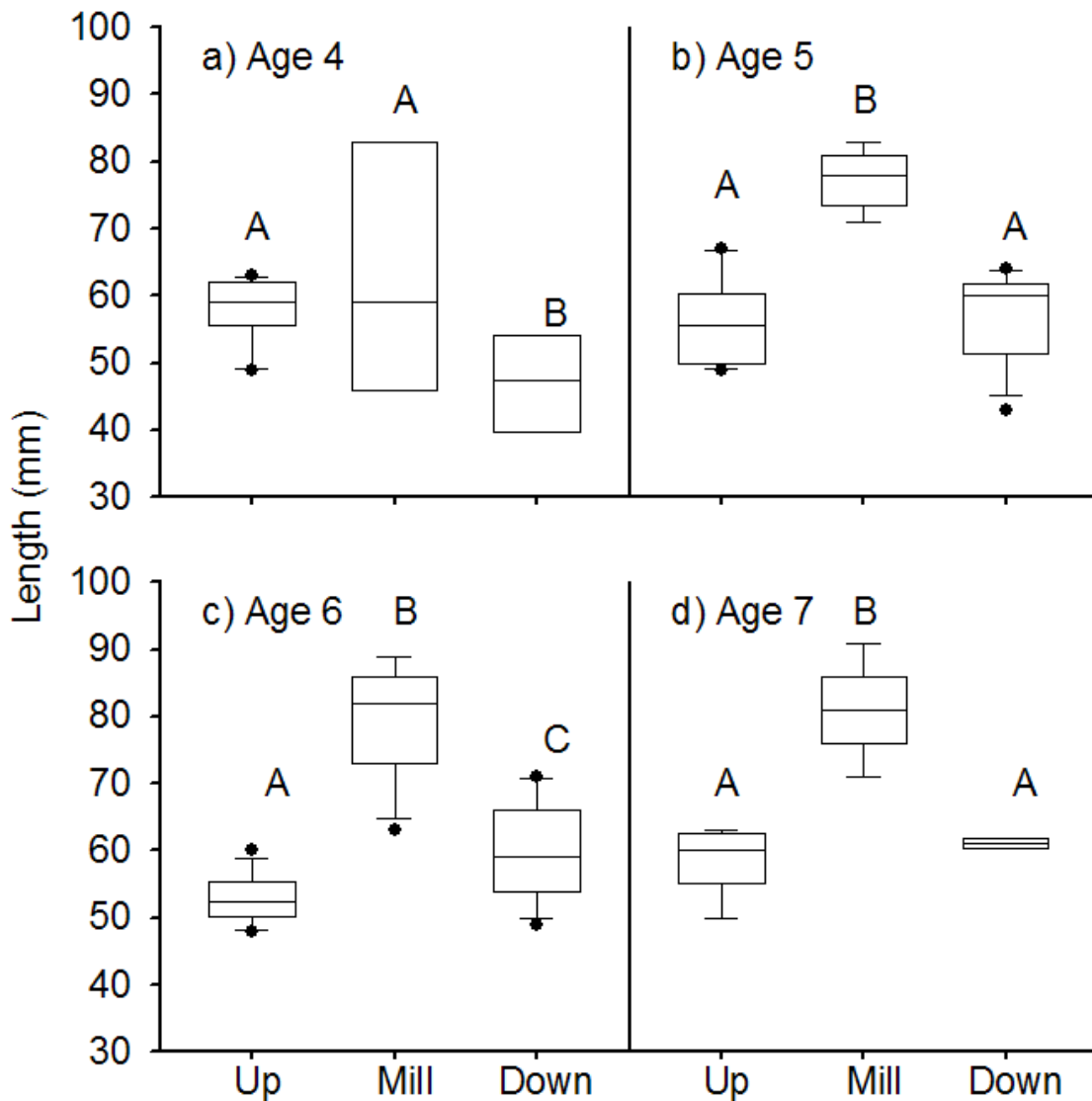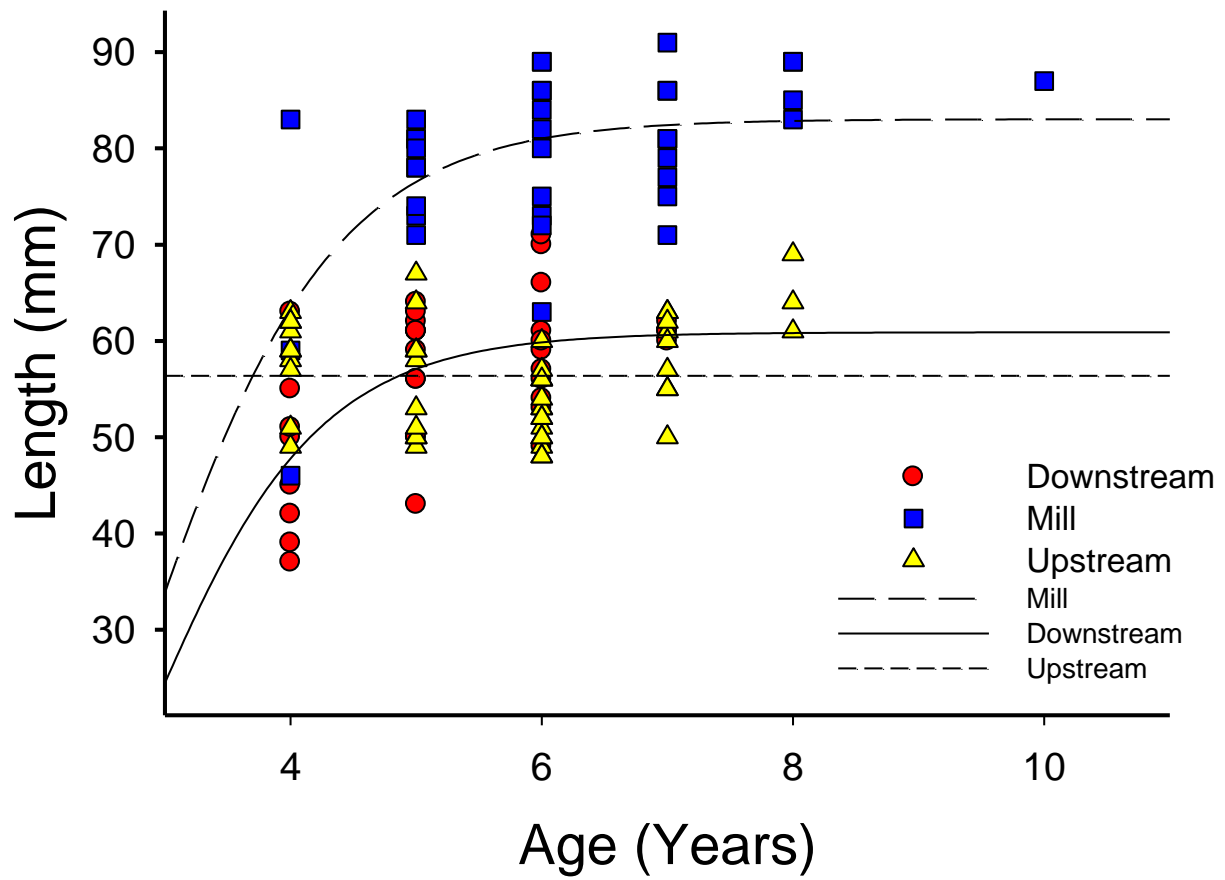
Figure 5. Length-at-age data with fitted curves from mussels in the upstream, mill, and downstream reaches of Jones Mill Dam on Sandy Creek, Chambers Co., AL.

Table 1. Length-at-age growth model parameters for *Elliptio arca* populations from the upstream, mill, downstream reaches, and all reaches together from Sandy Creek, Chambers Co., AL.

Model	Site	p	r^2	F
Linear	All	0.0001	0.186	27.589
	Upstream	NS		
	Mill	NS		
	Downstream	0.001	0.286	13.186
Logarithmic	All	0.0001	0.165	23.289
	Upstream	NS		
	Mill	NS		
	Downstream	0.001	0.307	14.651
Quadratic	All	0.0001	0.175	12.385
	Upstream	0.0001	0.296	9.47
	Mill	NS		
	Downstream	0.001	0.344	8.398
Compound	All	0.0001	0.174	24.802
	Upstream	NS		
	Mill	NS		
	Downstream	0.001	0.295	13.789
Growth	All	0.0001	0.174	24.802
	Upstream	NS		
	Mill	0.002	0.248	11.529
	Downstream	0.001	0.295	13.789
Exponential	All	0.0001	0.174	24.802
	Upstream	NS		
	Mill	0.002	0.248	11.529
	Downstream	0.001	0.295	13.789
Logistic	All	0.0001	0.174	24.802
	Upstream	NS		
	Mill	0.002	0.248	11.529
	Downstream	0.001	0.295	13.789
von Bertalanffy	All	NS		
	Upstream	NS		
	Mill	0.001	0.948	
	Downstream	0.0006	0.998	
Morgan-Mercer-Flodin	All	NS		
	Upstream	NS		
	Mill	NS		
	Downstream	NS		
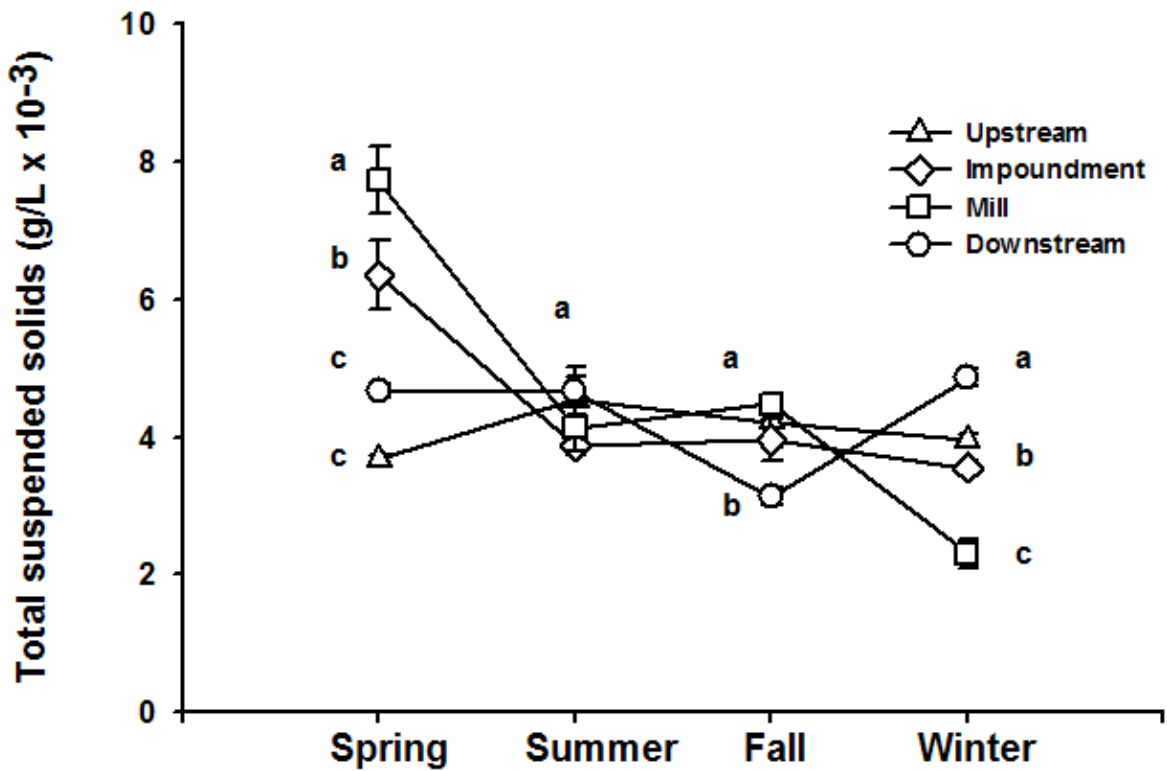
Figure 6. Concentrations of total suspended solids (TSS) g/L x 10^{-3} measured from water column samples collected from Sandy Creek, Chambers Co., AL during spring, summer, fall 2009 and winter 2010 at sites upstream, within, immediately downstream, and ~5 km downstream from Jones Mill Pond. Within-seasons, site means with the same letters are not significantly different from one another. We did not compare sites between seasons due to a significant interaction between site and season. The symbol marks the mean and the error bars indicate standard error.

Figure 7. Organic to inorganic ratio (O:I) measured from water column samples collected from Sandy Creek, Chambers Co., AL during spring, summer, fall 2009 and winter 2010 at sites upstream, within, immediately downstream, and ~5 km downstream from Jones Mill Pond. Within-seasons, site means with the same letters are not significantly different from one another. We did not compare sites between seasons due to a significant interaction between site and season. The symbol marks the mean and the error bars indicate standard error.
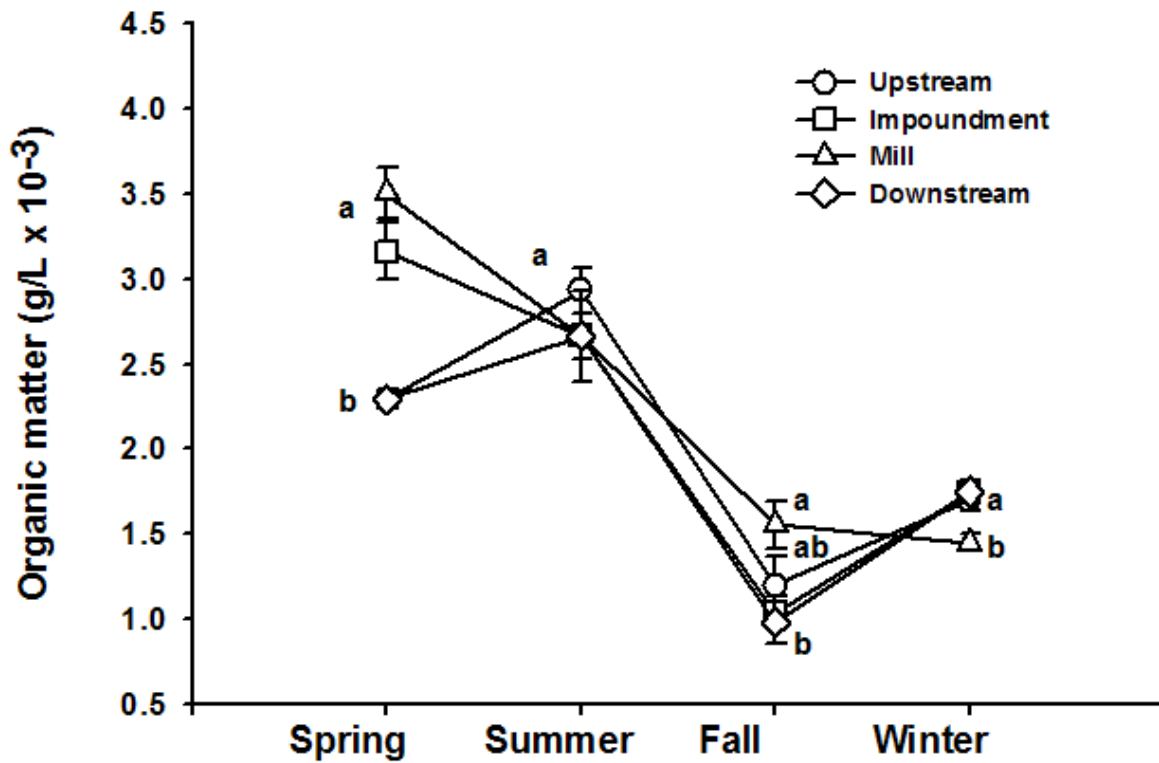
Figure 8. Concentrations of organic suspended material (OM) g/L x 10^{-3} measured from water column samples collected from Sandy Creek, Chambers Co., AL during spring, summer, fall 2009 and winter 2010 at sites upstream, within, immediately downstream, and ~5 km downstream from Jones Mill Pond. Within-seasons, site means with the same letters are not significantly different from one another. We did not compare sites between seasons due to a significant interaction between site and season. The symbol marks the mean and the error bars indicate standard error.
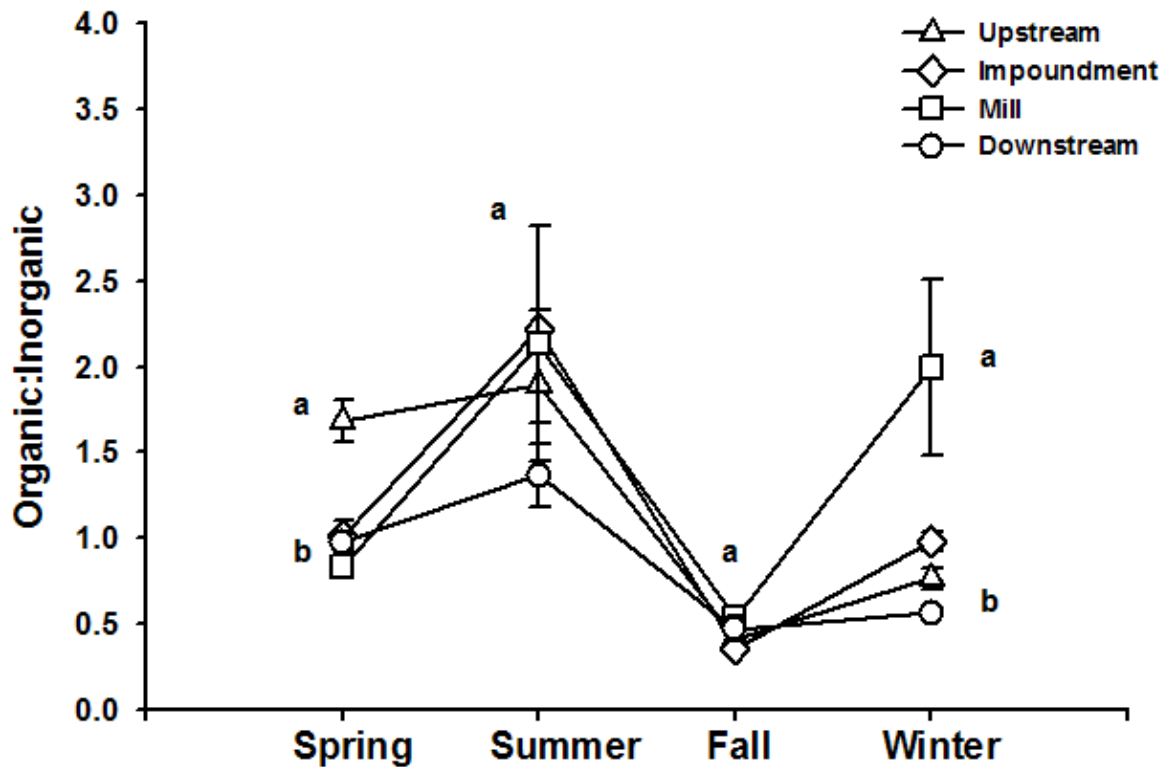
Figure 9. Concentrations of inorganic suspended material (OM) g/L x 10^{-3} measured from water column samples collected from Sandy Creek, Chambers Co., AL during spring, summer, fall 2009 and winter 2010 at sites upstream, within, immediately downstream, and ~5 km downstream from Jones Mill Pond. Within-seasons, site means with the same letters are not significantly different from one another. We did not compare sites between seasons due to a significant interaction between site and season. The symbol marks the mean and the error bars indicate standard error.
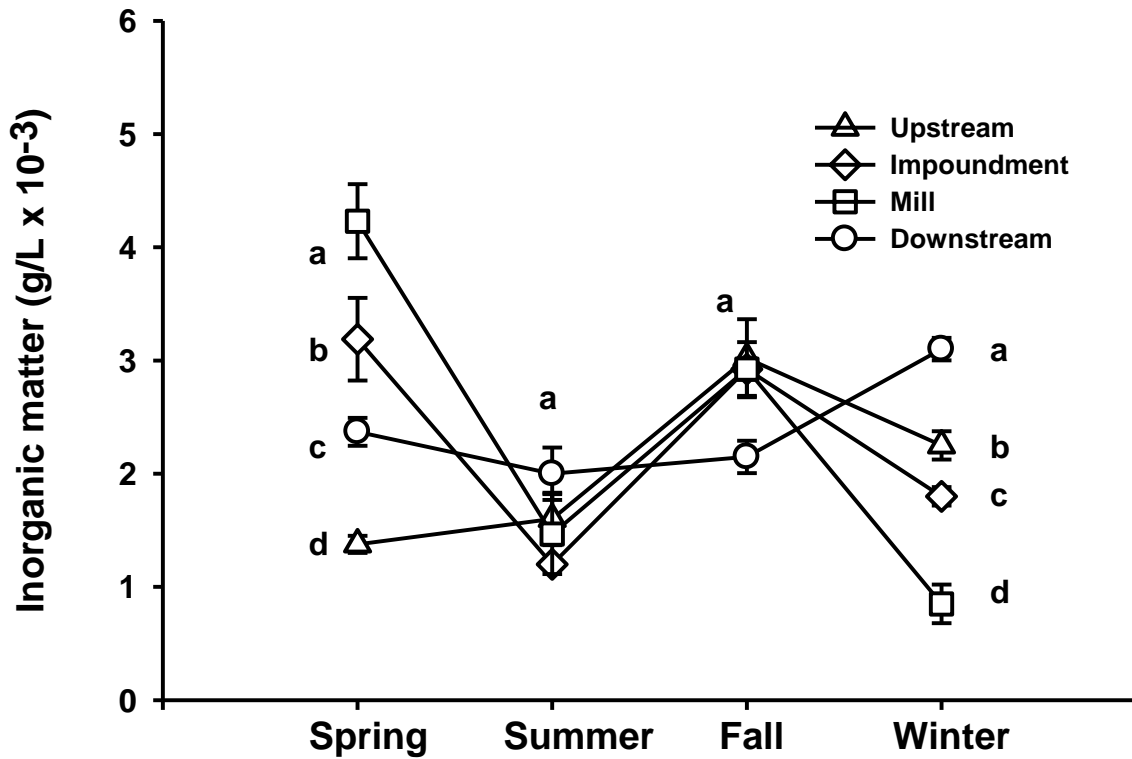
Table 2. Nutrients from the water column collected seasonally (March, June, and November 2009, and February 2010) from the upstream (UP), impoundment (IMP), immediately downstream of the mill dam (MILL), and downstream (DOWN) reaches in relation to Jones (Stephen's) mill dam on Sandy Creek, Chambers Co., AL.

| Season	Site	Ca	K	Mg	Al	As	Ba	B	Cd	Cr	Cu	Fe	Pb	Mn	Ni	P	Na	Zn	No3-N	EC	pH
Spring	UP	5.7	0.9	8.7				<0.1			<0.1	0.5		0.6			6	<0.1	0.3	0.051	7.22
Spring	IMP	5.2	0.9	7.1				<0.1			<0.1	0.4		0.3			6.2	<0.1	0.3	0.049	6.95
Spring	MILL	5.4	0.9	7.8				<0.1			<0.1	0.3		0.5			5.8	<0.1	0.3	0.049	7.02
Spring	DOWN	5.3	1	7.7				<0.1			<0.1	0.3		0.4			5.8	<0.1	0.3	0.049	6.94
Summer	UP	6.2	2.4	3.5	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	4.7	<0.1	1.1	3.3	<0.1	<0.1	<0.1	0.6	0.143	7.44
Summer	IMP	5.3	2.4	3.1	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	4.2	<0.1	0.9	3	<0.1	<0.1	<0.1	0.4	0.112	7.29
Summer	MILL	5.6	2.1	3.1	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	4.1	<0.1	1	2.8	<0.1	<0.1	<0.1	0.4	0.112	7.29
Summer	DOWN	5.4	2.1	2.8	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	3.1	<0.1	0.8	3	<0.1	<0.1	<0.1	0.3	0.104	7.31
Fall	UP	8.7	1.1	11.1	0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	2.1	<0.1	0.7	<0.1	<0.1	3.2	0.1	0.5	0.087	7.59
Fall	IMP	8	1.1	10.7	0.1	<0.1	0.1	0.1	<0.1	<0.1	<0.1	2.4	<0.1	0.2	<0.1	<0.1	3.2	<0.1	0.5	0.062	7.24
Fall	MILL	8.1	1.1	10.7	0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	2.2	<0.1	<0.1	<0.1	<0.1	3.1	<0.1	0.5	0.056	7.25
Fall	DOWN	7	1	9.6	0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	1.9	<0.1	0.8	<0.1	<0.1	3.3	<0.2	0.5	0.055	7.22
Winter	UP	4.8	1	7.2	0.7	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	1.8	<0.1	0.6	<0.1	<0.1	4.5	<0.1	0.3	0.068	7.06
Winter	IMP	5.4	1.2	7.3	0.7	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	2.2	<0.1	0.7	<0.1	<0.1	4.5	<0.1	0.2	0.056	6.92
Winter	MILL	5.5	1	7.3	0.7	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	2.1	<0.1	0.7	<0.1	<0.1	4.4	<0.1	0.2	0.043	7.02
Winter	DOWN	5.4	0.9	6.9	0.7	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	1.8	<0.1	0.5	<0.1	<0.1	4.7	<0.1	0.2	0.041	7.07

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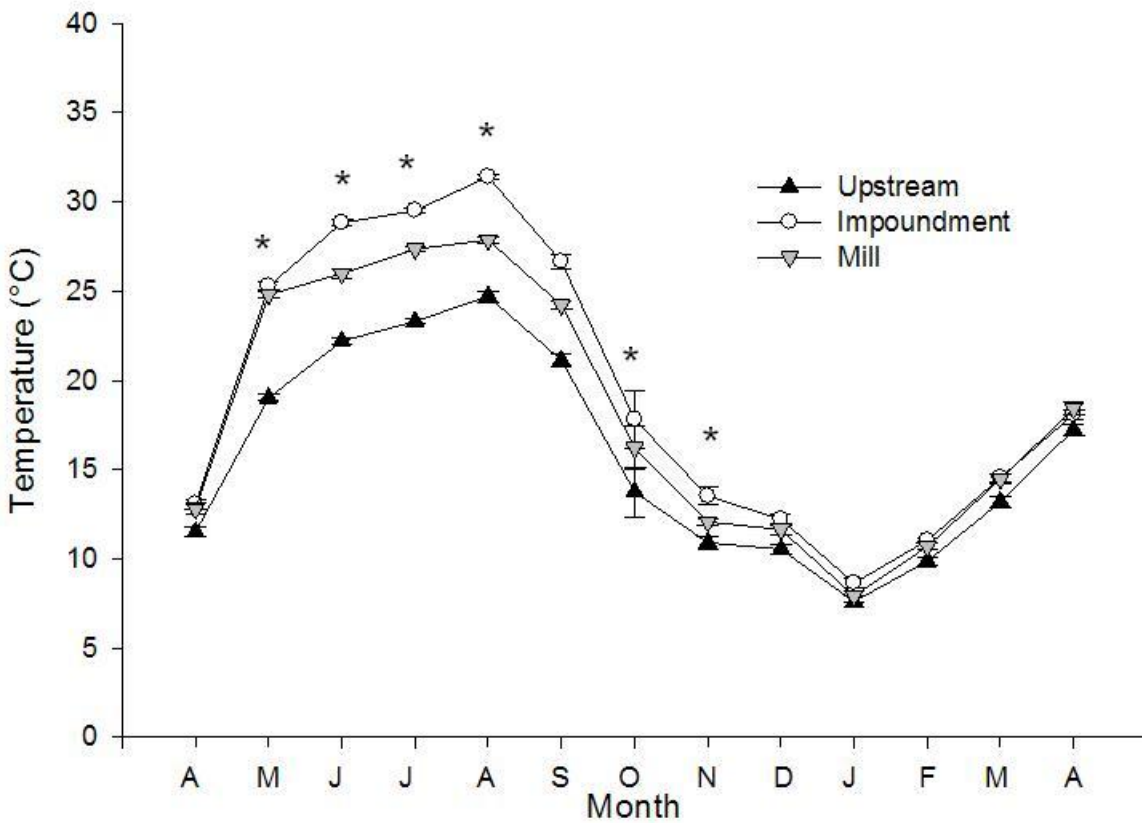
Figure 10. Temperature (˚C) means from each month from Sandy Creek, Chambers Co., AL from April 2007-2008 at sites located upstream, within the impoundment formed by, and immediately downstream from Jones (Stephens) Mill Dam. Months with the asterisks indicate that mean water temperature at all three sites were different from one another ($F > 11.0$, $p > 0.05$). The mill was warmer than upstream in all months except January.

BIOGRAPHICAL SKETCH

Erin Elizabeth Singer was born in Memphis, Tennessee, on February 28th, 1985. She attended elementary through high school in Memphis and graduated from Saint Agnes Academy in 2003. In the fall of 2003, Ms. Singer enrolled at Appalachian State University in Boone, North Carolina, to study biology and was awarded a Bachelor's of Science degree in 2007. Ms. Singer accepted a graduate assistantship in the Gangloff laboratory at Appalachian State University in the fall of 2008 and received a Master's of Science degree in biology in May 2010.

During her tenure at Appalachian State University, Ms. Singer was the founding president of the Boone local chapter of the North Carolina Wildlife Federation, PACT in the High Country. Ms. Singer's parents are Margaret Anne and James Frederick and her siblings are Brian James and Katherine Marie Singer.