MODELING THE VARIABLE EFFECTS OF LOW-HEAD DAMS ON FRESHWATER MUSSEL ASSEMBLAGES

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Honors Thesis

Appalachian State University

Submitted to the Department of Environmental Science

and The Honors College

in partial fulfillment of the requirements for the degree of

Bachelor of Science

December 2016

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Abstract

The widespread damming of lotic ecosystems is commonly associated with dramatic ecological effects such as decreased temperature, hypoxia, altered flow regime, physical changes to the structure of the river, and fragmentation of important habitats of stream organisms. However, the majority of the research that describes these negative effects was conducted on large-scale hydroelectric dams on large streams. Contrary to these studies, recent research suggests that the effects of intact low-head dams vary widely across taxa and may improve habitat conditions for some taxa, including native bivalves. The focus of this study was to examine a poorly understood phenomena that results in the formation of high-density mussel aggregations in the tailrace of some, but not all, low-head (<10 m) dams. I used mussel survey data from three 150-m reaches (tailrace, upstream, and downstream) for each dam site. These data were compared against a meta-database of dam features - structural height, hydraulic height, year built, length, upstream catchment area, stream order, depth/volume, elevation, forest cover - using a multivariate statistical analysis to determine the parameters most influential to this phenomenon. These results were used to inform the construction of a model meant to predict which low-head dams are likely to harbor high-density mussel aggregations. Currently dams are prioritized for removal based on funding and the logistical ease of the project. The results of this study may potentially inform improvements to best management practices for stream restorations with dam removal and benefit the regions' imperiled mussel populations.

ACKNOWLEDGEMENTS

This study was supported by the North Carolina Wildlife Federation. I would like to thank the following people for assisting me with my research: My committee, Dr. Michael Gangloff and Dr. Christopher Thaxton for guidance throughout my entire research and writing process. Worth Pugh and Dr. Alan Arnholt for guidance with statistical analyses. The ASU Aquatic Conservation Research Lab (ACRL) for assistance both in the field and in the lab. Finally, I wish to thank the members of the NCWRC and USFWS who provided me with invaluable data for my study.

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Introduction

The majority of major rivers in North America are affected by fragmentation by dams or reservoirs (Dynesius and Nilsson, 1994). Riverine habitats are among the natural systems most affected by human activity (Sala et al., 2000). One study estimates that there are over 2,000,000 dams in the United States alone (EPA, 1988). This widespread fragmentation stems from a historical need to control the movement of water for development, which dates back as far as 6000 BC when the Egyptians began diverting the flood waters of the Nile for irrigation (Goldsmith and Hildyard, 1984, Schnitter, 1994). Anthropogenic benefits of damming include hydropower generation, recreation, and navigation (Graf, 1999). However, this widespread fragmentation is associated with dramatic changes to environmental conditions in impounded and tailwater habitats including low dissolved oxygen, changes in water temperature (EPA 1988) and water chemistry, loss of upstream terrestrial and riparian habitats (Goldsmith and Hildyard, 1984) and altered sediment dynamics and geomorphology in reaches up- and downstream of dams (Csiki and Rhoads, 2010; Graf, 2006; Stanley and Doyle, 2002). These negative impacts have also been observed as they specifically relate to specific freshwater taxa, including freshwater mussel assemblages. Reservoirs are generally poor habitat for most freshwater mussels (Bates, 1962; Williams et al., 1992), and a study downstream of Norris Dam on the Clinch River, TN, found that mussels were extirpated from the dam tailrace and for a considerable distance downstream due to decreased water temperature and scouring effects of hydro-peaking flows (Cahn, 1936; Parmalee and Bogan, 1998).

Much of the prior research conducted to understand the negative impacts of dams on the riverine ecosystem was focused on large-scale hydroelectric dams that occur on 6^{th} order or higher streams (Gangloff, 2013). This has led to a widely accepted belief that all dams are injurious to the riverine ecosystem. Removal of dams in the United States is a popular stream restoration tool the number of small and large dams that have been removed has increased over in the last several decades (O'Connor et al., 2015; Bellmore et al., 2016). Benefits of these removals include increased connectivity and reintroduction of fish species to their native spawning grounds (Palmer et al., 2007). However, dam removals are not without potential impacts. Stanley et al. (2002) found deeper, narrower channels, and a greater concentration of fine particles and sand in reaches <500 m below a removed dam. American Rivers (2013) cites increased sediment deposition downstream as one of the major drawbacks of dam removal, and Sethi et al. (2004) found significant mussel mortality as a direct result of this increased sedimentation. It is also important to note that increased connectivity is not desirable in every situation. When planning for invasive species management, reduced connectivity allows for much easier and less costly management of invasive fishes and other motile aquatic taxa (Januchowski-Hartley et al., 2011).

Contrary to the well-studied impacts of large dams, recent research suggests that the effects of intact low-head dams vary widely across lotic taxa and may be a beneficial habitat for some groups including bivalves (Singer and Gangloff, 2011; Hoch, 2012; Holcomb et al., 2015). Freshwater mussels are a diverse but highly imperiled group of freshwater bivalves. Approximately 300 species in two families, Margaritiferidae and Unionidae are known to occur in the United States and Canada (Turgeon et al., 1998). The majority of this diversity in concentrated in the southeast U.S. (Lydeard and Mayden, 1995). Although few studies have been done to understand the roles that mussels play in freshwater ecosystems, Vaughn et al. (2004) found that, even at low densities, mussels are capable of overturning a large proportion of the water column. Freshwater mussels have a very complex life-cycle. Their larval stage, the glochidium, is parasitic. Male mussels release sperm into the water column, it is taken into the female, and fertilization occurs internally. Fertilized eggs are then released form the female and attach between spaces in the gills of fish where they mature into juvenile mussels and eventually drop off (Williams et al., 2008).

Of the 300 known species of freshwater mussel in North America, 71.7% are listed as endangered (Williams et al., 1993). Sedimentation, resulting from clearing of upland and riparian habitats as well as channel alteration and is believed to be one of the biggest causes of mussel declines (Ellis, 1936; Matteson, 1955; Way et al., 1989; Brim-Box and Mossa, 1999). Fine substrates are believed to inhibit mussel feeding and reproduction and individuals may succumb to hypoxia when they are covered by silt and unconsolidated sand (Watters, 1999). Because mussels are sensitive to habitat changes it is important to understand all factors influencing their distribution, positive and negative.

The phenomenon that results in high density mussel populations in the dam tailrace of some, but not all, low-head dams is poorly understood. Research attempting to explain this phenomenon has found that dams do not genetically isolate mussels (Abernethy et al., 2013), and that there is no significant relationship between the abundance of mussels and host fishes in tailrace habitats (McCormick, 2013). Previous studies have suggested that elevated food quality, relatively constant depth and velocity regimes, and higher dissolved oxygen levels in the tail-race may contribute to this phenomenon (Singer and Gangloff, 2011, Hoch, 2012). However, this phenomenon is not observed at all low-head dams, so these findings leave questions about its origin.

Variability in dam structure (composition, height) and placement in the watershed likely influence the response of stream habitats and tailrace mussel populations. The purpose of my study was to examine how the physical attributes of low-head dams influence mussel populations and to create a model of how these structures affect mussel populations.

Methods

Study sites

I obtained mussel survey data from 34 low-head (<10 m) dams in North Carolina and Alabama (Gangloff et al., 2009; Singer and Gangloff, 2011; McCormick, 2012; Table 1). The dams I analyzed were located in a range of physiographic provinces across the southeastern United States (Table 4).

Mussel Sampling

For each dam sampled, three study reaches were established: 1) a tail-race reach extending from the dam to 250 m downstream 2) a downstream control reach >500 m downstream of the dam, and 3) an upstream reach >500 m upstream (Gangloff et al., 2009; McCormick, 2012). The third site was selected in a free-flowing reach, above the effects of the impoundment. Mussels were collected through visual and tactile means, and searches were limited to reaches where snorkels could be used (<1 m). Mussels found were identified to species in the field and returned back to the stream. The upstream and downstream sites were free-flowing and selected to serve as control sites. Because I was not able to get into the field and sample the majority of these sites on my own, I relied on data gathered from previous studies including Hartfield (2010), McCormick (2012), agency (NCWRC, USFWS) reports from dam removal projects and Gangloff et al. (2009). Because mussel density and diversity generally increase with increasing stream order (Daniel and Brown, 2013) and water quality and habitat quality vary from stream to stream, the findings of these varied studies were normalized by calculating a response ratio for each dam. This allowed me to look solely at the effect the dam has on mussel populations in each stream and control for the different physical and landscape-scale attributes of each stream (Lajeunessei, 2011). The response ratio was calculated using the following equation:

$$R = \ln(\frac{M_d}{M_a}) \qquad (1)$$

Where M_d is the mussel CPUE or abundance of the tail-race region, and M_a is the average CPUE or abundance of the upstream and downstream reaches. The response ratio, R, results in a relative strength value of the mill-dam effect. A positive number indicates the presence of the effect and a negative number indicates that lower numbers mussels were found in the tail-race region of the dam than in the rest of the stream.

Dam and Stream Attributes

I obtained information on eight structural characteristics for each dam and the stream on which it was located. I determined percent forest cover, Structural height (ft), hydraulic height (ft), year built, length (m), mean site depth (m), link magnitude, and elevation by using the National Dam Database and GIS technology. I analyzed these variables to determine their independent and interactive influence on the response ratio. Both structural height and hydraulic height were most often recorded in state managed dam inventory databases (http://nid.usace.army.mil/cm_apex/f?p=838:4:0::NO) as was the year built. If the information was not available in those databases it was often recorded on historical society webpages, or in agency reports about dam removal projects. I measured length of the dam using google maps distance measurement tool (Google Maps 2016), and determined elevation using a web-based elevation finder tool (https://www.freemaptools.com/elevation-finder.htm). Mean stream depth was measured on-site during mussel surveys and US Geological Survey (USGS) topographic maps were used to compute link magnitude (the number of upstream 1^{st}-order tributaries) for all reaches. Link magnitude served as a proxy for stream size, discharge and upstream catchment area (Gordon et al., 2004). Upstream catchment area was calculated during previous studies using ArcMap, as was the percent forest cover (McCormick, 2012, Holcomb, 2014).

Data Analysis

I used spearman rank bivariate correlations to examine relationships between the mussel abundance response ratio and dam structural characteristics individually, and used the results of these correlations to inform a linear regression model. I carried out the bivariate correlation analysis in SPSS version 21 (IBM Corp., 2012) in the Windows 2016 environment.

Linear Regression ANOVA

I used linear regression analysis to assess the influence of each of the structural characteristics on the log response ratio of mussel abundance. This analysis allowed me to analyze the relationship between each of the dam parameters and mussel response ratio. I carried out the linear regression analysis in SPSS version 21 (IBM Corp., 2012) in the Windows 2016 environment. Thirty-four dams were included in my analysis along with their respective physical parameters. Missing data represent sites for which where the data were either not collected or do not exist (Table 1).

Results

Bivariate Correlation

The only physical parameter that showed a significant correlation with the log response ratio of mussel abundance was year built. As the year built increased, the log response ratio of mussel abundance decreased ($\rho = -0.500$, $n = 19$, $p = 0.029$, Figure 3). However, I also found a nearly significant and somewhat surprising positive relationship between mussel abundance and percent forest cover ($\rho = -0.432$, $n = 15$, $p = 0.108$, Figure 4). There were no significant relationships observed between mean site depth ($\rho = .089$, $n = 15$, $p = 0.753$), structural height ($\rho = 0.310$, $n = 10$, $p = 0.383$), hydraulic height ($\rho = 0.052$, $n = 9$, $p = 0.894$), dam length ($\rho = -0.015$, $n = 19$, $p = 0.950$), upstream catchment area ($\rho = 0.076$, $n = 10$, $p = 0.863$), elevation ($\rho = -0.378$, $n = 20$, $p = 0.100$), rank magnitude ($\rho = 0.119$, $n = 18$, $p = 0.638$) or link magnitude ($\rho = -0.018$, $n = 16$, $p = 0.946$, Figs 5-12, Table 2). A linear regression model, including year built and percent forest cover, and a randomly generated constant was not a significantly better (($p = 0.105$) predictor of tailrace mussel abundance than was year built alone (Table 3). Neither of the variables included in the model, percent forest cover ($p = 0.142$) and year built ($p = 0.129$) significantly informed the predictive model.

Discussion

Dams have varying effects on freshwater stream biota, and their effects on freshwater mussel assemblages are complicated. Many large dams have been observed to reduce water temperature, limit sediment movements, change the stream from a lotic to a lentic environment, and interrupt the migration of fishes (e.g., Ligon et al., 1993; Zedonis, 2001; Liermann et al., 2012). However, numerous studies have shown that when a stable mixture of sediment and gravel substrates and natural temperature and oxygen regimes are present, low-head dams (<10 m) may harbor high-density tailrace mussel aggregations (e.g. Gangloff et al., 2011; Haag, 2012; McCormick, 2012; Hornbach et al., 2014). Additionally, Singer and Gangloff (2011) found that the mussels in the tail-race region had higher growth rates than mussels in other areas of the stream.

In my study, mussel populations occurring at just over half of the sites analyzed exhibited a positive response to the presence of mill-dams. I attempted to identify physical parameters that predict the likelihood of this positive response and could be used to inform a predictive model. Year built had a statistically significant relationship with the mussel response ratio, and both percent forest cover ($p = 0.108$) and elevation ($p = 0.100$) showed near significant trends.

Watters (1993) found that in large streams, mussel diversity is correlated with fish diversity, but in smaller streams mussel diversity is related to drainage area. The majority of the dams I analyzed were located on smaller streams, so I expected to see a significant relationship between the upstream catchment area and the mill-dam effect. The correlation, however was relatively weak.

Rank magnitude, link magnitude, length, structural height, and hydraulic height did not exhibit a statistically significant relationship in a correlation with the mill-dam phenomena. All of these variables are strongly correlated with stream size (Hughes et al., 2011). Although stream size has been observed as a primary factor influencing mussel diversity in Michigan (Strayer, 1983; McRae et al., 2004) it appears that overall, stream size cannot be used to predict the presence of mussels in the tail-race region of a dam, and instead the phenomenon is present across a wide-variety of stream sizes. The majority of streams included in this study were 3rd to 6th order systems so it is possible that including dams on both smaller and larger streams in analyses would provide additional insights.

Gangloff et al. (2011) proposed that mill reach habitats may be unchanged from the conditions that existed at the time of dam construction, meaning that the natural stability of the stream is intact. This is important because stream stability is indicative of mussel suitability (Strayer and Ralley, 1993). I expected to see a stronger positive effect associated with older dams where tailrace habitats have had longer to stabilize. Very little is understood about the length of time it takes a stream to recover after a disturbance, but one study found that it takes riparian vegetation ~25 years to recover after the removal of a dam (Hasselquist et al., 2015), and another suggests that a stream will stabilize within months to years rather than decades (O'Connor 2010). However, neither of these studies defined "recovery" using biological indicators within the stream. Two recent studies, Gangloff et al. (2011)and McCormick (2012) both found that relict dams had the lowest abundance of mussels, suggesting that it takes a significant amount of time for biota to recover after dam removal. The negative significant relationship I observed between year built and the response ratio further indicates that it takes stream habitats longer than a few decades to stabilize, and a longer stabilization time is strongly correlated with higher abundances of mussels in the tail-race. My data suggests that even after 150-years, some streams may still be recovering from the effects of dam construction.

Although sediment limitation may lead to changes in mussel assemblages, fine sediments associated with urbanization and agriculture are generally considered to be bigger threats to freshwater systems (Ellis, 1936; Brim-Box and Mossa, 1999). Because dams impede downstream sediment movements, it is possible that one mechanism by which dams improve downstream habitat conditions is by limiting the export of fine sediments and or associated nutrients from developed or agriculturally-impacted watersheds (e.g. Kunz, 1898; Matteson, 1955; Clench, 1955; Way et al., 1989; Brim-Box and Mossa, 1999, Fairchild and Velinsky 2006). The fact that percent forest cover, and not the physical characteristics associated with stream size (i.e. height, length, upstream catchment area), showed a significant relationship with the response ratio suggests that dam effects may be most pronounced in streams with a high level of anthropogenically-derived sediments. As such, some low-head dams may be creating a small refuge for mussel populations in highly degraded systems.

Elevation, another physical characteristic associate with stream size, did show a near significant effect, but this may be due to a sampling bias. There are more extant dams at lower elevations, so the majority of my sample sites were located at elevations <500 m. The one site I have located at >1000 m appears to be driving this correlation, and when that point is removed from analyses, there is no longer a significant correlation between elevation and tailrace mussel response. Additional dams from intermediate and higher-elevation streams should be included in subsequent analyses but the low numbers of mussels in many of these streams may preclude effective resolution of this trend.

Because these physical dam and stream variables are generally not independent and interact dynamically in the natural world, I attempted to create a linear regression model to examine their additive effects. However, no multivariate models were better at explaining the response of mussels to dams than my univariate model (year built). This may be because the predictive power of multivariate models was limited by the fact that I only had a complete dataset for 13 dams. A more complete dataset may increase the predictive power of a multivariate model.

Ecosystem restoration is growing as both a science and an industry. As many dams become technologically obsolete or prove to be hazardous, dam decommissioning and removal has become increasing common and profitable (Doyle et al., 2008; O'Connor, 2015; Bellmore, 2016). Although removing dams is widely accepted as a way to improve stream habitat quality while restoring migratory fisheries and natural river function (American Rivers, 2013), dam removal is not without substantial impacts including the movement of large deposits of fine sediments from the impoundment or degraded upstream reaches downstream (Center, 2002). Release of sediment from impoundments has been shown to directly impact tailrace mussel populations (Stanley and Doyle, 2003; Sethi et al., 2004; Gangloff et al., unpublished data) and is suspected to be one of the reasons why breached and relict dams often have few mussels in their former tailraces (Gangloff et al., 2011; McCormick, 2012). Nationwide pre and post-removal habitat and biotic monitoring have been implemented for <10% of dam removal projects to date and the criteria used to determine success are inconsistent at best (Alexander and Allan, 2007; Bellmore, 2016). Of the restoration projects analyzed by Alexander and Allan (2007), 89% reported success, however only 11% of those projects were considered successful based on the response of specific ecological indicators. Additionally, most monitoring projects seldom last for >2 years, and most often focused on defining recovery in terms of simple stream geomorphologic responses (e.g., degree of sediment exported from the impoundment, re-establishment of floodplain benches/connectivity). Fewer than 10% of monitoring studies associated with dam removals examined potential effects on freshwater mussel populations (Bellmore, 2016).

When dam removal occurs it is imperative that management agencies require pre-removal surveys to identify whether there are mussels in the tailrace of the dam that may warrant more careful dam removal and that post-removal monitoring is conducted for a duration sufficient to document the future success of mussel populations in the restored reach. The time requited for mussels to recolonize tailraces downstream of restored dam sites is largely unknown, but Gangloff et al. (2011) and McCormick (2012), found that mussel abundances are lowest in the tail-race region of relict dams, suggesting that it takes a long time for streams to recover following a dam breaching. Heise et al. (2013) found that when adaptive dam removal procedures – including conducting restoration during the fall-winter and gradually drawing down water levels in the impoundment – were used, they appeared to minimize adverse effects on tailrace fish and mussels. Similar procedures should be followed for the removal of any dam with a dense tailwater mussel assemblage. My findings suggest that older dams and dams that occur in highly degraded watersheds should be considered low priority for removal because they are likely to support mussel aggregations and may be helping to control downstream sediment movements.

It is important to note that my results may be influenced by the patchy-nature of my data set, or by small sample size. Future research should focus on both compiling a larger, more robust, data set as well as incorporating substrate and water chemistry data to better understand this phenomena. Additionally parameters including mussel species richness, diversity, age class structure and host-fish assemblages should be included in models to better understand the interactions between small dams and native freshwater mussel population.

Appendix

Tables

Table 1. A list of the dams that were analyzed and their associated physical parameters.

	State	Structural Height (ft)	Hydraulic Height	Year Built	Length(m)	Upstream Catchment Area	Mean Site Depth	% Forest	Link Mag.	Elevation (m)
Calhoun Mill	SC				41.5					38
Orange-Alamance Lake Dam	NC	20	10	1968	29.65	205				180
Eno West Point Dam	NC	10			65.54					84
Kapps Mill	NC			1827	36.12					340
Carbonton Dam	NC	17	19	1922	38.36					72
Franklin Dam	NC	26	35	1925	106.79					609
Dillsboro Dam	NC	12	12	1913	46.47					1759
Atkinson Millpond Dam	NC	12	10	1930	53.48	240				49
Lowell Mill	NC	17			22.57	85	0.426	34.94	743	40
Mayo Dam	NC	21	21	1898	141.27					179
Days Mill Dam	NC						0.305		153	133
Ward Mill	NC			1885	48.86		0.568			797
Laurel Mill	NC	15	11	1860	53.1	196.14	0.53	46.47	264	68
Wiggin's	NC	16	14		62.17	608.46	0.379	34.51	676	23
Jessup's Mill	NC	17.6	12.8	1755	47.49	273.7	0.533		329	296
Hamme's	NC	19	14	1750	56.37	140.37	0.56	58.94	184	71
Washington Mill	NC	21.6	13	1898	123	803.94	0.441	73.83	982	178
Gooch's	NC			1797		209.74	0.314	61.26	274	115
Lizard Lick	NC			1871	51.33	145.49	0.637	37.84	213	68
Lassiter Mill	NC		12	1805	60.24	24				63
Bellamy's Mill	NC			1859	58.77			62.85		27
Little Cahaba Mill	AL	7.01		1926	53.64		0.4561	55.40	14	137
Grants Mill	AL			1940	26.54		0.2233		24	147
Bean's Mill	AL			1834	43.83		0.1394	53.96	21	181
Old AL Power Mill	AL				37.89		0.3739	79.38	34	207
Meadows Mill	AL						0.1415	68.07	8	162
Macon's Mill	AL				35.17		0.3424	62.08	10	171
Fergusons Mill	AL				15.65		0.1809		41	170
Rikard's Mill	AL			1868	30			76.20		46
Boshell Mill	AL		10	1901	32.96					107
Shannon Mill	AL			1850	41.59			38.96	6	160
Jones' Mill	AL			1830	21.87			54.13		207
Masterson Mill	AL		5	1870	35.26			19.67		187

Table 2. Measures of significance for a bivariate analysis in SPSS. Each of the physical parameters of the dam or stream above the dam was compared to the mill-dam effect. Only the mean-site depth was linearly significant.

Parameter	Correlation with dam response ratio	
Structural Height	Correlation Coefficient	**.310**
	Sig. (2-tailed)	**.383**
	N	**10**
Year Built	Correlation Coefficient	**.052**
	Sig. (2-tailed)	**.894**
	N	**9**
Length	Correlation Coefficient	**-.500***
	Sig. (2-tailed)	**.029**
	N	**19**
Upstream Catchment Area	Correlation Coefficient	**-.015**
	Sig. (2-tailed)	**.950**
	N	**19**
Percent Forested	Correlation Coefficient	**.076**
	Sig. (2-tailed)	**.836**
	N	**10**
Mean Site Depth	Correlation Coefficient	**-.432**
	Sig. (2-tailed)	**.108**
	N	**15**
Rank Magnitude	Correlation Coefficient	**.089**
	Sig. (2-tailed)	**.753**
	N	**15**
Link Magnitude	Correlation Coefficient	**.119**
	Sig. (2-tailed)	**.638**
	N	**18**
Elevation	Correlation Coefficient	**-.018**
	Sig. (2-tailed)	**.946**
	N	**16**

Table 3. ANOVA of the linear regression model as analyzed in SPSS. As can be seen from the significance and F value, the model is near significant.

	Sum of Squares	df	Mean Square	F	Sig.
Regression	5.333	2	2.666	2.786	0.105
Residual	10.529	11	0.957		
Total	15.862	13			

Table 4. A table detailing the source of all mussel survey data I used. This data was mostly gathered via personal communication or published reports.

Dam Name	Drainage	Stream	Source
AL			
Rikard's Mill	Alabama	Big Flat Creek	AMDI 2009, Hartfield 2010
Boshell Mill	Black Warrior	Lost Creek	AMDI 2009, Hartfield 2010
Little Cahaba Mill	Cahaba	Little Cahaba River	AMDI 2009, Hartfield 2010
Grants Mill	Cahaba	Cahaba Creek	AMDI 2009, Hartfield 2010
Bean's Mill	Chattahoochee	Halawakee Creek	AMDI 2009, Hartfield 2010
Meadows Mill	Chattahoochee	Uchee Creek	AMDI 2009, Hartfield 2010
Fergusons Mill	Chattahoochee	Osinippa Creek	AMDI 2009, Hartfield 2010
Old AL Power Mill	Coosa	Hatchett Creek	AMDI 2009, Hartfield 2010
Shannon Mill	Coosa	Yellow Leaf Creek	AMDI 2009, Hartfield 2010
Macon's Mill	Tallapoosa	Loblockee Creek	AMDI 2009, Hartfield 2010
Jones' Mill	Tallapoosa	Sandy Creek	AMDI 2009, Hartfield 2010
Masterson Mill	Tennessee	Town Creek	AMDI 2009, Hartfield 2010
NC			
Carbonton Dam	Cape Fear	Deep River	Tim Savidge (NCWRC)
Franklin Dam	Little Tennessee	Little Tennessee River	NCWRC (PAWS)
Dillsboro Dam	Little Tennessee	Tuckaseegee River	USFWS
Orange-Alamance Lake Dam	Neuse	Eno River	Self -Sampled
Eno West Point Dam	Neuse	Eno River	Self- Sampled
Atkinson Millpond Dam	Neuse	Little River	NCWRC (PAWS)
Lowell Mill	Neuse	Little River	Tim Savidge (NCWRC)
Wiggin's	Neuse	Contentnea Creek	McCormick 2012
Lizard Lick	Neuse	Little River	McCormick 2012
Lassiter Mill	Pee-Dee	Uwharrie River	Gangloff et al. Unpublished
Mayo Dam	Roanoke	Mayo River	NCWRC
Jessup's Mill	Roanoke	Dan River	McCormick 2012
Laurel Mill	Tar-Pamlico	Sandy Creek	McCormick 2012
Hamme's	Tar-Pamlico	Fishing Creek	McCormick 2012
Gooch's	Tar-Pamlico	Tar River	McCormick 2012
Bellamy's Mill	Tar-Pamlico	Fishing Creek	McCormick 2012
Ward Mill	Watauga	Watauga River	McCormick 2012
Kapps Mill	Yadkin	Mitchell River	NCWRC (PAWS)

Figures

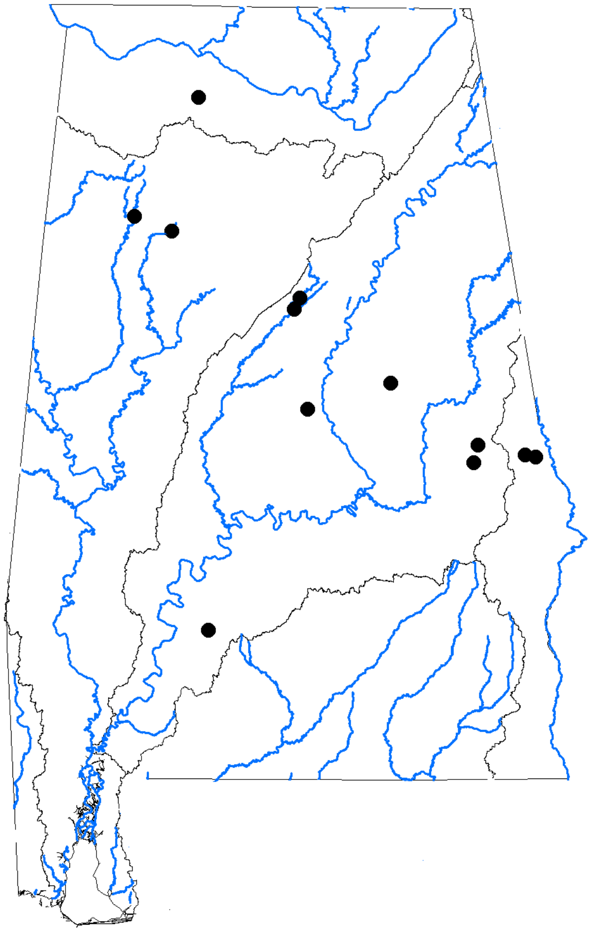

Figure 1. A map of the dam sites analyzed across Alabama. In Alabama one dam site was in the Alabama River Basin, 1 was in the Black Warrior River Basin, 2 were in the Cahaba River Basin, 3 where in the Chattahoochee River Basin, 2 were in the Coosa River Basin, 2 were in the Tallapoosa River Basin, 1 was in the Tombigbee River Basin, and 1 was in the Tennessee River Basin. The major rivers and river basins are also depicted.

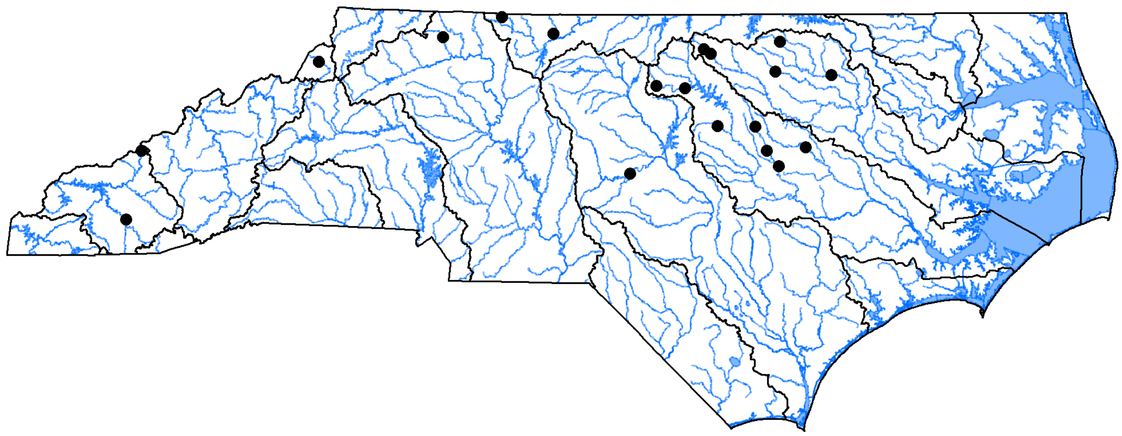

Figure 2. A map of the dam sites analyzed across North Carolina. In North Carolina one dam site was in the Cape Fear River Basin, 2 were in the Little Tennessee River Basin, 6 were in the Neuse River Basin, 1 was in the Pee- Dee River Basin, 3 were in the Roanoke River Basin, 5 were in the Tar-Pamlico River Basin, 1 was in the Watauga River Basin, and 1 was in the Yadkin River Basin. The major rivers and river basins are also depicted.

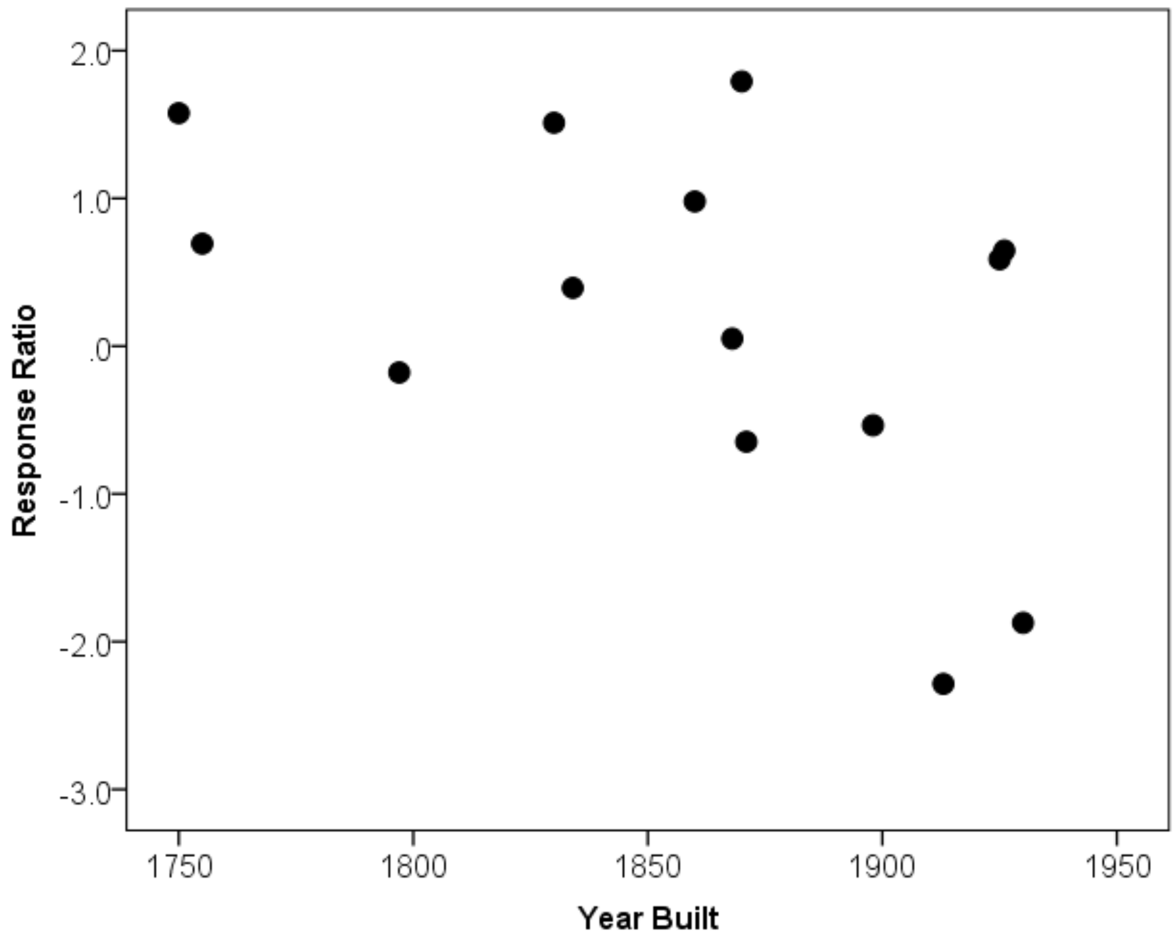

Figure 3. A graph of the correlation between mussel abundance response ratio and the year the dam was built. This correlation indicated a significant relationship (ρ = -.500, n = 19, p = 0.029), suggesting that the longer a stream has to stabilize after a disturbance, the more likely the tail-race region of a dam is to harbor mussels.

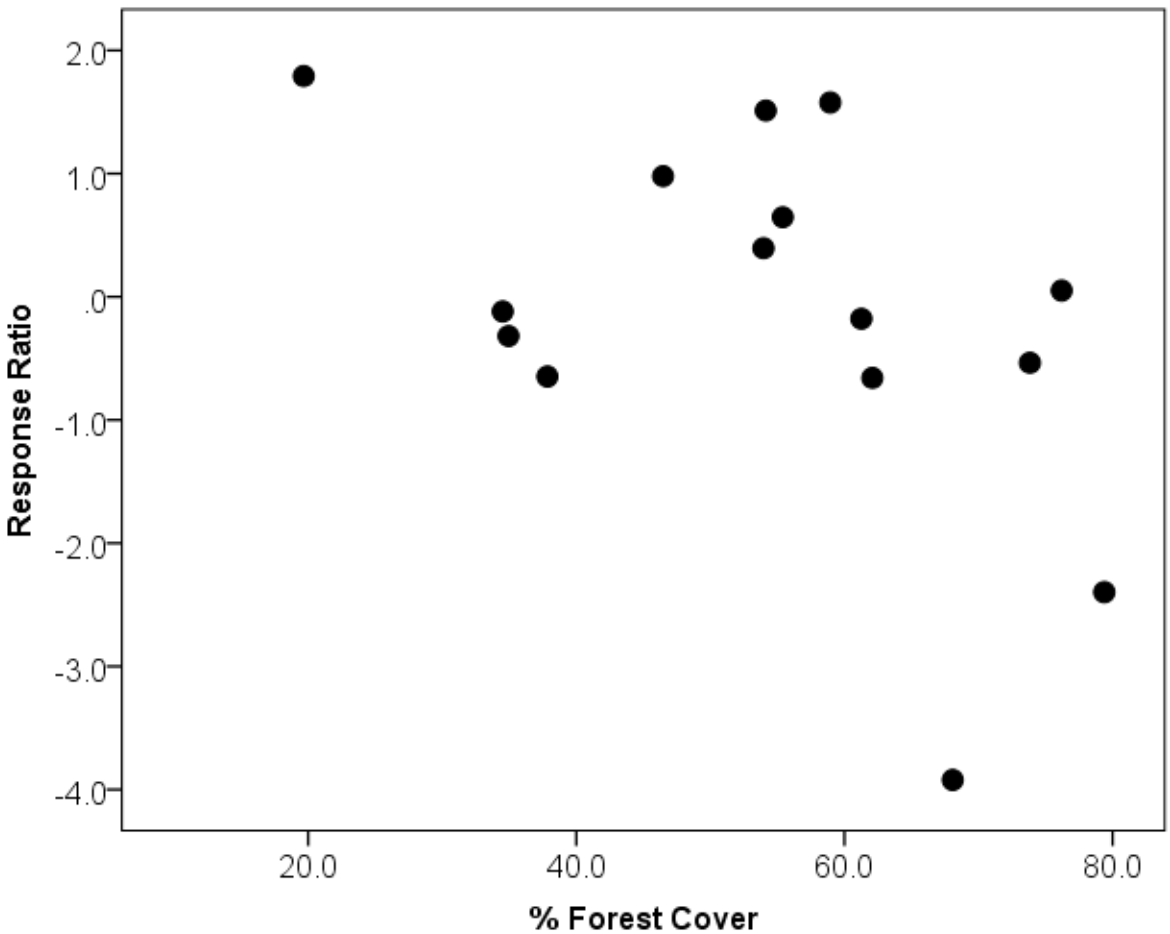

Figure 4. A graph of the correlation between mussel abundance response ratio and the % forest cover of the watershed where the dam is located. This correlation indicated a significant relationship (ρ = -0.018, n = 16, p = 0.946), suggesting that the lower the amount of forest cover in the watershed, the higher the abundance of mussels in the tail-race region of a low-head dam when compared to up and downstream sites.

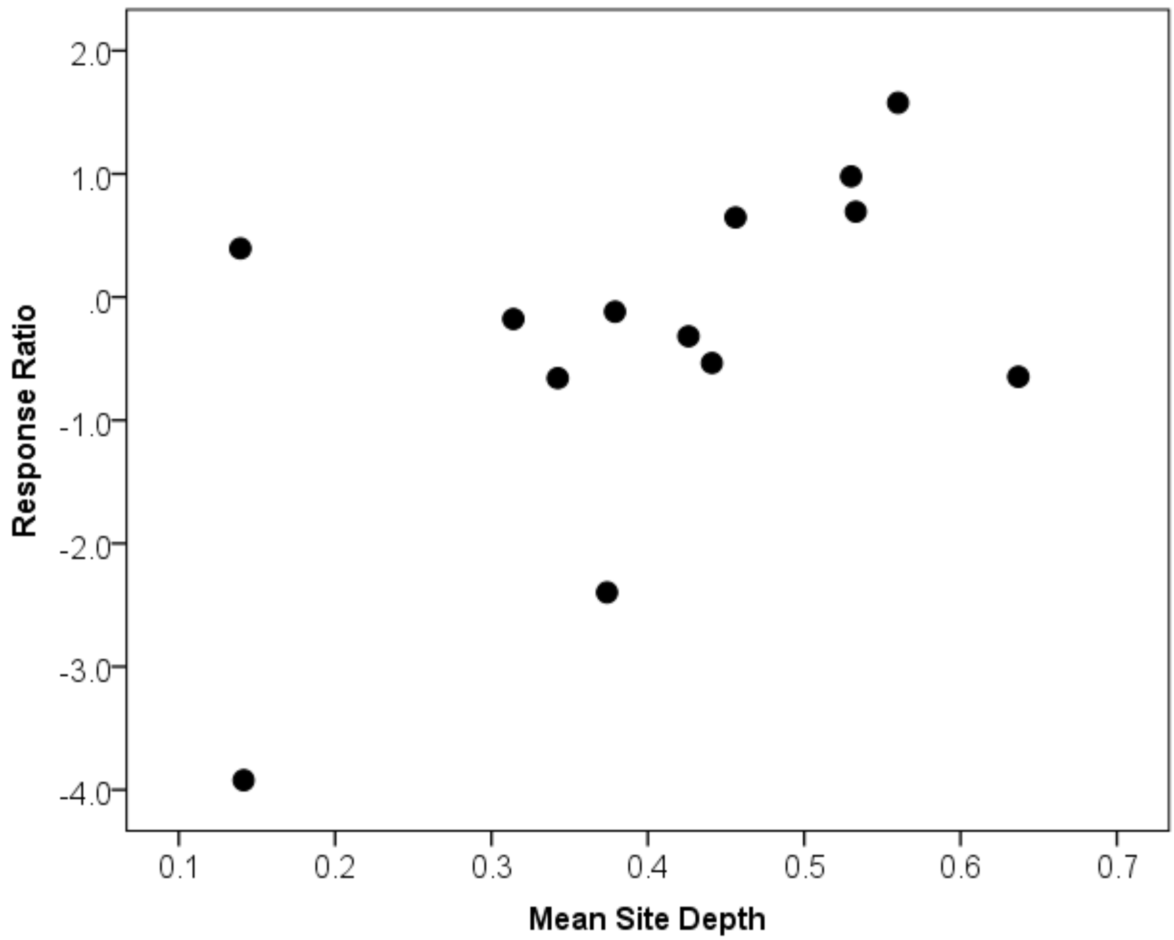

Figure 5. A graph of the correlation between the mussel abundance response ratio and the mean tailrace depth. This was the only significant correlation found with the mussel abundance response ratio (ρ = 0.089, n = 15, p = 0.753).

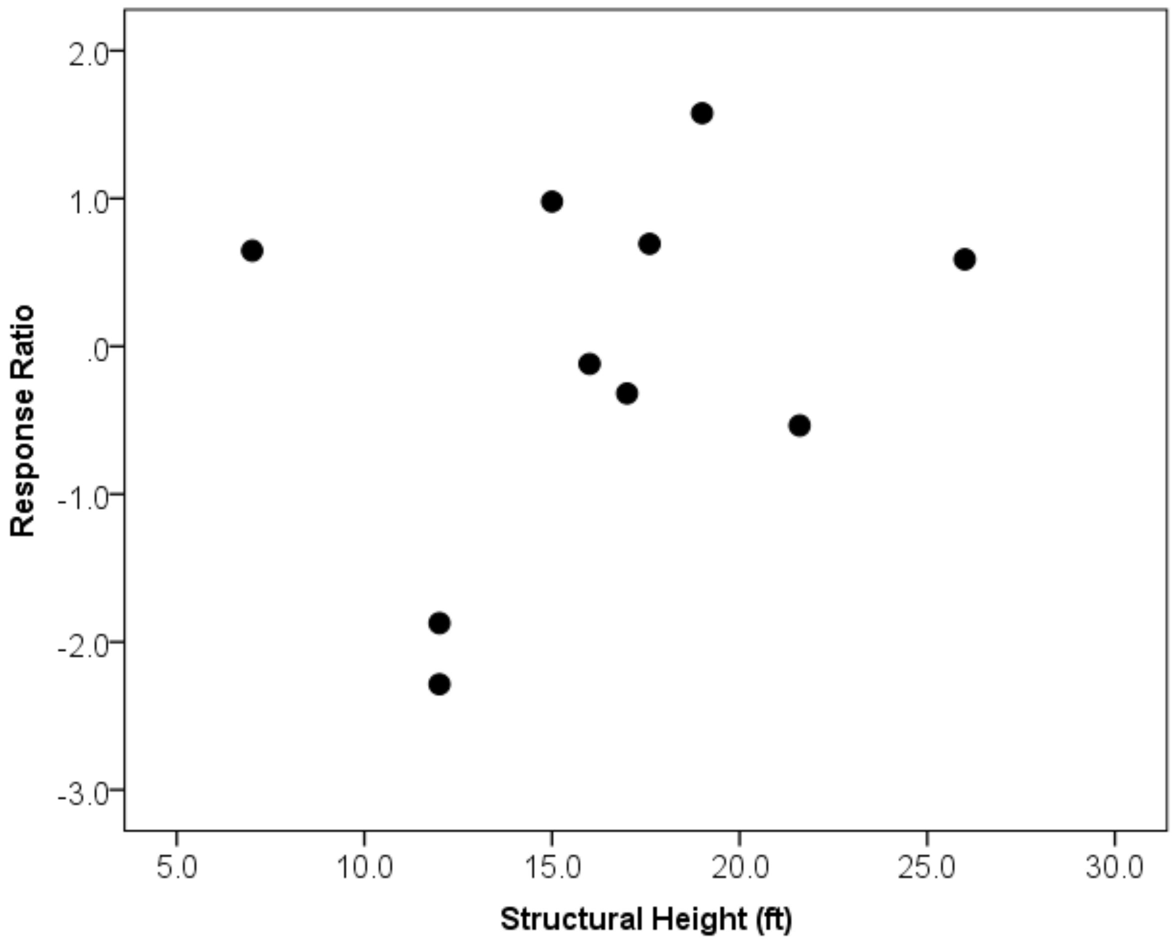

Figure 6. A graph of the correlation between mussel abundance response ratio and the structural height of the dam. This correlation did not indicate a significant relationship (ρ = 0.310, n = 10, p = 0.383).

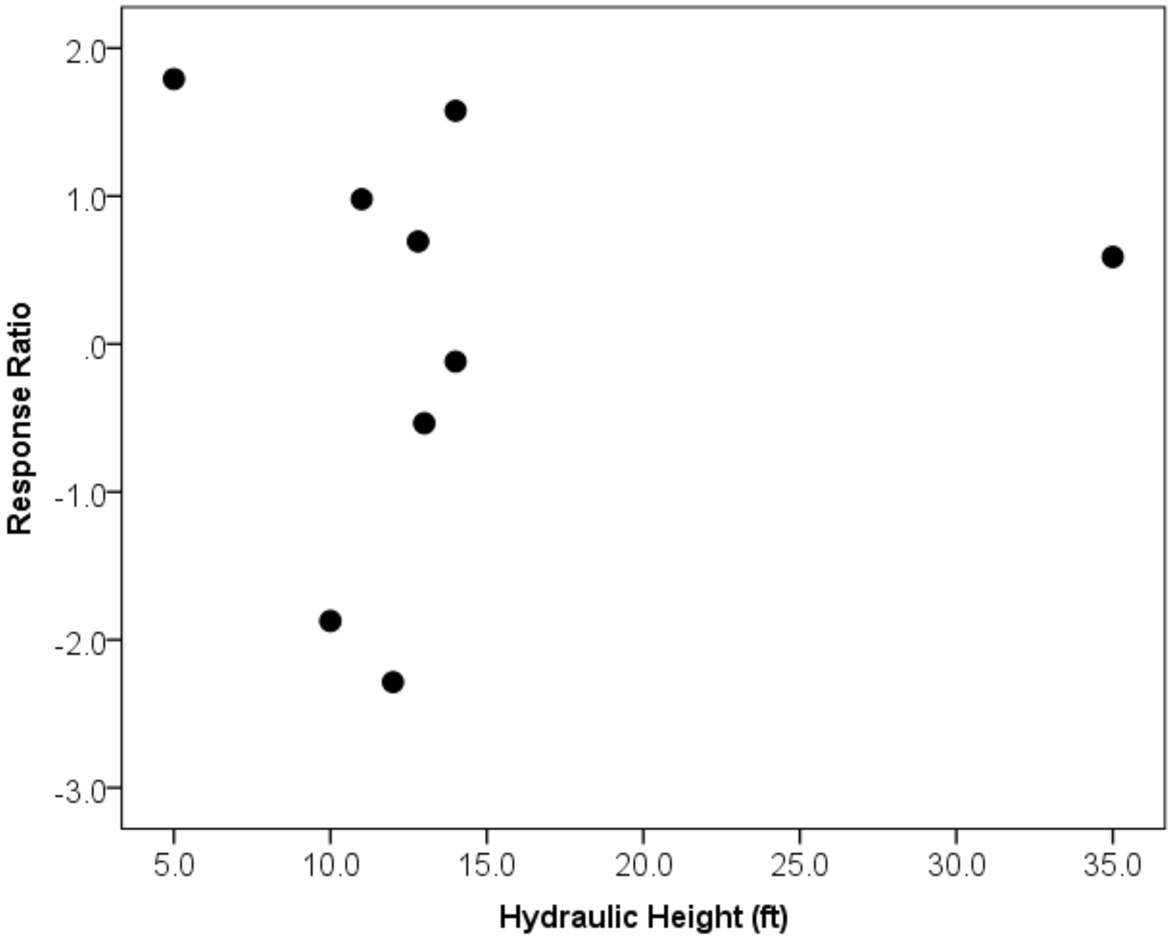

Figure 7. A graph of the correlation between mussel abundance response ratio and the hydraulic height of the dam. This correlation did not indicate a significant linear relationship (ρ = 0.052, n = 9, p = 0.894).

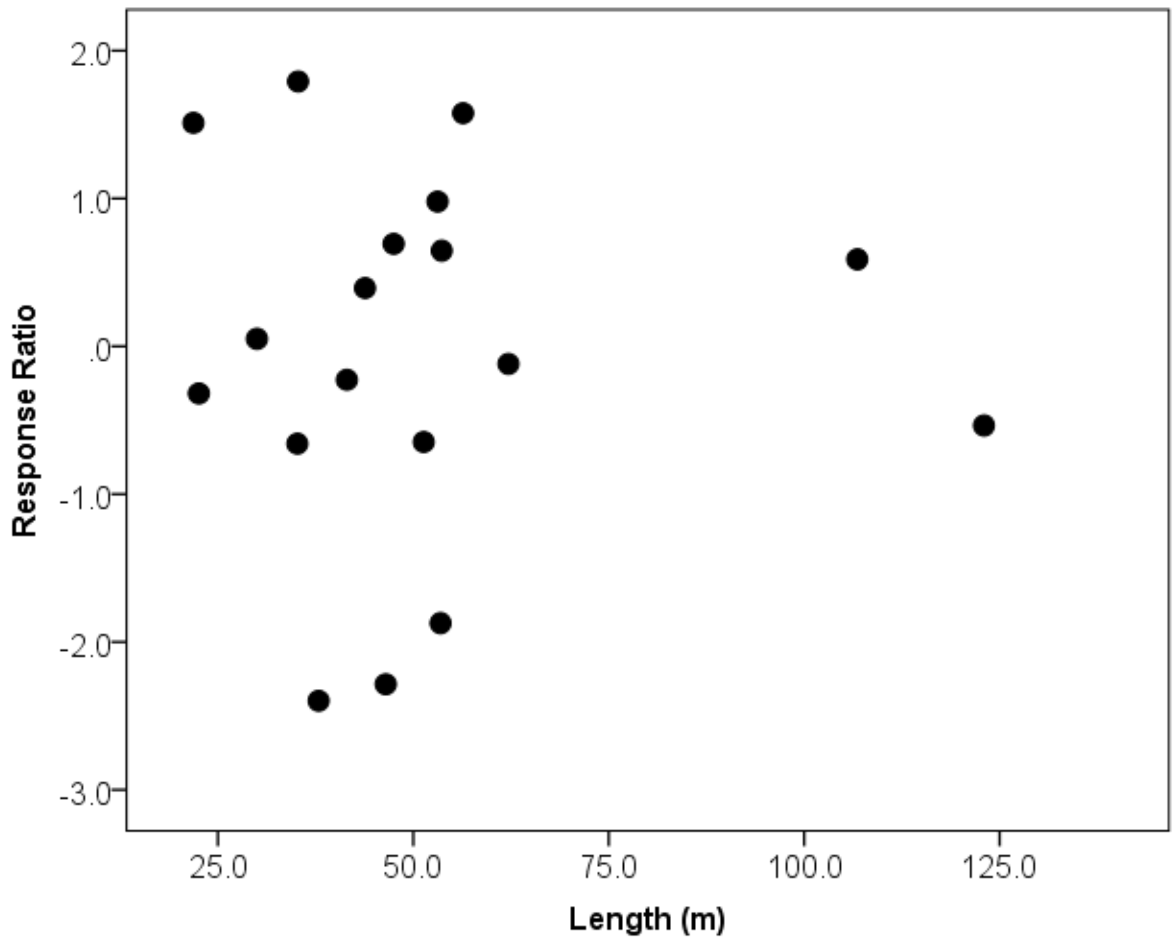

Figure 8. A graph of the correlation between mussel abundance response ratio and the length of the dam. This correlation did not indicate a significant linear relationship (ρ = -0.015, n = 19, p = 0.950).

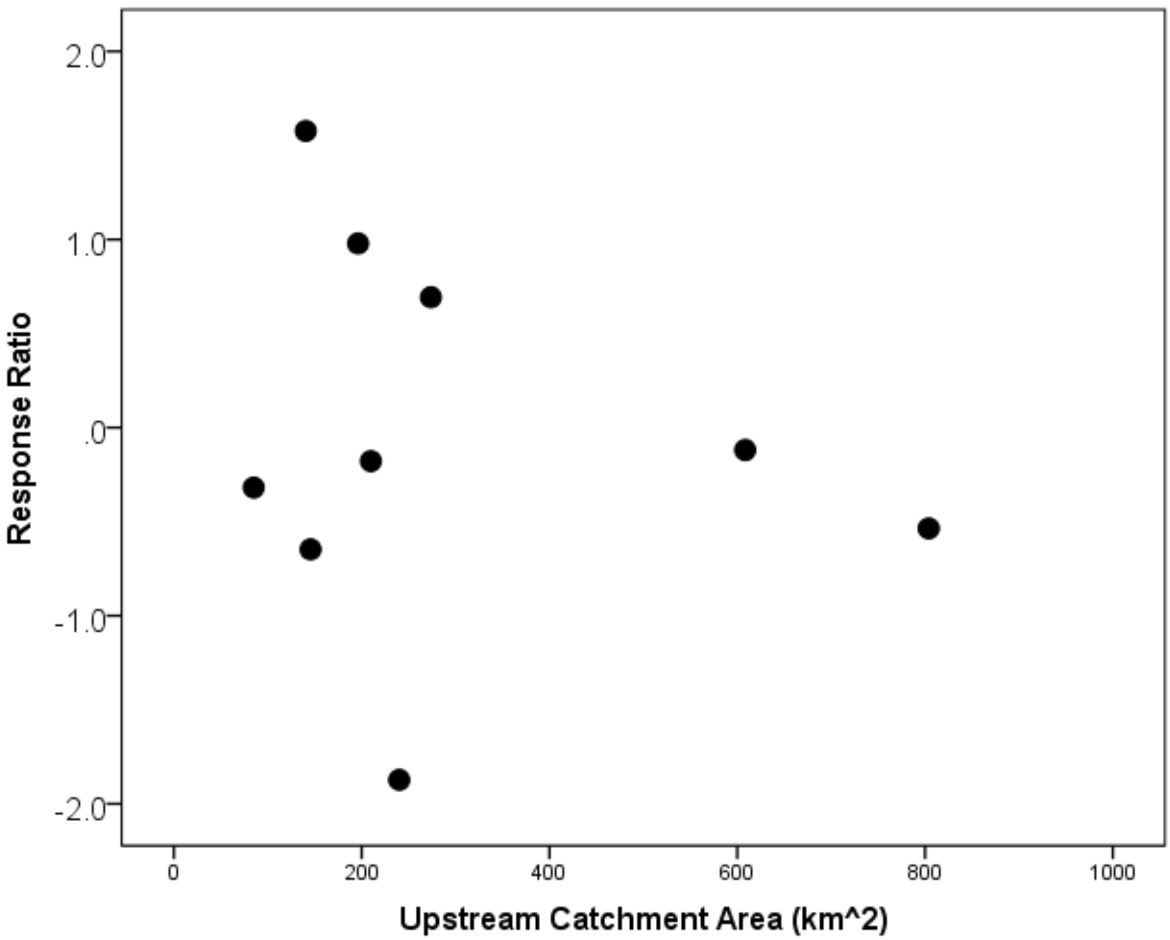

Figure 9. A graph of the correlation between mussel abundance response ratio and the upstream catchment area. This correlation did not indicate a significant linear relationship area ($\rho = -0.167$, $n = 9$, $p = 0.668$).

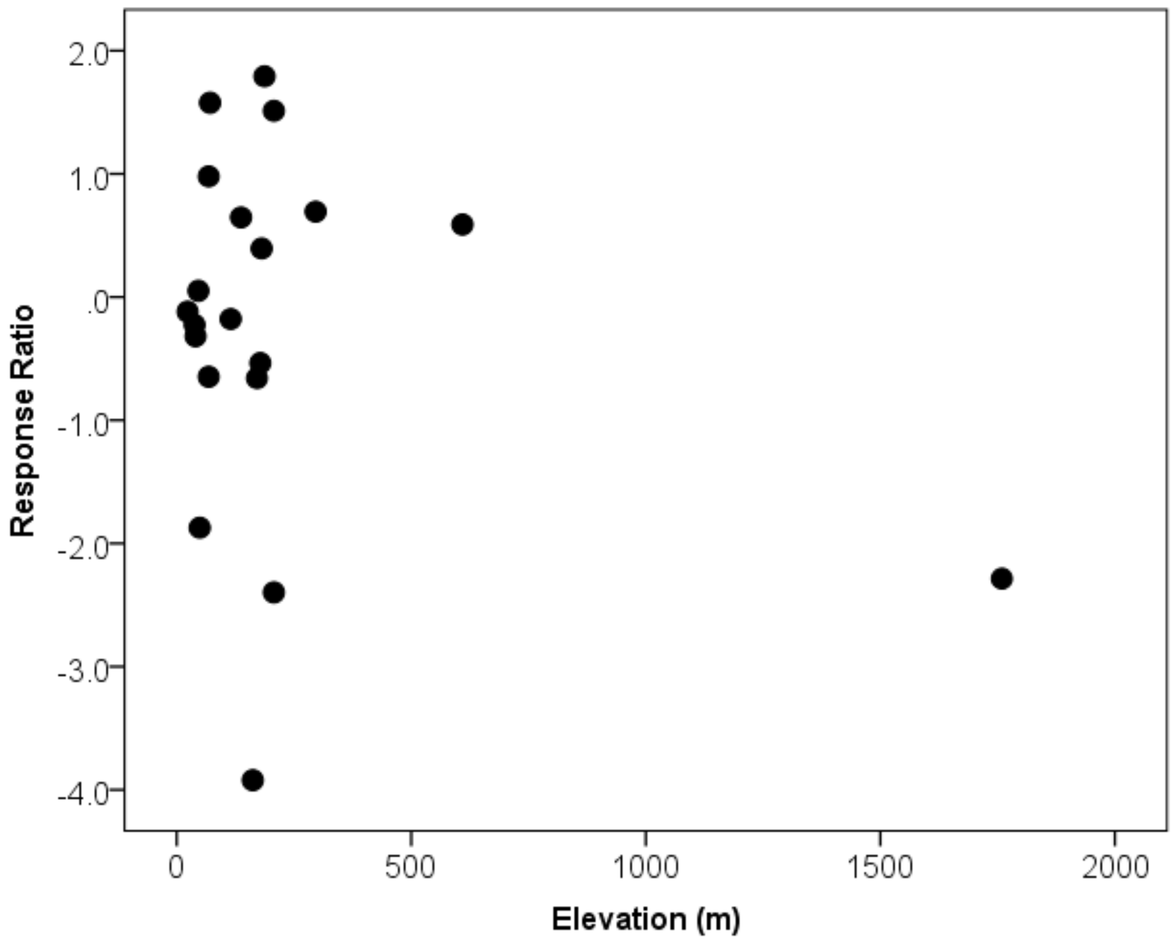

Figure 10. A graph of the correlation between mussel abundance response ratio and the year the dam was built. This correlation did not indicate a significant linear relationship (ρ = -0.378, n = 20, p = 0.100), it is clear that a great majority of the dams analyzed were located at <500m in elevation.

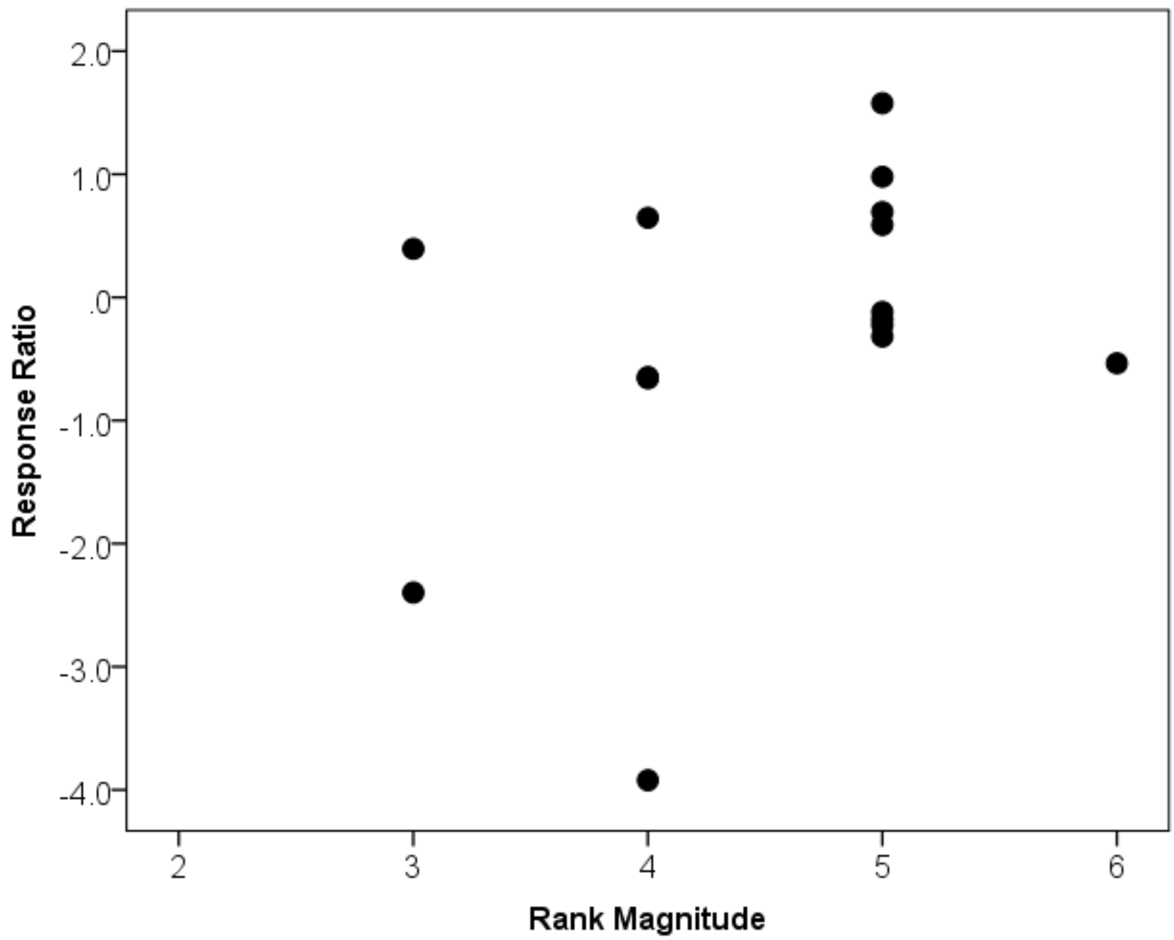

Figure 11. A graph of the correlation between mussel abundance response ratio and the rank magnitude of the stream the dam is located on. This correlation did not indicate a significant linear relationship (ρ = 0.119, n = 18, p = 0.638), likely because Rank Magnitude does not vary enough to predict differences in tail-race abundance.

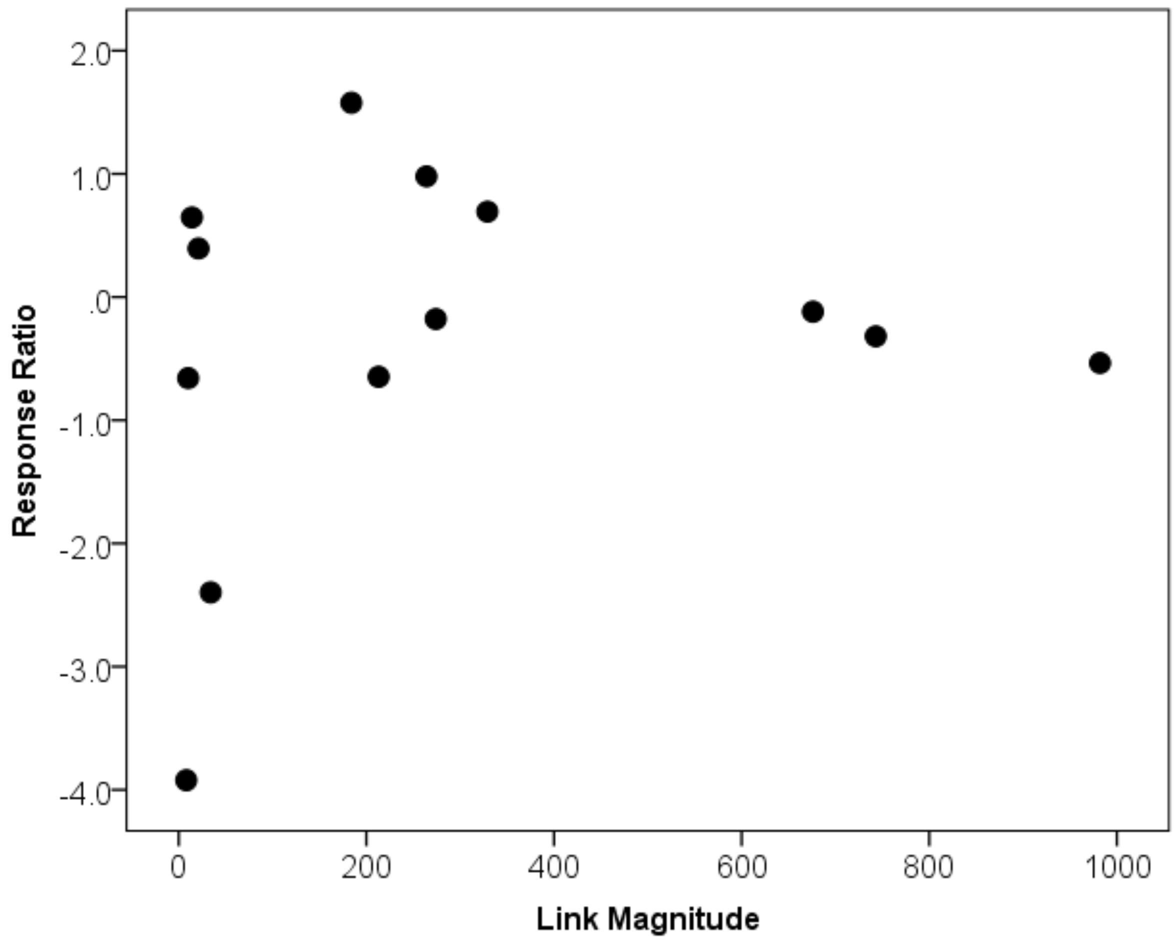

Figure 12. A graph of the correlation between mussel abundance response ratio and the year the link magnitude of the stream where the dam is located. This correlation did not indicate a significant relationship (ρ = -0.018, n = 16, p = 0.946).

REFERENCES

Abernethy E, McCombs E, Sieffermann L, and Gangloff M. (2013) Effects of small dams on freshwater mussel population genetics in two southeastern USA streams. Walkerana. 16 [1]:21-28.

Allan J D, Castillo M M. (1995) Stream Ecology: Structure and Function of Running Waters. London: Chapman and Hall.

American Rivers. NC River Restoration Updates. April 2013.

Alexander G G and Allan D J. (2007) Ecological Success in Stream Restoration: Case Studies from the Midwestern United States. Environmental Management. 40:245-255. DOI: 10.1007/s00267-006-0064-6

Bates J M. (1962). The impact of impoundment on the mussel fauna of Kentucky Reservoir, Tennessee River. The American Midland Naturalist. 68 [1]:232-236.

Bellmore J R, Duda J J, Craig L S, Greene S L, Torgersen C E, Collins M J, and Vittum K. (2016). Status and trends of dam removal research in the United States. Wiley Interdisciplinary Review: Water. DOI: 10.1002/wat2.1164.

Brim-Box J, and Mossa J. (1999). Sediment, land use, and freshwater mussels: prospects and problems. Journal of the North American Benthological Society. 18 [1]:99-117.

Clench W J. (1955). A freshwater mollusk survey of North Florida rivers. The Nautilis. 68 [3]:95-98.

Csiki S, and Rhoads B L. (2010) "Hydraulic and Geomorphological Effects of Run-of-river Dams." Progress in Physical Geography. 34 [6]: 755-80.

Doyle M W, Stanley E H, Havlick D G, Kaiser M J, Steinbach G, Graf W L, Galloway G E, Riggsbee J A. (2008) Aging Infrastructure and Ecosystem Restoration. Science. 319. DOI: 10.1126/science.1149852

Dynesius M and Nilsson C. "Fragmentation and flow regulation of river systems in the northern third of the world." Science. 1994 Nov 4; 266 [5186]:753-62.

Ellis M M. (1936). Erosion silt as a factor in aquatic environments. Ecology. 17 [1]:29-42.

Fairchild G W and Velinsky D J. (2006) "Effects of Small Ponds on Stream Water Chemistry." Lake and Reservoir Management. 22 [4]: 321-30.

Gangloff M M. (2013) "Taxonomic and ecological tradeoffs associated with small dam removals." Aquatic Conservation: Marine and Freshwater Ecosystems. 23 [4]: 475-480.

Gangloff M M, Hartfield E E, Werneke D C, and Feminella J W. 2011. Associations between small dams and mollusk assemblages in Alabama streams. Journal of the North American Benthological Society. 30 [4]:1107-1116.

Goldsmith, Edward and Nicholas Hildyard. (1984) *The Social and Environmental Effects of Large Dams.* Sierra Club Books. San Francisco, CA.

Map. *Google Maps*. Google, 2016. Web.

Gordon N D, McMahon T A, Finlayson B L, Gippel C J, and Nathan R J. (2004). Stream hydrology: an introduction for ecologists. 2nd edition. John Wiley and Sons. West Sussex, UK

Graf W L. (1999). “Damn nation: A geographic census of American dams and their large-scale hydrologic impacts.” Water Resources Research. 35 [4]: 1305-1311.

Graf W L. (2006). “Downstream hydrologic and geomorphic effects of large dams on American rivers.” Geomorphology. 79:336-360.

Haag W R. (2012). North American Freshwater Mussel Mussels: Natural History, Ecology, and Conservation. Cambridge University Press. Cambridge, UK.

Hartfield E E. (2010). Consequences of Low-head Dams on Crayfish Distribution and Gene Flow in Alabama Streams. Unpublished thesis. Auburn University. Auburn, AL.

Heise R J, Cope W G, Kwak T J, Eads C B. (2013) Short-tern effects of small dam removal on a freshwater mussel assemblage. Walkerana. 16 [1]:41-52.

Heinz Center. (2002). Dam Removal: Science and Decision Making. Heinz Center, Washington D.C.

Hoch R A. (2012). Beaver and mill dams alter freshwater mussel habitat, growth, and survival in North Carolina piedmont streams. Unpublished thesis. Appalachian State University. Boone, NC.

"Home - NID 2016." Home - NID 2016. http://nid.usace.army.mil/cm_apex/f?p=838:1:0::NO::APP_ORGANIZATION_TYPE,P12_ORGANIZATION:1.

Hornbach D J, Hove M C, Liu H, Schneck F R, Rubin D, Sansom B J. (2014) The influence of two differently sized dams on mussel assemblages and growth. Hydrobiologia. 724:279-291. DOI: 10.1007/s10750-013-1743-y

IBM Corp. Released 2012. IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY: IBM Corp.

Januchowski-Hartley SR, Visconti P, and Pressley RL. (2011) A systematic approach for prioritizing multiple management actions for invasive species. Biological Invasions. 13:1241-1253. DOI: 10.1007/s10530-011-9960-7

Kunz G F. (1898). A brief history of gathering of fresh-water pearls in the United States. U.S. Fish Commission Bulletin. 17:321-330.

Lajeunessei M J. (2011). On the meta-analysis of response ratios for studies with correlated and multi-group designs. Ecology. 92 [11]:2049-2055.

Liermann C R, Milsson C, Robertson J, and Ng R Y. (2012). Implications of Dam Obstruction for Global freshwater Fish Diversity. BioScience. 62 [6]:539-548. DOI: 10.1525/bio.2012.62.6.5

Ligon F K, Dietrich W E, and Trush W J. (1995). Downstream Ecological Effects of Dams. BioScience. 45[3]:183-192. DOI: 10.2307/1312557.

Lydeard C, Mayden R L. (1995). A divesre and endangered aquatic ecosystem of the southeast United States. Conservation Biology 9[4]:800-805.

Matteson M R. (1955). Studies on the natural history of the Unionidae. The American Midland Naturalist. 53[1]:126-145.

McCormick M. (2012). Effects of small dams on freshwater bivalve assemblages in North Carolina piedmont and coastal plain streams. Unpublished thesis. Appalachian State University. Boone, NC.

McCrae S E, Allan J D, Burch J B. (2004). Ratchet-and-catchment-scale determinants of the distribution of freshwater mussels (Bivalvia:Unionidae) in south-easter Michigan, U.S.A. Freshwater Biology 49:127-142.

O'Connor J E, Duda J J, and Grant G E. (2015). 100 dams down and counting. Science. 348 [6234]:469-497. DOI: 10.1126/science.aaa9204.

Parmalee P W, and Bogan A E. (1998). The Freshwater Mussels of Tennessee. The University of Tennessee Press. Knoxville, TN.

Palmer M, Allan J D, Meyer J, and Bernhardt E S. (2007). "River Restoration in the Twenty-First Century: Data and Experiential Knowledge to Inform Future Efforts." Restoration Ecology. 15 [3]:472-81.

Peng C Y, Lee K L, and Ingersoll G M. (2002). An Introduction to Logistic Regression Analysis and Reporting. The Journal of Educational Research. 96 [1]:3-14.

Sala O E, Chapin F S, Armesto J J, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke L F, Jackson R B, Kinzig A, Leemans R, Lodge D M, Mooney H A, Oesterheld M, Poff N L, Sykes M T, Walker B H, Walker M, Wall D H. (2000) Biodiversity – Global Biodiversity scenarios for the year 2100. Science. [287]5459: 1770-1774.

Schnitter N J. (1994) A History of Dams: the useful pyramids. A.A. Balkema. Netherlands.

Singer E E and Gangloff M M. (2011). "Effects of a Small Dam on Freshwater Mussel Growth in an Alabama (U.S.A.) Stream." Freshwater Biology. 56 [9]: 1904–1915.

Stanley E H and Doyle M W. (2002). "A Geomorphic Perspective on Nutrient Retention Following Dam Removal." BioScience. 52 [8]: 693.

Stanley E H, and Doyle M W. (2003) Trading off: the ecological effects of dam removal. The Ecological Society of America. 1[1]: 15-22.

Stanley E H, Luebke M A, Doyle M W, and Marshall D W. (2002) Short-term changes in channel form and macroinvertebrate communities follow low-head dam removal. Journal of the North American Benthological Society. 21: 172-187.

Strayer D L. (1983) The effects of surface geology and stream size on freshwater mussel (Bivalvia:Unionidae) distribution in southeast Michigan, U.S.A. Freshwater Biology. 13[3]:253-264.

Strayer D L, Ralley J. (1993) Microhabitat use by an assemblage of stream-dwelling Unionaceans (Bivalvia), including two rare species of *Alasmidonta.* Journal of the North American Benthological Society. 12:247-258.

Thoni R, Holcomb J, Nichols R, and Gangloff M M. 2014. Effects of Small Dams on Sunfish Assemblages in North Carolina Piedmont and Coastal Plain Streams. Transactions of the American Fisheries Society. 143[1]:97-103.

Tools, Free Map. "Elevation Finder." Elevation Finder. https://www.freemaptools.com/elevation-finder.htm.

Turgeon D D, Bogan A E, Coan E V, Emerson W K, Lyons W G, Pratt W L, Roper C F E, Schltema A, Thompson F G, and Williams J D. (1988). Common and Scientific Names of Aquatic Invertebrates from the United States and Canada: Mollusks. American Fisheries Society, Special Publication 26. 536 pages.

United States. Bureau of Reclamation. (1978). Sierra Ecology project: environmental impact statement.

Vaugh C C, Gido K B, and Spooner D E. (2004). Ecosystem processes performed by unionid mussels in stream mesocosms: species roles and effects of abundance. Hydrobiologia. 527[1]:35-47.

Ward J V and Stanford J A. (1979) "Ecological Factors Controlling Stream Zoobenthos with Emphasis on Thermal Modification of Regulated Streams." The Ecology of Regulated Streams. 35-55.

Watters G T. (1992). Mussel diversity as a function of drainage area and fish diversity: management implications. Conservation and management of freshwater mussels. Proceedings of an Upper Mississippi River Conservation Committee symposium. 12-14.

Watters G T. (1999). Freshwater mussels and water quality: A review of the effects of hydrologic and instream habitat alteration. Proceedings of the First Freshwater Mollusk Conservation Society symposium. 261-274.

Way C M, Miller A C, Payne B S. (1989). The influence of physical factors on the distribution and abundance of freshwater mussels (Bivalvia:Unionidae) in the lower Tennessee River. The Nautilis. 103[3]:96-98.

Williams J D, Bogan A E, and Garner J T. (2008). Freshwater Mussels of Alabama and the Mobile Basin in Georgia, Mississippi and Tennessee. The University of Alabama Press. Tuscoloosa, AL. 908 pages.

Williams J D, Fuller S L H, Grace R. (1992). Effect of impoundments of freshwater mussels (Mollusca: Bivalvia: Unionidae) in the main channel of the Black Warrior and Tombigbee rivers in western Alabama. Alabama Museum of Natural History Bulletin. 13:1-10.

Williams J D, Warren M L, Cummings K S, Harris J L, Neves R J. (1993) Conservation Status of Freshwater Mussels of the United States and Canada. Fisheries. 18[9]: 6-22.

Zedonis P A. (2001). Empirical and Theoretical Influences of a Pulse Flow from Lewiston Dam on Water Temperature and Dissolved Oxygen of the Lower Klamath River. Draft presented to the Trinity River Management Council.