Effects of hydrologic variation and water temperatures on early growth and survival of selected age-0 fishes in the Tallapoosa River, Alabama.

by

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Abstract

Altered flow regimes resulting from the construction of hydropower dams can negatively affect aquatic organisms in a variety of ways. The effects of flow and temperature variation on early growth, survival, and hatching success were examined at regulated and unregulated sites in the Tallapoosa River, Alabama. Previous research on the Tallapoosa River has focused on community responses to altered flow regimes in adult populations. However, very little information exists on specific impacts and responses of fish in early life stages. The objectives of this study were to: 1) estimate daily incremental growth rate and back calculate hatch dates of age-0 Redbreast Sunfish *Lepomis auritus* 2) examine relations between average daily incremental growth rate and age, hydrology, temperature, site type (regulated or unregulated) and year; and 3) examine relations between hatch success and frequency and hydrology at regulated and unregulated sites in the Tallapoosa River; and 4) quantify the effects of fluctuating water flow and decreased water temperatures on early daily growth and survival of age-0 Channel Catfish *Ictalurus punctatus* and Alabama Bass *Micropterus henshalli* through a series of laboratory experiments.

Effects of hydrology on early growth and hatching success of age-0 Redbreast Sunfish were examined at regulated and unregulated sites in the Tallapoosa River. Average daily incremental growth techniques were used to back calculate daily incremental growth and estimate hatch dates and predict hatch success. Early growth was impacted by site type and year and hatching success was impacted by flow and temperature variables. Overall daily growth rate and incremental growth rate varied among years and was higher at regulated sites than unregulated sites. Model comparison indicated that the best overall model that described average daily incremental growth included: site type, age, year, the number of hours discharge was greater than 220 cms (FLOW1), the number of cumulative degree days, and the day of year that the growth increment occurred as independent variables. However, overall model fit was poor. Additional models, with flow and temperature variables excluded, were evaluated and compared with Akaike's Information Criterion (AIC_c). The best overall model included site type, age, and year as independent variables and explained 33% of the variation in average daily incremental growth rate. These results suggest flow and temperature regimes are important predictors of hatching success, and that early growth is impacted more by site type and year. The number of reversals, number of hours discharge was between 0 – 60 cms, number of cumulative degree days, and year were predictors of hatch success. Hatch frequency was higher and occurred earlier in unregulated sites compared to later hatching in regulated sections. Managing instream flows to provide periods of low-stable flows and temperatures should positively affect growth rates, increase hatching success, and increase subsequent recruitment of redbreast sunfish downstream of R. L. Harris Dam.

In experimental studies, results suggest that strong fluctuating flows and decreased water temperatures negatively affected daily growth rates and survival of age 0 Channel Catfish and Alabama Bass. Mortality was highest in treatments with decreased water temperatures. Daily growth rates were lower in treatments with decreased water temperatures. Older fish had higher daily growth rates and decreased mortality, and were not as susceptible to the negative effects of treatments. These data also suggest that growth and survival may be impacted more by fluctuations in temperature (Δ10 °C) versus flow variation. However, treatments with high flow also exhibited decreased growth and some mortality. Management efforts should consider both flow and temperatures regimes together in an effort to increase growth rates, survival, and increase subsequent recruitment of fish in regulated rivers.

Managers are encouraged to use models and conclusions described in this dissertation as part of their decision-making and objective-setting processes, in an adaptive management framework, to manage flow regimes in regulated rivers. Specifically, we recommend 1) thermal modification technologies at hydropeaking dams be investigated for suitability and feasibility; 2) instream flow management include thermal regimes and variation as part of management objectives; and 3) spawning and rearing windows continue to be employed, with evaluations on an annual basis, as a management tool to increase recruitment of fish in regulated rivers. The models and variables herein described should be continually improved upon and updated as more information is learned and uncertainty reduced. Additional data collection and experimentation is necessary to monitor fish populations and their response to the flow and temperature regimes in regulated rivers.

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1. Introduction

Human induced changes in rivers disrupt functions that support healthy river ecosystems (Bowen et al. 2003). Large rivers have been altered by the construction of dams, diversions, channelization, levee construction, groundwater pumping, and changes in watershed land use (Ward and Stanford 1989; Benke 1990; Dudgeon 1992; Dynesius and Nilsson 1994; Bowen et al. 2003). Rapid increases and decreases in water volume downstream of hydropower impoundments can cause changes in species composition, decreases in species richness, modifications in life cycle patterns, and alteration in population abundances (Jalon et al. 1994). Although obvious and often irreversible impacts of large impoundments are now well recognized, there is growing awareness of the pivotal role of flow regime as a key driver of the ecology of rivers and their associated floodplain wetlands (Junk et al. 1989; Poff et al. 1997; Richter et al. 1997; Bunn and Arthington 2002).

Prior to construction of hydropower dams with large storage reservoirs behind them, flows normally were highest in winter and spring and lowest in autumn. Natural seasonal differences are now dampened because of hydropower generation and water releases when reservoirs are typically drawn down (Pringle et al. 2000). Year-to-year flow variability likely influences biotic assemblages in many lotic systems by facilitating recruitment of different species in different years (Grossman et al. 1982, 1998; Walker and Thoms 1993; Sparks 1995; Freeman et al. 2001). Hydropeaking can also substantially dampen seasonal and interannual variation in flows (Poff et al. 1997; Bowen et al. 1998). Imposing these artificially high, short-term variations may be detrimental to biota unable to adapt to rapid fluctuations (Cushman 1985). The type, magnitude, and extent of alterations strongly influence the interrelated responses of river flow regimes, sediment processes, thermal conditions, and associated ecosystem function and response.

In the Alabama River system, four hydropower dams have been constructed on the main stem of the Tallapoosa River (Boschung and Mayden 2004). In the Northern Piedmont region, flows have rapidly fluctuated between extremely low and high flows as a result of hydropeaking operations downstream of R. L. Harris Dam, in the Tallapoosa River (Irwin and Freeman 2002). These extreme fluctuations in discharge during a period of only four to six hours have generated a highly variable flow regime that has potentially threatened the persistence of several native fishes (i.e., fluvial specialists) downstream of the dam (Irwin and Freeman 2002). Irwin and Freeman (2002) reported that significant changes in hydrology occurred after the construction of R. L. Harris Dam in 1982, which included increases in high-pulse frequency, low-pulse frequency, fall rate, and the number of flow reversals. The relations between this type of hydrologic variability and subsequent growth and survival of fishes need to be assessed to ensure appropriate management and sustainability of fish populations.

Ecologists have argued that flow-regulated rivers should be managed to mimic, as closely as possible, flow patterns prior to the closing of dams (Stanford et al. 1996; Poff et al. 1997; Richter et al. 1997; Freeman et al. 2001). However, our knowledge of how large rivers function is often limited by the range of time scales involved, lack of data prior to changes, and the complexity of interactions among flow, sediment, and biota (Holly and Ettema 1993). Pressing demands on water use and continued alteration of rivers requires development of management protocols that accommodate economic uses while protecting ecosystem function (Poff et al. 1997). Management decisions are often complex with much uncertainty not only about the ecological system but also about which management objectives and alternatives to consider

(Peterson and Evans 2003). To aid in the decision-making process, managers need tools that will formalize these complexities into a common framework consisting of relations among management actions, sources of uncertainty, and multiple management outcomes (Peterson and Evans 2003). Adaptive management is such an approach where uncertainty, unknown information, and new knowledge gained through experimentation, are incorporated into flexible conservation and management (Walters 1986).

In an attempt to restore ecological function, Irwin and Freeman (2002) presented a conceptual iterative model for adaptive flow-management in the flow-regulated portion of the Tallapoosa River, Alabama, below R. L. Harris Dam. This approach allows managers and scientists to collect data on the biological consequences of differing flow alterations over a series of time while leaving open opportunities for improvement in the management of riverine biota (Irwin and Freeman 2002). The main goal of adaptive flow-management is to continually attempt to improve management strategies as uncertainty about a river system is reduced. This requires the cooperation and commitment among natural resource personnel, private industry, landowners, and other stakeholders. By quantifying relations between hydrology, growth, and recruitment of fishes in regulated rivers, models can be developed to predict responses in fish populations to the prescription of flow regimes. These models can be continually improved upon with increased knowledge regarding the effects of hydrologic variability on the dynamics of fish populations. In 2005, managers implemented this adaptive approach to managing flows below R. L. Harris Dam. One aspect of the approach is that flows are being manipulated during the spring to provide periods of stable low flows in the hopes of increasing spawning success and recruitment of targeted species such as black basses and sunfish.

In some instances, taxa dependent upon free-flowing riverine habitat have become imperiled due to hydrologic modifications associated with the construction of dams. Where riverine habitat exists downstream from dams, native fish and invertebrate populations are often limited by adverse water quality and altered thermal and hydrologic regimes (Cushman 1985; Schmidt et al. 1998; Pringle et al. 2000). Freeman et al. (2001) reported that abundance of juvenile fish at a flow-regulated site was correlated with persistence and stability of shallow water habitats, suggesting that suitable spawning or rearing habitat may be limiting recruitment. Young of the year habitat availability was correlated with year class strength of stream centrarchids in the Huron River, Michigan (Bovee et al. 1994) and salmonids in Colorado River stream populations (Nehring and Anderson 1993). Declines in abundance of Delta Smelt *Hypomesus transpacificus* in San Francisco Bay, California have also been associated with hydrologic modifications that have reduced freshwater flows and have provided less favorable habitat (Moyle et al. 1992). Providing periods of stable or minimum continuous flow conditions (e.g., spawning windows) downstream of hydropeaking facilities for varying periods of time may provide needed system stability to facilitate reproduction, larval development, and juvenile residence by native riverine fishes (Freeman et al. 2001; Irwin and Freeman 2002; Weyers et al. 2003). Continued monitoring of populations of target species is needed to determine if modifications of the flow regime, including addition of spawning windows, may improve native fisheries.

This dissertation is presented in four chapters: Chapter 1 (this chapter) includes an introduction and literature review, Chapters 2 and 3 are objective oriented, and Chapter 4 is a synthesis of research and provides management implications of this study. My specific objectives are to: 1) assess the effects of hydrology on growth and hatch success of young of the year Redbreast Sunfish *Lepomis auristus* at regulated and unregulated sites within the Tallapoosa River system, and 2) evaluate the effects of variable hydrology and decreased water temperatures on larval growth and survival of young of the year Channel Catfish *Ictalurus punctatus* and Alabama Bass *Micropterus henshalli*.

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2. Growth and hatching success of age-0 Redbreast Sunfish *Lepomis auristus* at regulated and unregulated sites of the Tallapoosa River, Alabama

Abstract – Effects of hydrology on growth and hatching success of age-0 Redbreast Sunfish *Lepomis auristus* were evaluation at regulated (downstream of R. L. Harris Dam) and unregulated sites in the Tallapoosa River, AL. Redbreast Sunfish were collected from sites in 2005 and 2007-2009 to describe hatch-date distributions, estimate average daily incremental growth rates, and predict hatching success, and describe early growth relations with flow and temperature variables. Fish were assigned daily ages using otoliths. Daily growth rate varied among years and was higher at regulated sites. Flow and temperature metrics were calculated for evaluation of relations with average daily incremental growth. Regression models were used to evaluate relations with average daily incremental growth and included various combinations of metrics including: flow, temperature, age, site type, and day-of-year of growth increment, and their interactions. Models were evaluated with Akaike's Information Criterion (AIC_c) to assess which models best described variation in average daily incremental growth. Model comparison indicated that the best overall model that described average daily incremental growth included: site type, age, year, the number of hours discharge was greater than 220 cms (FLOW1), the number of cumulative degree days, and the day of year that the growth increment occurred as independent variables. However, model fit was poor. Additional models, with flow and temperature variables excluded from models, were evaluated and compared with Akaike's Information Criterion (AIC_c). The best overall model included site type, age, and year as independent variables and explained 33% of the variation in average daily incremental growth rate.

Hatch dates were back calculated, and growth increments were estimated every 10 d post hatch from otolith sections. Hatch frequency was higher and occurred earlier in unregulated sites compared to later hatching at regulated sections. Hatch dates were variable based on site type and year. During most years initiation of hatch was earlier at unregulated sites. Logistic regression was used to predict the probability of hatch success when accounting for various metric combinations of flow, temperature, and site type. Models were also evaluated with Akaike's Information Criterion (AIC_c) to assess which models best predicted hatch success. Model comparison indicated the best overall model included: the number of reversals, number of hours discharge was between 0 – 60 cms, the number of cumulative degree days, and year were predictors of hatch success. This model had the highest weight of evidence of all other models examined (w_i = 0.63).

These results suggest that flow and temperature regimes are important predictors of hatch success but they do not necessarily have the same impact on average daily incremental growth. We recommend that instream flow recommendations include the thermal regime in management efforts, as variation in flow appears to affect variation in temperature. Periods of low flow (pulse flow generations 0 - 60 cms) with temperature mitigation will likely increase the probability of hatch success, positively affect growth rates, and increase subsequent recruitment of Redbreast Sunfish downstream of R. L. Harris Dam.

Introduction

Fish recruitment in regulated river systems has been negatively affected by hydrologic alteration, as a result of construction of dams (Wildhaber et al. 2000; Freeman et al. 2001; Irwin and Freeman 2002; Propst and Gido 2004). Hydrologic alteration and river fragmentation have adversely impacted the reproductive success of multiple fish species in the Alabama River system (Freeman et al. 2004). In a regulated site of the Tallapoosa River, Alabama, variable flow conditions have reduced the stability and persistence of habitat and, as a result, have negatively influenced young of the year fish recruitment for multiple species (Freeman et al. 2001). Irwin et al. (1997) and Irwin and Freeman (2002) hypothesized that lower water temperatures from pulsing hypolimnetic releases likely delayed spawning periods, impeded hatching success, and decreased rates of larval development. Irwin et al. (1997) reported lower abundance of age-0 black basses with increased severity of daily flow fluctuations, which may be indicative of decreased juvenile survival in association with hydropeaking flow regimes. Sabo (1993) suggested that age-0 Smallmouth Bass *Micropterus dolomieu* may be vulnerable to loss of low-velocity habitats for as long as six weeks after leaving their nests. Irwin et al. (1999) reported that juvenile Channel catfish *Ictalurus punctatus* and Flathead Catfish *Pylodictis olivaris* also occupied low-velocity habitats and exhibited nocturnal movements to these habitats. Juveniles also become vulnerable to loss of riffle habitats due to nighttime flow pulses released by hydropower facilities, which may cause displacement (Irwin et al. 1999).

In highly regulated rivers like the Tallapoosa River, where high-flow events can sometimes occur daily, fluctuating flows may limit populations by reducing availability and quality of spawning and juvenile habitat (Angilleta et al. 2008; Dutterer et al. 2012), limiting survival directly (by increasing mortality) or indirectly (by reducing foraging success and growth rates; see Walters and Juanes 1993), and by depressing tailwater temperatures (Clarkson and Childs 2000). Other impacts caused by lowered water temperatures include decreased gonadal maturation (Holden and Stalnaker 1975), decreased growth and swimming performance (Childs and Clarkson 1996), increased early life stage mortality, decreased survival to maturation, and reduced condition (Kaeding and Osmundson 1988; Clarkson and Childs 2000).

Though much is known about the effects of hydrologic alteration on the recruitment of fish, most studies have been conducted in reservoirs and coastal plain regions (Travnichek et al. 1996; Maceina and Stimpert 1998; Sammons et al. 1999; Sammons and Bettoli 2000; Sammons and Maceina 2009; Sammons et al. 2001). Little information is known about hydrologic effects on downstream fauna, especially early life history stages. Even fewer studies have directly examined the relations between hydrology, hatching success, and first year growth.

Providing spawning and rearing windows during the spawning season may allow for successful spawning and subsequent juvenile recruitment. Several studies of rivers in the southeastern United States have recommended the use of spawning windows (Irwin et al. 1997; Freeman et al. 2001; Andress 2002; Irwin and Freeman 2002; Sakaris 2006; Martin 2008). Andress (2002) recommended 10-11 calendar days in the second and third week in June as adequate spawning window time for successful Redbreast Sunfish *Lepomis auristus* spawning in a regulated site of the Tallapoosa River. These time periods may provide fish and their nests temporal refugia from high flows, thereby enhancing hatching success (Irwin et al. 1997; Freeman et al. 2001). Spawning windows could also reintroduce important elements of the natural flow regime that are currently missing or lacking, which could benefit fish during critical life-cycle stages when they are particularly susceptible to mortality (Irwin et al. 1997). Irwin et al. (1997) reported that populations of black basses in the Tallapoosa River exhibited complex responses to a fluctuating flow regime which included: increased growth, delayed spawning, and peaks in hatching associated with periods of stable flow. Andress (2002) and Martin (2008) reported that strongly fluctuating flow at the same regulated site adversely affected Redbreast Sunfish nest success. Nest failures can have deleterious effects on abundance and recruitment of fish year classes. Lack of suitable habitat for spawning during hydropeaking events could also negatively affect timing of spawning and survival of eggs and larvae.

For many organisms, events during early life history play an important role in determining population dynamics, species interactions, and community structure at the adult stage (Rice et al. 1987). High flow events have been reported as an important variable in explaining the variation in nest success of centrarchids (Lukas and Orth 1995; Andress 2002). To this end, this study endeavored to examine the early growth of Redbreast Sunfish *Lepomis auristus* and to describe relations with flow and temperature regimes in a highly regulated river. The objectives of this study were to: 1) estimate average daily incremental growth rate and back calculate hatch dates of age-0 Redbreast Sunfish; 2) examine relations among average daily incremental growth rate and hydrology, temperature, site type and year; and 3) examine relations between hatch success and frequency and hydrology at regulated and unregulated sites in the Tallapoosa River. Several a priori hypotheses were considered. They were: 1) fish at regulated sites experience slower growth at age than fish in unregulated sites and differences can be attributed to variability in hydrology and water temperature; 2) average daily incremental growth varies with age, hydrology, temperature, site type and year; and 3) rapidly fluctuating flows negatively affect hatching success such that successful hatching can be related to periods of flow stability and decreased temperature variation.

Methods

Juvenile Redbreast Sunfish were collected using pre-positioned area electrofishers (PAEs; Bain et al. 1985) and backpack electrofishing units in spring/summer and fall 2005, 2007-2009 at four sites within the Tallapoosa River Basin (Figure 2-1). Sites were classified as regulated (Wadley and Malone, Alabama) or unregulated (Heflin and Hillabee Creek, Alexander City, Alabama) depending on the influence of R. L. Harris hydropeaking Dam, a hydropower generating dam on the Tallapoosa River. Fish were collected at approximately 30, 60, and 90 – days after the onset of spawning. PAEs were constructed of two 6 - m long electrodes, separated by 1.5 m, and remotely powered with alternating current by a 3500 W generator and pulsator unit (Smith-Root 305 GP; Smith-Root, Vancouver, Washington, USA). The onset of spawning was determined by river water temperatures reaching 20-25 ºC (Davis 1972) and the presence of active nests in the river (Andress 2002; Martin 2008). After fish were stunned with electrical current, they were euthanized in tricaine methanesulfonate (MS-222; 140 mg/l), placed on ice, and transported to the laboratory.

Laboratory Methods

All fish were measured to the nearest 0.1 mm TL and weighed to the nearest 0.01 g. Sagittal otoliths were extracted using forceps under a dissecting microscope, at 60X magnification, and stored in centrifuge tubes prior to preparation. Daily ages and hatch dates of fish were calculated following the techniques of Taubert and Coble (1977), Santucci and Wahl (2003), and Roberts et al. (2004). Otoliths were embedded in crystal bond resin on glass slides and were ground to the core with fine sandpaper (400-grit) until a thin transverse section was obtained. To estimate age, daily otolith rings were counted, in duplicate, from the core to the outer edge at 400X magnification. Age was determined to be the average of the two counts.

Otolith radii were measured from the center of the core to the outer edge using an image analysis system to the nearest µm to estimate growth (Image-Pro® Plus, Media Cybernetics, Inc., Silver Spring, Maryland). Radii were also measured from the core towards the edge of each otolith at 10 d increments to estimate average daily incremental growth (i.e., 0 - 10, 10 - 20, 20 - 30, 30 - 40, 40 - 50, 50 - 60, 60 - 70, 70 - 80 d, Image-Pro® Plus). Hatch dates were estimated using the following formula:

$$1) \qquad Hatch\ Date\ = date - \ age - 6\ d,$$

where date was the calendar date of capture, age was the mean number of growth rings counted per fish, and estimates were less 6 d to account for the period of time between hatch and when fish began to lay down daily growth rings (Taubert and Coble 1977; Santucci and Wahl 2003; Roberts et al. 2004).

Statistical Analysis

Linear models were used to assess and estimate relations between the following variables: 1) overall daily growth rate (mm/day) and site type (regulate or unregulated) and year; 2) total length and age; 3) total length and otolith radius (µm), and; 4) age and otolith radius. Hatch frequency histograms were constructed for fish that were collected in 2005, 2007, 2008, and 2009.

Growth comparisons

Linear regression analysis was used to determine if and how average daily incremental growth rate differed among sites, age increment groups, and year. Site*age increment and year interactions were also evaluated. In Program R© (R Development Core Team 2005), the categorical variables of site and year were “dummy-coded” as numeric data (0,1) such that we were able to use regression analysis to estimate effect sizes and differences.

Hydrologic variables versus growth

Single and multiple regression models were constructed to assess relations between average daily incremental fish growth, hydrology and temperature at regulated and unregulated sites in the Tallapoosa River. Sub-hourly river discharge data (~30 min) were obtained from US Geological Survey (USGS) gaging stations located in close proximity to three sampling locations: 1) USGS 02412000, Upper Tallapoosa River near Heflin, Alabama, 2) USGS 02414500, Middle Tallapoosa River at Wadley, Alabama (for Malone-Wadley and Peter's Island sites), and 3) USGS 02415000, Hillabee Creek near Hackneyville, Alabama (http://waterdata.usgs.gov/nwis/rt). Water temperature data were obtained from Alabama Power Company data loggers located at the Wadley Bridge (regulated) and Heflin, AL (unregulated; sub-hourly ~20 min). Hydrologic and temperature variables were calculated in 10 d increments prior to the date of each growth increment per individual, to describe flow and temperature regimes and characteristics. These variables were used as independent variables in multiple regression models (Table 2-1). Discharge data from USGS gages was used to calculate reversals (REV) by summing the number of times/ 10 d the hydrograph changed directions. Number of hours discharge was at or above 220 cms (2 - unit generation levels; FLOW1) was calculated by summing the number of hours per 10 d discharge was greater than 220 cms. The number of hours discharge was between 60 – 220 cms (1 - unit generation levels; FLOW3) was calculated by summing the number of hours per 10 d discharge was between 60 - 220 cms. The number of hours discharge was between 0 – 60 cms (pulse generation or no generation levels; FLOW5) was calculated by summing the number of hours per 10 d discharge was between 0 - 60 cms. Using water temperature data, cumulative degree days (TEMP1) was calculated by estimating the number of cumulative degree-days per 10 d. Degree-days were used to determine the amount of heat energy needed for Redbreast Sunfish eggs to hatch and mature to swim-up fry stage. Degree-days per 10 d were calculated using hourly temperature data with the following formula:

$$2)\quad \left[\frac{Temperature_{max} + Temperature_{min}}{2}\right] - 17°\,C,$$

where 17° C was the lower threshold temperature, it is the lower limit for bluegill sunfish *Lepomis macrochirus,* development (Nakamura et al. 1971). Median temperature change (TEMP2) was calculated by estimating the median change in temperature (ΔT_{median})/10 d. Day of year the age increment occurred (DOY.Inc) was calculated by estimating the day of the year corresponding to the date of each 10 d increment per fish. Multiple regression models were developed similar to the model presented in Maceina (1992), with age (AGE) as the main independent factor explaining variability in growth and hydrologic and temperature variables (ENV), year and site type explaining the remaining variation. The global model to estimate average daily incremental growth was:

$$3)\quad Average\ Incremental\ Growth = \beta 0 + \beta 1(\mathrm{AGE}) \pm \beta 2(\mathrm{ENVflow}) \pm \beta 3(\mathrm{ENVtemp}) \pm \beta 4(\mathrm{Year}) \pm \beta 5(\mathrm{Site}),$$

where β_0, β_1, β_2, β_3, $\beta_4$and β_5 were the regression coefficients for the intercept and slopes, respectively (Maceina 1992). Incremental growth data from otoliths were used to estimate fish growth, and age was defined as the midpoint of each growth increment (e.g., 10 – 20 d post hatch, age = 15 d). Single and multiple variable models with only age, year, site type, flow, and/or temperature variables as independent variables were also considered. Multicollinearity diagnostics (variance inflation factors, VIF’s) were conducted to determine if independent variables co-varied in multiple regression models. Variables that were collinear were not included in the same models. Significance was set at $\alpha = 0.05$, and all statistics were conducted using Program R© (R Development Core Team 2005).

AIC model selection – Average daily incremental growth

Single and multiple regression models from combinations of non-collinear independent variables to describe average daily incremental growth were constructed and ranked using Akaike's Information Criterion (AIC_c) corrected for small sample size (Burnham and Anderson, 1998). We compared fit among models using a model selection approach. AIC balances the minimization of residual error (RSS) with problems associated with over-parameterization and can be used to identify the most parsimonious models with the least amount of bias from a set of candidate models (Burnham and Anderson 1998). Top-ranked models (i.e., models receiving substantial support) were those models having the smallest AIC_c values and ΔAIC_c values within 2 of the "best" model (i.e., $\Delta AIC_c < 2$; Burnham and Anderson 1998). Akaike weights indicate the probability or weight of evidence, relative to the best-fitting model, of the tested model being the best-fitting (Burnham and Anderson 1998). Adjusted R^2 was also calculated for each model.

Hydrologic variables and hatch success

Single and multivariable logistic regression models were constructed to predict the probability of hatch success at regulated and unregulated sites in the Tallapoosa River. An estimated hatch was recorded as one and no hatch was recorded as zero. Models included the same hydrologic and temperature variables estimated for average daily incremental growth as independent variables, with the exception of DOY.Inc and DOY.H (Table 2-2). Hydrologic and temperature variables used to describe flow and temperature regimes and characteristics were calculated in 10 d increments prior to the date of hatch per individual. The global model to predict hatch success was:

$$4)\quad Hatch\ Success = \beta 0 + \beta 1(\mathrm{ENVflow}) \pm \beta 2(\mathrm{ENVtemp}) \pm \beta 3(\mathrm{Year}) \pm \beta 4(\mathrm{Site}),$$

where β_0, β_1, β_2, $\beta_3$and β_4 were the regression coefficients for the intercept and slopes, respectively. Single and multiple variable models with only year, site type, flow, and/or temperature variables as independent variables were also considered. Multicollinearity diagnostics (variance inflation factors, VIF's) were conducted to determine if independent variables co-varied in multiple logistic regression models. Variables that were collinear were not included in the same models. Ninety five percent confidence intervals were also estimated for the best fitting model. Significance was set at $\alpha = 0.05$, and all statistics were conducted using Program R© (R Development Core Team 2005).

AIC model selection – Hatch success

Single and multiple logistic regression models predicting hatch success were constructed and ranked using Akaike's Information Criterion (AIC_c) corrected for small sample size (Burnham and Anderson, 1998). We compared fit among models using a model selection approach. Top-ranked models (i.e., models receiving substantial support) were those models having the smallest AIC_c values and ΔAIC_c values within 2 of the "best" model (i.e., $\Delta AIC_c < 2$; Burnham and Anderson 1998).

Results

A total of 583 age - 0 Redbreast Sunfish were collected and aged from regulated (n = 240) and unregulated sites in this study (n = 343; Table 2-3). Total length ranged from 23 to107 mm in regulated sites, and 14 to 119 mm at unregulated sites. Ages and growth rates of age - 0 fish ranged from 26 to 106 d and 0.25 to 1.52 mm/d at regulated sites, and unregulated sites 24 to 118 d and 0.27 to 1.80 mm/d at unregulated sites (Table 2-3). Daily growth rate varied between sites and among years ($R^2 = 0.24$, $p < 0.01$). Daily growth rate estimates were highest in 2005 at regulated sites (1.15 mm/day, SE = 0.11) and lowest in 2008 at unregulated sites (0.51 mm/day, SE = 0.04; Figure 2-2). Daily growth rate varied with age, however there were no strong linear relations between these two variables ($R^2 = 0.009$, $p < 0.05$). Total length was positively related to age ($R^2 = 0.38$, $p<0.01$; Figure 2-3), and did not differ between regulated and unregulated sites. Otolith radius (μm) was positively related to total length at unregulated sites ($R^2 = 0.82$, $p < 0.05$; Figure 2-4a) and regulated sites ($R^2 = 0.74$; Figure 2-5a). Otolith radius was also positively related to age at unregulated sites ($R^2 = 0.40$, $p <0.05$; Figure 2-4b) and at regulated sites ($R^2 = 0.45$, $p < 0.05$; Figure 2-5b).

Hatch dates varied between sites and among years ($R^2 = 0.36$, $p<0.01$). Hatches initiated earlier in 2005, 2007 and 2009 at unregulated sites versus regulated sites. In 2008 hatches initiated on the same day. At regulated sites, age-0 Redbreast Sunfish hatched between 28 June – 8 August in 2005 (Figure 2-6), 28 May-27 August in 2007 (Figure 2-7), 1 May – 23 September in 2008 (Figure 2-8), and 7 May – 7 August in 2009 (Figure 2-9). At unregulated sites Redbreast Sunfish hatched between 12 June – 3 September in 2005 (Figure 2-6), 11 May – 22 September in 2007 (Figure 2-7), 1 May – 30 September in 2008 (Figure 2-8), and 1 May – 2 August in 2009 (Figure 2-9). In 2005, the majority of hatches at regulated sites occurred in August (50%, 9/18). The majority of hatches at unregulated sites, in 2005, occurred between July and August (85%, 6/7). In 2007, the majority of hatches at regulated sites (48%, 21/44) occurred in June. The majority of hatches at unregulated sites, in 2007, occurred in August (74%, 32/43). In 2008, the majority of hatches occurred in August for both site types (regulated: 43%, 34/79; unregulated: 36%, 58/161). In 2009 the majority of hatches at regulated sites (90%, 104/115) occurred from June-July. At unregulated sites in 2009, the majority of hatches (44%, 52/117) occurred in June. In 2009, at the unregulated sites, there were incidences of early hatches in May continuing through June. Mean hatch date was earlier in regulated sites in 2005 and 2008 than in 2007. Examination of hatch frequency data indicated the majority of Redbreast Sunfish hatched when discharge was less than 220 cms (equivalent to a 2-unit generation; Figure 2-10-13).

Average daily incremental growth comparisons

Average daily incremental growth of age-0 Redbreast Sunfish varied between age groups, sites types and years ($R^2 = 0.07$, $p < 0.01$; Figure 2-14-15). Average daily incremental growth was highest during the first 10 d of life at regulated sites in 2007-2009 (mean =1.59 mm/day, SE = 0.03; Figure 2-14). In 2005, at regulated sites, average daily incremental growth increased from the first 10 d of life to 50-60 d post-hatch (1.65 -1.92 mm/day; Figure 2-14). Average daily incremental growth at regulated sites was consistently higher across all age groups in 2005. Average daily incremental growth rate was highest during the first 10 d of life across all years at unregulated sites (mean = 1.07 mm/day, SE = 0.03; Figure 2-15). Average daily incremental growth was lowest from 30-40 d post-hatch at regulated sites in 2009 (1.02 mm/day; Figure 2-14). Average daily incremental growth was lowest from 10-20 d post-hatch at unregulated sites in 2008 (0.46 mm/day; Figure 2-15).

Hydrologic relations with growth

Twenty-six candidate models (single and multiple variable linear regression) were considered for AIC model selection to evaluate daily incremental growth of Redbreast Sunfish at unregulated and regulated sites (Table 2-4). The global model included *Regulated*Age+Regulated*Year+Regulated*DOY.Inc+Regulated*FLOW1+Regulated*TEMP1* as independent variables and received the most support. This model had the lowest ΔAIC_c value ($\Delta AIC_c = 0.00$) and the highest AIC model weight ($w_i = 0.660$). However, even though the global model was considered the best-fitting model, it only explained 7% of the variability in average daily incremental growth ($R^2 = 0.07$, $p < 0.01$). The variables Regulated, REV, FLOW3, FLOW5, and TEMP2 were not included in models together due to multicollinearity. When flow and temperature variables were excluded from model selection (14 models, Table 2-5), the model that included *Regulated*Age+Regulated*Year+Age*Year* as independent variables received the most support. This model had the lowest ΔAIC_c value ($\Delta AIC_c = 0.00$), the highest AIC model weight ($w_i = 1.00$), and explained 33% of the variability in daily incremental growth ($R^2 = 0.33$, $p < 0.01$).

Hydrologic relations and hatch success

Twenty-eight candidate models (single and multiple variable logistic regression) were considered for AIC model selection to predict hatch success of Redbreast Sunfish at unregulated and regulated sites (Table 2-6). The model that included *REV+FLOW5+TEMP1+Year* as independent variables received the most support in predicting hatch success. This model had the lowest ΔAIC_c value ($\Delta AIC_c = 0.00$), the highest AIC model weight ($w_i = 0.63$). The number of reversals, number of hours discharge was between 0 – 60 cms, number of cumulative degree days, and year were significant predictors of hatch success (Table 2-7). The probabilities of hatch at regulated sites in 2005, 2007, 2008 and 2009 were 0.05, 0.16, 0.35, and 0.53 respectively. The probabilities of hatch at unregulated sites in 2005, 2007, 2008 and 2009 were 0.20, 0.20, 0.38, and 0.63 respectively.

Discussion

This study demonstrated that growth of age-0 Redbreast Sunfish is highly variable at regulated and unregulated sites in the Tallapoosa River, Alabama. Site type, Age, and Year accounted for much of the variation in average daily incremental growth rates. Average daily incremental growth was consistently higher at regulated sites than unregulated sites and across age groups. Highest average daily incremental growth occurred at regulated sites in 2005 which was also classified as a wet year. Increased growth at regulated sites is likely the result of lower fish densities (fewer fish collected at regulated sites) which decreases intraspecific competition for resources. Increased growth at regulated sites could also be a response to the disturbance of 2-unit generations from R. L. Harris Dam. Increased discharge during wet years potentially increases prey density for juveniles who have recently begun exogenous feeding. Redbreast Sunfish are known to be opportunistic feeders (Sandow et al. 1975) and therefore may be able to take advantage of increased prey densities during wet years. Redbreast Sunfish may take advantage of an increase in prey densities ultimately resulting in faster growth.

In wet years, at regulated sites, adults may make more of an investment in parental care of nests, than at unregulated sites. Redbreast Sunfish may be able to spend more time tending to their nests (e.g. fanning and aerating nests) which could result in increased hatch success and average daily growth rates of juveniles. Two years of our study, 2007 and 2008, were considered drought or dry water years (E. Irwin unpublished data) and likely had a negative effect on Redbreast Sunfish populations. Decreased water levels at unregulated sites likely resulted in a reduction of spawning habitat and juvenile habitat and prey items. During periods of drought fewer preferred habitat types are available, increasing competition for resources which could explain lower growth rates at unregulated sites. Sammons and Maceina (2009) reported increased growth rates of adult Redbreast Sunfish in Georgia coastal plain rivers in wet water years. However, in an unregulated stream in Wales, growth rates of Brown Trout *Salmo trutta,* and Atlantic Salmon *Salmo salar,* were not affected by a reduction prey in items as a result of drought (Cowx et al. 1984). A temporal examination of gut contents of fish and density of macroinvertebrates at both site types could determine if any relation occurs between prey availability and food intake. Hydrologic and temperature variables did not explain a high amount of variation in average daily incremental growth rates; however the importance of the role of flow and temperature regimes in regulated rivers should not be ignored.

Our analysis suggests that the number of reversals, number of hours discharge was between 0 – 60 cms and the number of cumulative degree days were important predictors of hatch success of Redbreast Sunfish. We agree with Irwin and Freeman (2002) and Irwin et al. (1997) that lower water temperatures from pulsing hypolimnetic releases likely delays spawning periods, impedes hatching success, and decreases rates of larval development. Redbreast Sunfish initiate spawning when water temperatures are between 20 – 25 ° C. However after generation events at R. L. Harris dam, downstream temperatures are known to decrease as much as 10 °C (see Figures 2-16-19). These often sudden changes (within hours of the generation events) in water temperature decrease the number of degree days needed for eggs to hatch and mature. Redbreast Sunfish spend much time and investment on parental care during spawning seasons (e.g. aerating and fanning eggs). Without the care of the adult male, nests likely do not survive. Males are also known to abandon their nest and presumably seek refuge from the increased discharge during 2-unit generation events (Martin 2008). Andress (2002) and Martin (2008) reported a decrease in nest success as a result of increased discharge from 2-unit generation events.

Hatch date estimates in this study support the hypothesis that successful recruitment is related to flow regime (Irwin et al. 1997). Comparisons of hatch frequencies and discharge in

2007 and 2008 indicated that most fish hatched during periods where discharge was less than 220 cms. Stable flow periods may provide greater availability of suitable spawning and juvenile habitat, temperature regimes that cue the onset of spawning, and flow conditions that encourage parental care of nests provided by adult Redbreast Sunfish. Martin (2008) reported that when discharge events were greater than 200 cms, adult Redbreast Sunfish frequently deserted their nests resulting in nest failure. Stable flow and temperature periods will likely increase survival, growth rates and increase subsequent recruitment. Stable flow and temperature periods during rearing windows will allow juveniles the opportunity to grow to a size where they can either withstand daily fluctuations, or allow individuals to seek refuge in available habitats or nearby tributaries. In 2005, increased rainfall resulted in higher and more frequent discharge from R. L. Harris Dam. The resulting wet water year may be attributed to fewer hatches. Subsequently, 2007 and 2008 were classified as drought water years (E. Irwin, unpublished data) and a higher number of hatches occurred in those years.

Specific temporal initiation and duration of Redbreast Sunfish spawning periods play an important role in determining appropriate management strategies for the species. It is critically important, especially in regulated rivers, that spawning times be determined and protected. The timing and periodicity of hatching relative to the timing of biotic events (e.g. hatch and swim-up) and abiotic conditions (e.g. flow and water temperature) has an impact on growth, survival, and recruitment of age-0 Redbreast Sunfish. In a system as highly variable as the Tallapoosa River, it would certainly benefit a juvenile fish to grow fast during early life history stages. Larger individuals typically have a greater chance of recruiting to the adult population due to body size decreasing vulnerability to starvation, predation, and other various environmental variables (Sogard 1997). Early hatches would typically be exposed to longer growing seasons than late hatches, and therefore may reach larger sizes and have higher survival during their first year of life (Cargnelli and Gross 1996; Ludsin and DeVries 1997). Variation in daily growth rates of age-0 centrarchids has been related to hatch timing; these relations were attributed to temporal patterns in ontogenetic diet shifts (Timmons et al. 1980; Ludsin and DeVries 1997) and water temperatures at the time of hatching (Sabo and Orth 1995; Pine and Allen 2001; Santucci and Wahl 2003). Ludsin and DeVries (1997) reported that early-hatched cohorts of Largemouth Bass *Micropterus salmoides,* in Alabama ponds, had a competitive advantage leading to higher first-year recruitment rates versus cohorts hatched later in the year. However in our study we did not observe early hatched individuals exhibiting faster average daily growth rates compared to later hatched fish. Sammons et al. (2001) reported that earlier hatched age-0 White Crappie *Pomoxis annularis,* grew at a slower rate than later-hatched White Crappie in a Tennessee Reservoir. Differences in growth were attributed to warmer water temperatures experienced by later-hatched fish. It should be noted that the dynamics of ponds and reservoir systems vary highly compared to riverine systems; therefore comparison of results should take into account these vast differences.

Our data for 2005 and 2007, suggest that the majority of hatches occured between July and August. These dates are slightly inconsistent with Andress (2002) and Martin (2008) who suggested a spawning window (prolonged periods of stable low flow <250 m^3/s) of 10-11 calendar days during the 2nd and 3rd weeks in June. However, 2009 was the only year in this study where we estimated that the majority of hatches occurred in June and July (normal water year). Size attained by age-0 centrarchids has frequently been shown to be related to timing of hatch, where earlier-hatched individuals generally attain larger sizes than fish hatched later (Goodgame and Miranda, 1993; Cargnelli and Gross; 1996; Ludsin and DeVries, 1997; Phelps et al., 2008). We concluded that hatching success could be improved by the provision of spawning window periods; however the exact timing of the spawning window may need to vary from year to year. Periods of stable low flow are expected to provide spawning fish and their nests refugia from higher, less stable flows and increase hatching success (Irwin et al. 1997). We recommend that spawning windows should continue to be implemented as a management action (E.R. Irwin, unpublished data) to increase spawning and hatching success of Redbreast Sunfish. However, we also recommend that the timing of spawning windows be determined annually, based on weather conditions and water availability in the system. This recommendation allows management to remain flexible while allowing managers to make decisions based on the yearly needs of the system.

Previous studies have used a similar sampling design as this study to estimate hatch dates of black basses (Sabo and Orth 1995; Ludsin and DeVries 1997; Sammons et al. 1999); however questions may arise as to whether this type of design is sufficient to account for the full range of Redbreast Sunfish hatching dates. Age-0 fish collected in this study are essentially survivors, and our design cannot account for fish that did not survive until the point of our collections. A wider range of hatch dates may exist at our study sites. However we feel that our sampling design of using PAE's coupled with back pack electrofishers during spring/summer and fall each year were robust enough to address our objectives.

Our data also suggest that manipulating the instream flow and temperature regime during the spawning season with periods of pulsed-low flow generation might be a powerful tool for managing fish communities in regulated rivers. By managing instream flows and temperatures to favor reproduction, hatch and rearing of Redbreast Sunfish, subsequent recruitment should increase. Additionally maintaining a productive recreational fishery for Redbreast Sunfish and other centrarchids could require other management alternatives, such as creel or length limits, depending on fishery objectives. We agree with Irwin and Freeman (2002), King et al. (2010), and Olden and Naiman (2010) that any recommended manipulations should take place within the adaptive management framework, and stakeholder objectives should be included in any potential management plan. Adaptive management is an approach that incorporates uncertainty, such as that due to environmental variation or incomplete understanding of system dynamics, and knowledge gained through the scientific process to prescribe flexible scenarios for the conservation and management of resources (Walters 1997). Because large-scale system manipulations (i.e., flow management experiments) are being conducted downstream of R. L. Harris Dam, ultimately our data can be used to help predict consequences of management on Redbreast Sunfish recruitment success.

Table 2-1. List of independent variables generated to explain average daily incremental growth of age-0 Redbreast Sunfish from sites in the Tallapoosa River, AL. Regulated, FLOW3, FLOW5, REV, and TEMP2 were not included in the global, model and not together in individual models due to collinearity.

Variable	**Definition**
REV	Number of times the hydrograph changed direction /10 d prior to the date of age increment per individual
FLOW1	Number of hours discharge greater than 220 cms /10 d prior to the date of age increment per individual; similar to 2-unit generation
FLOW3	Number of hours discharge between 60 - 220 cms /10 d prior to the date of age increment per individual; similar to 1-unit generation
FLOW5	Number of hours discharge between 0 - 60 cms /10 d prior to the date of age increment per individual; similar to pulse generation
TEMP1	Number of Cumulative degree days/10 d prior to the date of age increment per individual
TEMP2	Median change in temperature (°C)/ 10 d prior to the date of age increment per individual
DOY.Inc	Day of year corresponding to the date of each 10 d age increment per individual
DOY. H	Day of year corresponding to the date of hatch of each individual

Table 2-2. List of independent variables generated to predict hatch success of age-0 Redbreast Sunfish from sites in the Tallapoosa River, AL. Regulated, FLOW3, FLOW5, REV, and TEMP2 were not included in the global model, and not together in individual models due to collinearity.

Variable	**Definition**
REV	Number of times the hydrograph changed direction /10 d prior to the date of hatch per individual
FLOW1	Number of hours discharge greater than 220cms /10 d prior to the date of hatch per individual; similar to 2-unit generation
FLOW3	Number of hours discharge between 60 - 220 cms /10 d prior to the date of hatch per individual; similar 1-unit generation
FLOW5	Number of hours discharge between 0 - 60 cms /10 d prior to the date of hatch per individual; similar to pulse generation
TEMP1	Number of Cumulative degree days/10 d prior to the date of hatch per individual
TEMP2	Median change in temperature (°C)/10 d prior to the date of hatch per individual

Table 2-3. Age (days) and overall daily growth (mm/day) ranges of age-0 Redbreast Sunfish collected at regulated and unregulated sites in the Tallapoosa River, AL.

Site Type	**Year**	**n**	**Age (days)**	**Daily Growth Rate (mm/day)**
Regulated	2005	7	64-106	1.03-1.44
	2007	39	32-68	0.39-1.17
	2008	79	30-99	0.34-1.52
	2009	115	26-76	0.25-1.46
Unregulated	2005	21	37-118	0.66-1.69
	2007	44	25-73	0.29-1.31
	2008	161	24-117	0.27-1.80
	2009	117	28-81	0.31-1.15

Table 2-4. Candidate models from multiple and linear regression models describing average daily incremental growth of age-0 Redbreast Sunfish. The model with the lowest AIC_c value was considered the best model and received the most support among the candidate models. Number of parameters in each model (K), AIC_c, ΔAIC, AIC model weights (w_i) and R^2 values are given. All age increments are included in the variable Age (0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, and 70-80 days).

Model	**K**	**AICc**	**ΔAIC_c**	**w_i**	**R^2**
Regulated*Age+Regulated*Year+Regulated*DOY.Inc+ Regulated*FLOW1+Regulated*TEMP1	**28**	**6389.70**	**0.00**	**0.660**	**0.07**
Age+Regulated*Year	16	6393.20	3.48	0.116	0.07
REV*AGE+REV*Year+REV*DOY.Inc+REV*FLOW5+REV*TEMP1	29	6394.10	4.37	0.074	0.07
REV*AGE+REV*Year+REV*DOY.Inc+REV*FLOW3+REV*TEMP1	29	6394.60	4.84	0.059	0.07
Regulated*AGE+Regulated*Year	23	6395.30	5.59	0.040	0.07
REV*AGE+REV*Year+REV*DOY.Inc+REV*FLOW1+REV*TEMP1	29	6395.80	6.08	0.032	0.07
Regulated*AGE+Regulated*DOY.Inc+Regulated*FLOW3+ Regulated*TEMP1+Year	26	6398.20	8.43	0.010	0.07
Regulated*AGE+Regulated*DOY.Inc+Regulated*FLOW5+ Regulated*TEMP1+Year	26	6398.20	8.43	0.010	0.07
Regulated+Age+Year	13	6408.90	19.18	0.000	0.06
Regulated*Age+Year	20	6409.80	20.09	0.000	0.07
Age+Year	12	6412.20	22.49	0.000	0.06
Regulated+Age	10	6430.80	41.06	0.000	0.06
Regulated*Age	17	6431.60	41.90	0.000	0.06
Regulated*Age	9	6437.60	47.89	0.000	0.05
Regulated*Year	9	6562.70	172.96	0.000	0.01
DOY.Inc	3	6574.00	184.24	0.000	0.01
Regulated+Year	6	6574.90	185.19	0.000	0.01
Year	5	6577.30	187.56	0.000	0.01
FLOW1	3	6586.10	196.38	0.000	0.00
TEMP2	3	6592.40	202.65	0.000	0.00
FLOW3	3	6592.80	203.04	0.000	0.00
FLOW5	3	6593.50	203.74	0.000	0.00
Regulated	3	6594.80	205.09	0.000	0.00
REV	3	6595.30	205.57	0.000	0.00
Null	2	6599.90	210.15	0.000	0.00
TEMP1	3	6600.30	210.53	0.000	0.00

Table 2-5. Candidate models from multiple and linear regression models describing average daily incremental growth of age-0 Redbreast Sunfish. The model with the lowest AIC$_c$ value was considered the best model and received the most support among the candidate models. Number of parameters in each model (K), AIC$_c$, ΔAIC$_c$, AIC model weights (w_i) and R^2 values are given. All age increments are included in the variable Age (0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, and 70-80 days).

Model	**K**	**AIC$_c$**	**ΔAIC$_c$**	**w_i**	**R^2**
Regulated*Age+Regulated*Year+Age*Year	**65**	**664.5**	**0**	**1**	**0.33**
Age+Regulated*Year	16	721.4	56.93	0	0.32
Regulated*Age	20	793.3	128.82	0	0.31
Regulated+Age+Year	13	809	144.49	0	0.3
Regulated*Age+Year	34	814.7	150.25	0	0.31
Age+Year	12	863.5	199.04	0	0.3
Regulated*Age	17	1278.3	613.82	0	0.23
Regulated+Age	10	1292.9	628.4	0	0.23
Age	9	1322.4	657.88	0	0.23
Regulated*Year	9	2120.1	1455.67	0	0.09
Regulated+Year	6	2178.3	1513.79	0	0.08
Year	5	2218.2	1553.71	0	0.07
Regulated	3	2543.8	1879.27	0	0
Null	2	2565.3	1900.87	0	0

Table 2-6. Candidate models from single and multiple logistic regression models predicting hatch success of age-0 Redbreast Sunfish. The model with the lowest AIC_c value was considered the best model and received the most support among the candidate models. Number of parameters in each model (K), logLik (log likelihood), AIC_c, ΔAIC_c, and AIC model weights (w_i) values are given.

Model	K	**logLik**	**AIC_c**	**ΔAIC_c**	**w_i**
REV+FLOW5+TEMP1+Year	**7**	**-450.71**	**915.60**	**0.00**	**0.63**
FLOW5+Year	5	-454.03	918.10	2.57	0.17
TEMP2+FLOW5+Year	6	-454.03	920.20	4.60	0.06
Regulated+FLOW1+TEMP1+Year	7	-453.08	920.30	4.74	0.06
REV+FLOW1+TEMP1+Year	7	-453.13	920.40	4.83	0.06
REV+FLOW3+TEMP1+Year	7	-454.86	923.90	8.29	0.01
FLOW1+Year	5	-457.74	925.60	9.99	0.00
TEMP1+Year	5	-458.33	926.70	11.16	0.00
TEMP1+TEMP2+Year	6	-458.29	928.70	13.11	0.00
FLOW3+Year	5	-459.55	929.20	13.61	0.00
Regulated+Year	5	-463.34	936.80	21.19	0.00
REV+Year	5	-464.14	938.40	22.79	0.00
TEMP2+Year	5	-466.16	942.40	26.83	0.00
TEMP2+FLOW5	3	-493.56	993.10	77.58	0.00
REV+FLOW5+TEMP1	4	-494.03	996.10	80.55	0.00
REV+FLOW1+TEMP1	4	-494.77	997.60	82.02	0.00
FLOW5	2	-500.30	1004.60	89.05	0.00
Regulated+FLOW1+TEMP1	4	-498.50	1005.10	89.49	0.00
FLOW1	2	-500.76	1005.50	89.97	0.00
TEMP2	2	-503.48	1011.00	95.41	0.00
REV+FLOW3+TEMP1	4	-501.69	1011.40	95.86	0.00
TEMP1+TEMP2	3	-503.45	1012.90	97.36	0.00
REV	2	-505.60	1015.20	99.64	0.00
FLOW3	2	-507.23	1018.50	102.91	0.00
Regulated	2	-508.60	1021.20	105.65	0.00
Null	1	-509.93	1021.90	106.30	0.00
T1	2	-509.47	1023.00	107.38	0.00

Table 2.7. Estimates of effect for variables included in logistic regression models predicting hatch success. Coefficient estimates θ, standard error (SE), and confidence intervals (based on the log-likelihood function), are given.

Variable	Model Coefficient (θ)	SE	95% C.I.
REV	0.003	0.004	-0.004 – 0.011
F5	0.011	0.003	0.005 – 0.018
T1	0.004	0.002	0.001 – 0.008
Year 2007	-0.592	0.353	-1.278 – 0.111
Year 2008	0.695	0.317	0.084 – 1.334
Year 2009	1.855	0.333	1.215 – 2.525

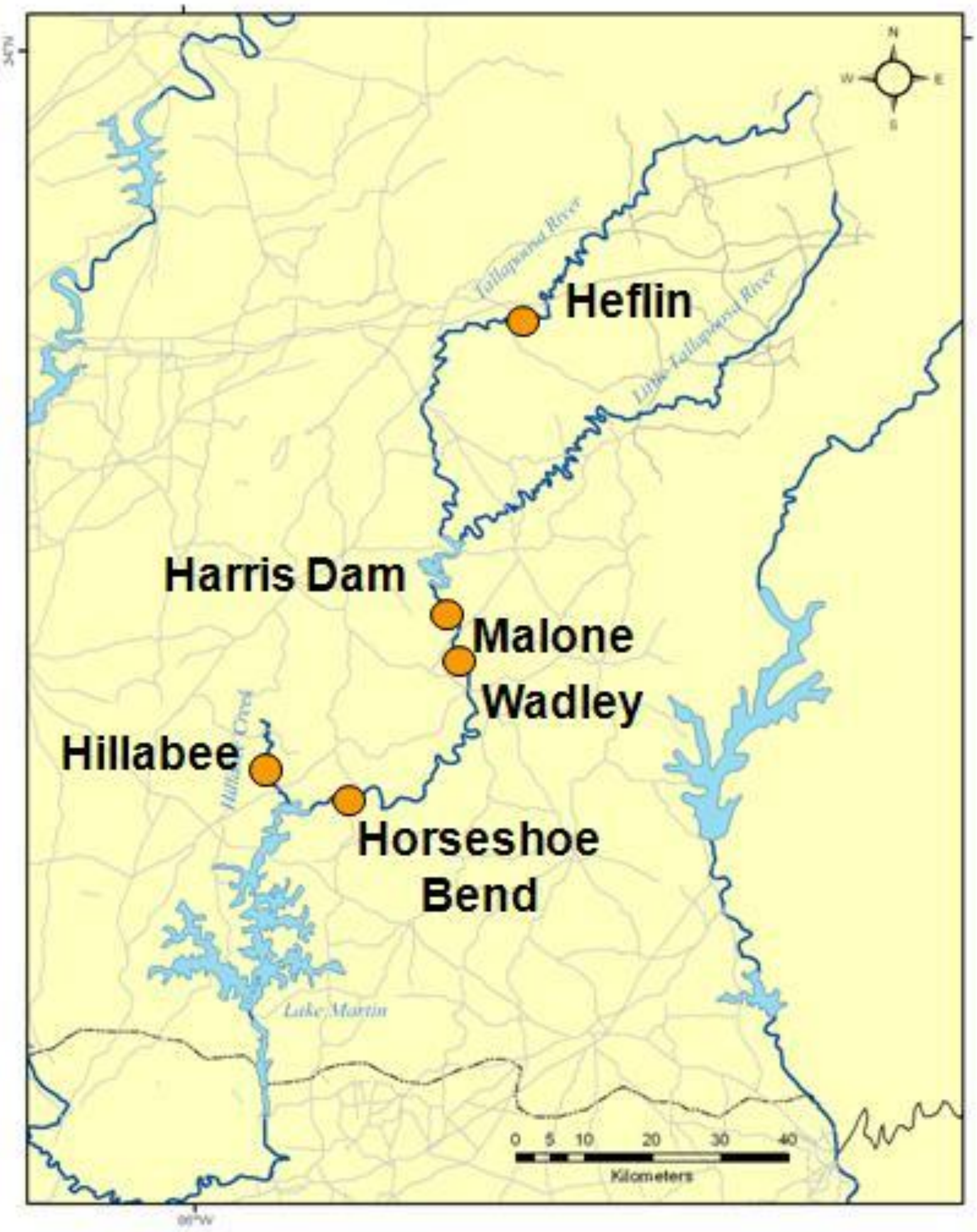


Figure 2-1. Map of sampling locations for this project, between Heflin, AL and Horseshoe Bend National Military Park Daviston, AL in the Tallapoosa River, AL.

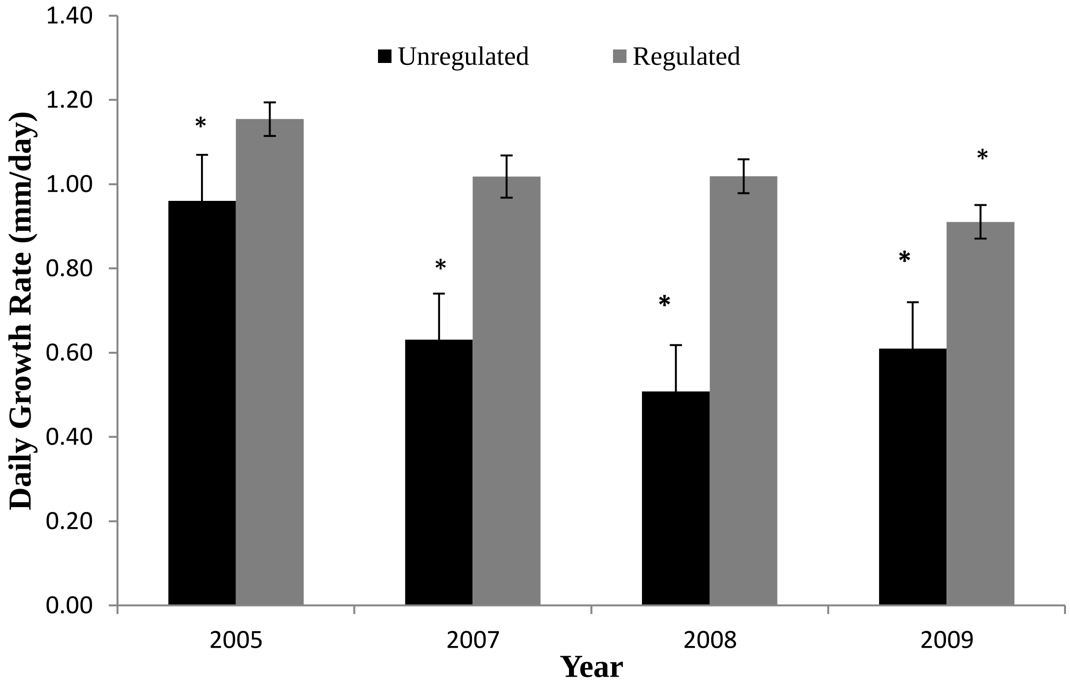


Figure 2-2. Daily growth rates by year of age-0 Redbreast Sunfish at regulated and unregulated sites in the Tallapoosa River, AL* indicates significance at $p < 0.05$.

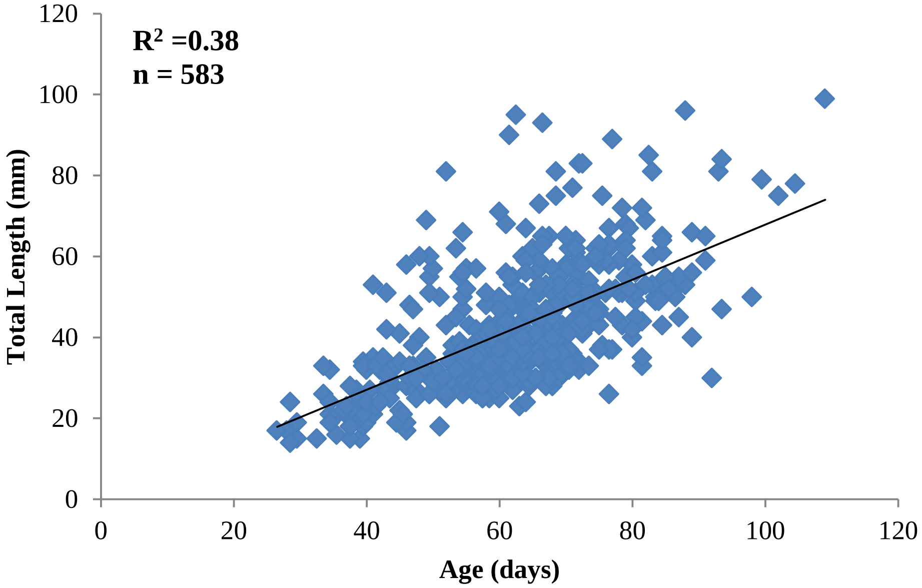


Figure 2-3. Positive relation between total length (mm) and age (days) of age-0 Redbreast Sunfish from regulated and unregulated sites in the Tallapoosa River, AL.

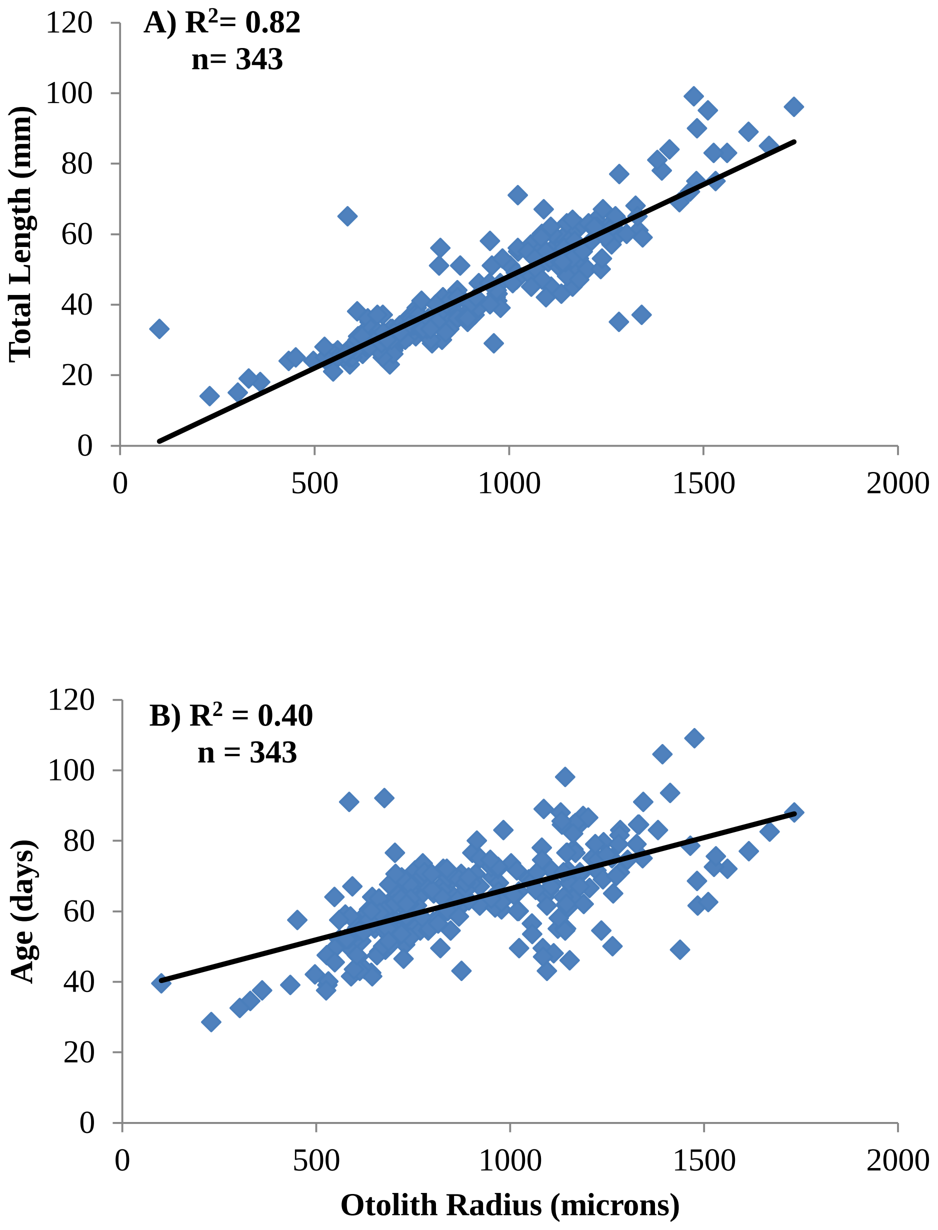


Figure 2-4. Relationship between A) total length and otolith radius and B) age and otolith radius for age-0 Redbreast Sunfish from unregulated sites in the Tallapoosa River, AL.

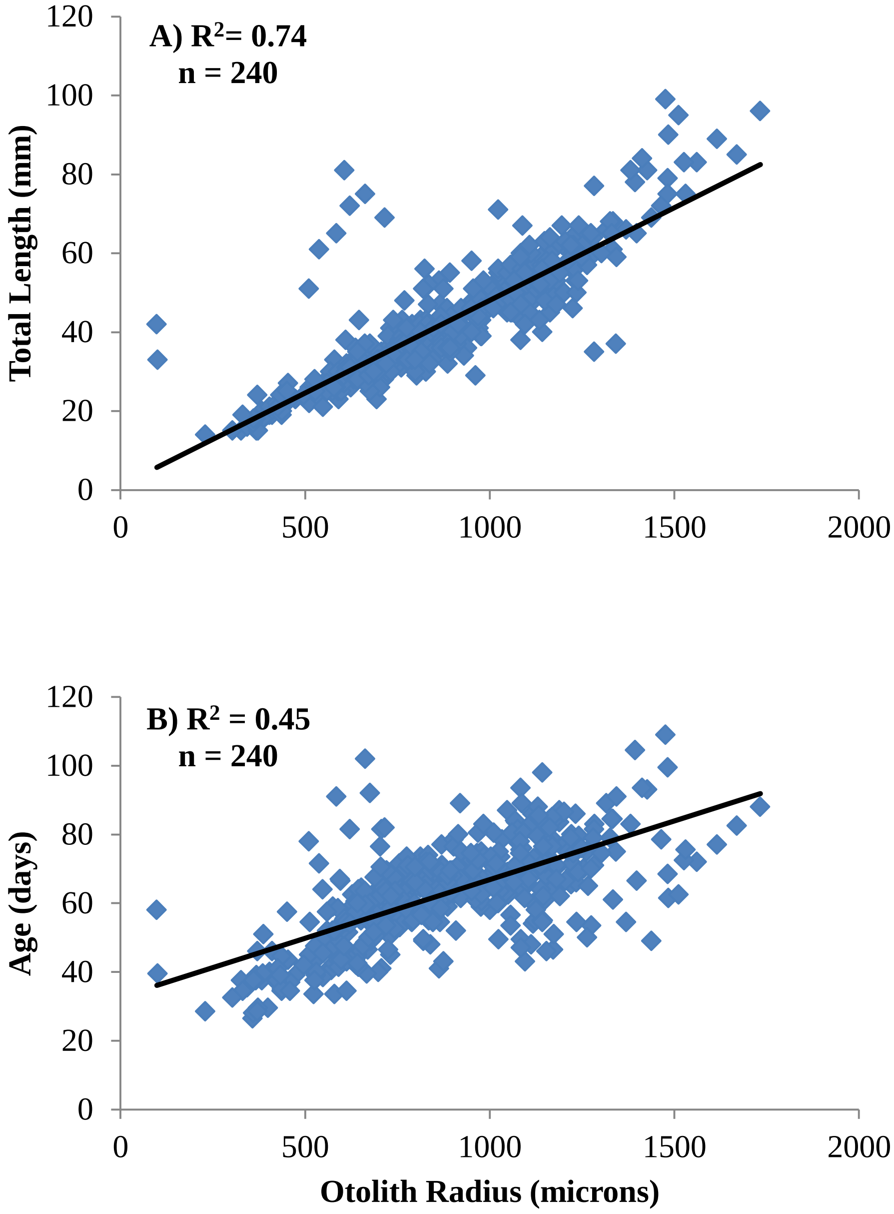


Figure 2-5. Relationship between A) total length and otolith radius and B) age and otolith radius for age-0 Redbreast Sunfish from regulated sites in the Tallapoosa River, AL.

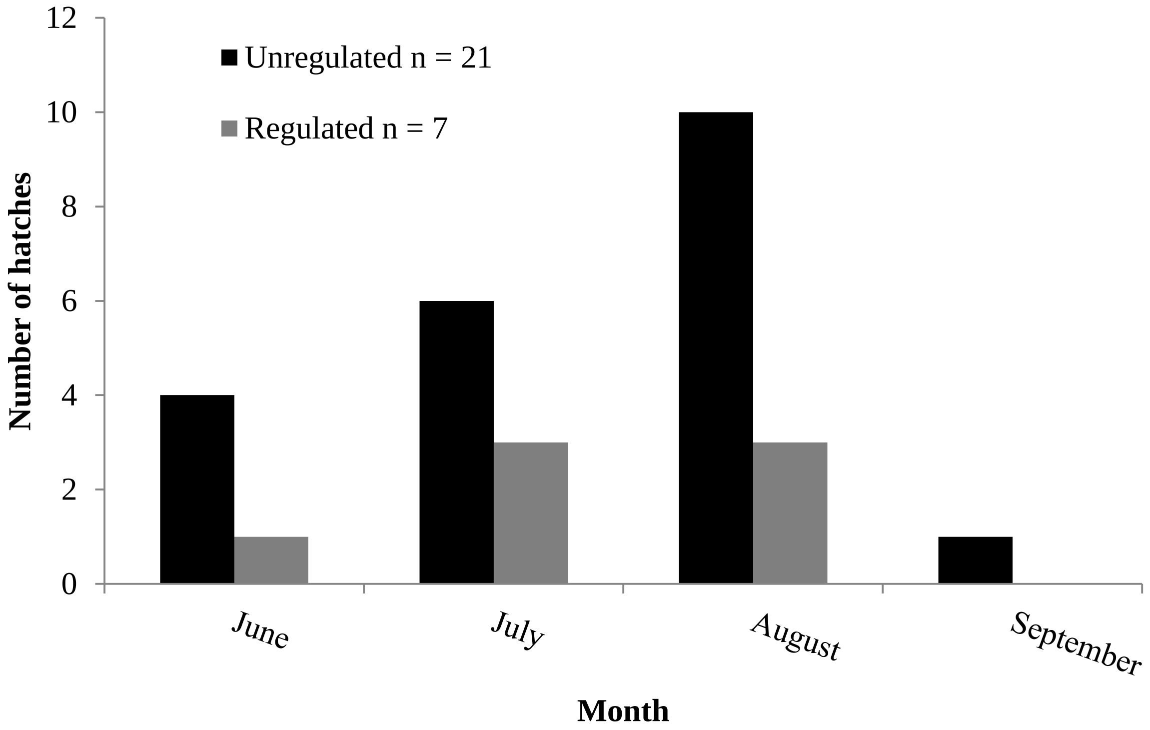


Figure 2-6. Hatch frequencies by month for age-0 Redbreast Sunfish from unregulated and regulated sites in the Tallapoosa River, AL in 2005.

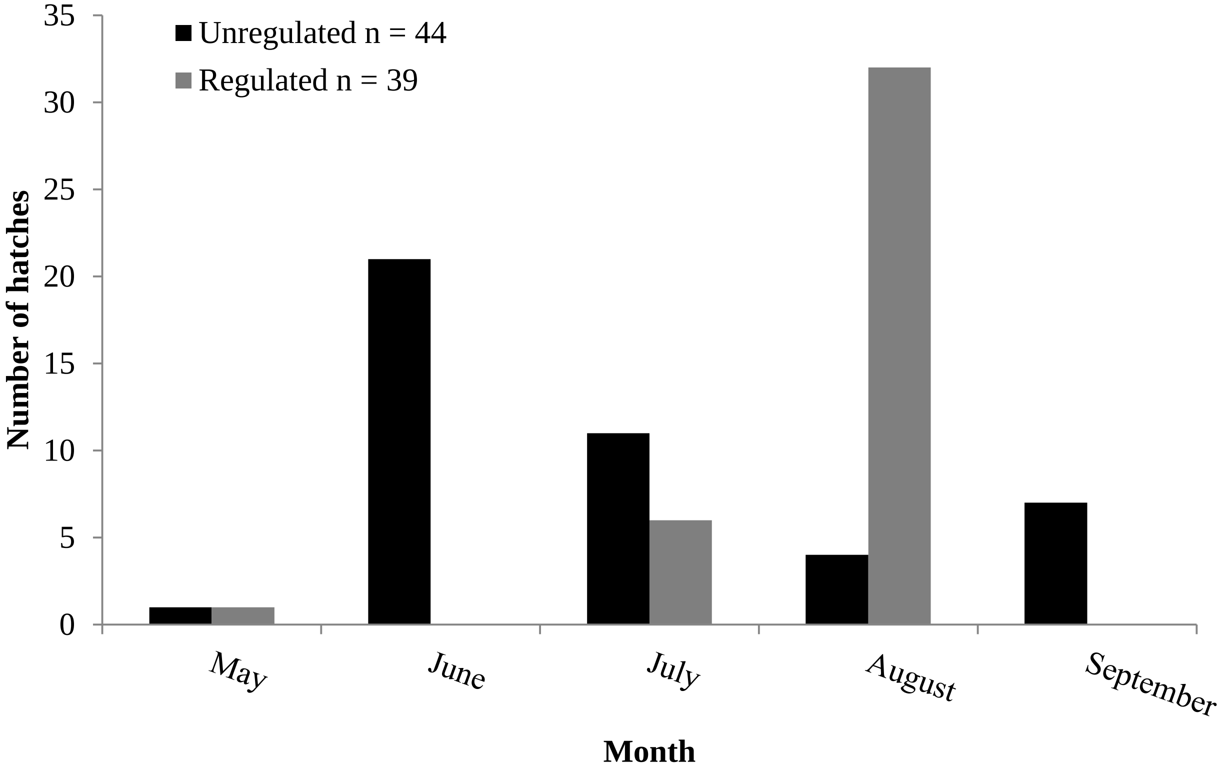


Figure 2-7. Hatch frequencies by month for age-0 Redbreast Sunfish from unregulated and regulated sites in the Tallapoosa River, AL in 2007.

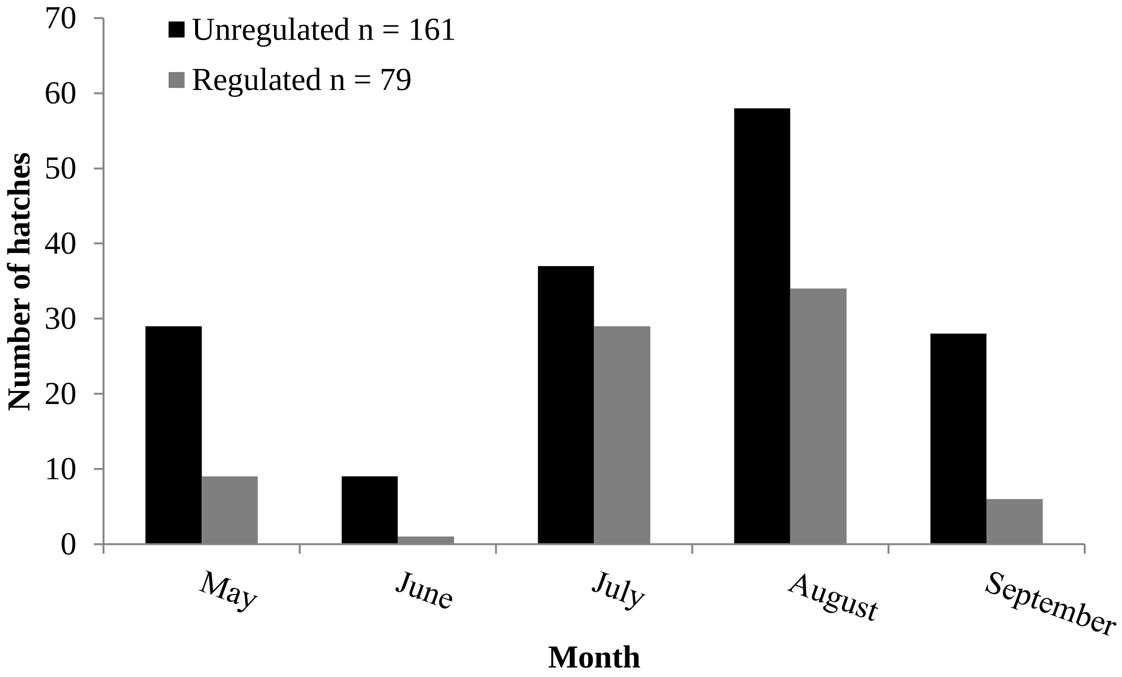


Figure 2-8. Hatch frequencies by month for age-0 Redbreast Sunfish from unregulated and regulated sites in the Tallapoosa River, AL in 2008.

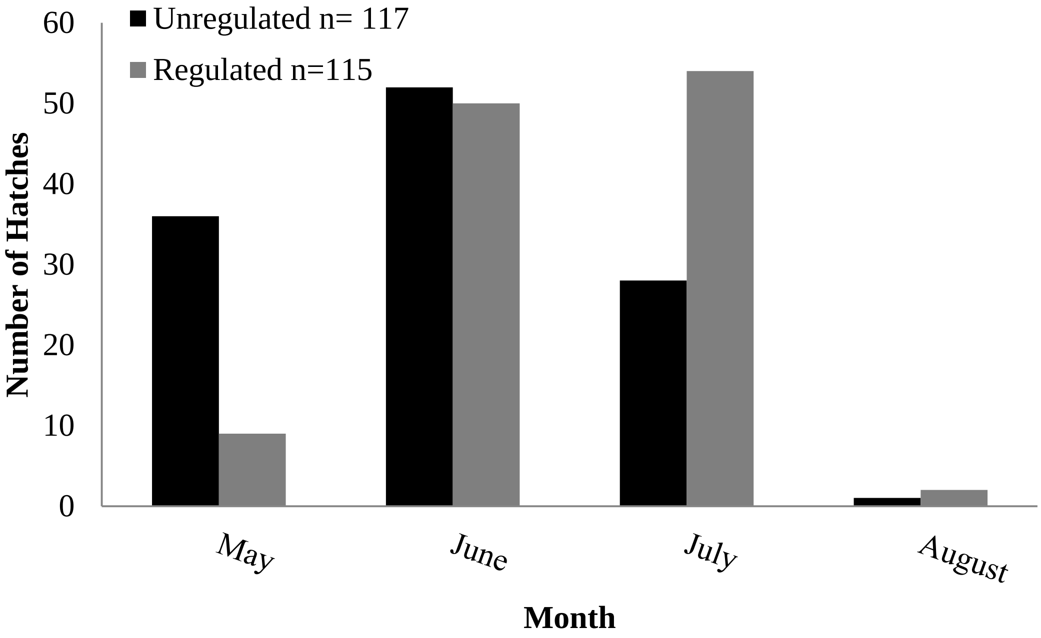
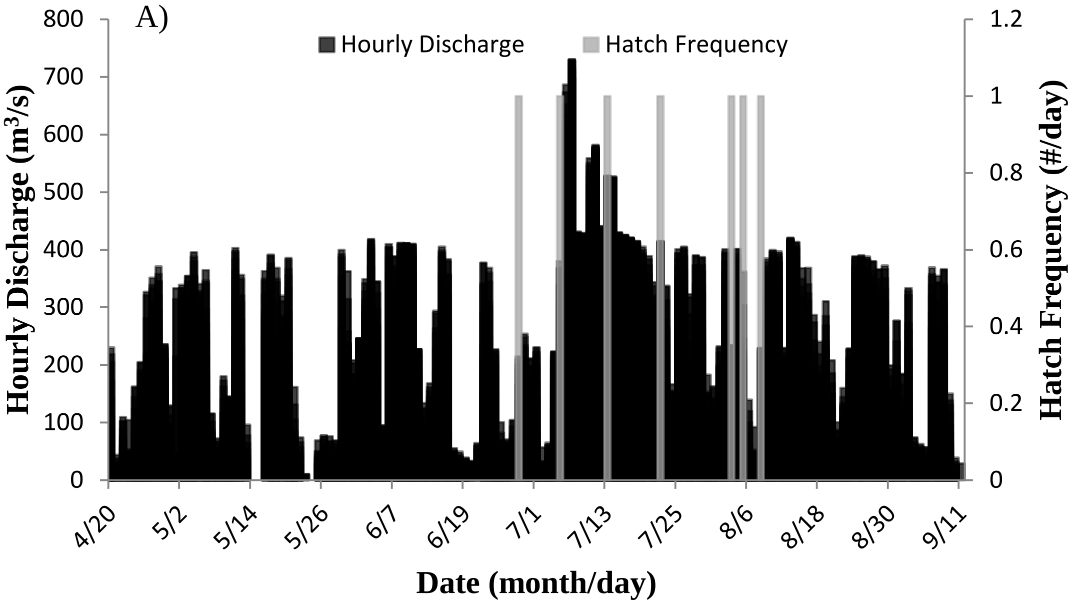


Figure 2-9. Hatch frequencies by month for age-0 Redbreast Sunfish from unregulated and regulated sites in the Tallapoosa River, AL in 2009.



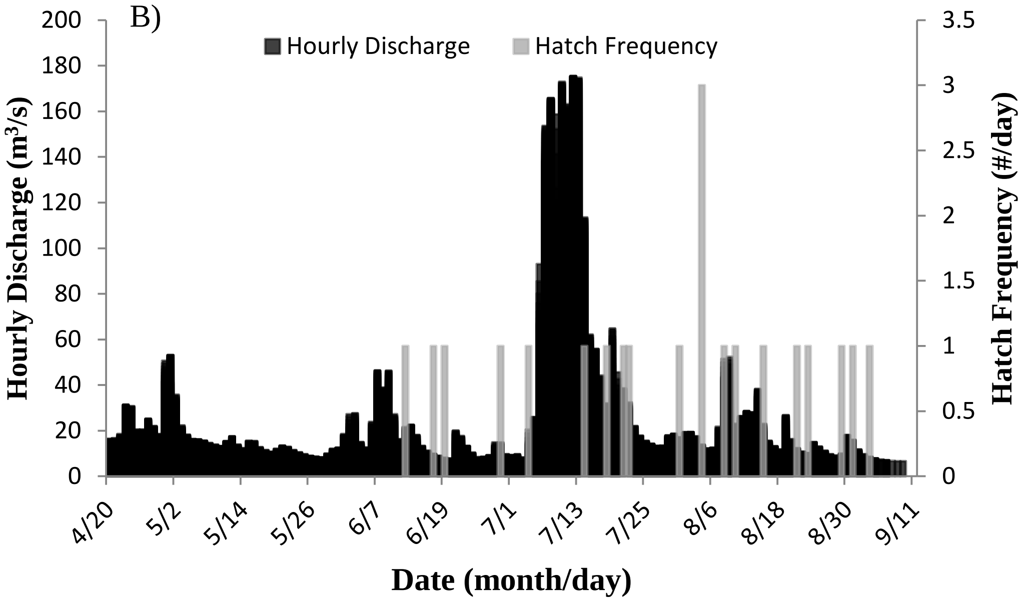


Figure 2-10. Hourly discharge and hatch frequency of Redbreast Sunfish at regulated (A) and unregulated (B) sites in the Tallapoosa River, AL in 2005.

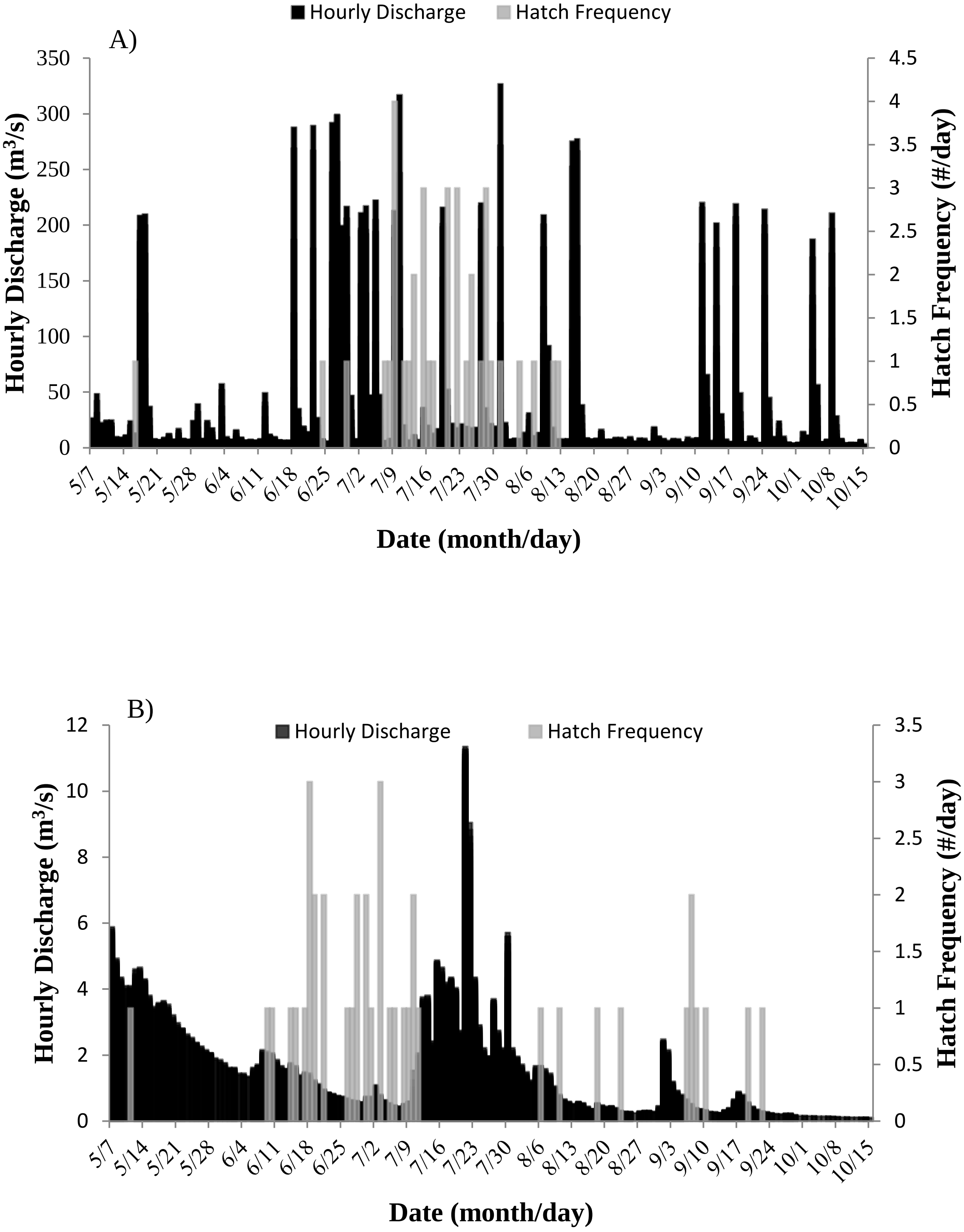


Figure 2-11. Hourly discharge and hatch frequency of Redbreast Sunfish at regulated (A) and unregulated (B) sites in the Tallapoosa River, AL in 2007.

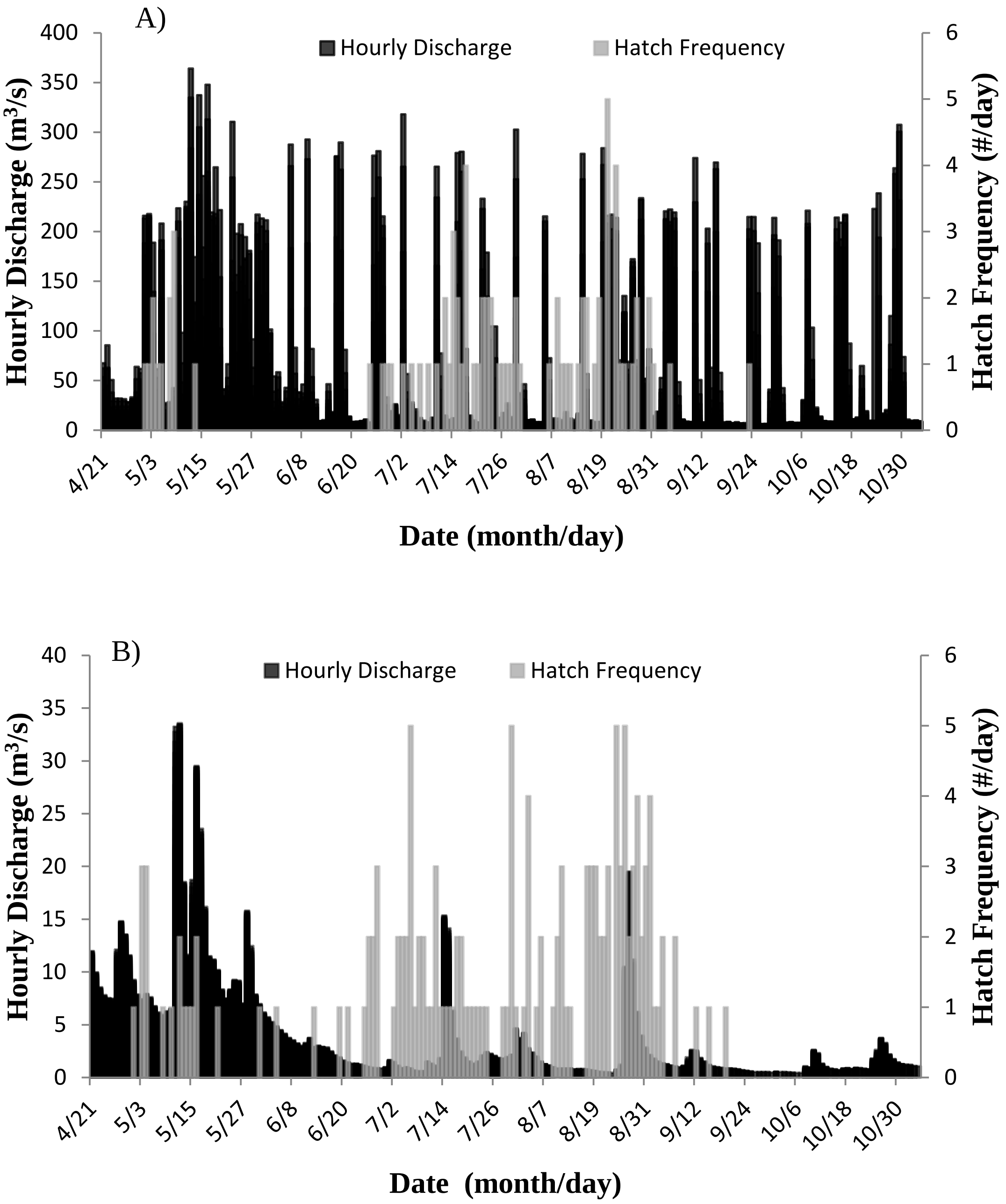


Figure 2-12. Hourly discharge and hatch frequency of Redbreast Sunfish at regulated (A) and unregulated (B) sites in the Tallapoosa River, AL in 2008.

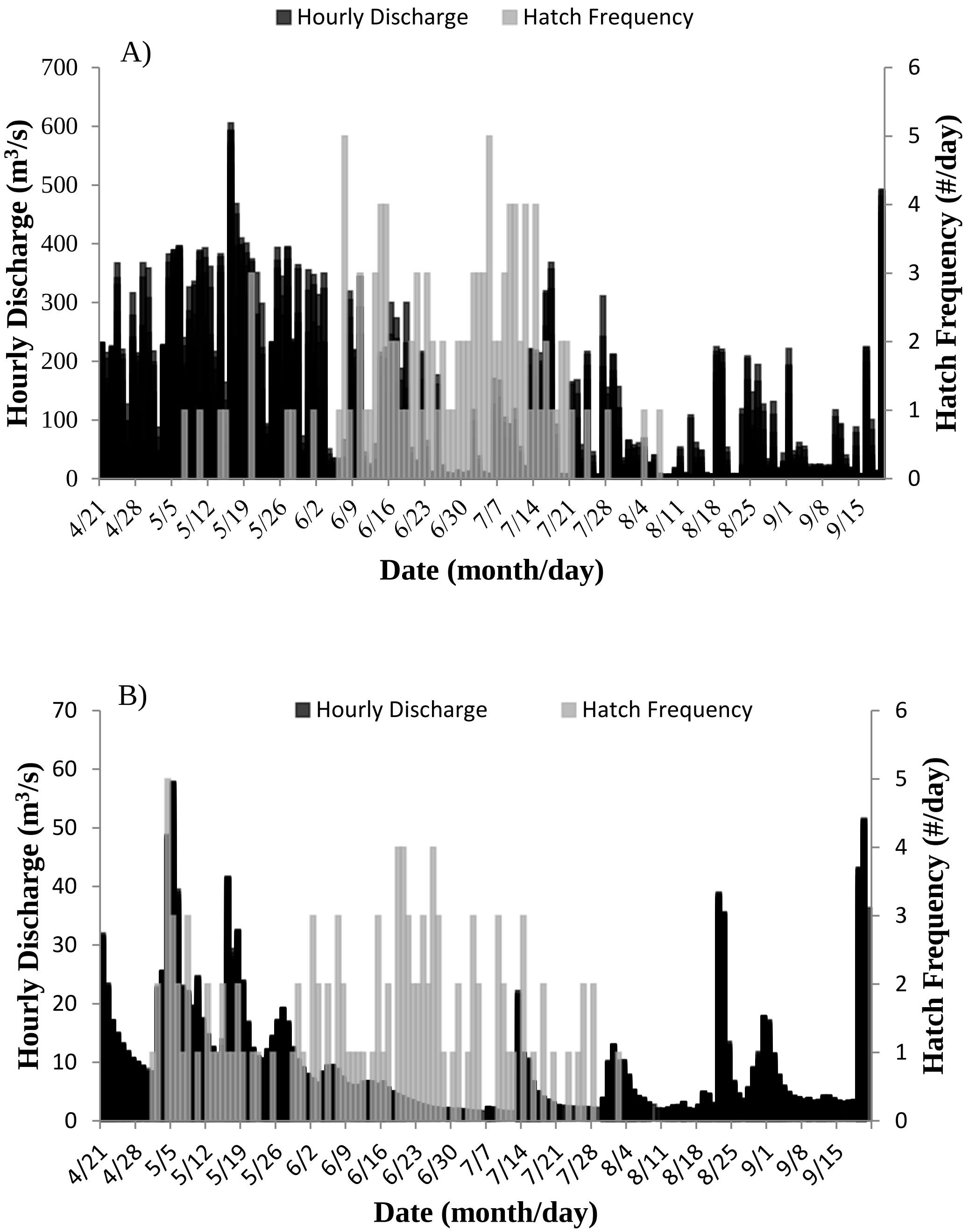


Figure 2-13. Hourly discharge and hatch frequency of Redbreast Sunfish at regulated (A) and unregulated (B) sites in the Tallapoosa River, AL in 2009.

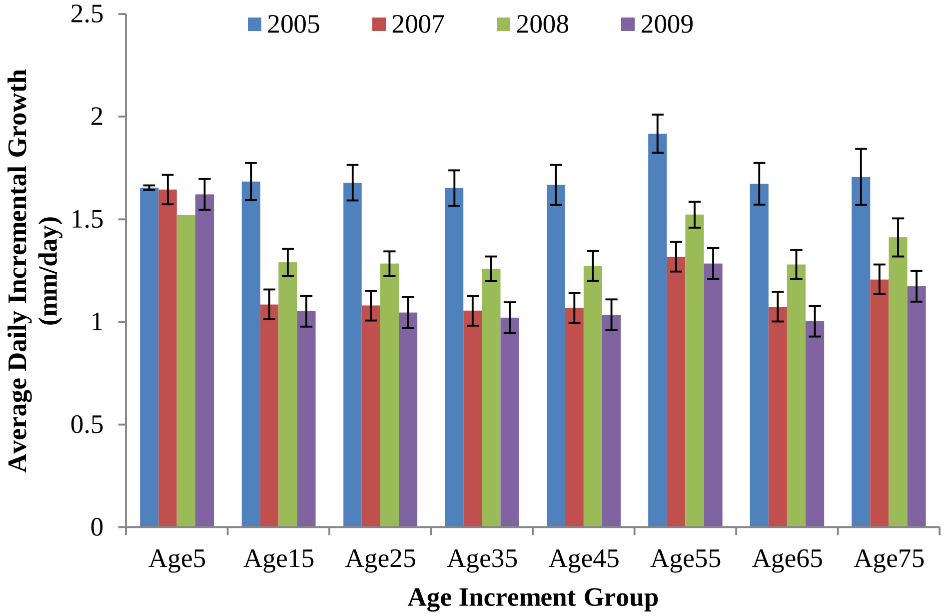


Figure 2-14. Average daily incremental growth (mm/day ± SE) of Redbreast Sunfish by year and age increment group (Age 5: 0-10, Age 15: 10-20, Age 25: 20-30, Age 35: 30-40, Age45: 40-50, Age55: 50-60, Age 65: 60-70, and Age 75: 70-80 days), at regulated sites in the Tallapoosa River, AL.

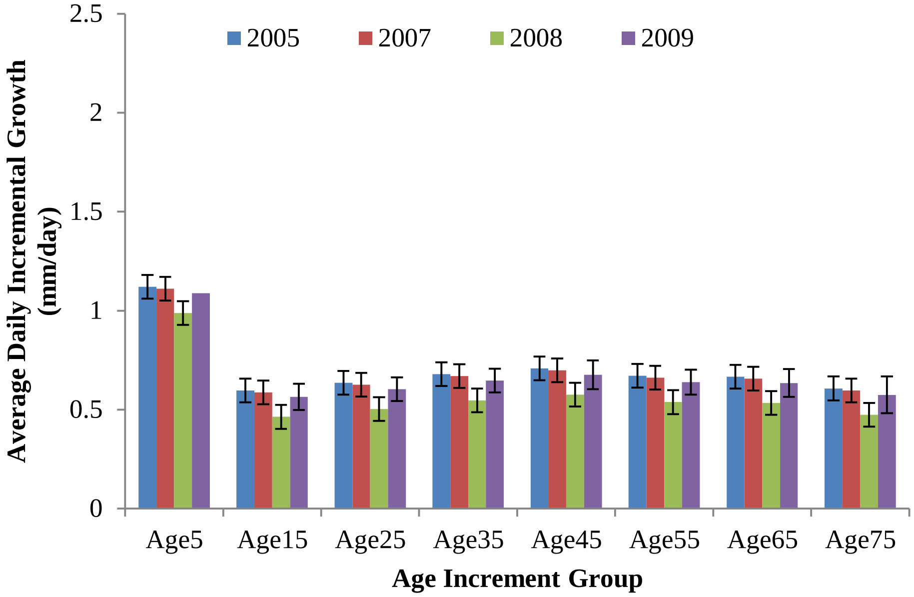


Figure 2-15. Average daily incremental growth (mm/day ± SE) of Redbreast Sunfish by year and age increment group (Age 5: 0-10, Age 15: 10-20, Age 25: 20-30, Age 35: 30-40, Age 45: 40-50, Age 55: 50-60, Age 65: 60-70, and Age 75: 70-80 days), at unregulated sites in the Tallapoosa River, AL.

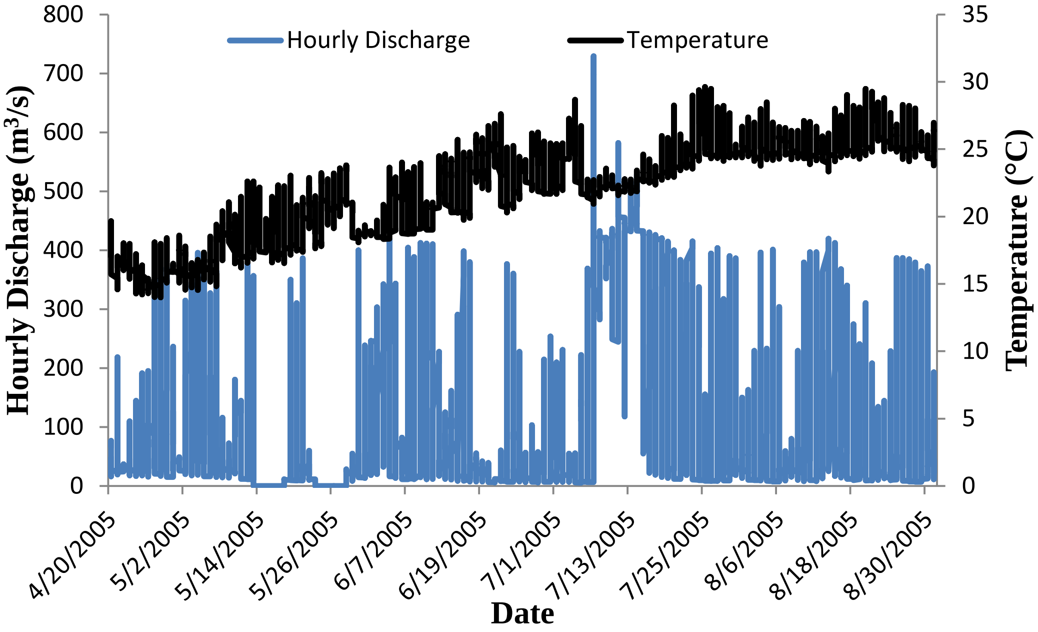


Figure 2-16. Hourly discharge (m^3/s; left y-axis) and hourly water temperature (°C; right y-axis) recorded from the USGS gage at Wadley, AL (02414500) and Alabama Power Company temperature logger at the Wadley Bridge, respectively (20 April – 31 October 2005). Discharges from Harris Dam between 150-200 m^3/s represent a one-unit generation, and discharges greater than 250 m^3/s represent a two-unit generation.

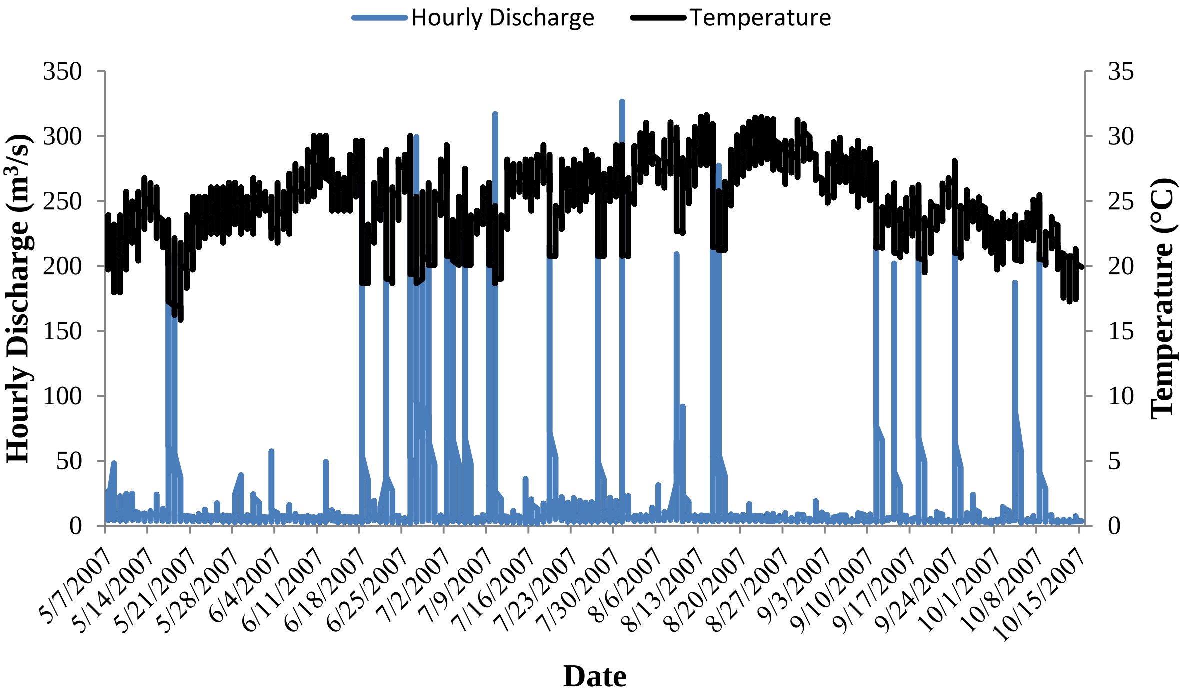


Figure 2-17. Hourly discharge (m^3/s; left y-axis) and hourly water temperature (°C; right y-axis) recorded from the USGS gage at Wadley, AL (02414500) and Alabama Power Company temperature logger at the Wadley Bridge, respectively (7 May – 15 October 2007). Discharges from Harris Dam between 150-200 m^3/s represent a one-unit generation, and discharges greater than 250 m^3/s represent a two-unit generation.

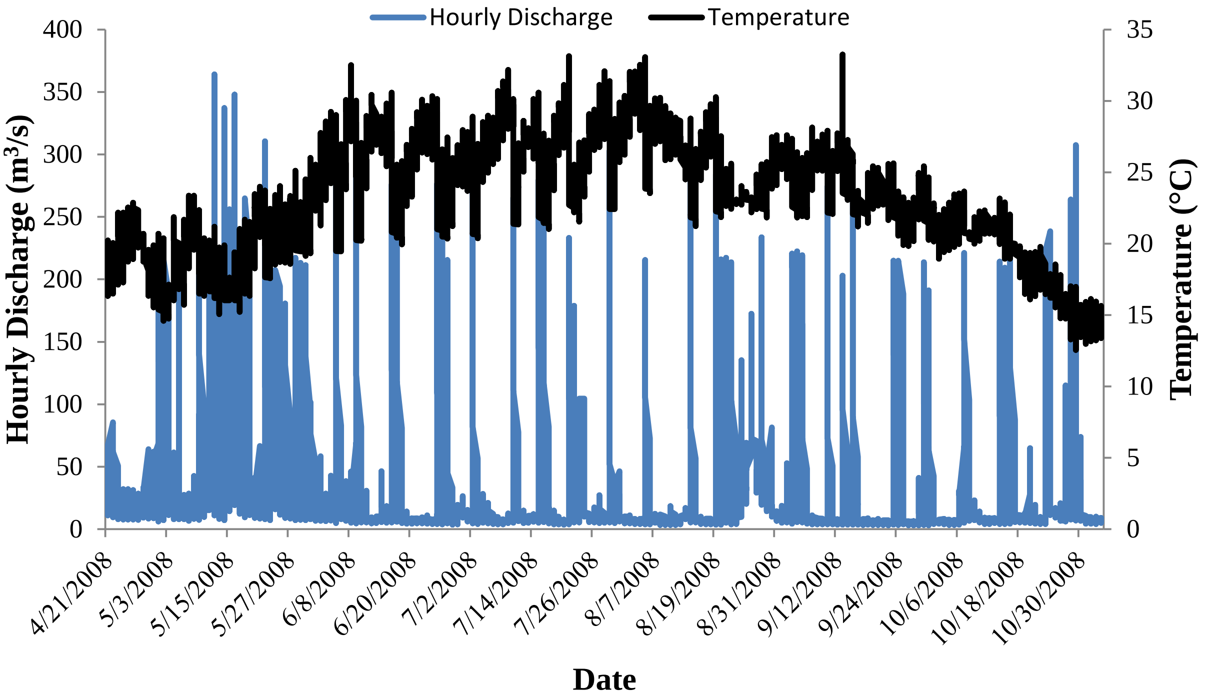


Figure 2-18. Hourly discharge (m^3/s; left y-axis) and hourly water temperature (°C; right y-axis) recorded from the USGS gage at Wadley, AL (02414500) and Alabama Power Company temperature logger at the Wadley Bridge, respectively (21 April – 3 November 2008). Discharges from Harris Dam between 150-200 m^3/s represent a one-unit generation, and discharges greater than 250 m^3/s represent a two-unit generation.

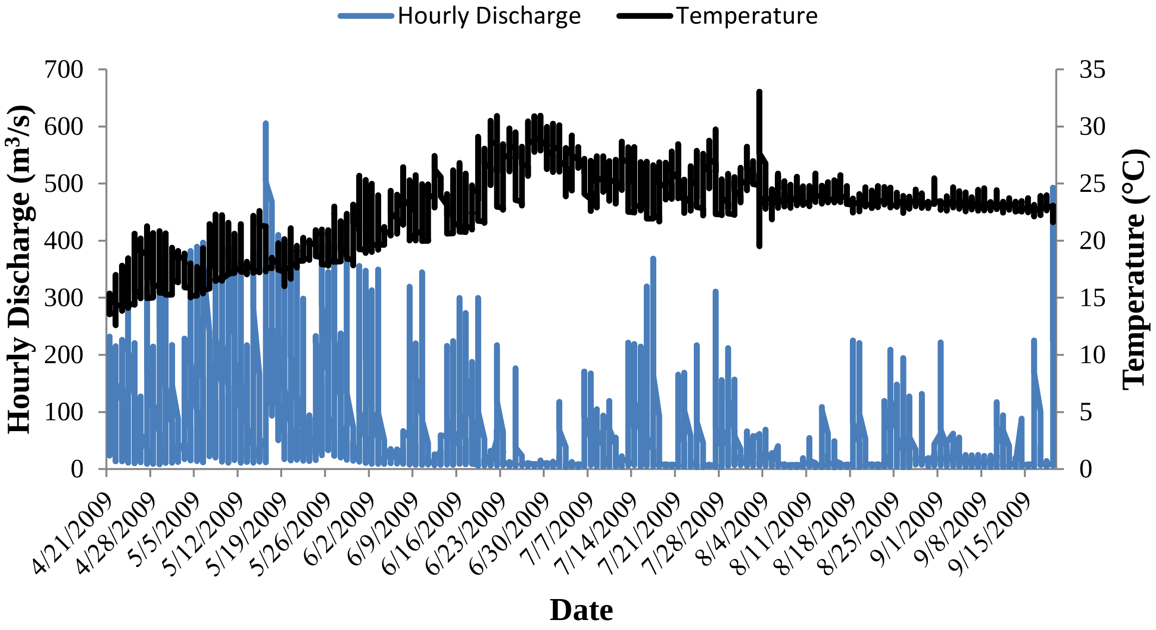


Figure 2-19. Hourly discharge (m^3/s; left y-axis) and hourly water temperature (°C; right y-axis) recorded from the USGS gage at Wadley, AL (02414500) and Alabama Power Company temperature logger at the Wadley Bridge, respectively (21 April – 19 September 2009). Discharges from Harris Dam between 150-200 m^3/s represent a one-unit generation, and discharges greater than 250 m^3/s represent a two-unit generation.

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3. Effects of experimentally fluctuating flows and water temperatures on early growth and survival Channel Catfish *Ictalurus punctatus* and Alabama Bass *Micropterus henshalli*.

Abstract - The effects of fluctuating flows and water temperatures on early growth and survival of Channel Catfish *Ictalurus punctatus* and Alabama Bass *Micropterus henshalli* were evaluated in four laboratory experiments. Channel Catfish and Alabama Bass were stocked into twelve, 38.0-L glass aquaria modified with Plexiglas inserts and an AquaClear adjustable flow powerhead. Four treatment levels were evaluated with three replicates per treatment. Experiments were conducted using 24-48 h swim-up fry (both species), 2-week old (Channel Catfish), and 7-week old (Alabama Bass) juveniles. Fish were exposed to treatments with varying levels of flow (high, med, low) and decreased water temperature (~10°C) in an attempt to replicate and simulate river conditions below R. L. Harris dam on the Tallapoosa River, AL. Growth rates and cumulative percent mortality were quantified and compared using linear models. Our results suggest that simulated high flows and decreased water temperatures negatively affect daily growth rates and survival of both species. Mortality was highest in treatments with decreased water temperatures. Daily growth rates were lower in treatments with decreased water temperatures. Older fish had higher daily growth rates and decreased mortality and were not as susceptible to the negative effects of treatments. These data suggest that growth and survival may be impacted more by fluctuations in temperature (Δ 10 °C) than flow. However it should be noted that fish exhibited decreased growth and some mortality in high flow treatments. The thermal regime should be included as an important part of the overall management of flows and temperature downstream of hydropeaking dams. Periods of time (spawning and rearing windows) where flows and temperature do not greatly fluctuate will increase growth rates and survival, and will increase subsequent recruitment of fish in regulated

rivers. These periods will also provide optimal conditions that allow fish to attain sizes adequate to withstand flow and temperature conditions below dams.

Introduction

The natural flow regime of rivers has been altered greatly for societal benefit by the construction of large dams that generate electrical power (Richter et al., 1997; Pringle et al., 2000). Although river regulation plays an important role in modern society, there are potential consequences that may negatively affect fish and fish habitat (Pringle et al., 2000; Freeman et al., 2001; Murchie et al., 2008). One primary impact below dams is the alteration of various components of the natural flow regime. In particular, most components of the flow regime are altered by hydropower production including: duration, magnitude, timing, frequency, and rate-of-change (Richter et al., 1997; Poff et al., 1997). Rapid fluctuations in discharge from dams are particularly disturbing to riverine ecosystems (Moog, 1993). There is evidence that ‘peaking’ hydropower dams, which produce power during periods of high energy demand, alter downstream flow and temperature regimes more than other types of facilities (e.g., run of river; Fette et al., 2007; Jager and Belvelheimer, 2007).

Peaking hydropower facilities, that produce pulsed high-velocity discharge, create an unstable environment that adversely affects availability and persistence of habitat variables such as water velocity, depth, and temperature (Cushman 1985; Bain et al. 1988; Freeman et al. 2001; Allan and Flecker 1993; Weyers et al. 2003). Early life history stages of fishes are exceptionally vulnerable to frequent “floods” produced by hydropower production (Humphries et al., 2002) and recruitment events may be dependent on periods of non-generation, or low flow (Humphries and Lake, 2000; Freeman et al., 2001). Brown and Ford (2002) and Weyers et al. (2003) reported that altered experimental water-flow patterns, typical of hydropower generation discharges, have negative impacts on the growth and survival of larval catostomid suckers.

Pulsed high-velocity water flow may also have an effect on the fauna of river systems (Freeman et al. 2001). Irwin et al. (1997) found a low abundance of juvenile black basses (*Micropterus* spp.) in a highly regulated section of the Tallapoosa River, Alabama, and hypothesized that low abundance was related to fluctuating flows and lowered water temperatures. Freeman et al. (2001) reported that young of the year abundance of several species of minnows and darters at a flow regulated site was more frequently correlated with habitat persistence, and that this association corresponded to the effect of flow regulation on habitat patterns. Although fish possess many physiological adaptations and reproductive behaviors to address thermal variation, variation downstream of some hydropower facilities is more extreme than the thermal conditions under which they have evolved (Cooke et al. 2003). Juvenile fish are more susceptible to disturbance (natural and anthropogenic) than are adults (Harvey 1987; Scheidegger and Bain 1995). Mortality during early life stages will, to a certain degree. determine the strength of subsequent generations of fish (Trippel and Chambers 1997).

Alteration of the hydrologic regime can change conditions suitable for the recruitment of fishes (Humphries and Lake, 2000; Freeman et al., 2001) and have significant impact on aquatic diversity (Bunn and Arthington, 2002). Holland-Bartels and Duval (1988) suggested that variation in Channel Catfish productivity was related to river discharge in the upper Mississippi River. A decline in age-0 Channel Catfish abundance was likely the result of an increase in river discharge that may have disrupted spawning activities or flushed young from their nests (Holland-Bartels and Duval 1988). Irwin et al. (1997) reported that hatch dates of age-0 *Micropterus* spp. were highly correlated with periods of no generation at R. L. Harris Dam on the Tallapoosa River, Alabama. Andress (2002) estimated nest success of Redbreast Sunfish *Lepomis auristus* and Longear Sunfish *Lepomis megalotis* in a flow regulated section of the

Tallapoosa River, AL and reported that strongly fluctuating flows adversely affected centrarchid nest success. Sakaris (2006) reported that age-0 Channel Catfish typically hatched during periods with low and stable flow conditions. Persistence of riffle habitats (i.e., shallow-fast and shallow coarse), utilized by juvenile Channel Catfish *Ictalurus punctatus* and flathead catfish *Pylodictis olivaris* may decrease in highly regulated systems compared with unregulated sites (Bowen at al., 1998; Irwin et al., 1999). Provision of these habitats is critical for recruitment of both species. Bowen et al. (1998) suggested that short-term persistence of key habitats and annual variation in key-habitat availability are important for maintaining diverse fish assemblages.

Water released from hydroelectric dams is typically colder than surface temperatures, which alters downstream temperatures (Walker, 1985; Humphries and Lake 2000). Downstream of R. L. Harris Dam, water temperatures have been found to decrease as much as 10 °C following generation events (see Chapter 2 of this dissertation). Andress (2002) found correlations between decreased water temperature and increased discharge along this same flow-regulated portion of the Tallapoosa River, AL. Lower downstream water temperatures resulting from pulsing hypolimnetic releases likely delay spawning periods (Irwin and Freeman, 2002), impede hatching success (Irwin et al., 1997), and decrease rates of larval development (Hamman 1982; Marsh 1985; Small and Bates 2001;). Small and Bates (2001) reported that in low temperatures the embryonic development period of Channel Catfish eggs was extended significantly compared to controlled hatchery incubation temperatures. Implementation of spawning and rearing windows during critical stages of targeted species would be beneficial, to evaluate how pulsed releases affect downstream water temperature, timing of spawning, hatching success, and larval development.

Despite the recognition that alterations of the hydrologic and thermal regimes are consequences of river regulation, the inherent relationship between the two has received little attention in the assessment of environmental flows. Researchers have proposed that streamflow and temperature act together to influence early survival of fish (Connor et al. 1998). Dams have altered the flow and temperature regimes in the United States, thereby contributing to declines in abundance and early survival (Poff et al. 1997). Olden and Naiman (2010) proposed that by viewing environmental flows together with various aspects of water quality (temperature included), the chances of long-term success in achieving ecologically sustainable water management are increased.

Few studies have quantified the effects of hydropeaking power generation on aquatic systems. Specifically, the effects of fluctuating flows and temperatures on early growth and survival of juvenile Channel Catfish or Alabama Bass have not been assessed. Among studies of hydropeaking, several involving fish have focused on severe impacts such as stranding (e.g. Bradford 1997; Valentin et al. 1996), and research on impacts of hydropeaking on non-stranded fish is lacking (e.g. Flodmark et al. 2002). There have only been a few published studies that have evaluated changes in fish abundance and diversity after flow regimes were prescribed or modified for regulated river sections below dams (Travnichek et al. 1995; Propst and Gido 2004). Pierson et al. (1986) found that species diversity was diminished near R. L. Harris Dam in the Tallapoosa River, where low, non-generation flows desiccated portions of the channel.

In 2005, an adaptive management approach for management of the regulated portion of the Tallapoosa River below R. L. Harris Dam was implemented. However, recruitment objectives have not been realized despite provision of spawning windows most years (E. Irwin unpublished data). One purpose of the adaptive management process is to reduce uncertainty relative to system dynamics (Williams et al. 2012). By quantifying the relations between hydrology and growth and recruitment in regulated rivers, models can be developed to predict fish response to instream flow prescriptions (Sakaris 2006). However, additional data are needed to predict the effects of management alternatives on fish populations and ultimately inform and improve management.

Channel Catfish and Alabama Bass are both important native sport fish in the Tallapoosa River; however, little information exists on growth in early life-stages and survival. The objectives of this study were to quantify the effects of increased water flow and decreased water temperatures on early daily growth and survival of age-0 Channel Catfish *Ictalurus punctatus* and Alabama Bass *Micropterus henshalli* through a series of laboratory experiments We tested several hypotheses: 1) variation in daily flow patterns have a negative effect on growth and survival; 2) decreased water temperatures, similar to those experienced downstream of R.L. Harris Dam on the Tallapoosa River, Alabama have an adverse effect on growth and survival; and 3) older fish will have lower mortality rates than younger fish exposed to similar treatments.

Methods

The effects of decreased temperature and varying water flow on the daily growth and survival of age-0 Channel Catfish *Ictalurus punctatus* and Alabama Bass *Micropterus henshalli* were assessed with a series of completely randomized experiments. Channel Catfish were used for Experiments 1 and 2, and Alabama Bass were used in Experiments 3 and 4.

Experimental aquaria

Twelve, 38.0-L glass aquaria were modified with Plexiglas inserts, an AquaClear adjustable flow powerhead, and substrate to simulate stream habitat and conditions similar to those that occur downstream of R. L. Harris Dam on the Tallapoosa River, AL (Figure 3-1). The inserts were shaped to form a curve to promote circular flow and were secured to the aquaria using aquarium grade silicone. A baffle constructed of Plexiglas was inserted in the middle of the aquarium to create a channel of flow. Water pumps were placed behind the inserts and secured through a hole in the Plexiglas, this prevented fish from being pulled through water intakes.

Water was supplied to each tank via a re-circulating aquaculture system designed to maintain water quality. In Experiment 1, a 1666 L sump tank containing 1 m^3 of shredded PVC biological filter, and a 0.3 m^2 mechanical filter box was used to maintain high water quality and supply water for cold water treatments (~10 ºC). Water for the ambient temperature control tanks was supplied from a separate 492 L holding tank and kept at ambient room temperature. In Experiments 2, 3, and 4, a 1666 L sump tank containing 1 m^3 of shredded PVC biological filter, and a 0.3 m^2 mechanical filter box to maintain high water quality was used to supply water for ambient temperature and control treatments (20 -25 ºC). A 337 L sump tank containing shredded PVC biological filter and a 0.3 m^2 mechanical filter box and an additional 492L tank was used to supply water for the cold water treatments. A water chiller was used to maintain temperatures as low as ~10°C for the cold water treatments.

Experimental design

All experiments consisted of four treatments (including a control) with three replicates each (Table 3-1). In Experiment 1, Treatment 1 – assessed the effects of 4 h of high water flow (> 0.5 cfs) and decreased water temperature (~10º C) on daily growth and survival. One AquaClear adjustable flow powerhead was used to generate and maintain flows during the treatments. Treatment 2 assessed the effects of 4 h of low water flow (0.1 cfs) and decreased water temperature (~10º C). Treatment 3 assessed the effects of moderate water flow (0.3 cfs) for 30-min twice each day (30-min in the morning and 30-min in the afternoon) and decreased water temperatures (~10º C). Treatment 4 (control group) consisted of stable low water flow (0.1 cfs) and ambient water temperature 24 h per day. Experiments 2, 3, and 4 differed from Experiment 1 in that in Treatment 2 we assessed the response of growth and survival of fish exposed to 4 h to high water flow (> 0.5 cfs) and ambient water temperature (~23º C). All other treatments were kept the same. Prior to stocking tanks, all fish were graded and measured to the nearest 0.01 mm TL. Fish were stocked in aquaria within 48 hours of reaching swim-up larval stage for Experiments 1 and 3, at 2 weeks for Experiment 2, and at 7 weeks for Experiment 4. Once stocked, fish were held in tanks for 24 h to acclimate to the tanks before experiments began. All treatments were kept to a photoperiod of 12 h light: 12 h darkness reflecting a 24 h light-dark cycle. Fluorescent lights were suspended over the tanks and were powered by an automatic timer (on 0600, off 1800). Fish were fed a mix of juvenile finfish feed and live hatched *Artemia* sp. at approximately 1.5% of body weight three times per day. At the end of each experiment, survivors were euthanized in tricaine methanesulfonate (MS-222; 140 mg/l), and removed from the aquaria. Fish were measured to the nearest 0.1 mm TL and weighed to the nearest 0.01 g. Sagital otoliths were extracted using fine-tipped forceps under a dissecting microscope at 60X magnification, and stored dry in centrifuge tubes for later preparation and analysis. Mortality and daily growth rates were calculated for each treatment.

Water quality

Temperature, dissolved oxygen, hardness, alkalinity, ammonia, and nitrite were monitored and measured daily using thermometers, Onset® HOBO Water Temp Pro v2 data loggers, YSI® Model 51B Dissolved Oxygen meter, Hach™ test kits. All water quality parameters were kept within previously established acceptable levels for this system (Taylor 2004).

Statistical Analysis

Linear models were used to estimate effect sizes and relations between 1) treatment and daily growth rate (Growth~Treatment) and 2) treatment and cumulative percent mortality of individuals (Mortality~Treatment). All summary statistics and analyses were conducted using Program R© (R Development Core Team 2005), and significance was set at $\alpha = 0.05$.

Results

Experiments were conducted with a total of 2326 age-0 fish (Table 3-2). Overall, daily growth rates of both Channel Catfish and Alabama Bass were lower in treatments with high flows and decreased water temperatures. Mortality was also consistently higher in these treatments. Younger fish (24 - 48 h swim-up fry) did not tolerate high flow/cold water treatments as well as older fish (2-week Channel Catfish and 7-week old Alabama Bass fry). As expected, in Experiment 1 daily growth rates were highest in control treatments (0.81 mm/day, SE = 0.05, $p < 0.05$, $R^2 = 0.81$; Figure 3-2). Daily growth rates were slowest in the 1-unit cold treatments (0.27 mm/day, SE = 0.05, $p < 0.05$, $R^2 = 0.81$). There was no difference in mortality in the pulse and (78%), 1-unit cold (76%), and 2-unit cold treatments (73%, $p > 0.05$, $R^2 = 0.14$; Figure 3-3). Lowest mortality occurred in the control treatments (50%; $p < 0.05$, $R^2 = 0.14$).

In Experiment 2, daily growth rates were highest in the 2-unit ambient treatments (0.70 mm/day, SE = 0.02, $p < 0.05$, $R^2 = 0.17$; Table 3-2). Slowest growth occurred in the 2-unit cold (0.51 mm/day, $p < 0.05$, $R^2 = 0.17$) and pulse treatments (0.51 mm/day, SE = 0.05, $p <0.05$, $R^2 = 0.17$). On Day 14, significant mortality occurred due to a power outage resulting in a rapid decline in water quality. The experiment was ended early and growth rates and mortality were only estimated to Day 14.

Daily growth rates were highest in the 2-unit ambient treatments in experiment 3 (0.67 mm/day, SE = 0.02, $p < 0.05$, $R^2 = 0.44$, Figure 3-4). Slowest growth occurred in the pulse treatments (0.36 mm/day, SE = 0.03, $p < 0.05$, $R^2 = 0.44$). Mortality was higher in the 2-unit cold treatments than the other treatments, and there were no survivors at the end of the experiment (100%, $p < 0.05$, $R^2 = 0.424$; Figure 3-5). Mortality in pulse treatments was lowest among the treatments (< 10%, $p < 0.01$, $R^2 = 0.42$, Figure 3-5). There was no difference in mortality in the 2-unit ambient and control treatments ($p > 0.05$, $R^2 = 0.42$).

In experiment 4, daily growth rates were highest in the 2-unit ambient treatments (0.82 mm/day, SE = 0.05, $p < 0.05$, $R^2 = 0.11$; Figure 3-6) and pulse treatments (0.77 mm/day, SE = 0.06, $p < 0.05$, $R^2 = 0.11$). Slowest growth occurred in the control treatments (0.56 mm/day, SE = 0.06, $p < 0.05$, $R^2 = 0.11$) and the 2-unit cold treatments (0.60 mm/day, SE = 0.06, $p < 0.05$, $R^2 = 0.11$). Overall, mortality was significantly lower in experiment 4 than all other experiments. Mortality was highest in the pulse treatments (32%; $p < 0.05$, $R^2 = 0.20$; Figure 3-7). Mortality was lowest in the 2-unit ambient treatments (25%, $p < 0.05$, $R^2 = 0.20$). There was no difference in mortality in the 2-unit cold (26%) and control treatments (27%, $p > 0.05$, $R^2 = 0.20$).

Discussion

Our study suggests that strongly fluctuating flows and decreased water temperatures negatively affect survival and early growth of age-0 Channel Catfish and Alabama Bass. Mortality was highest in treatments with decreased water temperatures; indicating that variation of the thermal regime could have significant impacts on survival of juvenile Channel Catfish and Alabama Bass. The thermal regime downstream of R. L. Harris dam on the Tallapoosa River, AL has been altered and fluctuates greatly on an hourly and daily time scale (see Chapter 2). We hypothesize that this variation negatively influences reproductive timing, early survival and growth of juvenile fish in regulated rivers. Early growth and development periods should be considered as temperature sensitive, and warrant further investigation and management efforts. Decreased water temperatures resulted in reduced hatch success and larval survival of Channel Catfish in Mississippi ponds (Small and Bates 2001). Small and Bates (2001) reported that a reduction in water temperature can extend the embryonic development period, however hatch success was also reduced. A reduction in hatch success and larval survival will have detrimental impacts on recruitment to age 1. Extending the embryonic development period to accommodate varying temperatures in theory may be appealing in terms of balancing flow management and conservation objectives. However, it is likely not an ideal option when the results include reduced hatch success and larval survival.

Flow management of regulated rivers should specifically address the interaction of flow and water temperature to reduce thermal variation in regulated rivers. We agree with Olden and Naiman (2010) that little attention has been focused on the modification of the thermal regimes by the construction and operation of dams. The consequences for ecosystems are major and have not been fully determined in flow management discussions. Thermal modification of dam discharges is a management option that may aid in reducing the variability of temperatures after generation events. Thermal modifications may require adjustments in the way water is released from dams. Several strategies were presented in Sherman (2000) including multi-level intake structures, floating intakes, destratification approaches, and shallow basins or ponds that delay downstream release. These methods should be fully investigated to determine suitability and feasibility (including cost, benefit, and performance) on a dam and river specific basis.

Our data indicate that decreased water temperatures have a negative effect on growth rates of age-0 Channel Catfish and Alabama Bass. Tidwell et al. (2003) and Coyle et al. (2009) reported similar results in experiments of Largemouth Bass *Micropterus salmoides,* exposed to reduced water temperatures. Tidwell et al. (2003) also reported decreased feeding efficiency at lowered temperatures. Feeding efficiency was not evaluated in this study, however we hypothesize that a decrease in feeding efficiency coupled with the effects of decreased water temperatures and varying flow negatively affected fish in this study. When considering environmental flows of hydroregulated rivers, the thermal regime must also be included in the assessment. Both discharge and temperature must be simultaneously considered for the successful implementation of environmental flow management below dams. Olden and Naiman (2010) proposed that the natural thermal regime of rivers could be evaluated in similar terms to the natural flow regime (e.g., magnitude, frequency, duration, timing and rate of change; Poff et al. 1997). Examining temperature variability in terms of these metrics will be useful. A flow and temperature regime that closely mimics the natural flow and temperature regimes in hydroregulated rivers will help increase early survival and restore populations downstream of dams.

Mortality, in this study, varied across all flow types (low, high, moderate). Holland-Bartels and Duval (1988) reported that river discharge had a negative effect on estimates of production of juvenile Channel Catfish. Holland-Bartels and Duval (1988) hypothesized that variable discharge may have flushed young from their nests reducing overall production estimates. Freeman et al. (2001) also reported that juvenile fish abundance was strongly associated with flow; in particular the temporal sequence of flows. Flow variability likely influences aquatic organisms and recruitment of many species. Stable low flows are critical for juveniles of many species in the Tallapoosa River (Freeman et al. 2001). Hydropeaking operations can substantially dampen seasonal and interannual variation (Poff et al. 1997; Bowen et al. 1998), while imposing artificially high, short-term variation detrimental to biota unable to adapt to rapid fluctuations in flow (Cushman 1985).

Our data also suggest that growth rates of Channel Catfish and Alabama Bass were reduced when exposed to varying rates of flow. We conclude that alteration of the flow regime in regulated rivers has a negative effect on growth of juvenile fish. Sakaris (2006) reported similar findings in the growth of age-0 Channel Catfish in hydroregulated sites in the Tallapoosa River. Additionally, Weyers et al. (2003) reported that experimentally altered water-flow patterns, like those released during hydropower generation, have a negative effect on growth and survival of larval catostomid suckers. However, Earley (2012) reported that the hydrologic regime had only a minimal effect on growth of age 1-3 Alabama Bass. We hypothesize that older fish exceeded a size that allowed them to withstand the flow variation in our experimental design. It is also possible that in hydroregulated rivers, faster growth early in life may be an evolutionary response to alteration of natural flow regime by the hydropower dam.

The effects of flow and temperature variation are not just an issue for regulated rivers in the Southeastern US. Connor et al. (2003) concluded that flow and temperature act together to influence fall chinook salmon *Oncorhynchus tshawytscha* survival in the Snake River Basin. Conversely, the same authors reported that survival increased with increased flows and decreased with increased temperatures during the summer; which was attributed to the biology of these species.

Prescribing spring/summer temperature and flow regimes, within an adaptive management framework will improve spawning success, early growth, and survival of Channel

Catfish and Alabama Bass (Irwin and Freeman 2002). These successes will improve productivity in the system and should be considered as a management option for increasing recruitment of these two species in the Tallapoosa River, AL. Specifically, designated times during the spawning and rearing periods where generation is significantly reduced ("spawning and rearing windows"), will give juveniles stable flow and temperature conditions and provide an optimal environmental for spawning, hatching, swim-up, and early growth. Implementation of spawning and rearing windows during these critical stages will be beneficial in the continual evaluation of how pulsed releases impact the thermal regime, timing of spawning, hatching success, and larval development (see Chapter 2).

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Table3- 1. Experimental design of all experiments; Treatment 1 = 2-unit simulation; Treatment 2 = 1-unit simulation; Treatment 3= pulsed flow simulation; Treatment 4 = Control (constant low flow); high water flow = > 0.5 cfs; low water flow = 0.1 cfs; moderate flow = 0.3 cfs; low temperature = 10° C; ambient temperature = 25° C.

		Treatments		
	Treatment 1	**Treatment 2**	**Treatment 3**	**Treatment 4**
Experiment 1 Channel Catfish 24-48 h swim-up	High water flow /Low water temperature	Low water flow /Low water temperature	moderate water flow/low temperature 30 min- 2 times/ day	constant water flow/ambient water temperature
Experiment 2 Channel Catfish 2- week old fry	High water flow /Low water temperature	High water flow /ambient water temperature	moderate water flow/low temperature 30 min- 2 times/ day	constant water flow/ambient water temperature
Experiment 3 Alabama Bass 24-48 h swim-up fry	High water flow /Low water temperature	High water flow /ambient water temperature	moderate water flow/low temperature 30 min- 2 times/ day	constant water flow/ambient water temperature
Experiment 4 Alabama Bass 7-week old fry	High water flow /Low water temperature	High water flow /ambient water temperature	moderate water flow/low temperature 30 min- 2 times/ day	constant water flow/ambient water temperature

Table 3-2. Summary statistics for each experiment by treatment and species; Treatment 1 = 2-unit simulation/low water temperature; *Treatment 2 = 1-unit simulation/low water temperature and 2-unit simulation/ambient water temperature; Treatment 3= pulsed flow simulation/low water temperature 30min 2x/day; Treatment 4 = Control; CCF = Channel Catfish, ALB = Alabama Bass. SUF = swim-up fry.

	Treatment 1 (2-unit/cold)	**Treatment 2* (1-unit/cold)**	**Treatment 3 (Pulse/cold)**	**Treatment 4 (Control)**
Experiment 1 (24-48 hr SUF) Channel Catfish				
# fish start	173	180	182	188
Total mortality	127	137	143	93
mean daily growth rate (mm/day ± SE)	0.43 (± 0.09)	0.27 (± 0.05)	0.37 (± 0.05)	0.81 (± 0.05)
Experiment 2 (7-week old) Channel Catfish		**(2-unit/ambient)**		
# fish start	141	142	140	141
Total mortality	1	92	94	94
mean daily growth rate (mm/day ± SE)	0.51 (±0.03)	0.70 (± 0.02)	0.51 (± 0.03)	0.66 (± 0.03)
Experiment 3 (24-48 hr SUF) Alabama Bass				
# fish @ start	195	195	195	195
Total mortality	189	96	16	90
mean daily growth rate (mm/day ± SE)	no survivors	0.67 (± 0.02)	0.36 (± 0.03)	0.63 (± 0.05)
Experiment 4 (2.5 week old)				
# fish @ start	62	69	62	66
Total mortality	16	17	20	18
mean daily growth rate (mm/day ± SE)	0.60 (± 0.06)	0.82 (± 0.05)	0.77 (± 0.06)	0.56 (± 0.06)

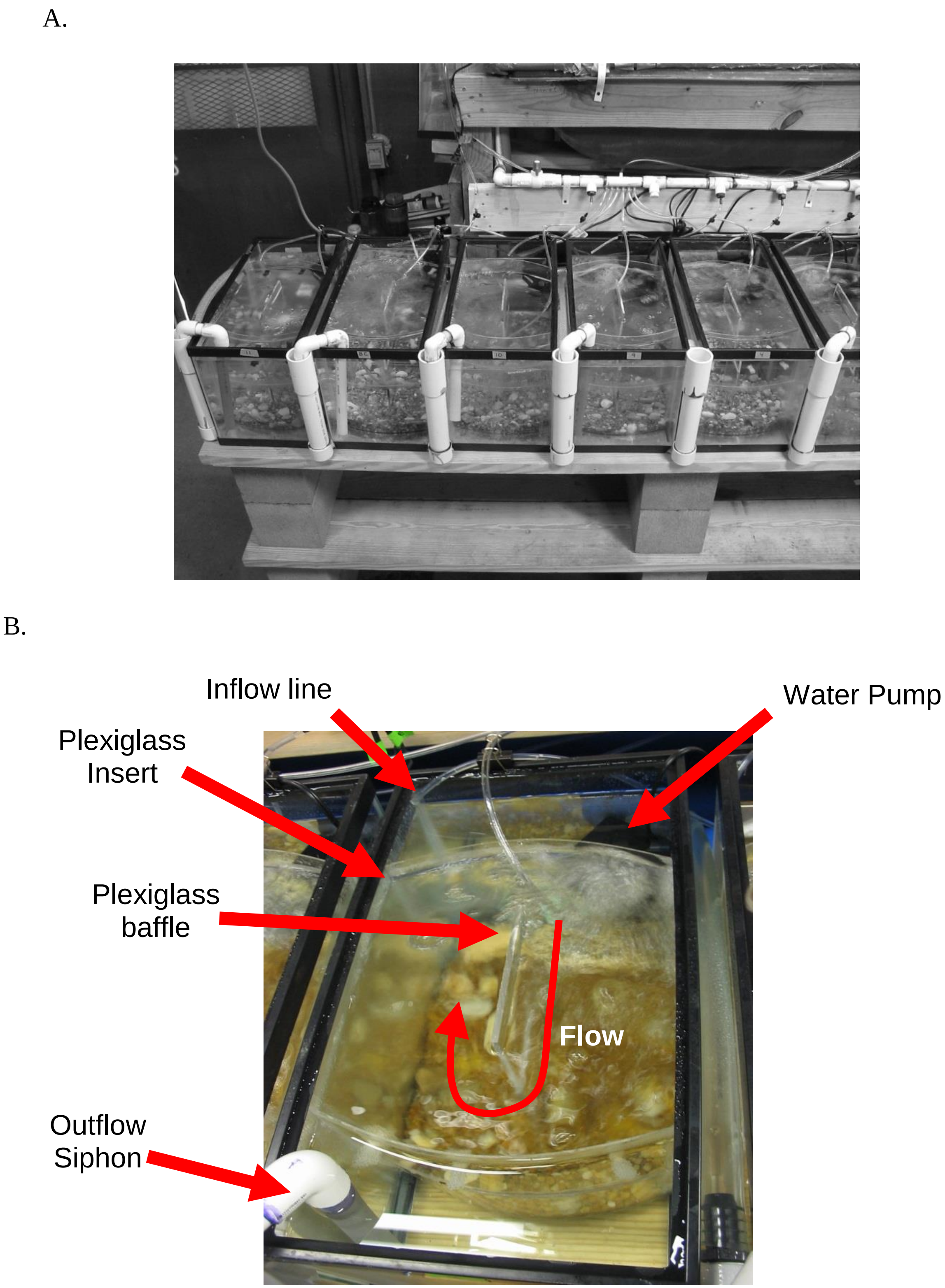

Figure 3-1. (A) Tank array for laboratory experiments; (B) Top view of aquarium with modifications for treatments (water pump, inflow line, plexiglass insert and baffle, and outflow siphon).

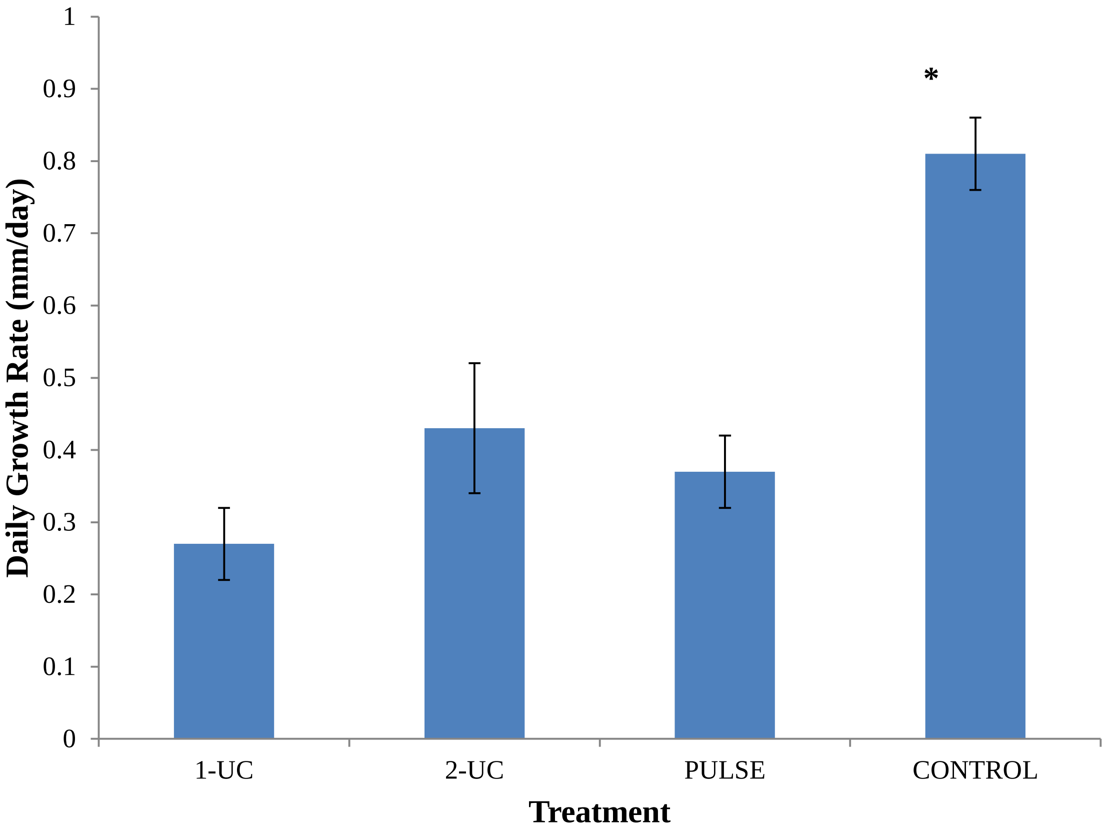

Figure 3-2. Daily growth rate (mm/day) of age-0 Channel Catfish in Experiment 1; * indicates significance at $p < 0.05$.

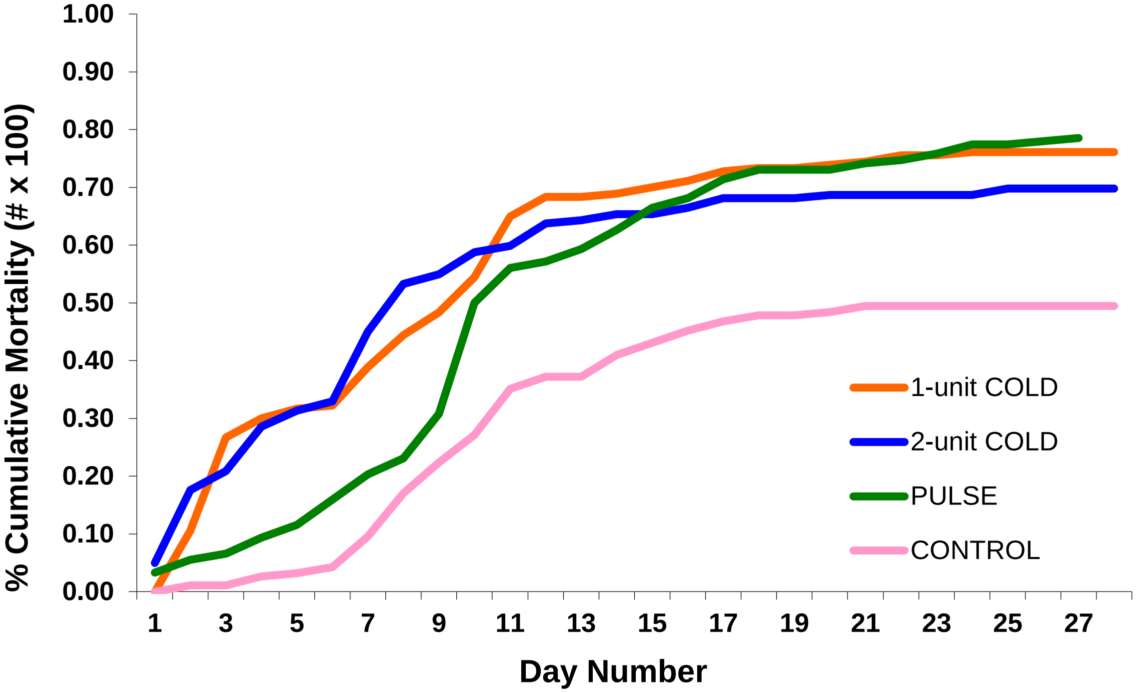

Figure 3-3. Cumulative percent mortality (# x 100) of age-0 Channel Catfish in Experiment 1.

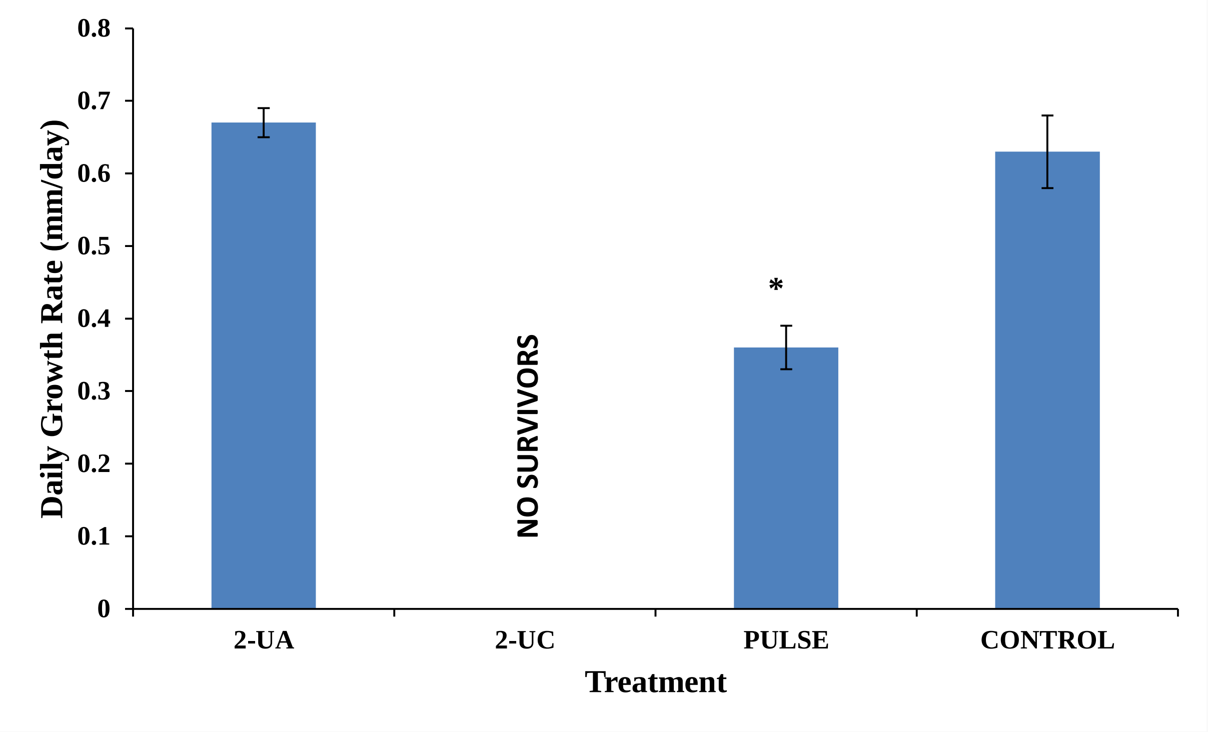

Figure 3-4. Daily growth rate (mm/day) of age-0 Alabama Bass in Experiment 3; * indicates significance at $p < 0.05$.

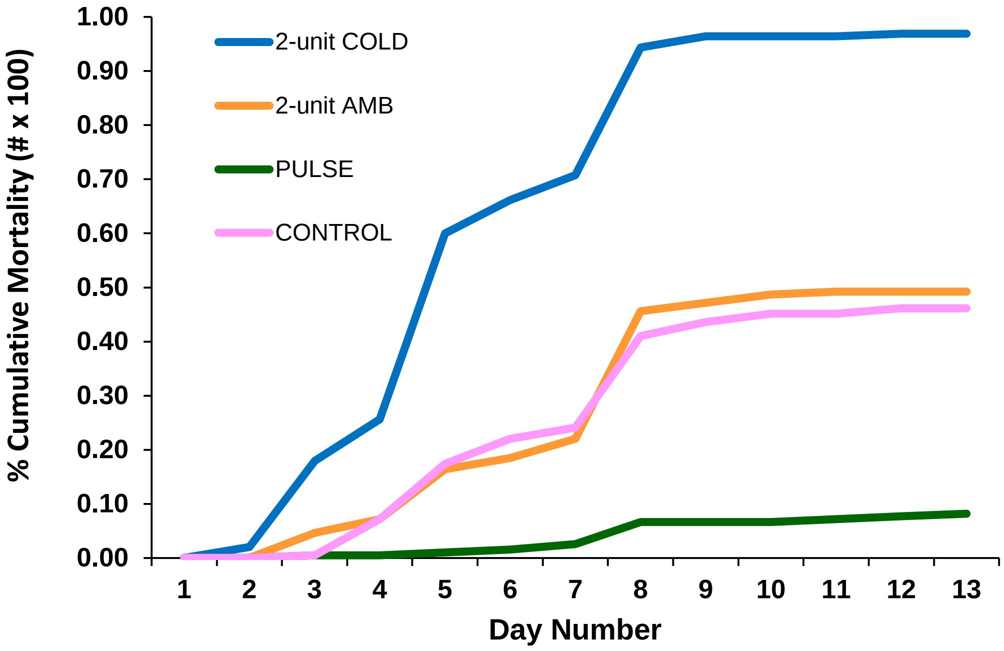

Figure 3-5. Cumulative percent mortality (# x 100) of age-0 Alabama Bass in Experiment 3.

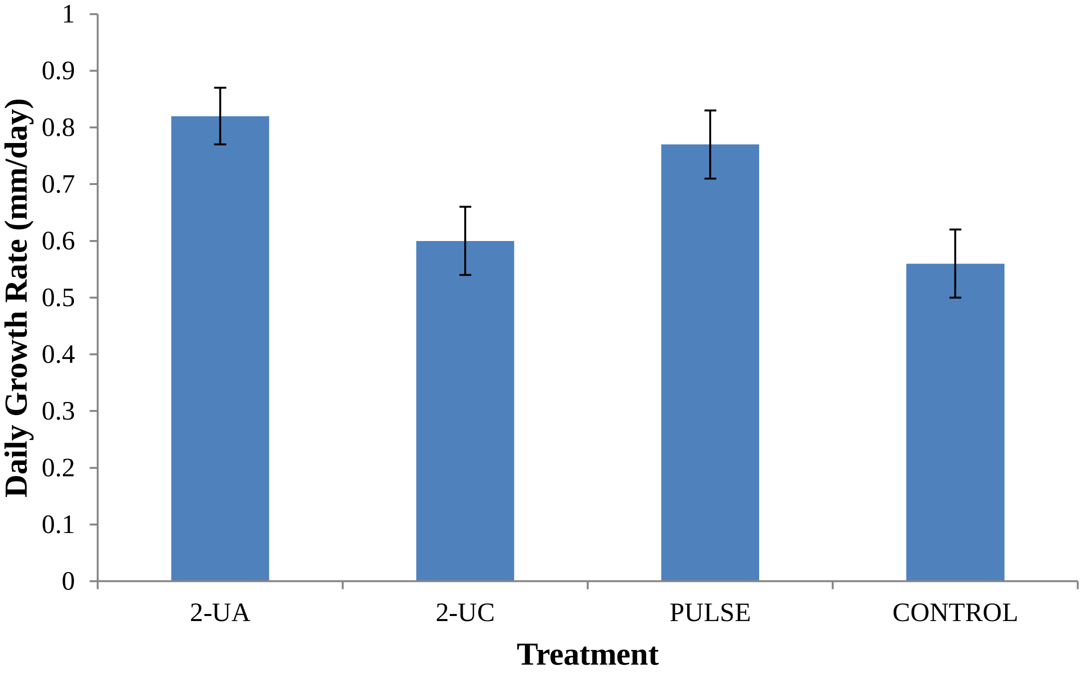

Figure 3-6. Daily growth rate (mm/day) of age-0 Alabama Bass in Experiment 4.

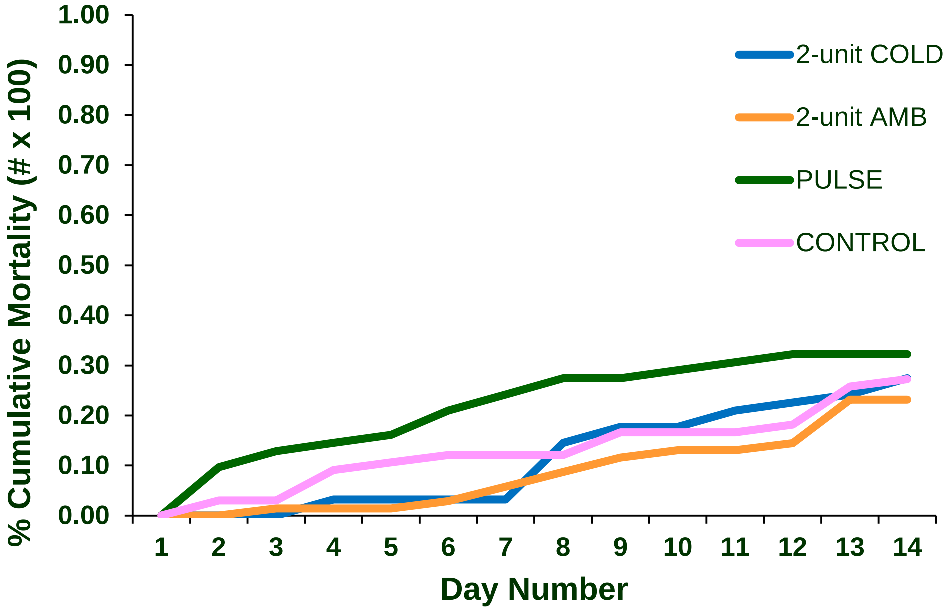

Figure 3-7. Cumulative percent mortality (# x 100) of age-0 Alabama Bass in Experiment 4.

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4. Summary and Conclusions

Flow and temperature regimes, particularly timing and intensity of high and low events, can have important effects on biodiversity and ecological processes of stream ecosystems (Brown and Ford 2002; Olden and Naiman 2010). Human activities including damming for hydropower operations, diversion and channelization, alter the flow regime of streams and rivers and severely alters ecological processes (Ward and Stanford1983 1995; Poff et al. 1997). Current instream flow management typically revolves around flow setting techniques and does not fully include effect of thermals variation. Restoration of the natural thermal regime should be considered as important as restoration of the natural flow regime. The impact of altered flow act together with temperature and cause deleterious effects downstream of hydropower dams. We suggest that the two be considered together, and that further investigations into their relatedness be conducted to evaluate current and future management options.

This study demonstrated that flow and temperature regimes are particularly important in early life stages of Alabama Bass, Channel Catfish, and Redbreast Sunfish. Our results support our hypothesis that high-velocity water flow and decreased water temperatures have negative impacts on the early life development of Alabama Bass and Channel Catfish. When evaluating environmental flows in hydro-regulated rivers, a flow pattern that closely mimics the pre-dam natural flow regime could help increase early larval survival and restore populations downstream of hydropower dams. Evaluating these metrics is essential in maintaining the Alabama Bass and Channel Catfish, Redbreast Sunfish fisheries. Our results also demonstrate the need for long-term in-situ monitoring programs especially of populations affected by river regulation. Furthermore, there is a need for managers to work with power utilities and other stakeholders to develop management plans that serve a variety of ecosystem services, needs, and objectives.

Management options and decisions addressing instream flows, temperatures and downstream processes, below R. L. Harris Dam, should be incorporated in an adaptive management framework such that as more information about the system is gained, management options can be changed and improved dependent upon response of the system.

Future research efforts should include additional laboratory studies with increased treatments to attempt to describe specific effects. Field studies should also be considered, in conjunction with current adaptive management pulse flows provided by the Alabama Power Company, to assess if similar lab produced effects can be replicated real-time in the river. Laboratory conditions were scaled, and effect estimates may be increased or decreased in the field.

Managers are encouraged to use models and conclusions described in this dissertation as part of their decision-making and objective-setting processes, in an adaptive management framework. Specifically, we recommend 1) thermal modification technologies at hydropeaking dams be investigated for suitability and feasibility; 2) instream flow management include thermal regimes and variation as part of management objectives; and 3) spawning and rearing windows continue to be employed, with evaluations on an annual basis, as a management tool to increase recruitment of fish in regulated rivers. The models and variables herein described should be continually improved upon and updated as more information is learned and uncertainty reduced. Additional data collection and experimentation is necessary to monitor fish populations and their response to the flow and temperature regimes in regulated rivers.

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