EFFECTS OF FLOW ALTERATION ON
THE AQUATIC MACROPHYTE *PODOSTEMUM CERATOPHYLLUM* (RIVERWEED);
LOCAL RECOVERY POTENTIAL AND REGIONAL MONITORING STRATEGY

by

JENNIFER P. PAHL

(Under the Direction of C. Ronald Carroll)

ABSTRACT

A survey of *Podostemum ceratophyllum* Michx. biomass and recovery rates was conducted in the Middle Oconee River, Athens, GA over a one-year time period under altered hydrology and severe drought. Biomass was found to be an order of magnitude lower than reported by previous studies conducted in non-drought years. An information-theoretic (AIC) modeling approach found variation in biomass within the study site to be related in part to variation in duration of low flow events. Recovery rates in the Middle Oconee River as well as Hunnicutt Creek, a tributary, were similar among sites and under varying hydrologic regimes. Re-colonization from vegetative growth seemed most prominent, and little support was found for seed dispersal as a major mechanism or recovery. Regionally, *P. ceratophyllum* range is likely expansive, and the impact of hydrologic alteration may be equally as widespread. Future monitoring could be accomplished through existing programs, focusing in basins where *P. ceratophyllum* is present and flow modification is prevalent.

INDEX WORDS: *Podostemum ceratophyllum*, hydrologic alteration, drought, Middle Oconee River, re-colonization, monitoring

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CHAPTER 1

INTRODUCTION

The natural flow regime paradigm (Poff et al. 1997) has been a foundation for understanding stream ecology since the 1990s. It implies that natural variations in flows are required for the life histories of organisms that have evolved to tolerate those conditions. Over the last 50 years however, a significant rise in the number of impoundments (McCully 2001) and surface water withdrawals have profoundly changed the patterns of flow across North American rivers (Rosenberg et al. 2000). Shifting flow regimes can alter the transport of important nutrients, sediment and biota across all planes laterally, longitudinally and vertically within the channel (Silk and Ciruna 2005) and at varying time scales (Poff et al. 1997).

Compounding these hydrologic changes, precipitation patterns in the southeastern United States have drastically reduced the amount of rain over Georgia, North and South Carolina over the last decade. This extreme drought (2007 to present) has resulted in fewer high flow events and prolonged durations of very low flows. Climate change models predict higher winter rainfall in the southeast, accompanied by increased evapotranspiration rates, which will likely yield less summer and fall runoff to streams and rivers (Mulholland et al. 1997). Population projections for the southeast, particularly Georgia indicate continued rapid growth (USCB 2008), which may further increase demand for water resources, resulting in lower base-flows (Mulholland et al. 1997). While these conditions alone may influence the productivity of aquatic organisms within a stream reach, perhaps the most challenging conditions for aquatic biota may occur as anthropogenic perturbations interact with climatically-induced low flows.

In streams that support low-head hydropower dams for example, consistent daily fluctuations in flow resulting from normal dam operations may result in minor discharge changes under normal flow conditions, however, under extreme drought, these fluctuations may affect a larger portion of the streambed over the course of 24 hours. The frequency and duration of these drying events and the duration may influence the productive capacity of stream biota. Short-duration drying events could lead to stress on macrophytes resulting in reduced growth, while long duration may result in mortality. Long-duration drying events that occur frequently will likely result in larger population declines, while infrequent long-duration events may result in initial mortality or extreme stress, but allow for macrophyte re-colonization.

The Middle Oconee River, near Athens, GA provides an example of how climate in combination with water management can alter natural flow regimes. The extreme drought conditions that have persisted since early 2007 through the present have resulted in lower than normal stream flow. Upstream of our study shoals, the Tallassee Shoals Hydropower dam operates as a low-head dam, producing power for the Jackson EMC which supplies the surrounding counties (Davis 2007). A pump-storage facility called Bear Creek Reservoir is operated by the Upper Oconee Basin Water Authority and supplies water to Athens-Clarke County, as well as three other counties (Williams 2007). An additional water withdrawal station downstream of these shoals is operated for municipal water supply by Athens-Clarke County (Knight 2007).

While the three features may influence the hydrology of this reach, the pump storage facility has had a great effect on flows during the drought. Neither the hydroelectric dam (Davis 2007) nor the Athens-Clarke County municipal withdrawal station (Knight 2007), were able to operate during the drought flows experienced over the course of our study. The remaining feature, Bear Creek Reservoir, resulted in daily changes on the order of 5 to 10 cubic feet per second (cfs), but up to 90 cfs under normal conditions. The reservoir was issued a special permit by the Georgia Environmental Division to withdrawal 7 to 15 Million Gallons per Day (13 – 28 cfs) under drought conditions (Williams, 2007). This created areas of the shoal that were continually wetted, continually exposed, and those that experienced fluctuations in flow that may result in short term drying events. The drought conditions increased the extent of the substrate that was fully exposed and possibly the areas experiencing daily changes in flow.

One of the major primary producers and habitat providers in this study shoal is the submerged aquatic macrophyte *Podostemum ceratophyllum* Michx. (*Podostemaceae*) *P. ceratophyllum* thrives in swift water on rocky substrate, and resists flows by attaching to bedrock and boulders with holdfast disks (raphes) rather than roots (Hammond 1937). *P. ceratophyllum* is the dominant macrophyte in riverine shoal habitats in Georgia and is ecologically significant for a number of reasons. *P. ceratophyllum* is an important habitat for many macroinvertebrate and fish species in this region. It is highly productive (Hill and Webster 1984) and has been linked with the highest secondary production of filter feeders (Grubaugh and Wallace 1995, Grubaugh et al. 1997) ever recorded in streams (Huyrn and Wallace 2000).

Hutchens et al. (2004) documented the importance of *P. ceratophyllum* for macroinvertebrate communities, finding that removal of this species resulted in a much lower total macroinvertebrate abundance and biomass. The authors also indicated that the recovery of such communities was extremely slow (Hutchens et al. 2004). *P. ceratophyllum* has also been correlated with increased presence of fish (Argentina 2006, Connelly et al. 1999, Hagler 2006, Marcinek 2003). *P. ceratophyllum* may provide fish, especially small ones, with refuge from predation, and food in the form of macroinvertebrates (Argentina 2006).

Over the past few decades, *P. ceratophyllum* has been in decline in many of the northeastern states due to various impacts such as reduced water quality, siltation or hydrologic alterations (NYSNHP 2008). In Georgia, *P. ceratophyllum* is not listed as endangered or threatened, as it is in the northeastern U.S.; however, recent climatic events may have caused significant stress.

Historically, *P. ceratophyllum* formed lush mats across shoal in the Middle Oconee River, Athens, GA during the growing season and persisted throughout the winter in a more dormant stage (Grubaugh and Wallace 1995). Due to the recent extreme drought of 2007-2009, much of the area that previously supported *P. ceratophyllum* has been exposed and the plant has died. Many of the remaining refuge areas for the plant are subject to fluctuating hydrology on a daily basis due to the upstream water withdrawals. Future human population growth in Georgia may demand more of our water resources, exacerbating the problem of water extraction resulting in low, variable flows.

To understand how the hydrology in the Middle Oconee River is affecting the productive capacity of *Podostemum ceratophyllum* and its ability to recover, the following research questions were addressed: (1) Does *P. ceratophyllum* biomass change seasonally over one year? (2) How has the biomass of *P. ceratophyllum* in this study shoal changed over the past 50 years? (3) How does hydrology influence *P. ceratophyllum* biomass within the shoal habitat? (4) What is the rate of *P. ceratophyllum* re-colonization through seed dispersal and vegetative growth within the shoal? (5) Are other areas of Georgia where *P. ceratophyllum* occurs that are also experiencing hydrologic changes?

To understand these questions, I collaborated with others (R. Katz and M. Freeman) to develop a number of methodologies and analytical strategies: First, we investigated effects of hydrologic stress on *P. ceratophyllum* in conjunction with a number of habitat covariates on standing stock biomass of *P. ceratophyllum.* We used an information theoretic approach to compare models predicting *P. ceratophyllum* biomass and to determine relative support for including the effects of hydrologic variables. We found that the best supported model included a hydrologic stress variable, and indicated that one or more hours of hydrologic stress resulted in loss of *P. ceratophyllum* biomass.

Second, I analyzed the rate at which *P. ceratophyllum* may recover from hydrologic stress or other forms of disturbance such as scour or grazing. To do this, a fixed-plot repeated-measures approach was taken to assess vegetative re-colonization rates as well as seed accrual over time in two locations under varying hydrologic conditions. An independent study looking at seed dispersal was problematic, but did provide insight into the potential resiliency of this species.

Third, we analyzed observed occurrences across north Georgia to establish a preliminary range for *P. ceratophyllum* above the fall line in Georgia. The basins in which these observations occurred were cross-referenced with U.S. Geological Survey stream gages to determine the possible extent of hydrologic alteration by basin (USGS 2008). Basins with *P. ceratophyllum* and high percentages of gages indicating hydrologic alterations such as water withdrawals or hydroelectric impoundments were determined to be priority areas for future monitoring work. These locations will also likely experience high rates of population growth in the future, which may lead to increased stress on water resources (Seager et al. 2007). Monitoring of *P. ceratophyllum* might be facilitated through the Georgia Natural Heritage Program.

CHAPTER 2

HIGH RESOLUTION ASSESSMENT OF ENVIRONMENTAL FACTORS THAT INFLUENCE BIOMASS OF *PODOSTEMUM CERATOPHYLLUM* (RIVERWEED) IN A SIXTH-ORDER PIEDMONT RIVER

ABSTRACT

Hydrologic alteration by impoundment structures and water extraction has significantly impacted aquatic systems for over a century. Some of the most vulnerable habitats are shoals which often occur at areas of high elevation gradients and are ideal sites for energy producing hydropower dams. Shoals in free-flowing rivers are often influenced by upstream alteration to hydrology such as frequent draw-downs or hydro-peaks. These hydrologic changes are amplified during drought conditions, such as those experienced in the Georgia Piedmont during 2007 - 2008. Our study in the Middle Oconee River, Athens, GA, investigated effects of hydrologic alteration at a fine scale with respect to the aquatic macrophyte *Podostemum ceratophyllum* Michx. (*Podostemaceae*). Through information-theoretic analysis (AIC), we found higher support for predictive models of *P. ceratophyllum* biomass that included hydrology factors such as the number of hours in the past 30 days with less than a water depth of 5cm. The relationship between *P. ceratophyllum* biomass and duration of low water depth was negative. We projected that about 2% of our transect may experience these stressed conditions at or above 45 cubic feet per second (cfs), which is the 7Q10. We modeled biomass loss to be close to 8% in 30 days under the average number of hours under 5 cm of water that our samples experienced. We found that *P. ceratophyllum* biomass in 2007-2008 was less than half as large compared to 1956-1957 and 1991-1992 studies, and investigated variations in annual hydrology to help explain this difference.

INTRODUCTION

Over the past fifty years, humans have modified aquatic habitats in significant ways. Surface water withdrawals have increased 20-fold over this time (Revenga et al. 1998 in Silk and Ciruna 2005), and impoundments have influenced 60% of large river systems (McCully 2001). These dams and water extractions alter the natural flow regime (Rosenberg et al. 2000) and change transport of nutrients, sediment and biota within the system (Silk and Ciruna 2005). Not only can hydrologic alteration reduce the overall flow (i.e. via water extractions), it can also change the magnitude, duration, timing and seasonality of biologically important flows (Poff et al. 1997). These alterations can occur at varying time scales, such as hourly, daily, monthly, annually and inter-annually (Gehrke and Harris 2001).

The historic pattern of flow variations in a specific riverine system influences composition of the resident biota. The life-histories of many aquatic organisms rely directly on flow characteristics to signal the onset of certain life stages. Many studies have examined how even small variations in the natural flow regime may have large impacts on fishes (Anderson et al. 2006, Dutterer and Allen 2008, Freeman and Marcinek 2006, Propst et al. 2008, Roy et al. 2005), macroinvertebrates (Dewson et al. 2007, Malmqvist and Englund 1999, McIntosh et al. 2002, Rader and Belish 1999, Suren et al. 2003a), byrophytes (Englund et al. 1997) and even periphyton (Suren et al. 2003b). Few studies exist however, that investigate aquatic macrophyte changes as a result of hydrologic modifications. A limited amount of research has looked at long-term consequences of hydrologic alteration for plant communities within the floodplain (Pettit et al. 2001), and emergent macrophyte growth and recession in rivers (Ham et al. 1981), though almost no reported effort has been devoted to effects of hydrologic alteration on submerged macrophytes. Given the limited range of movement for sessile aquatic plants, and the increasing frequency with which we are altering the natural flow regime of most rivers, it is important to understand how flow alterations may influence these important primary producers.

We chose to investigate the effects of hydrologic alteration on the aquatic macrophyte *Podostemum ceratophyllum* Michx. (Riverweed), as it is a key foundational species (Ellison et al. 2005) for shoal habitats, which support a large number of imperiled fishes and federally endangered fishes (Freeman and Freeman, 1994). *P.ceratophyllum* thrives in swift water on rocky substrates (Hammond, 1937), and provides a complex habitat structure for the benthic community (Argentina 2006, Grubaugh and Wallace 1995, Hutchens et al. 2004). It has been associated with increased abundances of macroinvertebrates (Hutchens et al. 2004, Grubaugh and Wallace 1995, Voshell and Parker 1985) as well as increased presence of fish species (Argentina 2006, Connelly et al. 1999, Hagler 2006, Marcinek 2003). *P.ceratophyllum* has been noted to have lower abundances in areas of scouring or daily pulses from upstream hydroelectric dams (Hill and Webster1984), and may dry, break and flow downstream after experiencing low flow events (Nelson and Scott 1962, personal observations 2007- 2008).

Often hydrologic alteration is quantified by modeling changes in hydrologic data at a daily timescale, assessing for deviations from historical norms (Richter et al. 1996). A commonly used program, Indicators of Hydrologic Alteration was developed through The Nature Conservancy to analyze hydrologic changes, but presents problems of redundancy (Olden and Poff 2003) with respect to parameters and a bias towards longer time frames. Many current hydrologic alteration studies are not focused on fine-scale hydrologic modeling. Our goal was to estimate the effects of low flows and exposure events at an hourly timescale on *P. ceratophyllum* biomass at specific sample localities within our study site. We used an Information Theoretic approach (Burnham and Anderson, 2004) to evaluate alternative models of factors affecting *P. ceratophyllum* biomass, because we believe it to be more biologically meaningful to determine the relative effect of parameters rather than to accept or reject them completely with traditional null hypothesis testing.

We expected lower *P. ceratophyllum* biomass today than the two previous studies (Grubaugh and Wallace 1995, and Nelson and Scott, 1962), which were conducted during non-drought periods (USGS 2008). We anticipated that variation in *P. ceratophyllum* biomass within this shoal would be related in part to low flow hydrology factors. We wondered, however, whether we would be able to quantify a linear effect of increasing frequency or duration of low flows on *P. ceratophyllum* biomass by examining patterns across a topographically varied shoal environment (where some areas were more subject to becoming shallow or dry than others).

METHODS

Study site

This study was conducted at the shoals of the Middle Oconee River at Ben Burton Park, Athens, Georgia. The Middle Oconee River is a sixth-order river in the upper Altamaha watershed. It has a number of tributaries and eventually joins with the North Oconee River in Athens to form the Oconee River, and ultimately the Altamaha River.

The headwaters of the Middle Oconee River are in the Piedmont physiographic province at an elevation of approximately 1,000 feet above the mean sea level (GA DNR, 1998). The headwater streams are entrenched, have small floodplains and steep longitudinal gradients ranging from 4.5-7.4 feet per mile (GA DNR, 1998). The steeper portions are often reflected by shoal habitats within the channel.

This study site on the Middle Oconee has a drainage area of about 641 km^2 (USGS, 2008). Over half of the land in this basin is forested (~55%), however approximately 20% is pasture and row crop, about 9.5% is low and high impact urban development, and 6.6% is clear cut (NARSAL, 2008). In the 1950's, approximately 40% of the basin was used as farmland and 10% of this was in cotton, and by the 1990's, less than 20% of the basin was in cropland (Grubaugh 1994).

Within the Oconee River Basin, there are 14 withdrawal points for drinking water supply, 5,467 instream impoundments that cover 147 square kilometers, and three major surface water reservoirs (GRN 2008). The Oconee River is part of the larger Altamaha River basin, and in 2002, the Altamaha River was listed as the 7th most endangered river in the country due to the loss of water flow from reservoirs and power plants (GRN 2008).

The study shoal is located within Ben Burton Park, Athens, GA and is characterized as a bedrock outcrop. The hydrology of the shoal study area is highly influenced by two upstream facilities. The first is Bear Creek Reservoir, which is privately owned by the Upper Oconee Basin Water Authority and supplies water to Athens-Clarke County Public Utilities and three other surrounding counties. Bear Creek

Reservoir, constructed in 2002, is a pump-storage facility that is located outside of the river channel (on the former location of the stream named Bear Creek) spanning 505 acres. The intake point used to fill the reservoir from the Middle Oconee River is located approximately 2 miles upstream of the study shoal. The reservoir pumps operate from 8AM to 4PM and may withdrawal between 7 and 15 million gallons per day (MGD) under drought conditions, and 20 and 60 MGD during non-drought conditions (Williams 2007).

The second facility above the shoal is the Tallassee Shoals Hydroelectric Dam, which is operated by FLHC, Inc., and is located about 800 meters downstream of the intake for Bear Creek. This dam maintains a federal permit and has been named a "green" dam based on its perceived low impact to the hydrology of the river. The dam operates by directing water through a chute which intersects a turbine and produces energy. Any water that enters the chute is released approximately 3000 meters downstream through the headrace. If there is more water in the river than the capacity of the chute, water flows over the dam. When the discharge is $<100\text{ft}^3$/sec or $>900\text{ft}^3$/sec the dam cannot operate, so the chute is closed allowing water to flow over the dam itself. Under these conditions, when the small reservoir behind the dam is full, the upstream discharge equals the downstream discharge over this structure. According to the dam operator, it has not been used since the summer of 2007 due to low flow conditions that made it inoperable; in this situation, the dam and did not affect the hydrograph and hydrology downstream (Davis 2007).

In the past, the combined effect of the dam and pumping water to fill the reservoir has significantly changed the natural hydrology of the shoals just downstream. In recent months, with no dam operation, the water withdrawals alone have caused changes in the hydrology. This alteration is evident by the differences between U.S. Geological Survey (USGS) gages upstream (Arcade, GA), and downstream (Athens, GA) of our study shoal (Figure 2.1). It is clear that these facilities between the gages have resulted in extreme alteration of the hydrograph on a daily basis over the one month period (October 1 – 31, 2007) illustrated in Figure 2.1.

An additional factor within this reach of the river is an Athens-Clarke County Public Utilities intake located at the intersection of the Middle Oconee River and Mitchell Bridge, just down-stream from Ben Burton Park, which withdrawals water for the city. This pump takes water directly out of the river to a larger treatment facility located on the north side of Athens. The facility had not been in operation since from mid-summer through autumn 2007, thus, is not likely a source of any of the variability illustrated in the hydrograph (Knight 2007).

The study shoal itself consists mainly of bedrock, large boulders, and small areas of sand and gravel. *P. ceratophyllum* is widespread throughout the shoals, covering large bedrock areas, boulders of various sizes, and in some cases gravel. Historically, *P. ceratophyllum* has formed lush mats across this shoal during the growing season and has persisted throughout the winter in a more dormant stage (Grubaugh and Wallace, 1994). Red algae (*Rhodophyta*) are also common.

Due to the recent extreme drought of 2007-2008, much of the area that previously supported *P. ceratophyllum* has been exposed and the plant has died (Image 2.1). Many of the remaining refuge areas however are subject to fluctuating hydrology on a daily basis due to the upstream water withdrawals, which is compounded by the already low flows from persistent drought conditions.

Data Collection

Samples

We sampled *P. ceratophyllum* along a 100-meter long transect that defined a cross-section of the channel from one bank to the other. We used a nylon cord on a spool as a transect line which was affixed to trees on either bank. The cord was labeled at approximately 1 meter intervals with a permanent marker and every 2 meters with flagging tape. We defined five distinct sections along this transect based on substrate and topographical differences (Table 2.1).

P. ceratophyllum was sampled monthly by collecting two samples per section for a total of 10 samples. Sample locations were randomly produced and never re-sampled. If a sample point was dry, we chose the next random location. At each sampling location, we used a 103.87 cm^2 t-sampler with a 250μm mesh sleeve to collect all materials from the substrate. The sampler was pressed firmly to the substrate to prevent loss of materials. We used a metal putty knife and our hands to scrape *P. ceratophyllum* and its associated macroinvertebrates and algae. These materials were then placed into a plastic zip-lock bag and stored on ice until we returned to the lab within 2 hours of collection.

We then used an Earl Dudley Associates Inc. (Birmingham, AL) TC600 Total Station to record the distance along the transect and relative elevation of the sample location. Velocity measurements were recorded at 60% depth for each sample using a Marsh-McBirney Flo-Mate^{TM} Model # 2000. A DataSonde 4a Water Quality Multiprobe (Hydrolab Corporation, Austin, TX) and a 2100P HACH Turbidmeter were used once in the same location at each sampling time to record water quality parameters including pH, turbidity, temperature, dissolved oxygen and specific conductivity.

After returning to the lab, the ten samples were stored in a refrigerator for no more than 48 hours (and usually less than 4 hours) before sorting. Macroinvertebrates, algae and remaining detritus were removed from the *P. ceratophyllum* under 0.8x and 5x magnification.

P. ceratophyllum separated from the samples was then placed onto pre-weighed aluminum trays and dried at 60^{o}C for at 5 to 7 days before weighing. The samples were then ashed in a muffle furnace at 500^{o}C for 5 hours and then cooled for 24 hours in a desiccator. The dry weight was subtracted from the final weight to determine the ash free dry mass (AFDM) of the samples.

Hydrology

In order to understand the hydrological changes experienced by each sample location, we developed a fine-scale hydrologic assessment. A USGS gage located downstream of our study shoal recorded discharge and stage at 15 minute intervals. An Athens-Clarke County (ACC) Public Utilities intake was located between our study site and this gage, so we added back discharges withdrawn from this facility to the discharge recorded at the USGS gage. This provided us with an estimate of the gage reading if this uptake did not exist. (The ACC data were only available in hourly format, so we used hourly USGS data for this study).

An Onset HOBO (model # U20-001-04) pressure transducer (HOBO 1) was installed in December 2008, at the deepest portion of our cross-section (which was adjacent to the bank on river-left) to allow for more detailed hydrologic analysis. To secure it, we drilled four holes in a large boulder using a DeWalt pneumatic drill, and attached four eye bolts using epoxy glue. Zip ties were then used to attach a PVC chamber to the boulder to house HOBO 1. A plastic-coated steel wire was affixed to HOBO 1cap and secured to shore and the boulder. The boulder was then placed in the deepest location accessible and wedged between other rocks. While rare extreme high flows could potentially move the boulder, the steel wire would prevent a total loss of the HOBO.

HOBO 1 recorded changes in pressure at 15 minute intervals at this location, and in April, 2008, we installed a second pressure transducer (HOBO 2) above the water and to a tree, to adjust the pressure readings of our submerged HOBO (HOBO 1) for changes in atmospheric pressure. Data from both pressure transducers were downloaded and formatted using the Onset HOBOware Pro for Windows software package. We used a linear regression correlation to relate the water depths at HOBO 1 with the USGS stage readings. This relationship resulted in an equation for estimating changes at HOBO 1 location before it was in place (September to December 2008). We used this correlation to estimate hourly water depths for the 30 days prior to collecting each sample over the course of our sampling year.

In order to estimate how changes at the HOBO 1 location related to changes in depths across the cross-section for every sample, we conducted a number of surface water elevation assessments at approximately 2 meter intervals identified by pre-measured flagging tape (Figure 2.2). We also recorded the elevation of the substrate underneath each flag, and thus were able to generate water depth at those points. A regression between the water depth at each flagged point along the cross-section over time and the HOBO 1 water depth at the same time intervals resulted in individual equations relating HOBO 1 depth to depth at each flag over time. In most cases, a third order polynomial fit the data best due to an apparent inflection point at the middle discharge levels. However, changes in depth over a range of low flows appeared approximately linear in relation to depth at the transducer, and so we fit and used linear regressions to predict temporal sequences of depths at low flows along this cross-section. We accept that this may have resulted in a larger error at the higher water elevations, however, we were interested in the lower water elevations and how those changes impacted biomass during drought. At this scale, we were able to estimate the hydrologic history at one hour intervals for each 2 meter interval along the transect.

We determined each flag to be the center point of a 2 meter section to which this history was applied. Water depths over time were then calculated for all samples falling within each 2 meter section. To do this, we determined the difference in elevation between the flag location and the sample location. If the elevation at the sample was lower, we added this difference to the simulated water depth history. If the elevation at the sample was higher, the difference was subtracted, as we assumed the water to be shallower.

We did not conduct regressions between HOBO 1 and the first 21 meters (flags 2 – 10) because we determined the surface water elevation to be relatively flat in that section, meaning that changes at HOBO 1 were similar if not the same across that section. We related all samples collected within the first 21 meters of the transect directly to the HOBO 1, by calculating the difference in elevation between HOBO 1 and the bed elevation at each sample. This difference was either added for deeper samples or subtracted for shallower samples to generate a depth history for each sample location.

To determine frequencies and durations of exposure or stress events experienced at each point along the transect prior to being sampled, we used a binary system to label depths equal to or less than zero (dry) as a “1” and those greater than zero as “0.” Additionally, in a separate analysis, we labeled depths less than five centimeters (stressed conditions) as “1” and those above five centimeters as “0.” This system allowed us to sum exposure or stress events in terms of hours of duration to determine the frequency with which these events occurred at various time intervals. We used five centimeters to represent a “stressed” condition because depths that low may result in a partial exposure due to the vertical structure of the plant.

Statistical analysis

An information-theoretic approach (Anderson et al. 2001) was used for statistical analysis to allow investigation into the effect of several hydrologic and habitat variables on *P. ceratophyllum* biomass. We hypothesized that a combination of hydrology variables as well as substrate type, velocity, day and location within the channel would influence the *P. ceratophyllum* biomass (the response variable). Biomass was log-transformed because it was not normally distributed (Box and Cox 1964).

We determined that "day" may have a significant effect on the biomass collected from a given sample because concurrent work on *P. ceratophyllum* re-colonization rates found that season was a significant driver of the rate of asexual colonization (Chapter 3, Pahl 2009). If drying events occurred within a specific season, biomass collected may have been influenced by the time of year. Day was recorded as Julian day, and due to the season effect, a quadratic relationship between Julian day and biomass was determined to be the most appropriate. Thus, we use day and day^2 to account for this.

Substrate is also an important factor, as *P. ceratophyllum* grows predominantly on bedrock and boulders, but occasionally gravel. We hypothesized that *P. ceratophyllum* biomass would reflect the substrate, where bedrock and boulders may allow more *P. ceratophyllum* biomass to accumulate than gravel and cobble. This variable was categorized as discrete with a "1" representing bedrock/boulder, and a "0" representing gravel/cobble.

Velocity was included in the analysis and was reported as the velocity on the day the sample was taken, and reflects the general velocity of that site over time. While changes in velocity may occur seasonally, thus we took our samples at base flow, and hypothesized that if they were reflective of the prevailing base flow velocities, then our measured velocities should relate positively to *P. ceratophyllum* biomass. Based on previous work (Hammond 1937), we hypothesize that faster velocities will generally positively influence *P. ceratophyllum* biomass.

The location factor is an indication of the location of the sample within the channel. It is a binary variable with a "1" representing samples taken within the 12 meters of either edge of the channel (representing 25% of the transect) where shading occurs for the longest period of time, and a "0" representing samples taken on the center 75% of the channel. We hypothesize that location in the center of the channel with full sun for the longest period of time will positively influence *P. ceratophyllum* biomass (Argentina 2005).

For hydrology factors, we determined, through basic growth simulation models, that the single longest exposure event within the last 30 days, and the total number of hours of exposure during the last 30 days may be the largest drivers of change in biomass. We also hypothesized that water depths less than 5 cm might "stress" *P. ceratophyllum*, and therefore we identified total hours of water depths less than 5 cm as well as the longest time under 5 cm. These two variables represent "stressed" hydrologic conditions.

To understand how all of these variables related to *P. ceratophyllum* biomass, we first analyzed the effects of the five non-hydrologic covariates (day, day^2, substrate, velocity and location) using multivariate linear regression in SAS v 9.1 (SAS Institute, Inc., Cary, NC, USA). There were no strong correlations among the covariates (except of course day and day^2, all $r^2 < 0.52$). Our 32 covariate models included combinations of all five variables as well as the interaction between location and day/day^2, as we believed that the location effect was influenced by the time of year, as more riparian foliage was present for shading during spring and summer. We did not test other interactions because we did not believe they were scientifically relevant (Anderson and Burnham 2002). We used Akaiki's Information Criterion (AIC), adjusted for a small sample size (AICc) to evaluate the relative support for each of these models (Anderson and Burnham 2002) using Proc GLM. We then chose the most supported models (those with AICc values within two of the best supported model) to analyze with our four hydrology variables. We did not include models with more than one hydrology variable or interactions because they were highly correlated.

Our final model set included the best supported habitat covariate models and each of these models with one of the four hydrology variables included for a total of 30 models evaluating 92 samples. This design resulted in a balanced representation of all variables within the models (Anderson and Burnham 2004), thus we were able to test the relative support for each hydrology parameter and the habitat covariate models independently. To do this, we used the total weights for each model that contained each variable and added them for a total parameter weight (Anderson et al. 2001, Anderson and Burnham 2004).

RESULTS

Biomass comparisons

A comparison between our study, Grubaugh and Wallace 1995, and Nelson and Scott 1962, indicates a significant decline in *P. ceratophyllum* in recent years (Figure 2.3). Biomass values are significantly lower on average than those reported by Grubaugh and Wallace (n=24, Fcrit=4.30, P < 0.0001) and Nelson and Scott (n=24, Fcrit=4.28, P < 0.0001). Mean annual standing crops for our 2007-2008 study was 54.04 ± 7.14 gAFDM/m^2. Compared with mean monthly standing crop from Nelson and Scott's 1956-1957 study (350.2 ± 33.8 gAFDM/m^2) and Grubaugh and Wallace's 1991-1992 study (514.0 ± 53.2 gAFDM/m^2), our results were an order of magnitude lower (Table 2.2).

Covariate Analysis

Comparison of relative support among the models using habitat and time of year variables to predict *P. ceratophyllum* biomass resulted in six models with AICc values within 2 of the top model (Table 2.3). The most supported model included the substrate, location, day and day^2 covariates, and was 1.35 times more likely to be the true model than the second model. The top six models had about 68% of the total model weight, and location in the channel was included in all six models along with time of year (day and day^2).

Hydrologic Analysis

We ran the six best-supported covariate models with each of the four hydrology variables added, giving 24 models, and combined these with the six habitat-covariate only models to yield a final set of 30 models. Of these 36 models, there were 8 models within 2 delta AICc values of the top supported model (Table 2.4). The top model with an AIC Weight of 0.11, was 1.55 times more likely to be true than the second most supported model, and 1.72 times more likely to be true than then most supported null model. The top model consisted of substrate, location, velocity, day and day^2 and total number of hours under "stressed" conditions (< 5cm). We summed total AIC weights across all models containing each hydrologic variable. We found the most support for the hydrology variable describing of the total time under 5 centimeters (Total AIC weight: 0.37), which was 1.57 times more likely to be true than total AIC weight of null covariate models (Table 2.5). We also calculated the parameter estimates for the most supported model (Table 2.6).

Parameter estimates from the top model were used to estimate percent log biomass loss at a range of total hours spent with less than 5 cm of water (Table 2.7. Samples experiencing the minimum time under low water (2 hours) may lose approximately 0.06% biomass in 30 days, while those experiencing the longest duration (687 hours) may lose up to 21% biomass in 30 days. The average of percent loss expected under average low water conditions is approximately 8% in 30 days.

Effect on the cross-section

In order to determine the effect of low flows as described by the hydrology factor (total hours below 5 centimeters) in the best-supported model on *P. ceratophyllum* standing crop along the cross-section, we first estimated the discharge at which the cross-section would theoretically become stressed. Using the water depth regression equations for each two-meter interval, we determined the depth at HOBO 1 at which the interval would go dry (depth = 0 cm) and become stressed (depth = 5 cm). We used a regression equation between HOBO 1 and the USGS stage downstream to determine discharge in cubic feet per second (cfs) at the cross-section. Flows at 55 cfs resulted in 2% of the transect experiencing stressed conditions (depth = 5cm), while discharges of 10 cfs resulted in 85% of the cross-section stressed with 51% completely exposed (Figure 2.4).

To understand how much of this biomass reduction may be due to water withdrawals vs. drought induced low flows, we calculated the difference between drainage areas at the upstream gage in Arcade, GA and Athens, GA. This difference was used to adjust the Arcade gage discharges to what we might expect at Athens with no withdrawals (Figure 2.8). Adjusted flows for the Middle Oconee River did not fall below 20 cfs, which indicates that flows less than 20 cfs may be the result of withdrawals from the upstream pump storage reservoir. Flow at our study site was below 20 cfs for 460 hours over the last year.

DISCUSSION

The results of our study indicate some substantial changes in *P. ceratophyllum* biomass within the shoal of the Middle Oconee River at Ben Burton Park, Athens, GA. Inter-annual declines in biomass appear to be significant, and hydrologic stress may be a factor in this reduction.

One possible reason for the difference in *P. ceratophyllum* biomass reported in our study and Grubaugh and Wallace's 1995 study was the sampling protocol. We sampled randomly, and only avoided locations that were dry or sandy depositional areas. Grubaugh and Wallace (1995) report avoiding locations where shallow conditions occurred and exposure events were possible. Although this might have influenced the overall averages, only 2 out of 104 samples taken in the present study were above 296.8 g-AFDM/m^2 which was Grubaugh and Wallace's lowest recorded biomass (no samples were as large as Grubaugh and Wallace's average of 514g-AFDM/m^2; Figure 2.6). Whereas our sampling protocol may have been expected to result in lower average *P. ceratophyllum* biomass estimates compared to the earlier studies, the overall lack of samples approaching those previously reported averages strongly supports the notion that *P. ceratophyllum* was considerably reduced.

Additionally, Grubaugh and Wallace (1995) report a decline in cropland coverage, specifically cotton and corn, as a possible reason for water quality conditions that supported slightly higher *P. ceratophyllum* biomass results in their study compared with an earlier study by Nelson and Scott (1962). Today, cropland coverage in the same three counties, Barrow, Clarke, and Jackson, remain at similar acreages with 27% in 1991, and 28% in 2005 (NARSAL 2008). The only county in which cropland and pasture acreage increased since 1991 is in Jackson County, but only by approximately 6500 acres (NARSAL, 2008). The lack of change in cropland indicates that this may not be the driver of decreased biomass in this study compared with the last two studies, given that Grubaugh and Wallace (1995) predicted that increasing cropland would negatively affect water quality and consequently *P. ceratophyllum* biomass.

Changes in impervious surface however have been quite significant, as the three counties experienced an increase from 9% low and high impact urban land cover in 1991 to 17% in 2005 (NARSAL 2008). As our study site is located upstream of much of Clarke County, we also looked at this change with respect to Barrow and Jackson county alone (upstream counties). In these two counties, low and high intensity urban land cover went from 5% in 1991 to 10% in 2005: a change of only 5% (NARSAL 2008). While the increase in urban land cover is undoubtedly bound to change water chemistry, data are not available for this comparison. Roy et al. (2005) report that impervious surfaces can change hydrologic regimes, including increased flashiness and possible reductions in base-flow due to declines in infiltration. Reduced base-flow from impervious surfaces may further exacerbate the effect of daily hydrologic changes from water withdrawals or hydroelectric operation. Increasing urban land use is also linked to rising populations, which require more extractive water use.

Subsequent to the studies conducted in the 1950's and 1990's, a pump storage facility (Bear Creek Reservoir) was constructed in 2002. No water return structure exists between Bear Creek Reservoir and our study shoal, thus less water is reaching the shoal today than before 2002. Figure 2.5 illustrates the differences in hourly discharges across this site over each study year. Flows were higher during Grubaugh and Wallace's 1991-1992 study, so despite hydrologic alteration likely due to dam operations (Figure 2.1), low flow conditions did not occur to the extent that they do today. Comparisons between hydrographs in Athens, GA and upstream of these facilities in Arcade, GA, indicated that over the year of our study, 175 withdrawal events occurred, spanning 47.9% of the year, where average withdrawals were 35.6 cfs.

Another source of declining biomass between study years could be herbivory by geese and crayfish (Parker, 2005). As water levels declined during the drought of 2007-2008, low flows resulted in easier access to *P. ceratophyllum* through shallower depths and lower velocities. Parker (2005) notes that deeper faster water was problematic for geese as they tended to be washed downstream and as a result are unable to graze.

Although our results indicated a negative effect of the number of hours *P. ceratophyllum* experienced water depths less than 5 cm, the standard error spanned zero (-0.0013 ± 0.0014 log g-AFDM/m^2/hr), indicating the possibility of a positive effect of such flows. This may relate to heavy periphyton coverage during the summer months, which could die during short exposure events and move downstream during subsequent storm flows. This would remove periphyton from its location on top of *P. ceratophyllum* where it competes for sunlight.

The estimated loss of *P. ceratophyllum* biomass over 30 days varies quite widely based on the number of hours spend under low water conditions, however the average of all samples experiencing low water depths indicates over an 8% loss. Based on predicted base flows using an upstream gage, we think that up to 83% of the low flows may be due to drought; however the remaining 17% may be due to water extraction to fill Bear Creek Reservoir. These results indicated that water withdrawals for consumptive use may have repercussions for benthic macrophytes under drought conditions.

While information-theoretic approaches may not illicit causality for different variables in relation to the *P. ceratophyllum* biomass, we feel it provides insight into the nature of the relationships and reasonable support for the inclusion of certain variables when thinking about *P. ceratophyllum* work. Our study indicates that indeed, hydrology does influence *P. ceratophyllum* biomass to some degree, as a hydrology variable was included in the most supported model. While the estimated effect of this hydrology parameter has an error that spans zero, it is likely that future work to increase the precision of this estimate will result in a negative association between low flows and *P. ceratophyllum* biomass.

As we look towards the future, it is becoming more evident that the southeastern United States may experience increases in winter precipitation as well as increased evapotranspiration in many climate change scenarios (Mulholland et al. 1997). The combination of these two factors may result in declines in summer and fall runoff which influences stream flow (Mulholland et al. 1997). To compound this problem, population growth rates in this region remain some of the highest in the country, and will likely require more surface water extraction. Dewatering of rivers for consumption will likely increase the severity of future droughts and low flows (Seager et al. 2007).

Through this research, we have indicated that hydrologic changes, as a result of droughts and water extractions, may have negative implications for aquatic macrophytes that are key foundational species in shoal habitats. While the effects of hydrologic alteration are difficult to separate from all environmental factors which shape species persistence and productivity (Rosenberg et al. 1997), this type of analysis has allowed us to investigate the relative likelihood that hydrology, particularly very low flows, plays a role in shaping *P. ceratophyllum* biomass.

In order to better estimate the effects of variable hydrologic regimes, we recommend a more spatially expansive approach, investigating hydrology effects at the shoal-wide scale, and ultimately reach and basin scale. This type of work may provide more precise estimates of low flow effects on *P. ceratophyllum* biomass that are meaningful for management. We also recognize the possible contributions of field or mesocosm experiments looking at *P. ceratophyllum* productivity changes during various hydrologic regimes through the use of ^{14}C uptake chambers (Hill and Webster 1984) to measure use of dissolved inorganic carbon, which is a common method to quantify aquatic plant productivity. This type of analysis may provide more evidence of causality.

CHAPTER 3

RECOVERY AND RE-COLONIZATION POTENTIAL FOR *PODOSTEMUM CERATOPHYLLUM* (RIVERWEED) IN A SOUTHEASTERN PIEDMONT RIVER

ABSTRACT

Shoal habitats in southern Piedmont streams provide a unique environment for a multitude of aquatic organisms. Hydrologic alterations through reservoir and dam installation, as well as surface water withdrawal for municipal, industrial and agricultural uses, have impacted the natural flow regimes of riverine shoals. Pronounced drought, as has been documented in northern Georgia in 2007 and 2008, exacerbates these impacts. The aquatic macrophyte *Podostemum ceratophyllum* Michx. (*Podostemaceae*), is a major primary producer in these shoal habitats that generally support a diversity of macroinvertebrates and fishes. As a result of the current drought, large areas of *P. ceratophyllum* have become desiccated or stressed in the Middle Oconee River, which may have implications for species at higher trophic levels. My study in the Middle Oconee River shoals, Athens, GA investigated local rates and mechanisms of re-colonization after disturbances such as those experienced over the last two years. *P.ceratophyllum* was able to recover rapidly (within a month), primarily through vegetative growth, during the growing season (May-October), but experienced very little colonization during the winter and early spring. It appears as though recovery through seed dispersal is limited; however more in depth studies could clarify this. Ultimately, this research can be utilized to aid in the development of more comprehensive in-stream flow recommendations in order to sustain macrophyte abundances and their associated biota.

INTRODUCTION

Throughout the past century humans have greatly modified natural riverine flow regimes. Today, over 5,500 dams higher than 15 m tall exist in the United States alone and over 7,000 in North America (Pringle et al. 2000). These impoundments have considerably changed flow regimes and altered ecosystems along river continua (Freeman et al. 2007, Bunn and Arthington 2002, Naiman et al. 1995, Sparks 1995, Ward et al. 1999)

There has been a substantial response by the scientific community resulting in a large body of work illustrating upstream and downstream effects of stream diversions and impoundments on macroinvertebrates (Dewson et al. 2007, Malmqvist and Englund 1999, McIntosh et al. 2002, Rader and Belish 1999, Suren et al. 2003a), fishes (Anderson et al. 2006, Dutterer and Allen 2008, Freeman and Marcinek 2006, Propst et al. 2008, Roy et al. 2005) as well as bryophytes (Englund et al. 1997) and periphyton (Suren et al. 2003b). In some cases, the removal of impoundments has allowed for studies of fish and invertebrate re-colonization (Catalano and Bozek 2007, and Kanehl et al. 1997). While some of these systems have experienced restorative management, there has been little support for long- term monitoring of the recovery of the benthic community after such efforts (Bernhardt et al. 2007).

Though there have been a number of studies investigating long-term changes from hydrologic alteration in plant communities within the floodplain (Pettit et al. 2001), and emergent macrophyte growth and recession in rivers (Ham et al. 1981), this study offers one of the first investigations into the potential for recovery of a submerged macrophyte, *Podostemum ceratophyllum*.

The flowering aquatic plant *P. ceratophyllum* thrives in the swift, bedrock- and boulder-dominated streams and rivers of eastern North America (Hammond 1937). *P. ceratophyllum* is the most dominant macrophyte in riverine shoal habitat in Georgia and is ecologically significant for a number of reasons. *P. ceratophyllum* is highly productive (Hill and Webster 1984) and has been linked with the highest secondary production of filter feeders (Grubaugh and Wallace 1995, Grubaugh et al. 1997) ever recorded in streams (Huyrn and Wallace 2000). *P. ceratophyllum* on bedrock appears to be particularly important for secondary filter-feeders when compared with cobble habitats (Rosi-Marshall and Meyer, 2004).

Hutchens et al. (2004) documented the importance of *P. ceratophyllum* for macroinvertebrate communities, finding that removal of this species resulted in a much lower total macroinvertebrate abundance and biomass. They also indicated that the recovery of such communities were extremely slow. *P. ceratophyllum* presence has also been correlated with the presence of a number of fish species through the southeast (Argentina 2006, Connelly et al. 1999, Hagler 2006, Marcinek 2003). *P. ceratophyllum* may provide fish, especially small ones, with refuge from predation, and food in the form of macroinvertebrates (Argentina 2006).

Over the past few decades, *P. ceratophyllum* has been in decline in many of the north-eastern states presumably due to various impacts such as poor water quality or hydrologic alterations. In Georgia, *P. ceratophyllum* is not listed as endangered or threatened, as it is in the northeastern U.S., however recent climatic events have caused significant negative impacts.

The drought of 2007-2009 has sent river water levels to record lows causing a widespread desiccation of *P. ceratophyllum.* The areas of remaining *P. ceratophyllum* are under additional stressors in some regions where hydrologic alteration, in the form of extreme fluctuations in discharge, increases the severity of daily trauma to the plants. Increasing human populations in Georgia may demand more of our water resources, exacerbating this problem in the future.

This study is designed to investigate how *P. ceratophyllum* recovers from removal disturbances such as short term desiccation under a variable hydrology due to anthropogenic alteration of the natural flow or scarification from debris flow. It is imperative to understand recovery potential and growth of *P. ceratophyllum* given that it is an important base to the biological structure within southern Piedmont Rivers.

To assess the rate of re-colonization of *P. ceratophyllum* under the current conditions, I conducted a removal study. Most studies to date collect *P. ceratophyllum* samples at discrete locations and compare these over time. In these cases, the sampling occurs in random locations so there is no temporal aspect to the individual sample itself, beyond the season. To understand how a specific location may change in terms of *P. ceratophyllum* biomass over time, I utilized a repeated measures experimental design to examine re-colonization.

METHODS

Study Sites

This study was conducted at two different sites; the Middle Oconee River and Hunnicutt Creek, a tributary to the Middle Oconee. The two sites allow comparison of *P. ceratophyllum* re-colonization in contrasting hydrologic regimes.

Middle Oconee River (MOR):

The Middle Oconee River at Ben Burton Park, Athens, Georgia is a sixth order river within the upper Altamaha watershed. It has a number of tributaries and eventually joins with the North Oconee River in Athens to form the Oconee River, and ultimately the Altamaha River. The study site is located in the north-west corner of Athens-Clarke County, and is north of a USGS gauging station.

The study site is characterized by bedrock a bedrock outcropping and scattered boulders, gravel and sandy pools. The hydrology of this site is heavily altered by upstream water extraction (see Chapter 2 for more details) as well as prevailing drought which has impacted this region beginning in 2007. Due to the extreme drought conditions, much of the area that previously supported *P. ceratophyllum* has been exposed, resulting in mortality of the Riverweed. Many of the remaining refuge areas however, are influenced by the upstream water extraction which causes daily fluctuations in discharge on the order of 13 to 28 cfs (7-15 MGD) which is permitted under drought conditions.

While current conditions do not allow for widespread re-colonization within this shoal due to low base flow and continuing fluctuations, a manipulative study has allowed us to assess the rates of *P. ceratophyllum* recovery from two different mechanisms. We intend to use these data to inform management plans regarding current water withdrawals and future extractions. As the local rates may be influenced partially by the recurring withdrawals, a comparison was made with an adjacent tributary population that was not subjected to major daily fluctuations in hydrology.

Hunnicutt Creek (HCC):

Hunnicutt Creek is a tributary to the Middle Oconee River and enters at Ben Burton Park. Hunnicutt Creek is spring fed with a generally unaltered hydrology, except for the possibility of runoff from localized impervious surfaces. The lowest 100 meters of the stream before its confluence with the Middle Oconee is predominantly bedrock and supports one main patch of *P. ceratophyllum* as well as a number of very small patches approximately 30m upstream. Within the study area of Hunnicutt Creek, *P. ceratophyllum* is only found on bedrock.

Hunnicutt Creek was subjected to an oil spill in October of 2003 (Shearer, 2003). The Upper Oconee Watershed Network has been monitoring this creek since then. It appears as though the stream has recovered however, and *P. ceratophyllum* coverage is near 100% where wetted bedrock occurs in the lower portion (the upper portion contains bedrock as well, but heavy shading likely excludes *P. ceratophyllum* from these locations).

Experimental Design

P. ceratophyllum populations may be affected by small-scale disturbances, such as scouring during a storm event or when a change in hydrology temporarily desiccates a patch. It is important to understand how much re-colonization occurs from local processes such as from vegetative in-growth versus seeds or cloning propagules from distant sources. This information will be especially important if climate change and modified hydrology continue to impact the quantity of remaining viable habitat.

In order to assess re-colonization of disturbed areas of *P. ceratophyllum*, it is important to consider the two major pathways of dispersal: seed germination and vegetative cloning (Hammond 1937). *P. ceratophyllum* can undergo sexual reproduction; however it predominantly undergoes pre-anthesis cleistogamy, a form of self-pollination (Philbrick et al. 2006). Philbrick (1984) also reports that *P. ceratophyllum* can form seeds above or below the water level, and that the seeds then flow downstream until the outer mucilaginous coat allows them to attach to a surface (usually a bare hard substrate). Philbrick (1984) also found that these seeds were often dislodged by rising water levels. Low flow conditions could either enhance germination through increased area of bare lodging sites, or decrease it through drying stress on new seedlings. Philbrick (1984) found that only one of his three study populations produced viable seeds, indicating that this mechanism may not be the most important.

In the field, these differing types of common colonization, seed dispersal and vegetative growth, can be studied through two experimental designs. First, small scale disturbances could result in patches of destroyed *P. ceratophyllum* surrounded by a larger colony. If the patch within the larger colony has the same substrate, bedrock in this case, the mechanisms for re-colonization could include vegetative spread through cloning, seed accrual, or the acquisition of a dislodged piece of *P. ceratophyllum* from upstream that contains growth meristems, which can reestablish. In an alternative situation, where a boulder is isolated by a substrate type that is not suitable for the vegetative spread of *P. ceratophyllum*, such as sand or silt, the only theoretical source for re-colonization would be seed accrual or plants dislodged upstream.

To determine what types of substrate are not suitable for *P. ceratophyllum* growth, I conducted a preliminary study in September of 2007, in which I assessed forty 30 cm transects from the center of boulder and bedrock substrate perpendicular to the flow. At each transect I characterized the substrate and *P. ceratophyllum* coverage at 5 cm intervals. I found sand and silt to be unsuitable as *P. ceratophyllum* substrate, while bedrock, boulders, and some cobble were acceptable.

Compounding factors influencing re-colonization post-disturbance could include the following: 1. the altered hydrology, including presence or absence of strong daily fluctuations beyond the natural variation, 2. percent of the area wetted at the time re-colonization was examined, 3. season, which influenced temperature and sunlight, 4. quality of the surrounding source patch, for example, in the case where the disturbance was within a patch of *P. ceratophyllum.*

I investigated colonization of disturbance sites through two different experiments, taking into account the applicable compounding factors described above. A repeated measures approach was taken to assess *P. ceratophyllum* re-colonization both within an existing patch and when isolated from remaining patches.

The following research questions were addressed: 1. What are the different mechanisms by which *P. ceratophyllum* re-colonized areas? 2. What is the rate of *P. ceratophyllum* productivity in terms of re-colonization rates within the shoal? 3. How do different local site conditions influence *P. ceratophyllum* productivity as affected by water depth and velocity? To understand these questions, two different methodologies and analytical strategies were utilized.

Patch Study:

I conducted a split-plot repeated measures study of re-colonization within an existing patch of *P. ceratophyllum* (Patch Study). The experiment consisted of two blocks of four 20cm x 20cm plots in the Middle Oconee River (MOR) as well as in one of its tributaries, Hunnicutt Creek for a total of 16 plots. In the MOR, two large patches (blocks) of *P. ceratophyllum* were identified, both near the center of the channel. Patches selected were predominantly bedrock, and appeared to maintain some flow at all times (100% area wetted) despite low discharge conditions during the drought of 2007-2008. These patches also maintained similar quality *P. ceratophyllum*, in color, average length and density of cover. The purpose of the two location blocks within the MOR was to allow for analysis of any additional spatial factors in the river that may have influenced re-colonization. As Hunnicutt Creek maintains just one major patch of *P. ceratophyllum*, only one location (block) of eight 20cm x 20cm plots was assessed there.

Four or eight 20 x 20cm plots were located within each patch by identifying areas that were relatively flat and uniform in coverage. These areas were then assessed for depth and velocity and assigned a treatment label that reflected its combination of depth and velocity (shallow: slow or deep: fast).

A comparison of velocities among plots at the beginning of this study using a student's t-test in the Middle Oconee River (MOR) and Hunnicutt Creek (HCC), found ambient velocities of the shallow plots within each site to be significantly different ($P<0.013$, $P=0.0003$ respectively) from deep plots, and no significant difference between the two sites in shallow plot velocities ($P=0.99$), or deep plot velocities ($P=0.08$).

Ambient depths of the "shallow" and "deep" plots within each site were found to be significantly different ($P<0.013$ MOR, $P=0.022$ HCC), however "shallow" plots were not significantly different between MOR and HCC ($P=0.57$), nor were the "deep" plots ($P=0.07$).

Water depth and velocity measurements were recorded during the monthly base flow when no apparent hydrological changes were occurring (early morning before upstream pumping began). The two different velocity and depth ranges found in the preliminary work are labeled "Deep" treatment, and "Shallow" treatment. The Deep treatment consists of the faster, deeper water, while the Shallow treatment is the slower, shallower water. (A factorial analysis was not conducted with the remaining two possible combinations of velocity and depth (deep: slow and fast: shallow) because they either did not exist or did not contain any *P. ceratophyllum* patches).

Each plot was scraped of any existing *P. ceratophyllum* on October 22, 2007 using a metal putty knife. A sub-sample 5cm^2 was collected during the scraping process, dried at 50^{o}C for at least 7 days, weighed, ashed at 500^{o}C for 5 hours in a muffle furnace, and the re-weighed to find the ash free dry mass (AFDM) for later comparison. The scraped plots were then marked with stakes in the two upstream corners. Holes were drilled into the bedrock using a DeWalt pneumatic drill and cement drill bits. The holes were ¼" to ½" deep. One corner was marked with a 2" metal tension rod painted orange, and the other was marked with a 1" wooden pin also painted orange. This set-up was to reduce the number of permanent objects but ensure at least one marker did not decay and was able to withstand the high flows in the river.

Each plot was observed monthly using a 20cm x 20cm x 10cm wooden box with a woven wire grid providing 400 1cm x 1cm squares. The bottom of the box was lined with upholstery foam to help create a seal on the bottom of the rock and prevent flow-through during observation at lower flows. At flows exceeding visual assessment with the box, a viewing bucket with the same grid drawn on plexi-glass bottom with a permanent marker was used. A high powered flashlight was used to illuminate the plots for easier assessment.

At each observation day, the number of 1cm x 1cm squares intersected by spreading *P. ceratophyllum* was recorded as well as the number of cells with new propagules that did not appear to be attached to spread from the surrounding patch. Water depth, velocity, and time were also recorded. The results of each observation were recorded as the number of 1 cm^2 squares intersected by *P. ceratophyllum* and the number of squares with new propagules per 20cm x 20 cm plot.

Three hypotheses were tested: 1. Recovery rates will be faster in the deep: fast plots in terms of vegetative spread because of the superior quality of the *P. ceratophyllum* in those patches (longer and greener), and the general understanding that this species grows best in fast flowing water. 2. Recovery rates from new propagules will be faster in the shallower plots as they might have the opportunity to temporarily dry down allowing for seed deposition and germination. 3. Recovery rates will be faster in Hunnicutt Creek than the Middle Oconee River despite depth: velocity treatment due to the possibility of fluctuating flow stress on plots in the Middle Oconee.

This study was conducted for 11 months. The complete methodology was repeated on May 30, 2008 to separately assess the growing season re-colonization rates and mechanisms (figure 3.4). I hypothesized that the growing season would have a higher occurrence of new propagules due to the life-history characteristics of *P. ceratophyllum*. Many of the annual plots reached 100% coverage by May, thus a growing season assessment allowed for continued re-colonization rate calculations.

Throughout the early time period of the study, it became evident that perhaps some of the "new propagule" recordings were the result of incomplete scraping that left part of the plant in the plot. To account for this, I added dry flat rocks with no initial *P. ceratophyllum,* that were approximately the same size as the plots to the patches, so they were also within a patch. I recorded percent coverage on these over time as well to better understand the rates of propagule recruitment.

Boulder Study:

To understand how *P. ceratophyllum* may re-colonize an area with no local source for vegetative spread, I evaluated boulders that were isolated by sandy substrate (Boulder Study) within the Middle Oconee River (similar conditions did not exist in Hunnicutt Creek). In October 2007, I identified three blocks across the shoal that contained a number of boulders greater than 30cm in diameter that were surrounded by sandy substrate (Figure 2.5). Within each block, the six closest boulders to the center point that were not connected to any other bedrock or boulder substrate were selected. All boulders contained remnant *P. ceratophyllum* holdfast markings, indicating that they had previously served as a suitable substrate for the plant (Image 3.1). Some boulders contained a small fringe of live *P.*

ceratophyllum where the water levels covered a small portion of the boulder. To ensure that re-colonization rates could be determined with no local spread, these fringe areas were scraped with a putty knife and wire brush to remove all remnant *P. ceratophyllum.* As a control, each block contained one boulder that was completely dry at the start with no fringe *P. ceratophyllum* population to scrape.

Each boulder was observed monthly to quantify the number of new propagules landing on the boulder, as well as the amount of spread expressed in cm^2. The rocks were observed using the underwater viewer described in the first experiment. I hypothesized that there would be no vegetative spread due to the isolation of the boulders from other substrates containing *P. ceratophyllum*, and that the rate of re-colonization would be slower than on the plots surrounded by *P. ceratophyllum* because of the lack of vegetative spread and distance from neighboring propagule or seed sources.

Originally I planned to measure the surface area of the boulder as well as water depths over time to model the area wetted. The wetted area would be the possible re-colonization area to be compared with the *P. ceratophyllum* growth in cm^2. Unforeseen changes in the substrate, due to seasonal storm flows that caused shifting sand and silt, made this comparison ultimately impossible. Thus, this study does not afford comparisons between boulders, only on a given boulder over time.

Data Analysis

Patch Study:

The Patch Study was developed as an a priori split-plot repeated measure design with a block effect. Each patch of *P. ceratophyllum* is a whole-unit, subjected to two levels of depth treatment. The sub-unit factors are the time levels applied to each whole unit. The experimental units within these treatments are the *P. ceratophyllum* plots. A repeated measures split-plot design allows for analysis of the sub-units (time) within the whole-units (treatments).

The response variable in this study is the percent of the plot occupied by *P. ceratophyllum* over time. This number was calculated by taking the number of 1 cm x 1 cm squares crossed by spread as well as those occupied by a new propagule and dividing that by the total number of 1 cm x 1 cm squares in the plot. This number was then converted into a percentage. Initially an independent assessment of the new propagules and vegetative spread was intended, however due to the control rocks indicating that there were no actual new propagules, these data were pooled to form the percent cover values.

A split-plot repeated measures design was analyzed in SAS v 9.1 (SAS Institute, Inc., Cary, NC, USA) to determine sources of variance between the rates of re-colonization among the blocks over time. All comparisons regarding time were made with a univariate procedure adjusted for Huynh-Feldt epsilon due to insufficient degrees of freedom. The only exception is the comparison between the Middle Oconee River and Hunnicutt Creek during the growing season, as degrees of freedom allowed for a multivariate comparison between time factors. A profile analysis was used to illustrate the sources of any significant interactions between time and treatment, time and block or time, treatment and block.

Boulder Study:

No statistical analysis was possible with the data, given that I was unable to calculate boulder wetted area over time. It is however, valuable as a descriptive study.

RESULTS

Patch Study (Biomass accumulation):

P. ceratophyllum biomass at the start of this study was not significantly different among depth treatments within each site (P = 0.24, MOR; P = 0.63, HCC), nor was there a difference between blocks in the Middle Oconee River (P = 0.29) or between the Middle Oconee River and Hunnicutt Creek (P = 0.79).

Annual accumulation of biomass (over 352 days) was different between depth treatments within Hunnicutt Creek (P=0.04) with more accumulation in deep plots, but not in the Middle Oconee River (P=0.75) (Figure 3.5). Overall average biomass accumulation was greater between the Middle Oconee River than Hunnicutt Creek (P=0.029) (Figure 3.5 A) but there was no significant difference between blocks in the Middle Oconee River (P=0.85). Growing season (May 30, 2008 – September 17, 2008) average biomass accumulation did not differ significantly among treatments within each site (MOR, P=0.13; HCC, P=0.08). Growing season average biomass was not significantly different between the Middle Oconee River and Hunnicutt Creek (P=0.10), nor was it different between blocks in the Middle

Oconee River (P=0.31). A general trend in biomass suggests that there is lower biomass accumulation in shallower plots versus deeper plots, despite the lack of significance among all comparisons (Figure 3.5 A & B).

Growth rates varied among months, and between the two study systems. Based on the biomass data, growth rates over the annual study were approximately 0.15 ± 0.03 g-AFDM/cm^2/day in the Middle Oconee River, and slightly slower at 0.04 ± 0.01 g-AFDM/cm^2/day in Hunnicutt Creek. During the growing season the rates both the Middle Oconee River (0.07 ± 0.04 g-AFDM/cm^2/day) and Hunnicutt Creek (0.27 ± 0.11 g-AFDM/cm^2/day) had slightly faster growth rates than the annual average, although the rate was much higher in Hunnicutt Creek.

Patch Study (Percent-cover):

The null hypotheses investigated in this study were that there is no difference in *P. ceratophyllum* percent cover over time, among treatments over time, among blocks over time, or among an interaction between treatment and block over time. First, a repeated measures analysis of the two blocks within the MOR over an annual time frame resulted in a significant time effect (F=6.25, df=12, P<0.0001), but no significant effects of treatment, block, block*treatment interactions, or time*treatment, time*block, time*treatment*block interactions when $\alpha = 0.05$ (Table 3.1). Figure 3.6 illustrates how block # 2 in the MOR lagged behind block # 1 with respect to average percent cover from May 2008 until September 2008, when it surpassed percent cover in block #1.

Interestingly, the depth and velocity treatments were not significant over time in general or within specific locations when analyzing average *P. ceratophyllum* percent cover between the MOR and HCC (Table 3.2). Time, however, was a significant variable with respect to average *P. ceratophyllum* percent cover in both the MOR (blocks combined) and HCC (F=26.88, df=12, P<0.0001) (Table 3.2). The time*block interaction was also significant (F=3.01, df=12, P=0.0355) when $\alpha = 0.05$ (Table 3.2). A profile analysis of this interaction indicated that the average percent cover of *P. ceratophyllum* was similar between the MOR and HCC from October 2007 through February 2008, but became significantly greater in the MOR from March to May (Figure 3.7). In June, average percent cover in HCC surpassed the MOR and remained higher until October, 2008 when the two sites became very similar (Figure 3.7).

The growing season plots were analyzed similarly to the yearly data, first comparing the two plots within the MOR, and then comparing the MOR with HCC. Within the MOR, there was a significant effect on the average percent cover of *P. ceratophyllum* from the treatment (F=80.06, df=1, P=0.0009), block (F=37.87, df=1, P=0.0035), and block*treatment interaction (F=29.56, df=1, P=0.0056) reported in Table 3.3. There was also a significant among-subject effect of time (F=5.05, df=5, P=0.0104) which indicates that average percent cover changed significantly over time (Table 3.3). Average percent cover was significantly different among the two blocks in the first month of the growing season (May-June) as well as later from August to September (Table 3.3). These differences are the result of a treatment effect in block # 2, which likely caused the shallow/slow plots to become drier during low flows, which might reduce average percent cover of *P. ceratophyllum* (Figure 3.8).

A comparison between the combined blocks in the MOR and the block in HCC during the growing season indicates that time was significant (F=15.96, df=5, P=0.0006) as well as the time*block interaction (F=8.52, df=5, P=0.0046) reported in Table 3.4. It appears as though while HCC had smaller average percent values than the MOR, they changed over time in similar ways; both declining in August and October during low flow conditions with no significant difference between plots that were in deeper/faster water than those in shallower/slower water.

While average *P. ceratophyllum* percent cover varied among months and between the MOR and HCC, the variance followed similar patterns. The only major difference between the growing season study and the year-long analysis is that treatment became significant within the MOR in one month where the shallow plots became much drier than the deeper plots. The growing season analysis was integral to quantifying *P. ceratophyllum* growth over time, as it allowed for continued surveillance after plots reached 100% cover.

The rate of *P. ceratophyllum* spread in percent cover was fastest from April to May during the annual study in both locations (MOR: 0.0186 ± 0.0037 m^2/day; HCC: 0.0140 ± 0.0009 m^2/day), but the growing season plots indicate that this rate may continue to increase through June and July (MOR: 0.0267 ± 0.0023 m^2/day; HCC: 0.0255 ± 0.0019 m^2/day)

Boulder Study:

Monthly observations found that no boulders acquired any *P. ceratophyllum* for the first four months (November – February). March marked the beginning of *P. ceratophyllum* colonization with 39% of the boulders containing from 2 to 300 cm^2 of *P. ceratophyllum*. The average coverage was 24.4cm^2. Coverage persisted throughout September (Figure 3.11) but did appear to peak in May and June. The predominant pattern of re-colonization was through spread on the upstream side of the boulder. In many cases, shifting sand and silt uncovered unknown patches of *P. ceratophyllum* in close proximity to the boulders. In other cases, sand and silt covered boulders completely.

DISCUSSION

Initial biomass pooled from both sites was not significantly different from biomass 352 days later, suggesting that there were no extenuating environmental circumstances throughout this year beyond recognized hydrological changes. Plots in the Middle Oconee River gained less biomass during the growing season than those in Hunnicutt Creek, perhaps due to the influence of the treatment effect on shallow plots between May –June and August-September which negatively impacted average percent cover.

The results of the patch study indicate that there was no significant difference in average *P. ceratophyllum* percent cover among plots in the MOR and between MOR and HCC with regard to the two treatment levels, or location. The percent cover was significantly different however during the growing season comparisons within the MOR. This may be due to occurrence of a drying event in block 1 (Figure 2.7) which desiccated and removed all *P. ceratophyllum* during that time interval. By mid summer, this difference had disappeared, indicating recovery.

Expectedly, time was a significant factor in *P. ceratophyllum* percent cover at some point in each of the four comparisons (MOR blocks annual, MOR and HCC annual, MOR blocks growing season, and MOR and HCC growing season). In the annual comparisons between MOR and HCC, time was a significant factor in average percent cover during March, April, May and June, indicating that *P. ceratophyllum* spread occurred at the fastest rates during this time. Before March, there was not a significant difference in cover between sampling times because of the slow growth that resulted in values close to zero. After June, time is not significant, indicating that the plots have reached 100% cover in most cases; however density and length may have continued to increase.

The growing season comparisons within the MOR blocks provide insight into the growth rates during the later summer and early fall months. The MOR growing season plots had significant increases in average *P. ceratophyllum* cover within each time interval, indicating a continued spreading pattern, likely due to the physiological response to acceptable temperature, available light and substrate in a neighboring location. The block effect, and interactions between time and block were also significant, but I think this is mainly driven by the drying event, which impacted block 2 (Figure 2.7). The drying event resulted in a significant treatment and time*treatment effect, as the two shallow: slow plots were the ones that dried. These results indicate that within one month, drying can decimate a patch of *P. ceratophyllum*, but if it occurs within the growing season, that area may recover within a very quickly if surrounding *P. ceratophyllum* remains intact as a source of vegetative re-colonization.

These results are important because they provide a time-line for recovery. If water levels were to return to historic base-flow conditions, a large area would be submerged providing expansive opportunities for re-colonization. If these areas remained wetted, it is possible that *P. ceratophyllum* could grow as much as 0.0267 ± 0.0023 g-AFDM/m^2/day during the growing season in the Middle Oconee River, and 0.0255 ± 0.0019 g-AFDM/m^2/day in Hunnicutt Creek. This would depend on the size and position of the neighboring patch, as this study looked at *P. ceratophyllum* spread inward from a completely surrounding patch.

The results of the boulder study were the most surprising. I hypothesized that re-colonization would be slower and driven by new propagules rather than vegetative spread given the isolation from surrounding patches. Monthly observations found however, that re-colonization appeared to come from remnant *P. ceratophyllum* patches under the sand and silt that were exposed through winter high flow events. *P. ceratophyllum* spread upward from these refuges onto the boulders in many cases. In other instances, it appeared as though re-colonizing *P. ceratophyllum* was predominantly on the upstream side, which may relate to the increased velocities at that location, or perhaps some propagule recruitment. Given the coarse scale of observation techniques, I do not believe that I was able to accurately determine propagule presence, and often, what I determined to be local spread, may have actually been propagule recruitment that spread downward. A more in-depth study using magnification would be appropriate in the future for understanding the impact of seed dispersal on re-colonization potential in this shoal.

Future work should focus on comparing recovery rates in a multitude of larger river systems as well as tributaries. This will be important for understanding *P. ceratophyllum* growth dynamics more broadly. While we know that macroinvertebrate abundance is correlated with *P. ceratophyllum* presence (Hutchens et al. 2004), as well as presence of fishes (Argentina 2006, Hagler 2006, Marcinek, 2003, Connelly et al. 1999), further study regarding how and at what rate those communities recover would be useful in developing restoration predictions and goals. While *P. ceratophyllum* does possess the capacity to recover quickly under certain conditions (i.e. sufficient water, substrate, and season), it will be important to continue to monitor this important foundation species as well as the rest of the benthic community in this region (Kominoski et al. 2007) in order to detect declines and implement management strategies in a timely manner.

CHAPTER 4

MONITORING PRIORITY FOR *PODOSTEMUM CERATOPHYLLUM,* (RIVERWEED), IN MAJOR BASINS ABOVE THE FALL LINE IN GEORGIA, USA

ABSTRACT

Anthropogenic sources of stream flow alteration have increased in magnitude over the last 50 years. These changes may be stressors to populations of aquatic plants, including *Podostemum ceratophyllum*, a common fixture in southeastern shoals. *P. ceratophyllum* is ecologically important as it provides habitat for the benthic community, including imperiled species. While this plant ranges from Georgia north through Canada, it has declined in the northeastern portion of its range. Current work has indicated that hydrologic changes as a result of upstream water withdrawals and drought may result in biomass loss through stress. As Georgia continues to grow in population and demand for water resources, and as climate change may result in less runoff to feed river systems, it may be necessary to monitor this species. Other states such as New York and Massachusetts have employed their Natural Heritage Programs to monitor *P. ceratophyllum*, which may also be an option in Georgia. An analysis of the likely range of *P. ceratophyllum* in Georgia with respect to indicators of hydrologic alteration within this range provides some focal watersheds to begin a monitoring process, including the Conasauga, Upper Oconee, Upper Chattahoochee and Etowah basins.

INTRODUCTION

Aquatic macrophytes are experiencing significant changes within their habitat as our larger river systems continue to be altered by dams (Dynesius and Nilsson,1994), and water extractions. Changes to the natural flow regime can influence plants by changing the timing of critical flows (Poff et al. 1997) that may be necessary for seed dispersal, or by creating more pronounced low flow events, which can cause direct stress on or loss of aquatic species.

Often aquatic macrophytes occur in mid-order rivers where an open canopy allows for necessary sunlight (Argentina, 2006). These regions also tend to be most impacted by hydrologic alterations, as headwater streams are dewatered for development and mid and downstream portions are often impounded (Freeman et al. 2007).

An important foundational macrophyte along the east coast of the United States is *Podostemum ceratophyllum.* It thrives in high velocity conditions on rocky substrates typical of shoal habitat (Hammond 1937). It is a root-less species that attaches to rocks with a disk-like appendage called a raphe (Hammond 1937).

P. ceratophyllum plays an important ecological role as it provides a complex habitat matrix for other benthic organisms (Argentina 2006, Grubaugh and Wallace 1995, Hutchens et al. 2004). Its abundance has been correlated with increasing abundances of macroinvertebrates (Hutchens et al. 2004, Grubaugh and Wallace 1995, Voshell and Parker 1985) and presence of fish species (Connelly et al. 1999, Argentina 2006, Hagler 2006, Marcinek 2003), including a number of imperiled fishes (Freeman and Freeman 1994, Hagler 2006).

While *P. ceratophyllum* plays a key role as a major primary producer in middle order streams, it has been in decline across its range, particularly in the northeastern U.S. (USDA 2008). According to the U.S. Department of Agriculture (USDA) (2008), it is listed as a species of concern in Connecticut, Maine, Massachusetts and Tennessee. *P. ceratophyllum* is threatened in New York, endangered in Ohio and considered “historic” in Rhode Island (USDA 2008) (Figure 4.1). A “Historic” classification in this state implies that no specimens have been observed since 1982 (USDA 2008).

Although *P. ceratophyllum* is not listed as of special concern in any southeastern U.S. states, researchers have noted declines or population changes. Hill and Webster (1985) note that *P. ceratophyllum* productivity found in their study in the New River, VA was higher than that of Rogers et al (1983), whose site was just 128 km downstream and experienced strong daily fluctuations in flow from an upstream hydroelectric dam. Nelson and Scott (1962) also note that *P. ceratophyllum* was vulnerable to low flow events in a middle order Georgia Piedmont River, where short drying events caused the plant to dry, break off and flow downstream as detritus.

A study in a middle order Georgia Piedmont River by J. Pahl, R. Katz and M. Freeman (2008) (Chapter 2) found that hydrologic events such as low flows at an hourly scale may have a negative effect on *P. ceratophyllum* biomass. Often short low flow events are the result of upstream water extraction or hydropower generation, and longer duration events may be caused by drought conditions.

The goal of this chapter is to assess the likely range of *P. ceratophyllum* above the Fall Line in Georgia, and the possible extent of hydrologic alteration which may be affecting populations. Areas with the highest percentage of habitats impacted are cross-referenced with projected population growth to better understand the possible threats to *P. ceratophyllum* in the future through increased water extraction (Seager et al. 2007) and impoundment construction (SB 346 2008).

METHODS

In order to determine the possible range of *Podostemum ceratophyllum* within the Piedmont, Valley and Ridge, Appalachian, and Cumberland Plateau regions of Georgia (above the Fall Line), we used a subset of the Georgia Museum of Natural History database of fish collections in Georgia containing records from 1995-2007. The presence of *P. ceratophyllum* was recorded at shoal sites, as it is an indicator of good fish habitat (Argentina 2006, Hagler 2006, and Marcinek 2003). The sampling locations where *P. ceratophyllum* was present are shoal habitats and were characterized in terms of stream order, link magnitude and downstream link for a descriptive analysis of *P. ceratophyllum* general range requirements.

Strahler stream order is a process for defining stream size based on a hierarchy of tributaries (Strahler 1952). Link magnitude is a surrogate for upstream watershed size, as it is a count of all first order streams and is correlated with drainage area. Downstream link refers to the number of first order streams draining into the closest downstream segment to the site. This may be important, as tributaries close to larger order segments may be more likely to be colonized from larger patches of *P. ceratophyllum* located in large shoals.

We chose to use Geographic Information Systems (GIS) to view this data on the USGS National Hydrography Data Set 1999, 1:100,000 scale stream cover, because this is available to the public (http://nhd.usgs.gov/data/html) and most commonly used for similar research. The stream coverage was underlain by the USGS 1946 Physical Divisions of the United States, automated from Fenneman's 1:7,000,000 scale, physiographic provinces map. County designations were delineated using the USGS 1994 1:100,000 scale County Boundary-DLG map and watersheds were identified using a modification of the USGS HUC 8 watershed boundaries map. USGS gage locations were mapped using the USGS stream flow gage coverage available at (http://water.usgs.gov/waterwatch/?m=real&r=ga).

Due to the lack of a non-random sample of *P. ceratophyllum* locations and of specific non-presence data, a model to predict *P. ceratophyllum* presence was not possible at this time; however my descriptive approach may provides information on where *P. ceratophyllum* is known to occur on a larger scale. Based on this non-random sampling of *P. ceratophyllum* sites, we accept that there are likely locations outside of this range that are also suitable for *P. ceratophyllum* habitat.

In order to assess the possibility of hydrologic alteration near these *P. ceratophyllum* observations, I identified U.S. Geological Survey (USGS) gages within watersheds that contained *P. ceratophyllum* (Figure 4.2) and assessed the 15 minute interval hydrograph for signs of hydrologic alteration over the previous 60 days for each gage. Daily patterns in fluctuating discharge were determined to be the likely result of upstream water withdrawals or hydropower dam releases (Figure

4.3). While many of the hydrographs for each gage had easily distinguished patterns of alteration, others were more difficult and possibly the result of natural daily variations, particularly where the flow was extremely low (<1 cfs). In these cases, if there was a pattern of reductions or rises in flow with each day, and if daily fluctuations were 10% or more of the daily base flow, the gages were identified as altered.

To better understand the extent of hydrologic alteration, we determined the percent of USGS gages within each major watershed that showed signs of alteration. We believe this is the most informative approach given the lack of knowledge regarding locations of the source of alteration with respect to each gage (exact municipal and industrial surface withdrawal locations are not public information due to Homeland Security regulations).

Ideally, the use of a hydrology model such as the Indicators of Hydrologic Alteration (IHA) may be useful to quantify specific changes in hydrology that may be biologically meaningful to *P. ceratophyllum* such as low flow durations (Richter et al. 2007), however adequate before/after data were not available within the time frame of this project. Models such as IHA also typically work with daily data, so development of a model that works with more fine-scale hydrology measurements at the 15 minute or hourly time interval would be necessary to detect some of the short-term changes in hydrology which may negatively affect *P. ceratophyllum* biomass.

RESULTS

The results of this analysis indicate that a conservative estimate of the range of *P. ceratophyllum* above the Fall Line in Georgia spans almost all HUC 8 watersheds; exceptions are the Tugaloo, Hiawassee and Middle Tennessee-Chickamauga, although no sampling occurred there, so it is possible the range extends into these basins also.

Most of the *P. ceratophyllum* observations occur in middle order streams (Figure 4.4), and there seems to be some patterns involved with link magnitude and downstream link. For all data, link magnitude and downstream link are highly, positively correlated ($R^2 = 0.88$; Figure 4.5), but are less so for the samples under a value of 100 in link magnitude ($R^2 = 0.14$; Figure 4.5). The correlation between downstream link and link magnitude is actually negative for the samples with link magnitudes equal to or less than 10 (R = -0.19) (Figure 4.5), indicating that sites where *P. ceratophyllum* occurs may have a slight tendency to have higher downstream links when link magnitudes are very small. This type of pattern results when patches are in smaller streams but closely connected to larger systems, which may provide a better source for colonization.

Within this range, there are 159 USGS gages, 83 of which that indicate some form of hydrologic disturbance. The most altered basins (>50%) are the Oostanaula, Conasauga, Middle Savannah, Upper Chattahoochee, Etowah and the Upper Oconee (Figure 4.6, Table 4.1). The Ocoee Basin contains *P. ceratophyllum*, however no USGS gages were present in this basin for analysis.

DISCUSSION

Based on previous work by J. Pahl, R. Katz and M. Freeman (2009) (Chapter 1), it appears that shoals within waters upstream and downstream of USGS gage locations indicating hydrologic alteration may be areas to focus future monitoring of *P. ceratophyllum*. As *P. ceratophyllum* observations in other states indicate upstream water withdrawals or impoundments may be responsible for changes in *P. ceratophyllum* population sizes over time (NYSNHP 2008), these locations and drainages may be important focal points for a monitoring approach.

As we come to understand the critical role *P. ceratophyllum* plays in providing good habitat for a number of fish (Argentina 2006, Hagler 2006, Marcinek 2003) and macroinvertebrate species (Hutchens et al. 2004, Grubaugh and Wallace 1995, Voshell and Parker 1985), including imperiled species (Freeman and Freeman 1994, Hagler 2006), the need for monitoring of this species in Georgia is becoming more apparent. The results of this exercise highlight areas where attentive monitoring of this species could occur, as they may represent the most challenging places for *P. ceratophyllum* to maintain populations.

Podostemum ceratophyllum is typically found in large drainage areas (> 400 km^2, Etowah River: Hagler, 2006 and > 2000km^2, Flint River: Marcinek 2003) which may be related to increased sunlight availability (Argentina 2006), however one notable exception may be the Conasauga River where percent cover declines in relation to drainage area (Argentina 2006). J.E. Argentina and B.J. Freeman note in unpublished data that *P. ceratophyllum* has declined approximately 50% at some sites in the Conasauga

River over the last 20 years (2005). While there may be a number of causes for this decline, one possibility could be the higher percentage of altered flows experienced in that basin as a result of water extractions or impoundments (Table 4.1) relative to the Etowah or Upper Flint. (The possibility of this effect would depend however on the relative location of these site experiencing declines to sources of flow alteration).

Monitoring of aquatic species in Georgia such as *P. ceratophyllum* may be increasingly important as human population projections indicate a 46.8% increase between 2000 and 2030 (USCB 2008). More people will undoubtedly increase stress on our aquatic resources. Population projections by county in Georgia show that 88% of the counties expected to grow by more than 50% between 2000 and 2015 were above the Fall Line, with the highest growth rates occurring in counties in the following basins: Upper Chattahoochee, Etowah, Upper Oconee and the Upper Flint (GAOPB 2005). Table 4.2 highlights the top 12 counties and their projected growths in percent.

Particularly disturbing is the projection that by 2015, Gwinnett county (located in the headwaters of the Upper Oconee), will house one out of every eleven people in Georgia (GAOPB 2005), and already has a high proportion of hydrologic alteration. By 2015 the 28 county Atlanta-metro area is expected to house about 57% of the state's population, and require potable water for this growth. Most of the projected population growth is for the region above the Fall Line, where there is a large area of headwater streams and middle order rivers, and the majority of *P. ceratophyllum* populations likely exist.

In conjunction with increasing populations, climate change projections for the north Georgia region include increased precipitation along with increased evapotranspiration rates, likely resulting in decreased runoff to fuel river systems (Mulholland et al. 1997). Low flows on top of increased water extraction may result in perilous conditions for *P. ceratophyllum* in the future.

To meet some of the future demand as well as to mitigate some of the problems due to the recent drought in the southeast, Georgia's Legislature has passed the Georgia Water Conservation and Drought Relief Act (SB342 2008) which encourages and provides funding for reservoir construction. Impoundment structures alter flows, and during droughts, may be sources of debate regarding outflows, as was experienced during the drought of 2007-2009 when Lake Lanier outflows became a legal warfare between the states of Georgia and Florida. It may be critical to assemble baseline data on *P. ceratophyllum* now to better understand its population dynamics and stressors; this may help us mitigate the effects of future impoundments and manage impoundment outflows to benefit people and the benthic community.

Monitoring approaches for *P. ceratophyllum* in other states where it is listed as of special concern or threatened (NY and MA) are based in the Natural Heritage Program. The New York Natural Heritage Program, a contract unit housed in the New York State Department of Environmental Conservation's Division of Fish, Wildlife and Marine Resources, was established in 1985 and is a partnership with The Nature Conservancy (NYSNHP 2008). The mission of this organization is to "facilitate conservation of New York's biodiversity by providing comprehensive information and scientific expertise on rare species and natural ecosystems to resource managers and other conservation partners (NYSNHP 2008)." *Podostemum ceratophyllum* is currently monitored by this program in cooperation with Cornell University, at an un-specified time interval. Records show monitoring to occur fairly randomly but closer to a decadal time scale. A number of field observation records indicated a decline in *P. ceratophyllum* within locations among years, and potentially attribute this to upstream impoundments or water diversions (NYSNHP 2008).

The Massachusetts Natural Heritage and Endangered Species Program was founded in 1978 and serves as the State's branch of the National Natural Heritage program in cooperation with The Nature Conservancy. This organization's primary goal is to protect the State's range of native biological diversity (MANHESP 2008) It is responsible for conservation and protection of the State's non-game non-commercial species and has over 176 invertebrate and vertebrates and 259 plant species listed as of special concern, threatened or endangered (MANHESP 2008). Unfortunately state funding for this project was discontinued in 2004, and it now relies solely on grant money for specific projects, private donations, and over 20,000 residents who contribute via their state income tax forms (MANHESP 2008). The program currently monitors *P. ceratophyllum* as it is listed of special concern, occurring in only eight locations across the state. Monitoring occurs at five year intervals for species of this listing to document any changes in population vigor and to identify any possible sources of decline.

The NY and MA Natural Heritage Programs are comparable to the Georgia Department of Natural Resources (GADNR) Wildlife Resources Division Natural Heritage Program, now referred to as the Nongame Conservation Section. The GADNR program was established in 1986, and focuses on rare, threatened or endangered species and communities (GADNR 2008). Like the NY and MA Programs, it is geared towards providing an objective source of information regarding plant and animal communities for conservation purposes and land use decision making. Both NY and MA include an expansive data base regarding rare, threatened and endangered organisms; however *P. ceratophyllum* has not yet made the Georgia list. The resource base afforded to such programs, and the general use of data for management decisions, may make the Natural Heritage Program a key universal monitoring entity in Georgia.

In addition to monitoring, further research by the scientific community may enhance our understanding of the biological response of *P. ceratophyllum* to hydrologic stress and other anthropogenic sources of decline. Ideally this information along with patterns in *P. ceratophyllum* population abundance and quality will help inform management of Georgia's water resources.

CHAPTER 5

CONCLUSIONS

Hydrologic alterations in the form of extreme drought, water impoundments and extraction have profoundly shaped riverine systems in the southeastern United States. Low annual rainfall, in conjunction with special permits for continued water use, has come close to dewatering some major rivers. While many aquatic organisms may be impacted by these conditions, some of the most affected are sessile aquatic macrophytes.

In Georgia, and many southeastern states, the predominant aquatic macrophyte is the riverweed, *Podostemum ceratophyllum*, an important foundational species. This plant has been in decline in northeastern states, and the results of this research show that there is the potential for local declines due to hydrologic stress. Reductions in flow and continued daily disturbances from upstream dams or extractions result in extremely low water depths (< 5 cm), which were found to have a negative effect on *P. ceratophyllum* biomass. It is likely that a low flow threshold exists below which *P. ceratophyllum* biomass is significantly affected on a larger scale.

While this study also indicated that *P. ceratophyllum* may be able to re-colonize previously disturbed areas through asexual spread, seed dispersal ability may be limited and should be investigated further. Local recovery will depend on remnant populations that manage to exist in wetted refuge areas.

This work found substantially lower *P. ceratophyllum* biomass in the Middle Oconee River compared to studies conducted 16 and 50 years ago; an issue which may extend beyond the Upper Oconee watershed. Hydrologic alteration seems to be prevalent across Georgia above the Fall Line, where the range of *P. ceratophyllum* is extensive. Projected population growth in the region threatens to compound the problem and further reduce biomass of this important species.

State-wide programs, such as the Georgia Natural Heritage Program, may be employed to conduct base-line monitoring of this species to better understand how we may mitigate the effects of future water consumption and impoundments. Scientific research should continue and focus on determining shoal-wide effects of varying hydrology as well as estimating the quality and quantity of *P. ceratophyllum* across its range.

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Table 2.1: Characteristic sections of the cross-sectional transect. Each section is described in terms of substrate and surface water slope.

Section	**Meters**	**Substrate**	**Surface Water Elevation**
1	2 – 22	Sand/silt with random boulders	Fairly uniform (flat)
2	22 – 38	Varied (boulders, gravel, sand)	Sloping towards section 1
3	38 – 61	Gravel and Cobble, some boulders	Fairly uniform (flat) and relatively shallow
4	61 – 85	Mostly Bedrock	Fairly uniform (flat) and relatively shallow
5	85 – 94	Mostly Bedrock	Sloping towards the bank

Table 2.2: Comparison of annual mean P. ceratophyllum biomass between three decades. Our data is compared with that of Nelson and Scott, 1962 and Grubaugh and Wallace, 1995. The range of biomass values recorded during our study was 0 – 371.3 g-AFDM/m^2, however we reported the next lowest biomass value for comparison (only one sample had a biomass value of 0 g-AFDM/m^2).

Year of Study	**Mean *P. ceratophyllum* ± SE**	**Range**
Nelson & Scott 1956-1957	350.2 ± 33.8	136.8 - 635.0
Grubaugh & Wallace 1991-1992	514.0 ± 53.2	296.8 - 1044.8
Pahl 2009	54.0 ± 7.1	0.11 – 371.3

Table 2.3: Best-supported models of *P. ceratophyllum* standing stock biomass using habitat and time of year variables. Results are number of model parameters (K) and AIC values for the five (of 32 total covariate models) within two of the lowest AIC value. Model parameters include substrate (Bedrock/boulder or gobble/gravel), location (center 75% of channel or edges), velocity (cm/s; measured when sample was taken), time of year (represented by day and day^2 terms), and an interaction between location and time of year.

Covariates in Model	**K**	**AICc**	**delta AICc**	**AIC Weights**
Substrate, Location, Day, Day^2	6	41.97	0	0.19
Substrate, Location, Velocity, Day, Day^2	7	42.57	0.59	0.14
Location, Day, Day^2, Day*Location, Day^2*Location	8	43.36	1.39	0.09
Location, Day, Day^2	5	43.37	1.40	0.09
Substrate, Location, Velocity, Location*Day, Location*Day^2, Day, Day^2	9	43.39	1.42	0.09
Location, Velocity, Day, Day^2	96	43.90	1.94	0.07

Table 2.4: Best-supported models of *P. ceratophyllum* standing stock biomass using habitat, time of year and hydrology variables. Results are number of model parameters (K) and AIC values for the three (of 25 total models) within two of the lowest AIC value. Model parameters include substrate (Bedrock/boulder or gobble/gravel), location (center 75% of channel or edges), velocity (cm/s; measured when sample was taken), time of year (represented by day and day^2 terms), the total number of hours water depth was less than 5 cm during 30 days prior to sampling (T5), and the longest single duration in hours of water depth less than 5 cm during 30 days prior to sampling (L5).

Variables in Model	**K**	**AICc**	**Delta AICc**	**AIC Weights**
Substrate, Location, Day, Day^2, T5	7	40.88	0	0.11
Substrate, Location, Velocity, Day, Day^2, T5	8	41.76	0.87	0.07
Substrate, Location, Day, Day^2	6	41.97	1.09	0.07
Location, Day, Day^2, T5	6	42.07	1.19	0.06
Substrate, Location, Day, Day^2, L5	7	42.14	1.26	0.06
Substrate, Location, Velocity, Day, Day^2	7	42.57	1.68	0.05
Substrate, Location, Day, Day^2, Day*Location, Day^2*Location, T5	9	42.71	1.82	0.05
Substrate, Location, Velocity, Day, Day^2, L5	8	42.83	1.94	0.04

Table 2.5: A comparison of the total weight of relative support for each variable. The AIC weights of each model containing each hydrology model were summed, and all models containing only covariates were summed to represent null (no hydrology) models. The most supported variable is the total number of hours with less than 5 cm of water depth of the last 30 days. This parameter is 1.57 times more likely to describe *P. ceratophyllum* biomass than the next highest variable (null variable with no hydrology).

Variable	**Relative AIC Weight (sums)**
Total Hours <5cm	0.37
Null (no hydrology)	0.23
Longest Hour <5cm	0.21
Longest Hour <0cm	0.09
Total Hours <0cm	0.09

Table 2.6: Top AIC model variable estimates. The estimated effect on the response variable (*P. ceratophyllum* log g-AFDM/m^2) for each factor within the top model (n=92) and standard error are displayed below. The intercept is the model intercept. T5 refers to the total number of hours 30 days prior to collection that the sample experienced water depths less than 5 cm.

	Intercept	**Substrate**	**Location**	**Day**	**Day2**	**T5**
Estimates	1.4447	0.6012	-1.1364	0.0232	-0.00006	-0.0013
Standard error	0.6005	0.3301	0.2629	0.0062	0.00002	0.0007

Table 2.7: Hydrology effect on *P. ceratophyllum* biomass. Based on the variable estimates from the top model, the following biomass loss (in percent) are estimated for a range of total hours spent with less than 5 cm of water during the last 30 days. The shortest total duration was the smallest recorded number of hours greater than zero. The average values refer to hours spent in less than 5 cm of water among samples that experienced at least some shallow water (n=40). The longest duration was the greatest number of hours recorded within 30 days of sample collection, spent with less than 5 cm of water.

	Hours < 5 cm	**Log Biomass loss (%)**
Shortest	2	0.06
Average (all >0 hours)	256.40	7.83
Longest	687	21.12

Table 3.1: Middle Oconee River block annual comparisons. A split-plot repeated measures analysis was conducted. Time is the only significant factor. A univariate approach adjusted for the Huynh-Feldt epsilon was used to calculate p-values for parameter involving Time due to insufficient degrees of freedom for a multivariate test.

Variable	**Degrees of Freedom**	**F value**	**P value**
Time	12	6.25	<0.0001*
Time*Treatment	12	0.70	0.6973
Time*Block	12	1.42	0.2203
Time*Treat*Block	12	0.48	0.8705
Treatment	1	1.65	0.5562
Block	1	0.03	0.2688
Block*Treatment	1	1.40	0.3022

Table 3.2: Middle Oconee River and Hunnicutt Creek comparisons. A split-plot repeated measures analysis with only two blocks (MOR all plots equal one block, HCC has one block). Time is significant as well as the Time*Block interaction. Due to this interaction, a profile analysis was conducted to determine at which time interval the significant interaction occurred. The significant time intervals and parameters are displayed in this table. A univariate approach adjusted for the Huynh-Feldt epsilon was used to calculate p-values for parameters involving Time due to insufficient degrees of freedom for a multivariate test.

Parameter	**Degrees of Freedom**	**F value**	**P value**
Time	12	26.88	<0.0001*
Time*Treatment	12	0.94	0.4459
Time*Block	12	3.01	0.0355*
Time*Treat*Block	12	0.72	0.5662
Treatment	1	0.03	0.8632
Block	1	1.08	0.3228
Block*Treatment	1	0.00	0.9659
Time Intervals/Parameter			
5:6 Time	1	16.22	0.0024*
5:6 Block	1	9.44	0.0118*
6:7 Time	1	5.65	0.0387*
7:8 Time	1	9.25	0.0124*
8:9 Block	1	7.17	0.0232*
12:13 Block	1	5.72	0.0379*

Table 3.3: Middle Oconee River growing season block comparisons. A split-plot repeated measures analysis was used. Time, treatment, block and block*treatment interaction factors were significant at α = 0.05. Due to this interaction, a profile analysis was conducted to determine at which time interval the significant interaction occurred. The significant time intervals and parameters are displayed in this table. A univariate approach adjusted for the Huynh-Feldt epsilon was used to calculate p-values for parameters involving Time due to insufficient degrees of freedom for a multivariate test.

Parameter	**Degrees of Freedom**	**F value**	**P value**
Time	5	5.05	0.0104*
Time*Treatment	5	3.14	0.0501
Time*Block	5	3.00	0.0573
Time*Treat*Block	5	2.60	0.0834
Treatment	1	80.06	0.0009*
Block	1	37.87	0.0035*
Block*Treatment	1	29.56	0.0056*
Time Intervals/Parameter			
1:2 Treatment	1	19.68	0.0114*
1:2 Block*Treatment	1	15.40	0.0172*
4:5 Time	1	109.45	0.0005*
4:5 Treatment	1	85.05	0.0008*
4:5 Block	1	67.23	0.0012*
4:5 Block*Treatment	1	52.46	0.0019*

Table 3.4: Middle Oconee River and Hunnicutt Creek growing season comparisons. A split-plot repeated measures analysis was applied to the growing season re-colonization rates with only two blocks (MOR all plots equal one block, HCC has one block). Block is significant at time interval 1:2, and time is significant between time intervals 2 and 3. A Wilks' Lambda multivariate test was used for Time and its interactions, and a univariate approach was used to assess Treatment, Block, and their interaction.

Parameter	**Degrees of Freedom**	**F value**	**P value**
Time	5	15.96	0.0006*
Time*Treatment	5	0.40	0.8364
Time*Block	5	8.52	0.0046*
Time*Treat*Block	5	0.48	0.7820
Treatment	1	0.14	0.7150
Block	1	2.19	0.1648
Block*Treatment	1	0.44	0.5176
Time Intervals/Parameter			
1:2 Block	1	11.22	0.0058*
2:3 Time	1	24.13	0.0004*

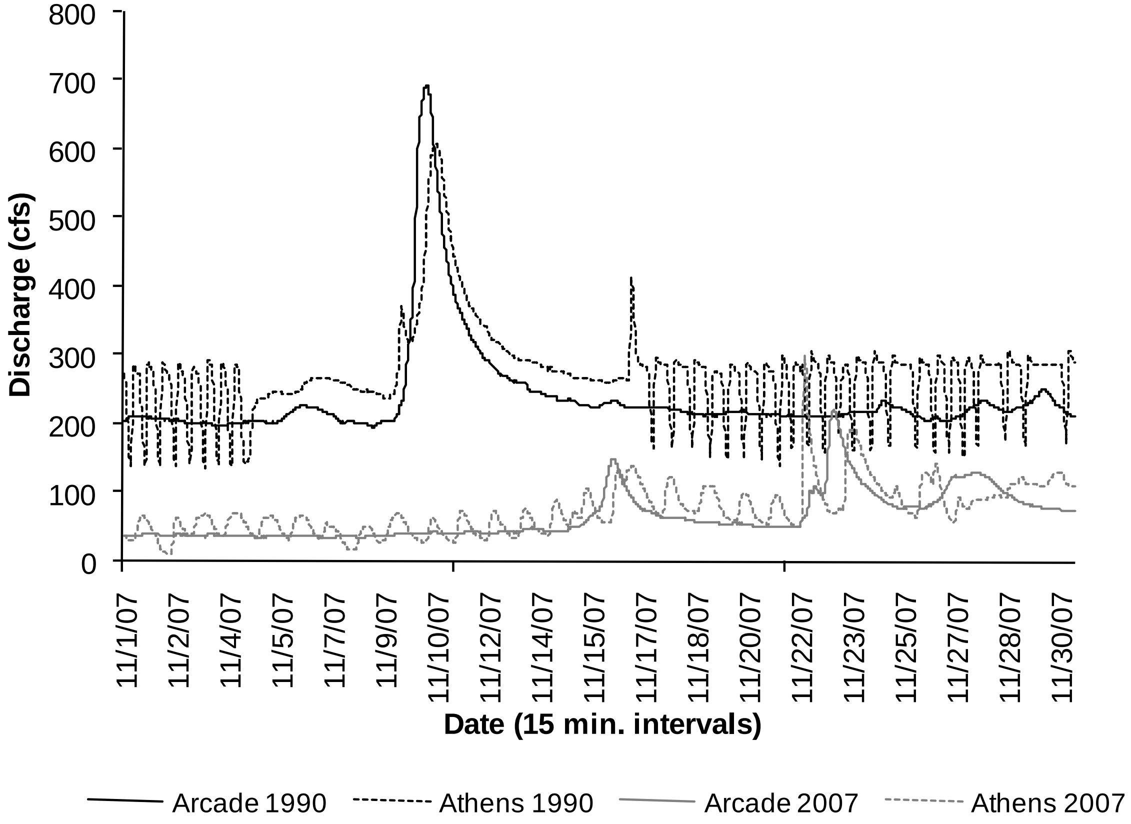
Table 4.1: Hydrologic alteration by major Georgia river basin. Percent of U.S. Geological Survey gages showing signs of hydrologic alteration within each major river basin above the fall line where *Podostemum ceratophyllum* has been observed. The Middle Tennessee and Upper Coosa basins indicate 100% alteration, however they have very few (1 and 3 respectively) gages within GA, so it is likely that analysis of gages in Alabama and Tennessee would change this percentage. The most impaired basins according to this analysis include the Oostanaula, Conasauga, Middle Savannah, Upper Chattahoochee, Etowah and the Upper Oconee. The Little, Broad and Upper Savannah Rivers indicate no hydrologic alteration, possibly due to the small number of gages, and only partial overlap with the state of Georgia.

River Basin	**% USGS gages Altered**	**Number of gages**
Middle Tennessee	100	1
Upper Coosa	100	3
Oostanaula	71	7
Conasauga	71	7
Middle Savannah	67	3
Upper Chattahoochee	63	31
Etowah	60	21
Upper Oconee	56	9
Coosawattee	50	6
Middle Chattahoochee	50	20
Tugaloo	50	2
Upper Ocmulgee	45	22
Upper Flint	43	11
Upper Tallapoosa	33	3
Little	0	2
Broad	0	2
Upper Savannah	0	1

Table 4.2: Projected population growth in north Georgia. Population growth projected to occur from 2000 to 2015 in percent change for the top 12 fastest growing counties in Georgia. The watershed in which they occur is also noted. Data is from the Georgia 2015 Population Projections Report from the Georgia Office of Planning and Budget: Policy, Planning and Technical Support. 2005. A single asterisk (*) represents one of the top 12 counties in terms of population, in which half of the state of Georgia will live by 2015. A double asterisk (**) represents where 1/11th of Georgia's population will live by 2015, more than the population of Georgia's 79 smallest counties.

County	**Growth (%)**	**Watershed**	
Forsyth	137	Upper Chattahoochee	*
Henry	135	Upper Flint/Upper Ocmulgee	*
Newton	121	Upper Ocmulgee	*
Paulding	117	Etowah	
Cherokee	91	Etowah	*
Lee	91	Ichawaynachaway, Lower Flint, Kinchafoonee-Muckalee (below fall-line)	
Pickens	90	Etowah / Coosawattee	
Butts	88	Upper Oconee	
Dawson	87	Etowah/Upper Chattahoochee	
Barrow	84	Upper Oconee	
Walton	75	Upper Oconee	
Gwinnett	75	Upper Oconee	**

Figure 2.1: Hydrographs from the USGS gages in Athens, GA and Arcade, GA. These hydrographs illustrate the changes in natural flow regime as a result of upstream hydroelectric dam operations and municipal water withdrawals. The Arcade, GA gage is upstream of our study site, and the Athens, GA gage is downstream. The source of the alterations during the 1990's is likely the Tallassee Shoals Hydropower Dam, located approximately two miles upstream from Ben Burton Park. The source of hydrologic alteration during our study in 2007-2008, is Bear Creek Reservoir, a pump-storage facility constructed in 2002. The hydroelectric dam was not in operation throughout the course of our study due to historic drought conditions that did not enable the dam to produce electricity.



Discharge (cfs)
800
700
600
500
400
300
200
100
0
11/1/07
11/2/07
11/4/07
11/5/07
11/7/07
11/9/07
11/10/07
11/12/07
11/14/07
11/15/07
11/17/07
11/18/07
11/20/07
11/22/07
11/23/07
11/25/07
11/27/07
11/28/07
11/30/07
Date (15 min. intervals)
Arcade 1990
Athens 1990
Arcade 2007
Athens 2007

Figure 2.2: Water surface elevation changes across our study shoal. Changes along a cross-sectional transect in the Middle Oconee River, Ben Burton Park, Athens, GA. This figure illustrates the variability in flows across the channel. The legend refers to a subset of varying discharge levels in cfs (cubic feet per second). The substrate and water surface elevations are displayed using data collected at the 2 meter interval.

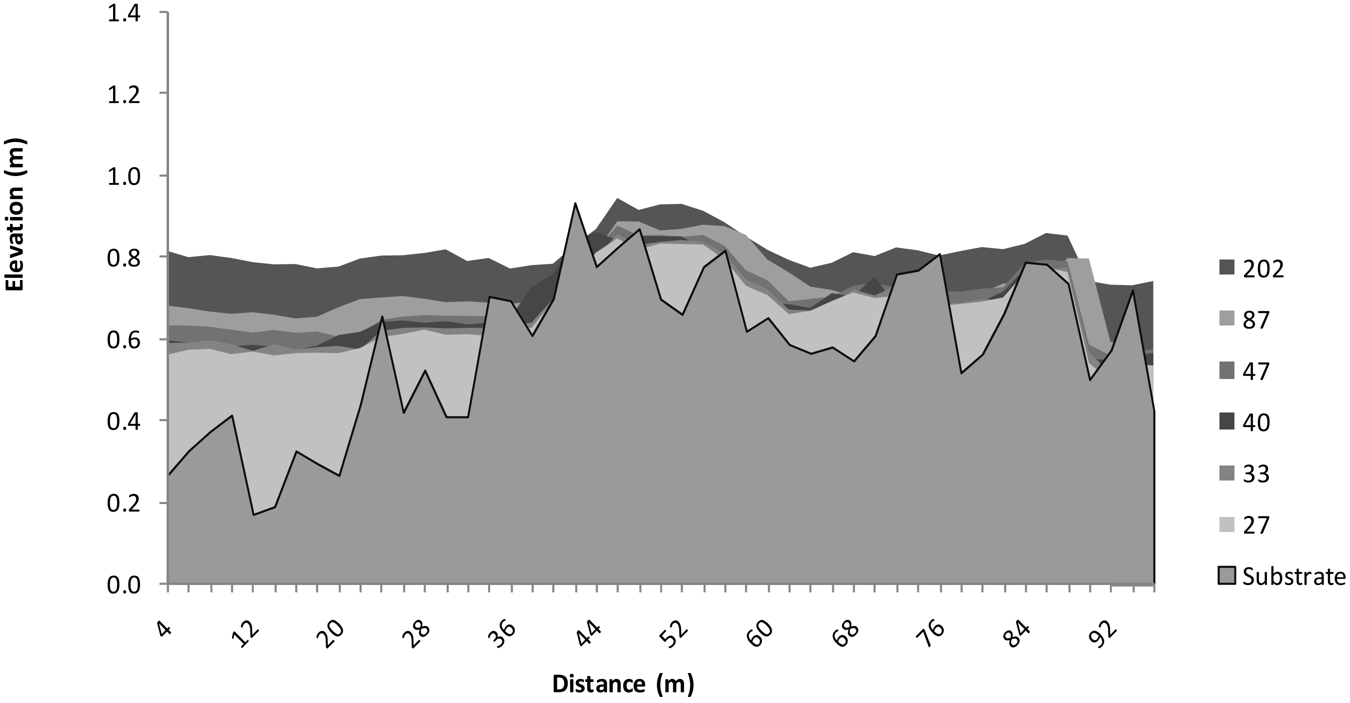

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Elevation (m)
4
12
20
28
36
44
52
60
68
76
84
92
Distance (m)
202
87
47
40
33
27
Substrate

Figure 2.3: Monthly average P. ceratophyllum biomass comparisons between three studies. Our study 2007-2008 is compared with Grubaugh and Wallace (1995), who examined *P. ceratophyllum* biomass between 1991 and 1992, and Nelson and Scott (1962), whose study spanned 1956-1957. Error bars were not available from the two previous studies because they were not reported in their papers, however our error bars indicate that our monthly average biomass valued did not come close to the other studies. The lowest biomass reported by both authors was 136.8 g-AFDM/m^2 (Nelson and Scott, 1962), which is still higher than our highest monthly average.

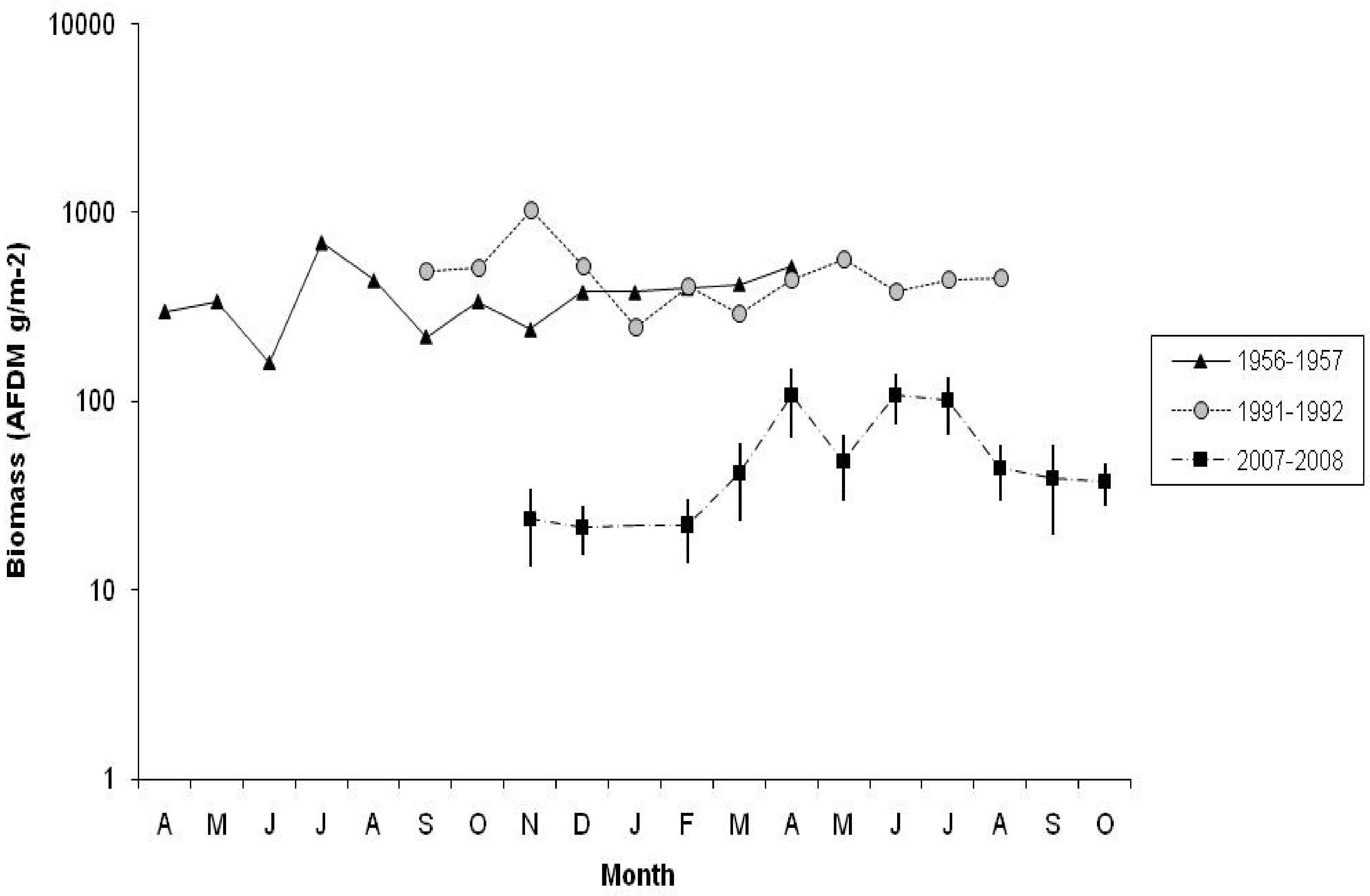
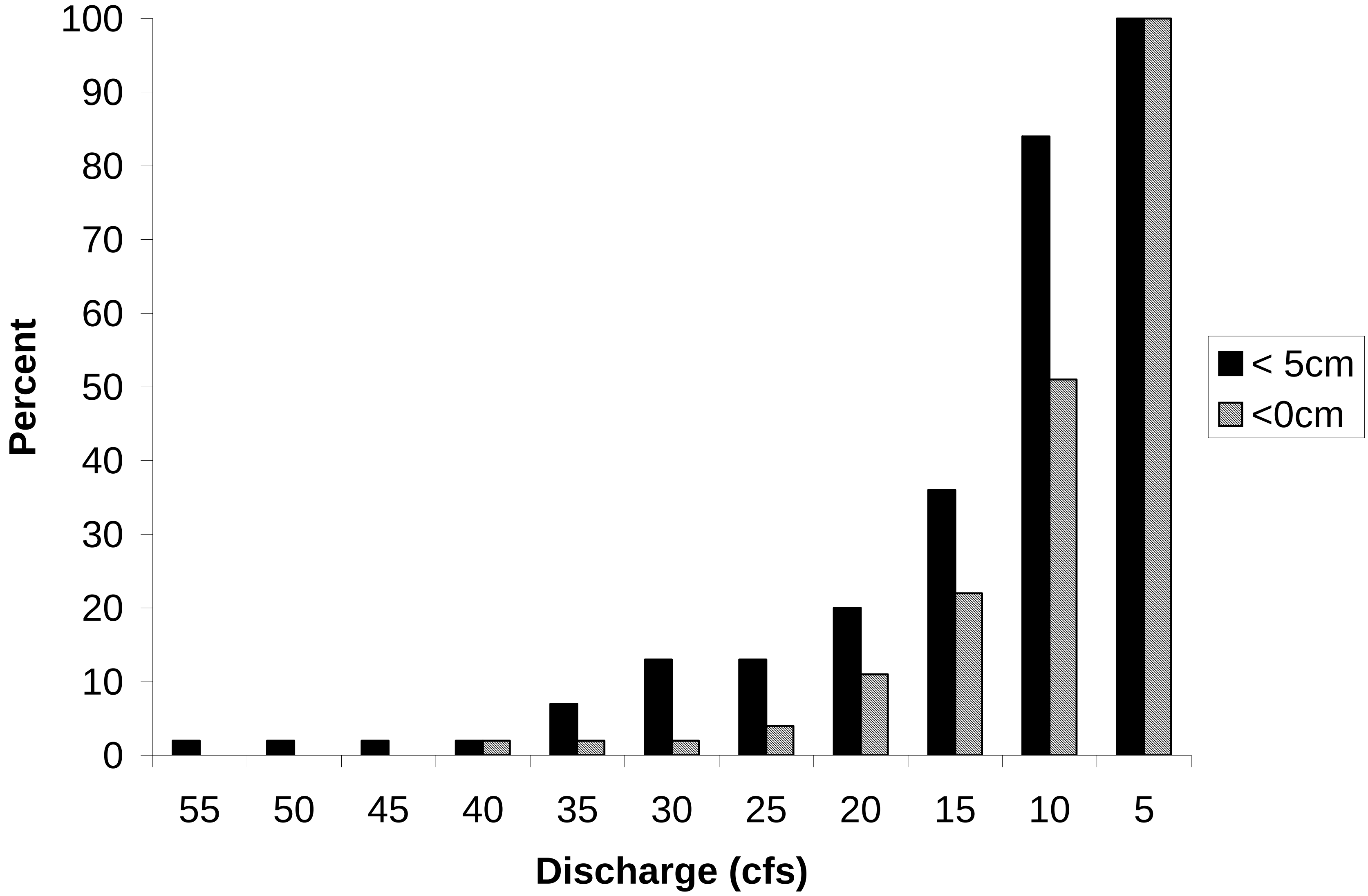

10000
1000
100
10
1
Biomass (AFDM g/m-2)
A
M
J
J
A
S
O
N
D
J
F
M
A
M
J
J
A
S
O
Month
1956-1957
1991-1992
2007-2008

Figure 2.4: Frequency of low flows across transect. Frequency analysis of flows across the cross-sectional transect at which areas will become stressed (< 5cm) or exposed (<0cm). The discharge at which a percentage of our transect would be stressed or exposed was calculated by using the regression equation between water depth at each interval and our pressure transducer to determine the depth reading on the pressure transducer when the flag location would be dry (0 cm) or stressed (5cm). These values were then converted to discharges using the relationship between our pressure transducer and the USGS gage downstream. Stressed conditions (<5 cm) begin to occur across our transect at a discharge of 55 cubic feet per second (cfs), and exposures begin at discharges of 40 cfs.



Percent
100
90
80
70
60
50
40
30
20
10
0
55
50
45
40
35
30
25
20
15
10
5
Discharge (cfs)
< 5cm
<0cm

Figure 2.5: Frequency analysis of annual flows in the Middle Oconee River, Athens, GA. Hourly intervals for a year during Grubaugh and Wallace's study (8/27/1991 -8/28/1992) and one year during our study (8/27/2007-8/27/2008) are represented. The red dotted vertical line represents 55 cubic feet per second (cfs), the discharge at which our cross-section began to experience stressed conditions, and the blue dotted vertical line represents the 7Q10 for this site (45 cfs). There were approximately 2700 hours spent under 55 cfs during our study, but none during Grubaugh and Wallace's study. We were not able to make comparisons between our study and that conducted by Nelson and Scott (1962) due to the lack of hourly data available from that time period.

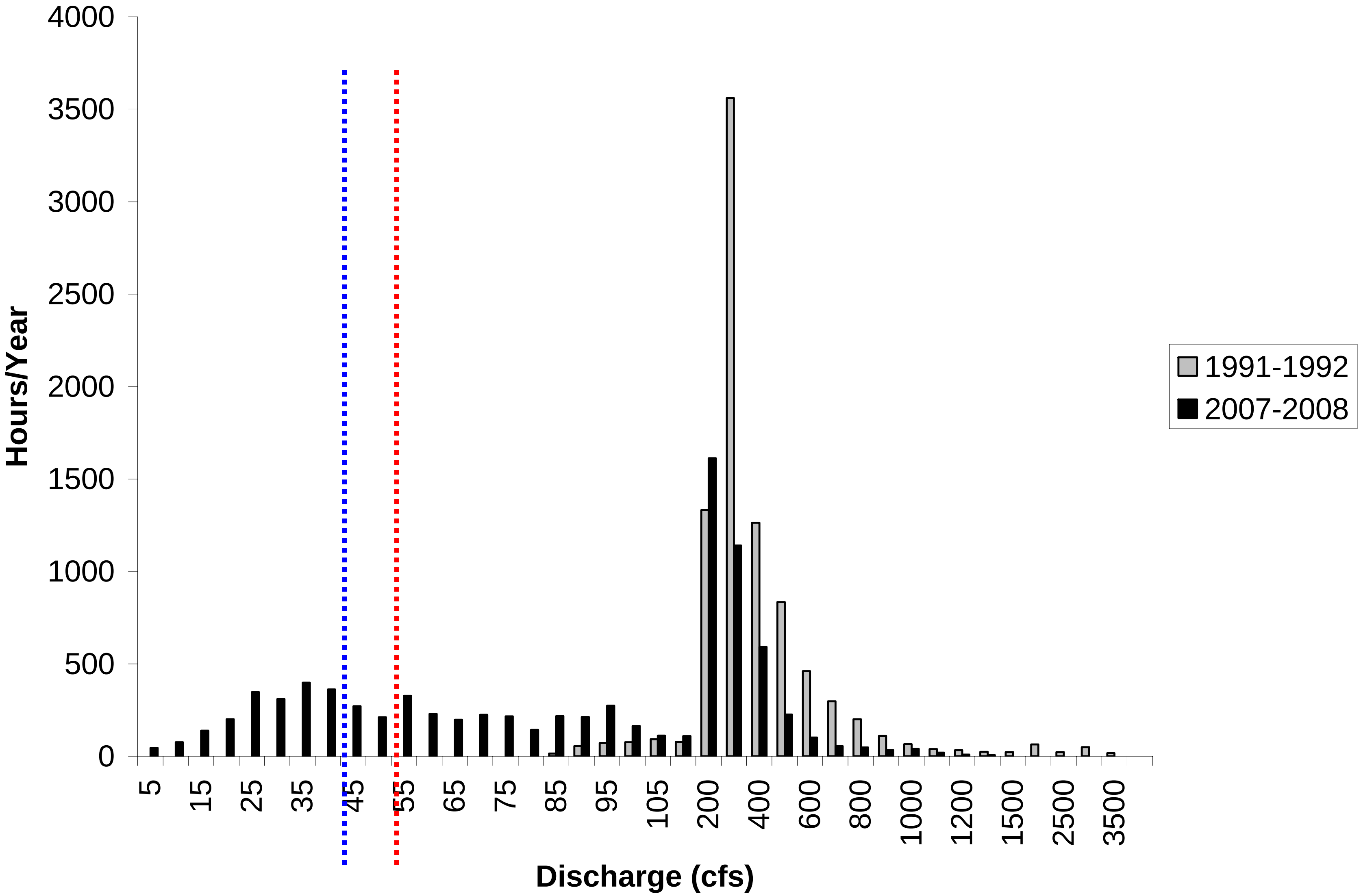

4000
3500
3000
2500
2000
1500
1000
500
0
Hours/Year
5
15
25
35
45
55
65
75
85
95
105
200
400
600
800
1000
1200
1500
2500
3500
Discharge (cfs)
1991-1992
2007-2008

Figure 2.6: Frequency analysis of *P. ceratophyllum* biomass. Only 14 out of 104 samples or 13.3% of the total samples exceeded 136 g-AFDM/m^2, which was the lowest recorded biomass in the Nelson and Scott (1962) study. Only 2 out of 104 samples or 1.9% were as large as or larger than Grubaugh and Wallace's (1995) lowest biomass value (296.8 g-AFDM/m^2).

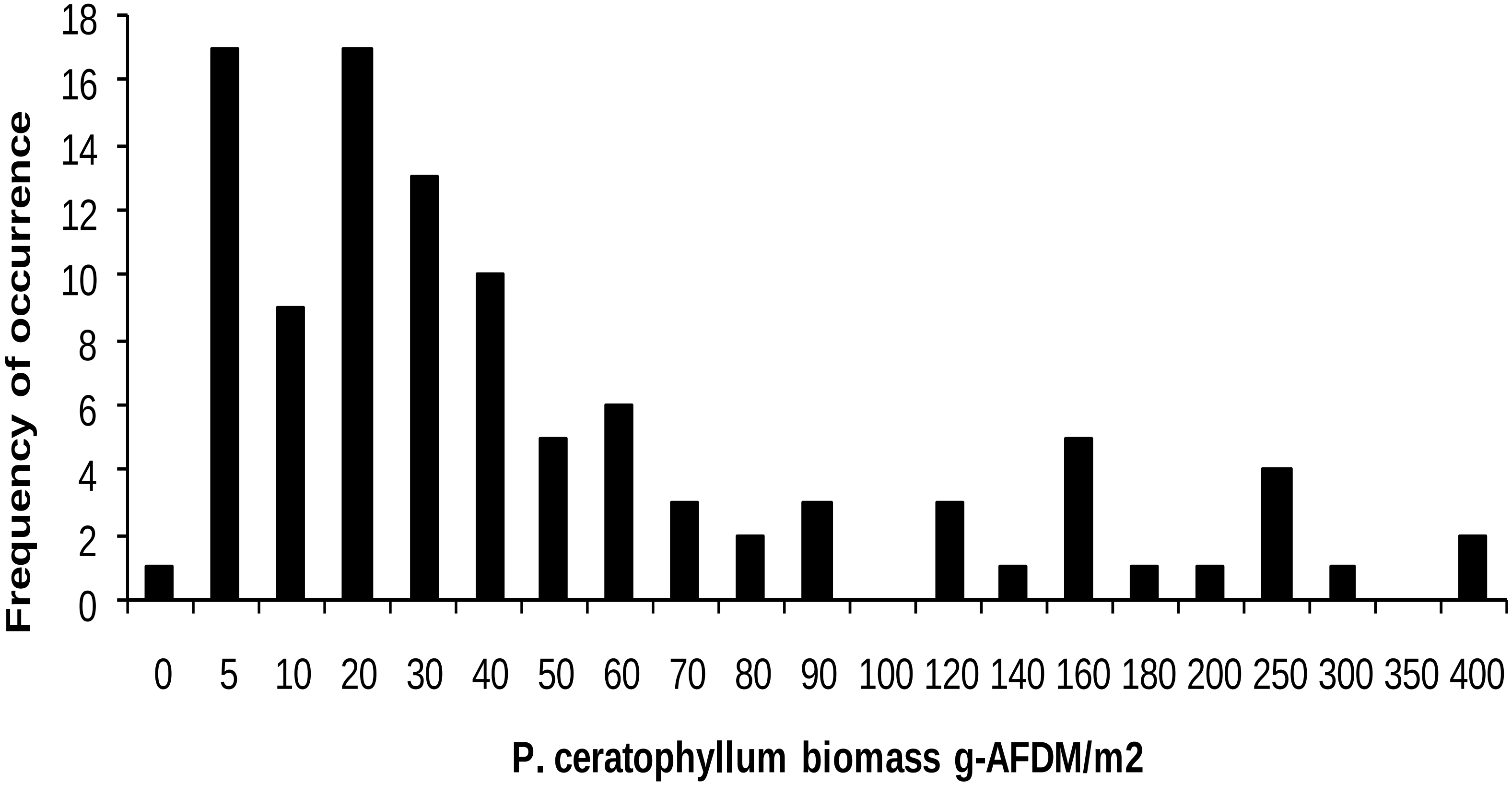

18
16
14
12
10
8
6
4
2
0
Frequency of occurrence
0
5
10
20
30
40
50
60
70
80
90
100
120
140
160
180
200
250
300
350
400
P. ceratophyllum biomass g-AFDM/m2

Figure 2.8: Yearly flows in the Middle Oconee River; drought vs. water extraction. Watershed adjusted estimated flows at Middle Oconee River (based on the upstream USGS gage in Arcade, GA) illustrating likely flows without Bear Creek Reservoir, in contrast to recorded flows at the USGS gage in Athens, GA. The difference between these may be the result of pump storage activities at Bear Creek Reservoir.

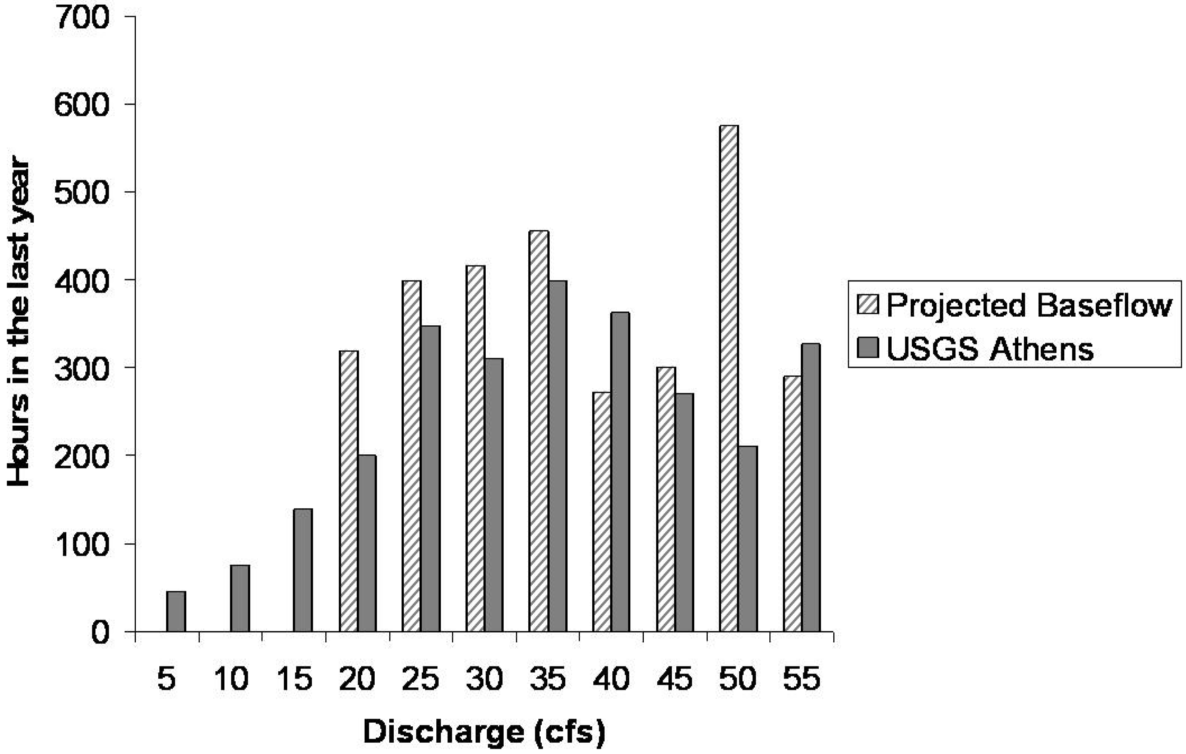

700
600
500
400
300
200
100
0
Hours in the last year
5
10
15
20
25
30
35
40
45
50
55
Discharge (cfs)
Projected Baseflow
USGS Athens

Figure 3.1: Hydrographs from the USGS gages in Athens, GA and Arcade, GA. These hydrographs illustrate the changes in natural flow regime as a result of upstream hydroelectric dam operations and municipal water withdrawals. The Arcade, GA gage is upstream of our study site, and the Athens, GA gage is downstream. The source of the alterations during the 1990's is likely the Tallassee Shoals Hydropower Dam, located approximately two miles upstream from Ben Burton Park. The source of hydrologic alteration during our study in 2007-2008, is Bear Creek Reservoir, a pump-storage facility constructed in 2002. The hydroelectric dam was not in operation throughout the course of our study due to historic drought conditions that did not enable the dam to produce electricity.

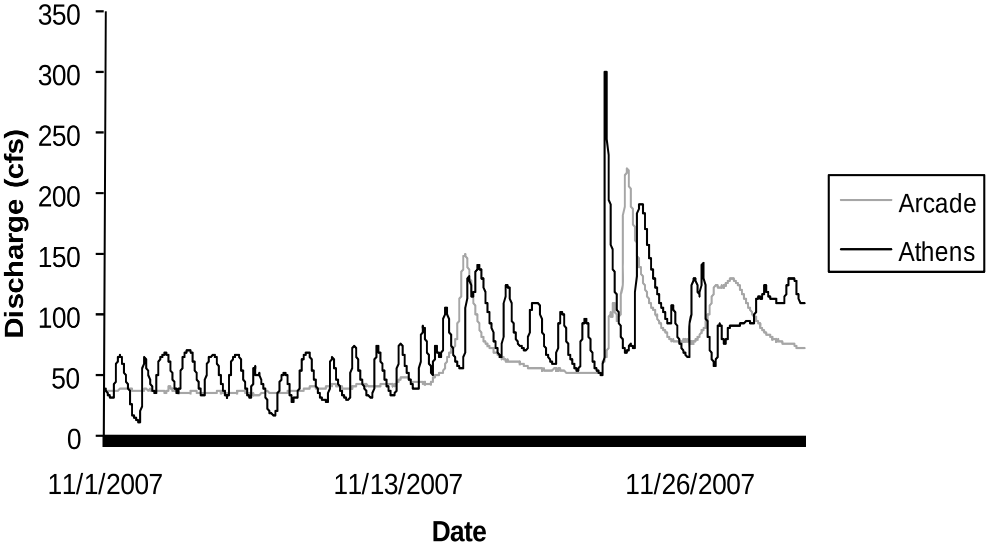

350
300
250
200
150
100
50
0
Discharge (cfs)
11/1/2007
11/13/2007
11/26/2007
Date
Arcade
Athens

Figure 3.2: Experimental Design of Middle Oconee River Plot Study. Solid block represent those under a shallow treatment, and striped blocks represent the deep treatment. White blocks are those analyzed throughout the entire year, and gray blocks represent the growing season.

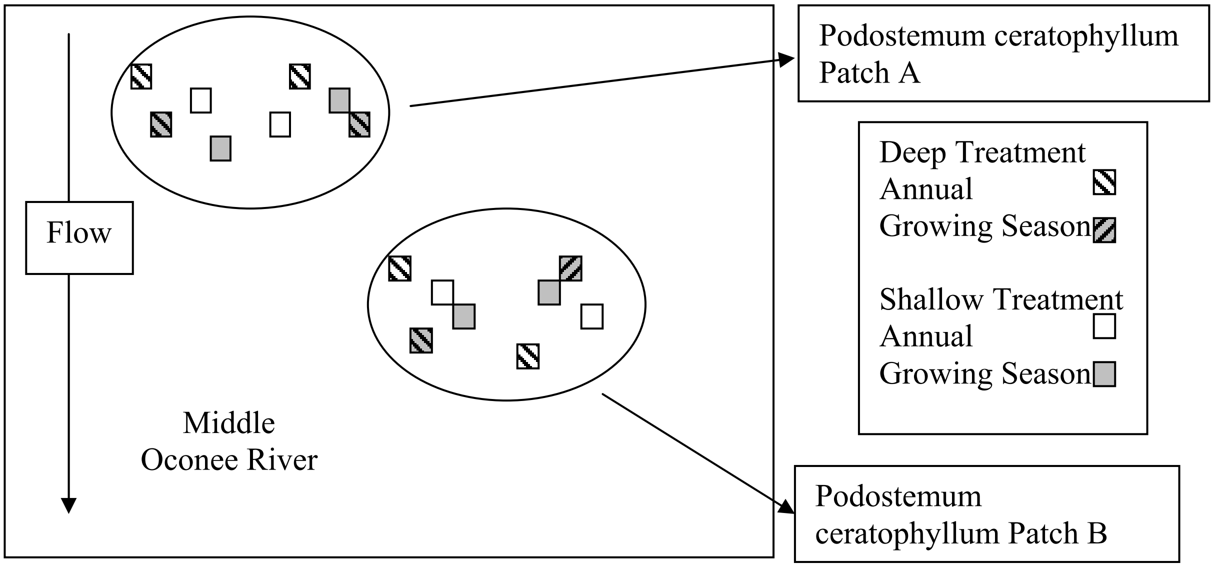

Flow
Middle Oconee River
Podostemum ceratophyllum Patch A
Podostemum ceratophyllum Patch B
Deep Treatment
Annual
Growing Season
Shallow Treatment
Annual
Growing Season

Figure 3.3: Experimental Design of Hunnicutt Creek Plot Study. Solid block represent those under a shallow treatment, and striped blocks represent the deep treatment. White blocks are those analyzed throughout the entire year, and gray blocks represent the growing season.

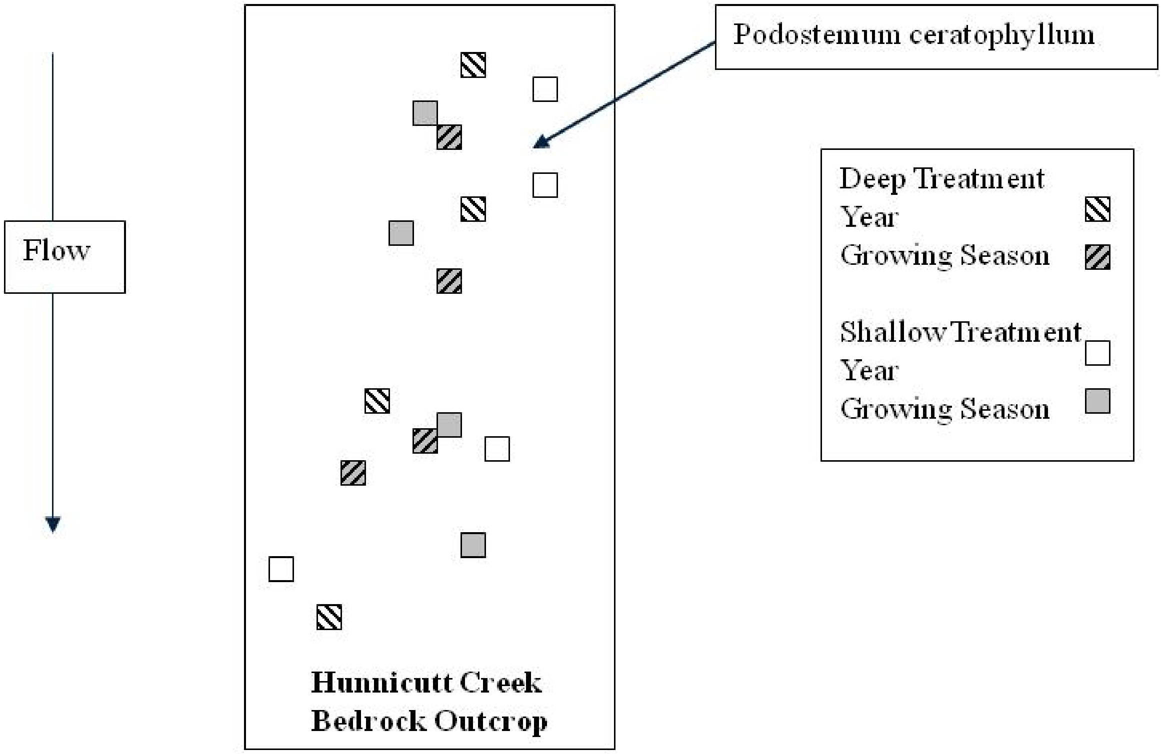

Flow
Podostemum ceratophyllum
Hunnicutt Creek
Bedrock Outcrop
Deep Treatment
Year ▧
Growing Season ▨
Shallow Treatment
Year ☐
Growing Season ■

Figure 3.4: Experimental Design of Middle Oconee River Boulder Study. The white circles represent boulders within one of three blocks, and the gray circles represent the control boulder within each block. The control boulders were fully exposed at the beginning of the study, thus had no possibility for missed *Podostemum ceratophyllum* in the scraping process.

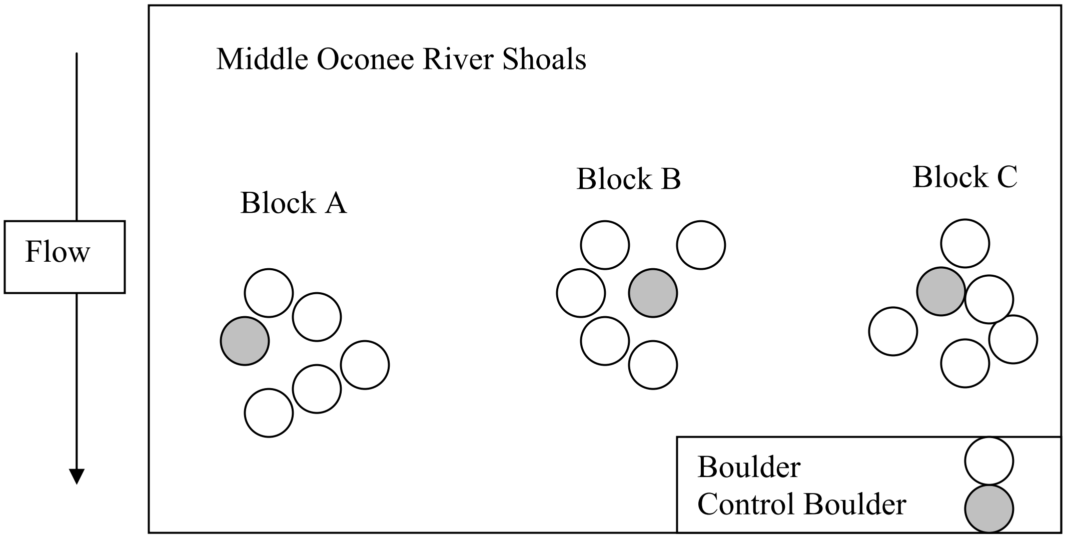
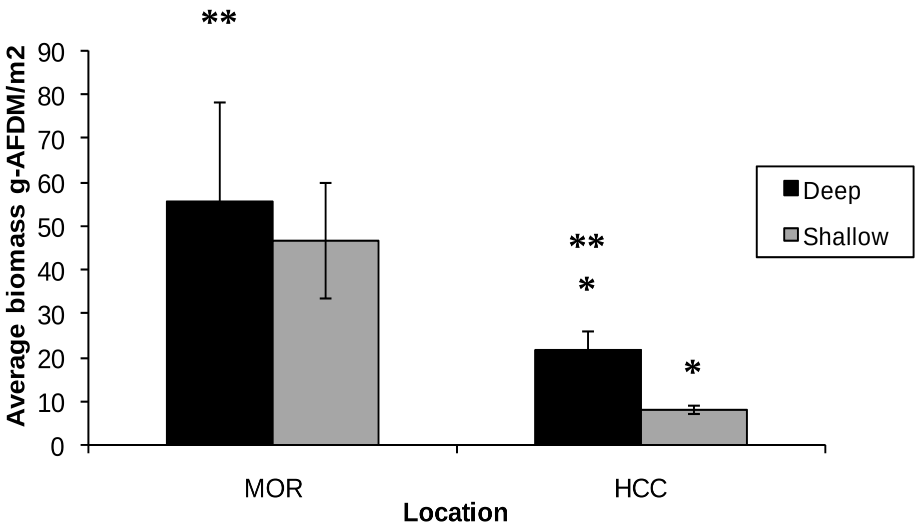

Flow
Middle Oconee River Shoals
Block A
Block B
Block C
Boulder
Control Boulder

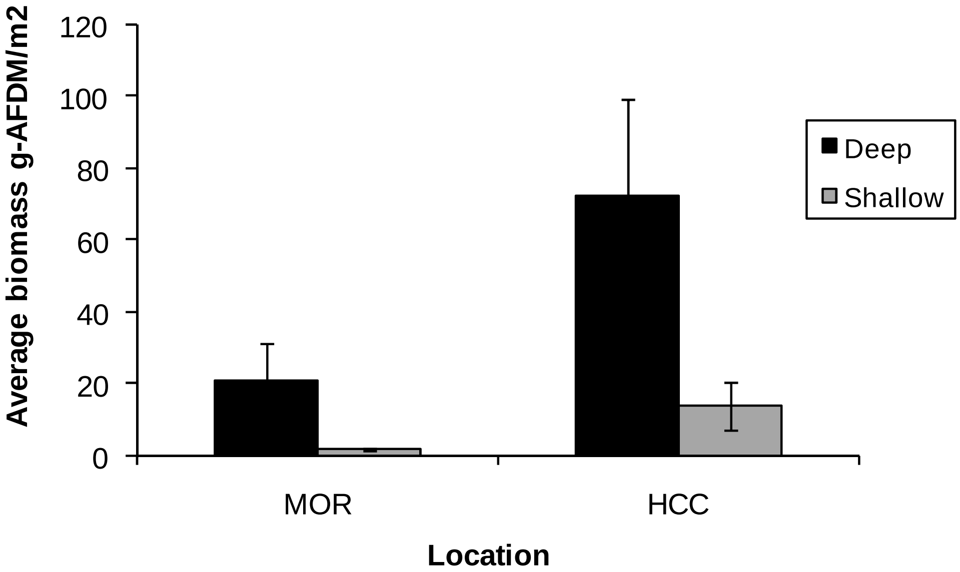
Figure 3.5: Biomass comparisons between sites and seasons. **A.** Year-long average *P. ceratophyllum* biomass comparisons between MOR and HCC by treatment and location. **B.** Growing season average *P. ceratophyllum* biomass comparisons between MOR and HCC by treatment and location.

A.



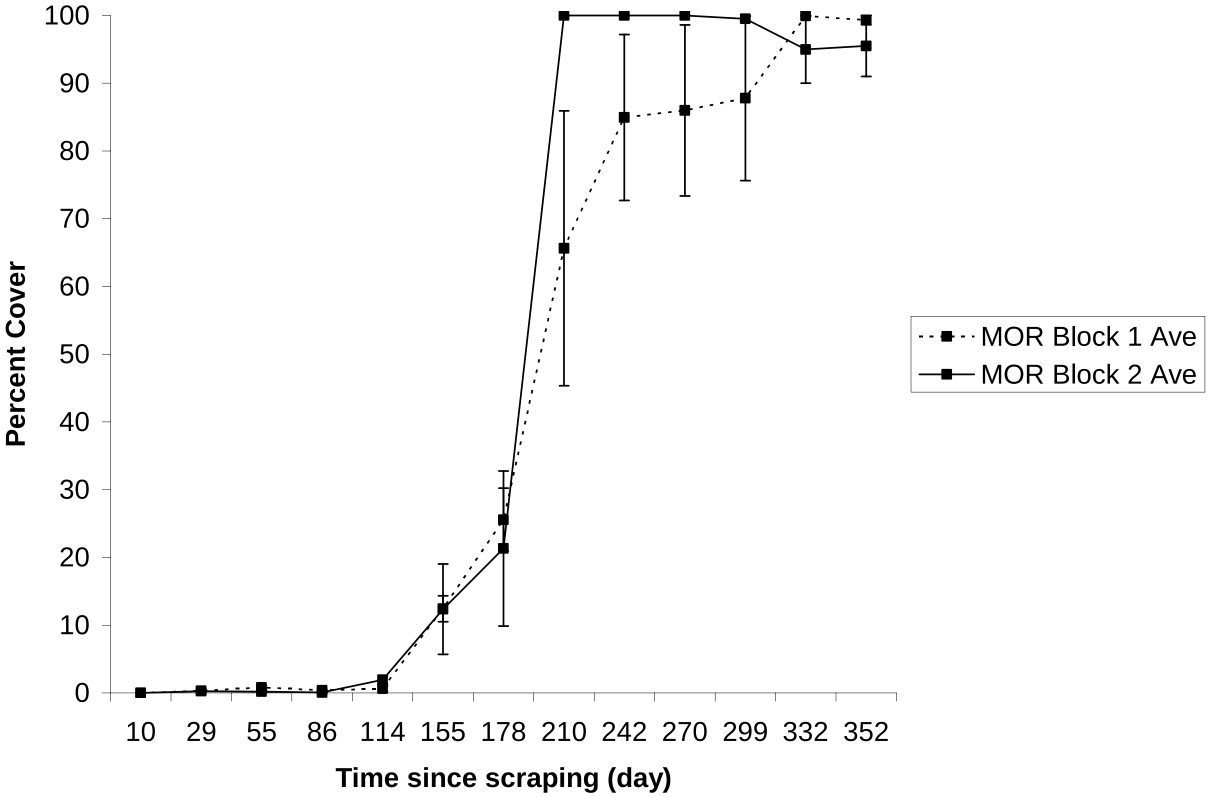
**
Average biomass g-AFDM/m2
90
80
70
60
50
40
30
20
10
0
Deep
Shallow
**
*
*
MOR
HCC
Location

B.



Average biomass g-AFDM/m2
120
100
80
60
40
20
0
Deep
Shallow
MOR
HCC
Location

Figure 3.6: Middle Oconee River blocks: annual average percent cover. Block 1 appeared to lag behind Block 2 in re-colonization rates, with Block 2 reaching 100% cover by day 210. Block 1 reached 100% cover 122 days later.



100
90
80
70
60
50
40
30
20
10
0
Percent Cover
10
29
55
86
114
155
178
210
242
270
299
332
352
Time since scraping (day)
MOR Block 1 Ave
MOR Block 2 Ave

Figure 3.7: Annual average percent cover comparison between sites. While re-colonization rates in plots in Hunnicutt Creek appeared to be initially slower (as signified by the lagging percent cover line), it eventually surpassed the Middle Oconee plots. Both sites neared 100% cover after around 320 days.

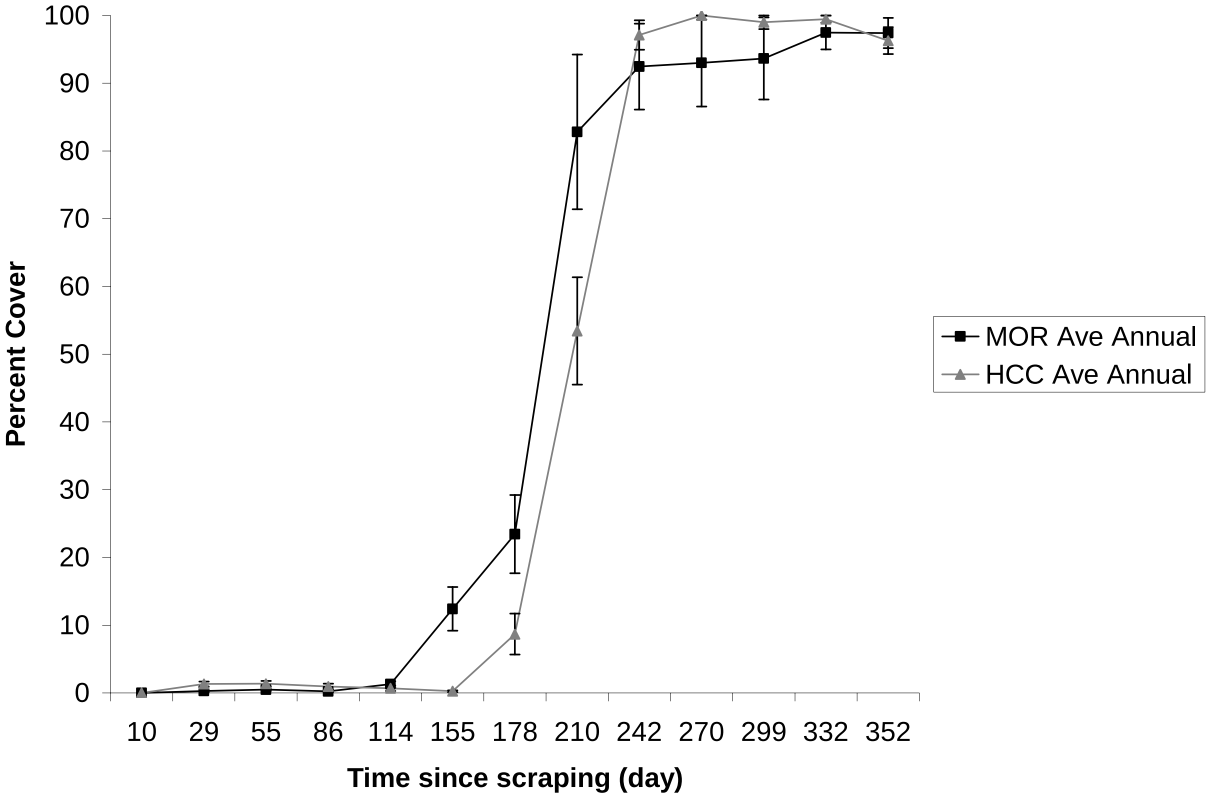

100
90
80
70
60
50
40
30
20
10
0
Percent Cover
10
29
55
86
114
155
178
210
242
270
299
332
352
Time since scraping (day)
MOR Ave Annual
HCC Ave Annual

Figure 3.8: Middle Oconee River blocks: growing season average percent cover. On day 79, two of the plots in Block 1 dried and no *P. ceratophyllum* survived. Flows remained relatively low in the following days, likely explaining the fluctuating and ultimately declining percent cover.

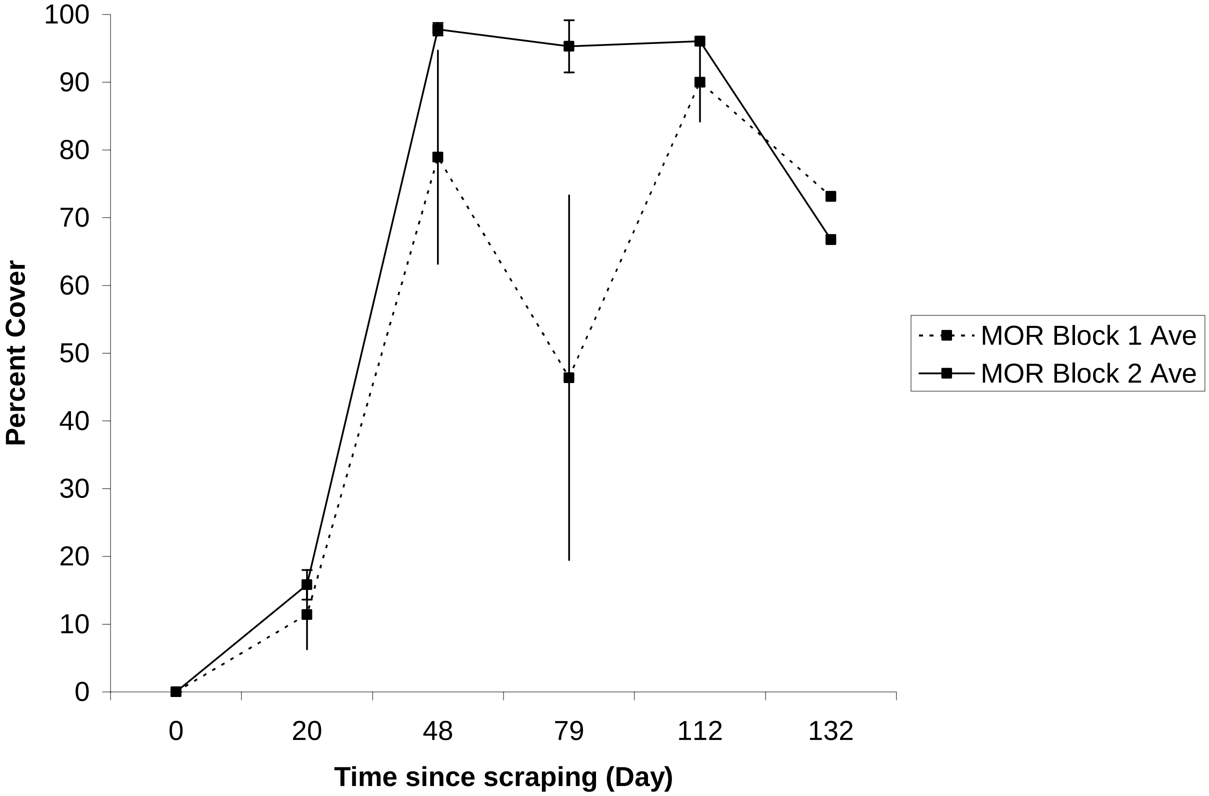

100
90
80
70
60
50
40
30
20
10
0
Percent Cover
0
20
48
79
112
132
Time since scraping (Day)
MOR Block 1 Ave
MOR Block 2 Ave

Figure 3.9: Growing season average percent cover comparison between sites. On day 79, a drying event left many plots with little or no water, resulting in some mortality. This may be responsible for the lower average percent cover on that day. Flows remained relatively low in the following days, likely explaining the lack recovery to 100% cover.

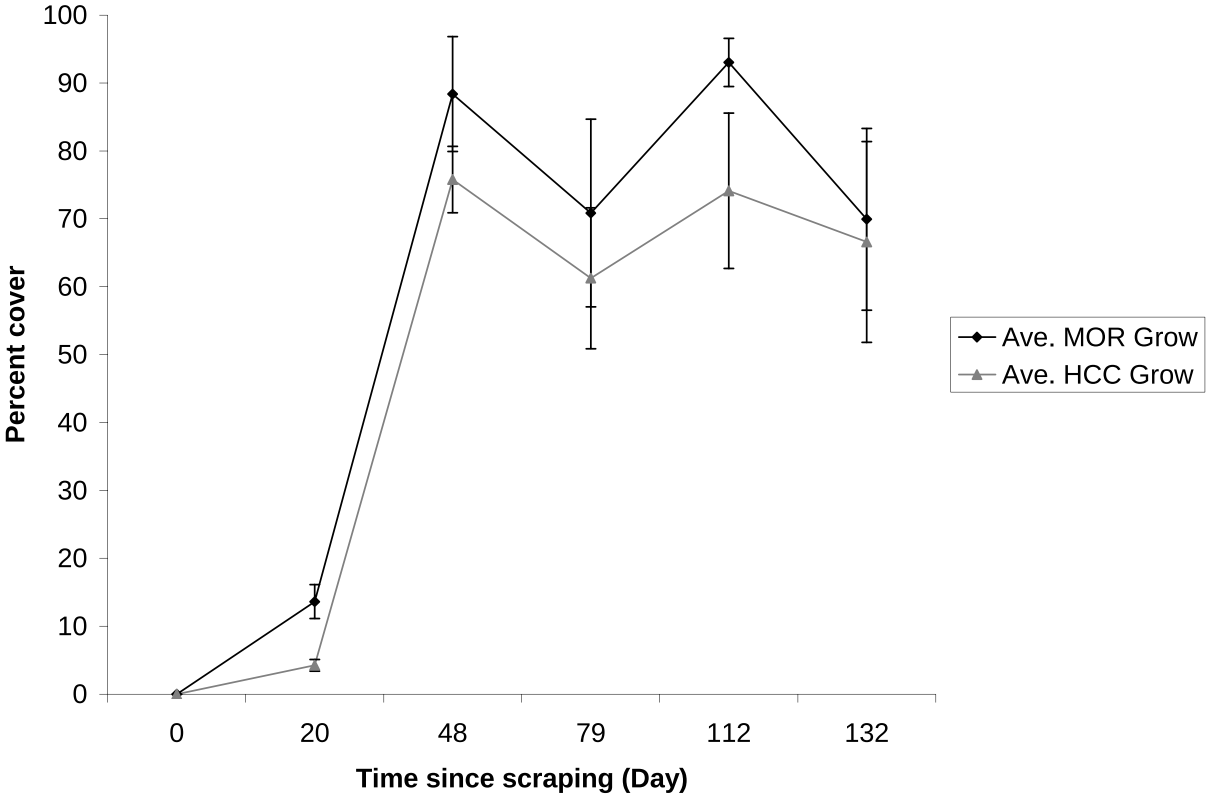
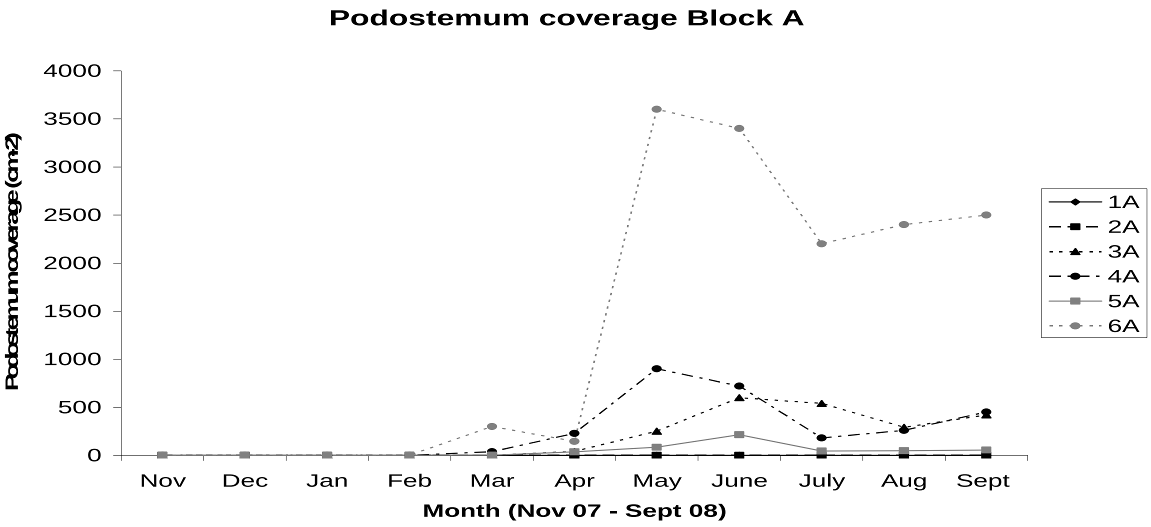
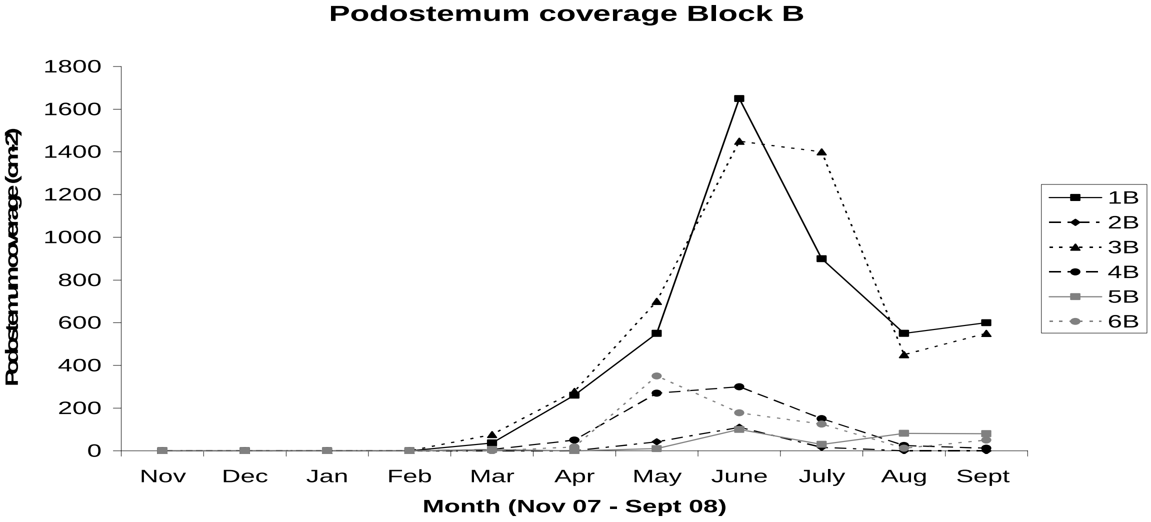

100
90
80
70
60
50
40
30
20
10
0
Percent cover
0
20
48
79
112
132
Time since scraping (Day)
Ave. MOR Grow
Ave. HCC Grow

Figure 3.10: Boulder *P. ceratophyllum* coverage comparisons. *P. ceratophyllum* coverage (cm^2) by boulder in 3 Blocks in the Middle Oconee River.


Podostemum coverage Block A
Podostemum coverage (cm2)
4000
3500
3000
2500
2000
1500
1000
500
0
Nov
Dec
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Month (Nov 07 - Sept 08)
1A
2A
3A
4A
5A
6A


Podostemum coverage Block B
Podostemum coverage (cm2)
1800
1600
1400
1200
1000
800
600
400
200
0
Nov
Dec
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Month (Nov 07 - Sept 08)
1B
2B
3B
4B
5B
6B

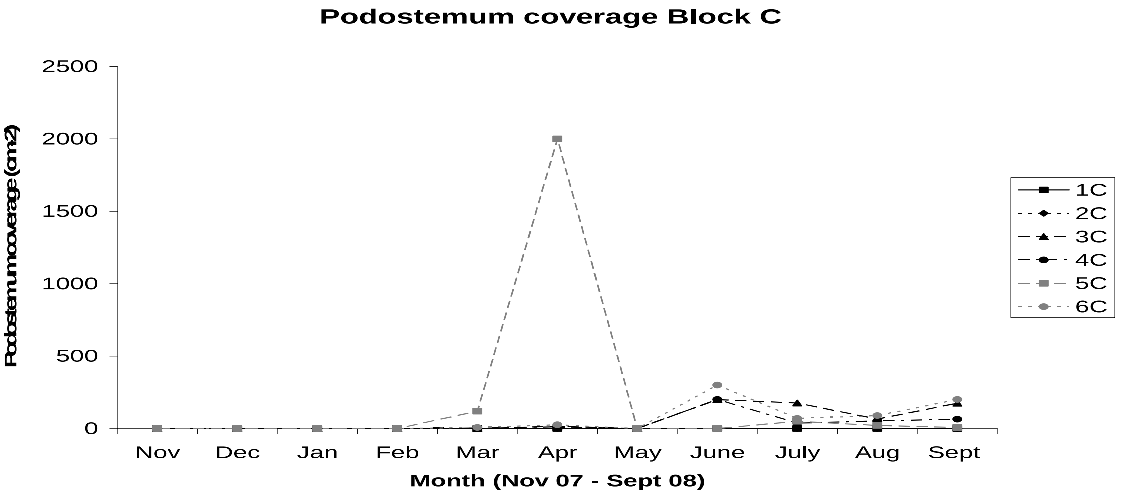

Podostemum coverage Block C
Podostemum coverage (cm2)
2500
2000
1500
1000
500
0
Nov
Dec
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Month (Nov 07 - Sept 08)
1C
2C
3C
4C
5C
6C

Figure 4.1: *P. ceratophyllum* distribution. Distribution of *Podostemum ceratophyllum* (USDA Plant Database) ranging from Georgia north along the east coast through northern Canada. States where *P. ceratophyllum* is state listed as a species of special concern, threatened, endangered or historic are highlighted accordingly.

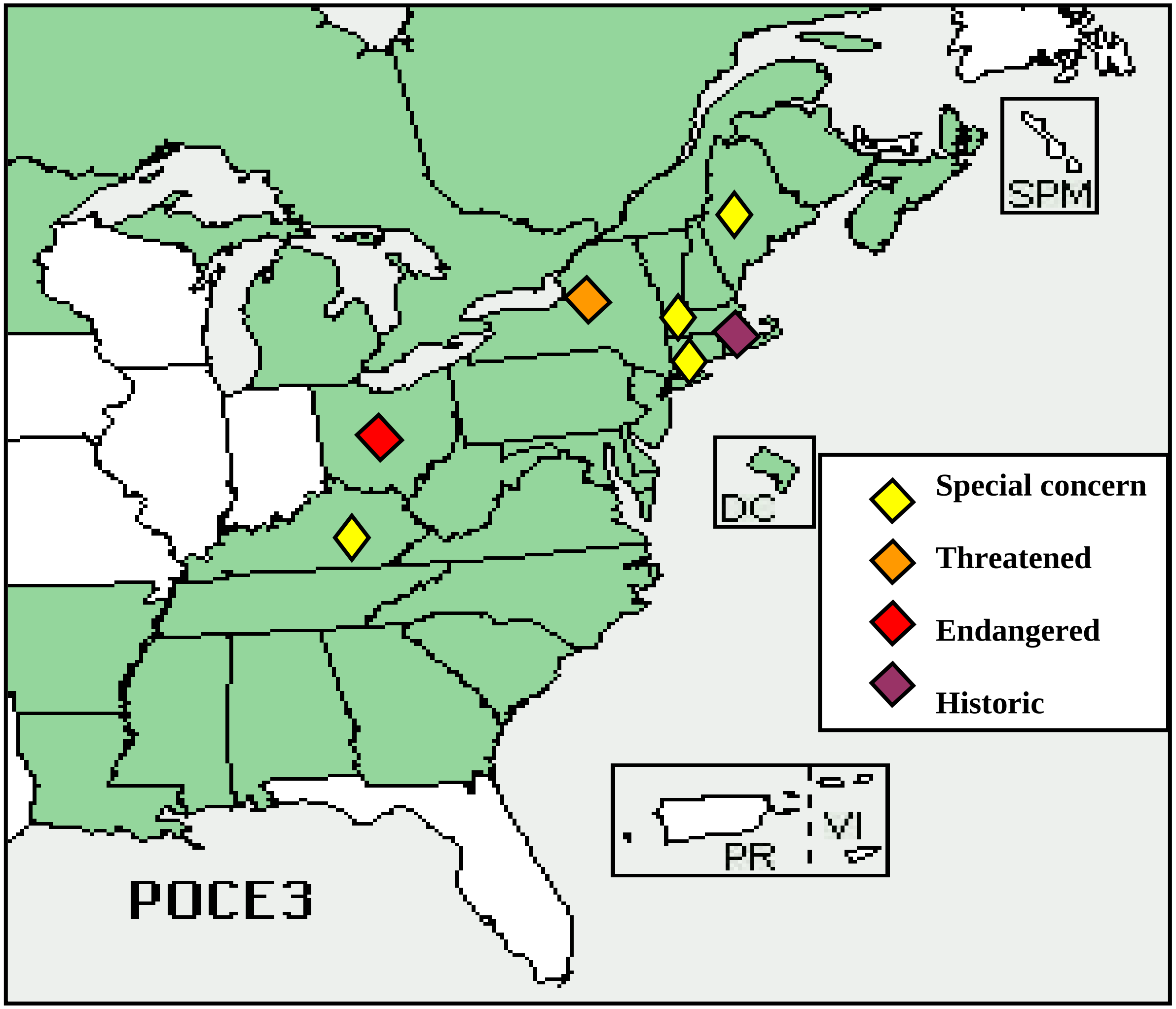

SPM
DC
PR
VI
Special concern
Threatened
Endangered
Historic
POCE3

Figure 4.2: *P. ceratophyllum* survey distribution in Georgia. 1:100,000 meter scale stream coverage map of Georgia highlighting physiographic province, *Podostemum ceratophyllum* observation locations (plus signs), and U.S. Geological Survey gages (circles). *P. ceratophyllum* observations were collected through fish surveys by B.J. Freeman and M.C. Freeman over the past 20 years, and are not random observations. This map represents an initial *P. ceratophyllum* range identification.

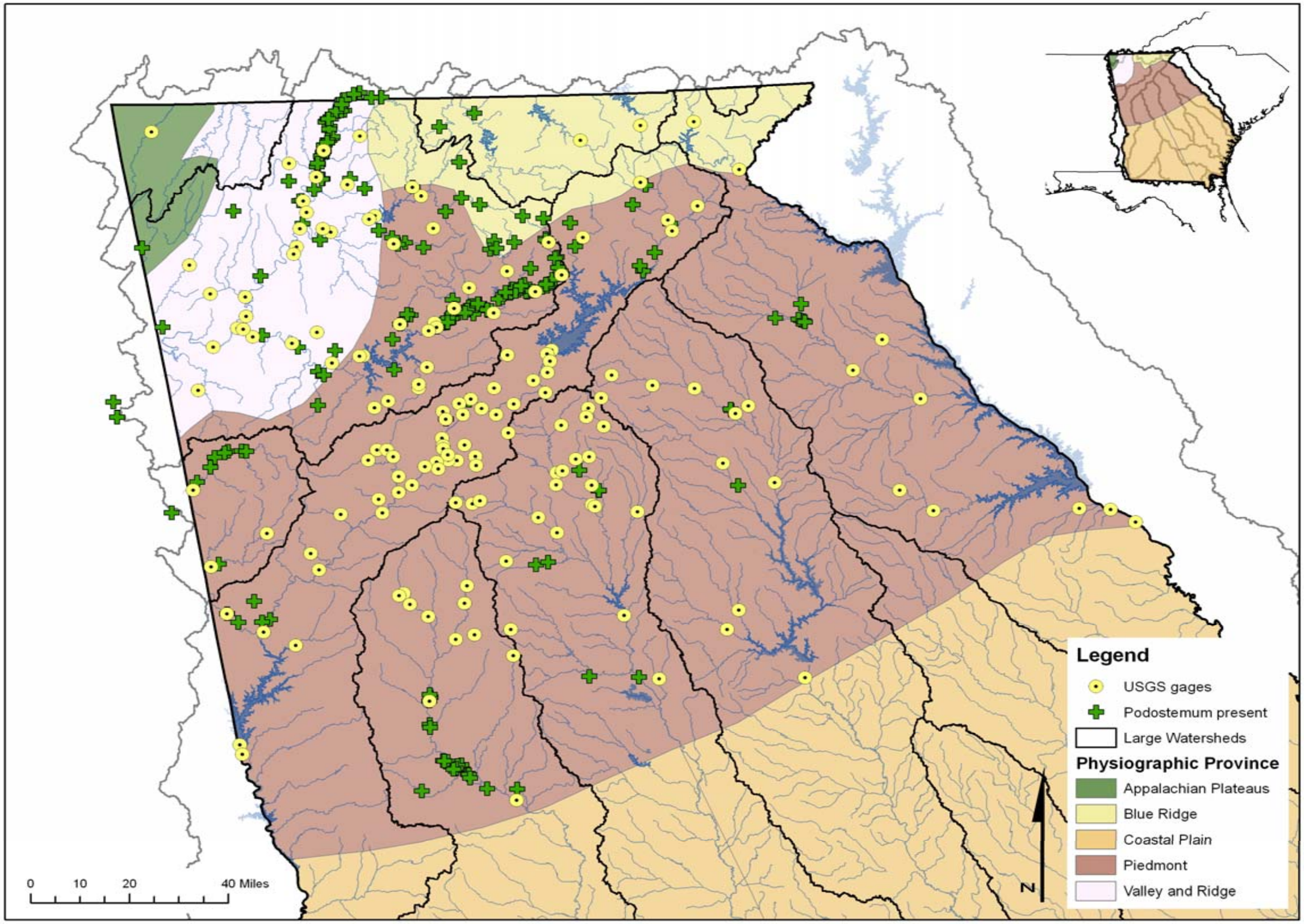

Legend
USGS gages
Podostemum present
Large Watersheds
Physiographic Province
Appalachian Plateaus
Blue Ridge
Coastal Plain
Piedmont
Valley and Ridge
0
10
20
40 Miles
N

Figure 4.3: Examples of altered and unaltered hydrology. Hydrographs of three U.S. Geological Survey gages at the 15 minute time scale to illustrate gages that had hydrologic alteration present and those that were classified as not altered. USGS gage number 02392950 is from Noonday Creek at Hawkins Store Rd, near Woodstock, GA, and represents a normal hydrograph. USGS gage number 02389150 is from the Etowah River at GA 9, near Dawsonville, GA, and indicates upstream water extraction. USGS gage number 0239400 is from the Etowah River at Allatoona Dam, above Cartersville, GA and reflects the presence of the upstream dam operation.

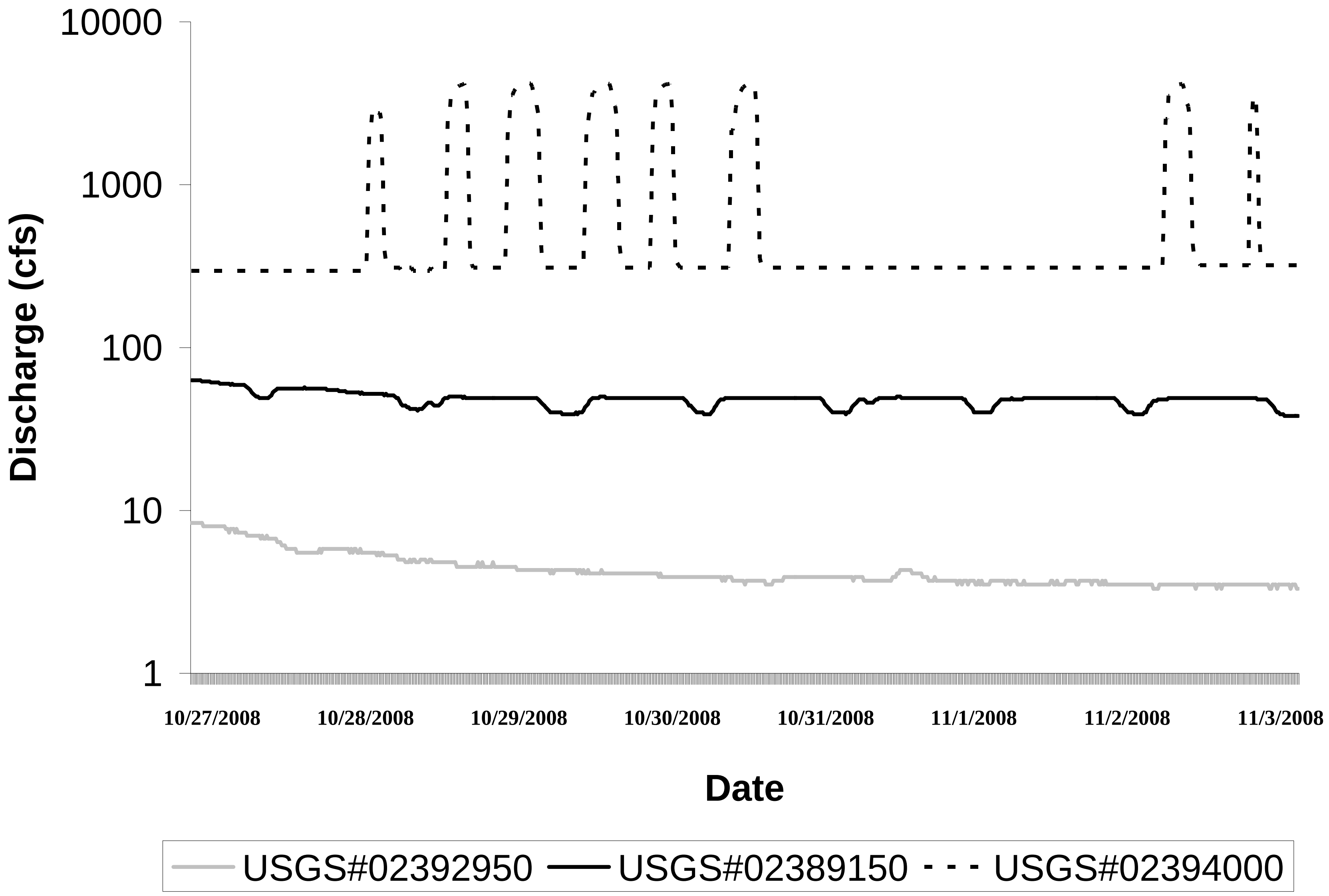

10000
1000
100
10
1
Discharge (cfs)
10/27/2008
10/28/2008
10/29/2008
10/30/2008
10/31/2008
11/1/2008
11/2/2008
11/3/2008
Date
USGS#02392950
USGS#02389150
USGS#02394000

Figure 4.4: Histogram of *Podostemum ceratophyllum* observations classified by stream order.

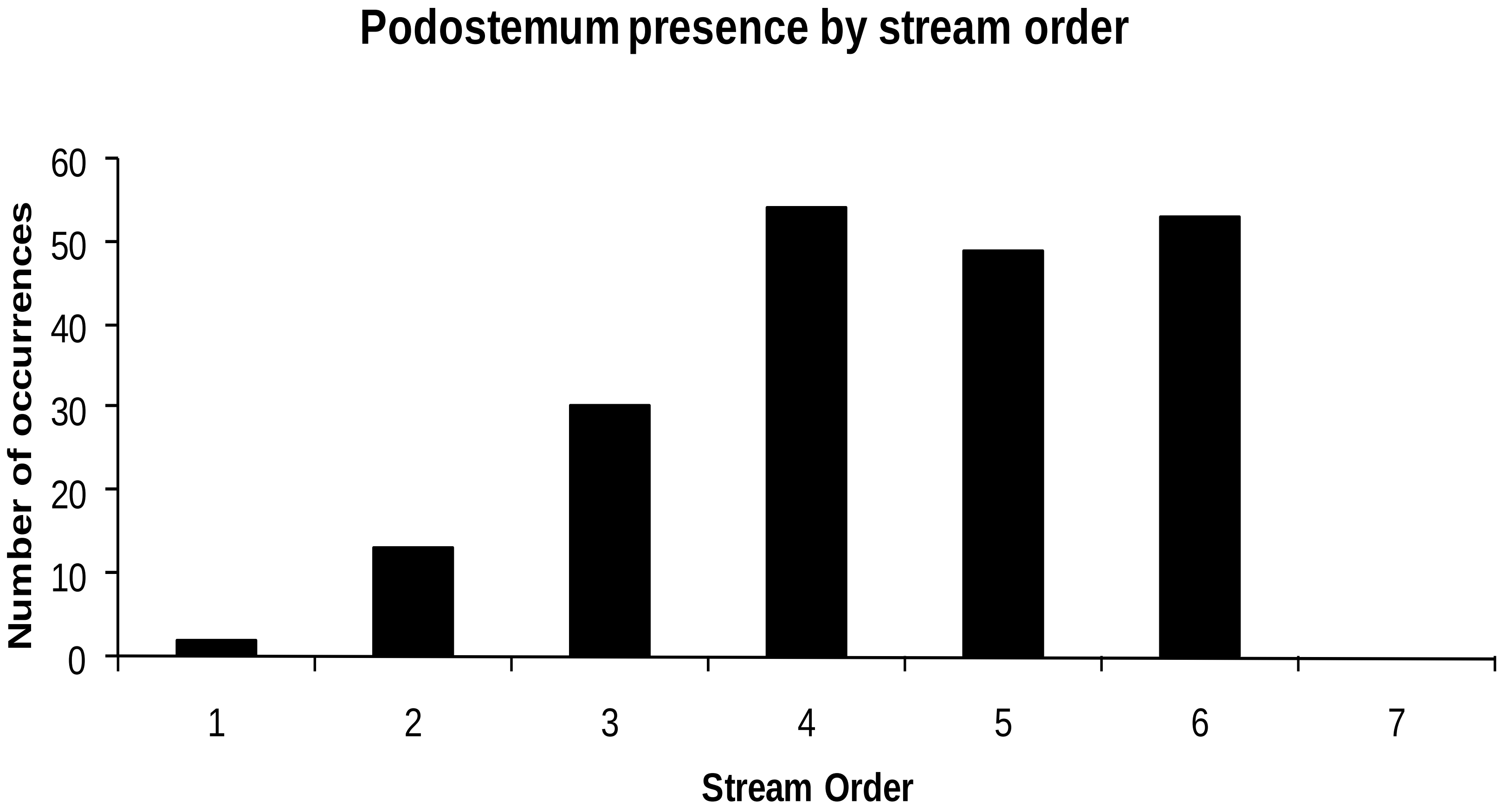
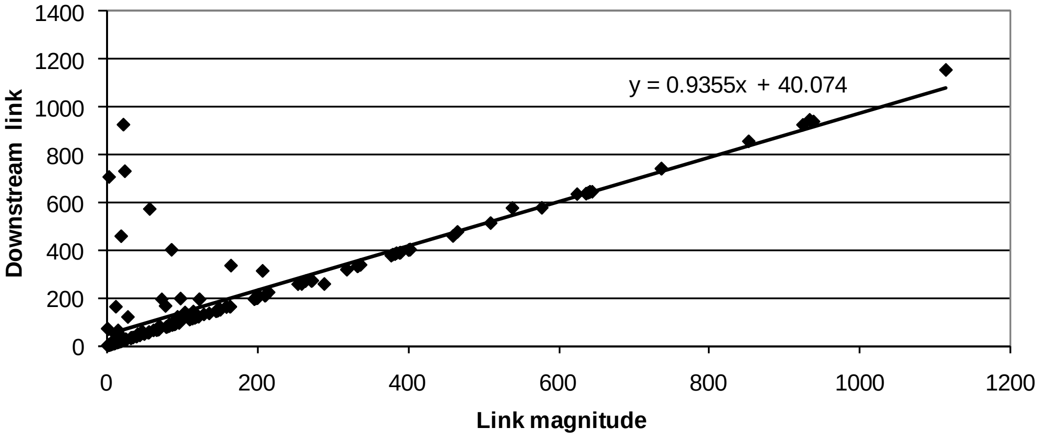
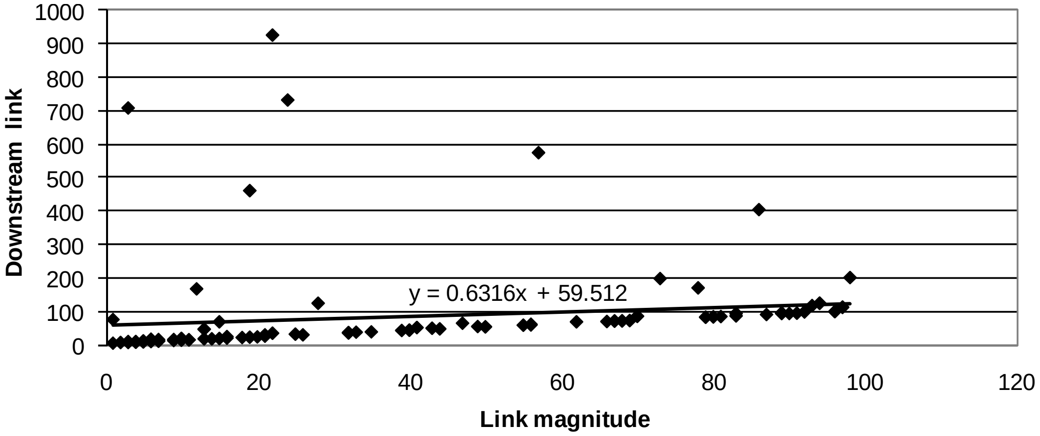

Podostemum presence by stream order
Number of occurrences
60
50
40
30
20
10
0
1
2
3
4
5
6
7
Stream Order

Figure 4.5: Link magnitude and downstream link associations. Regressions between link magnitude and downstream link for all observation sites, those with link magnitudes under 100, and those equal to or less than 10. These figures indicate that link magnitude and downstream link are well correlated for link magnitudes greater than 200, but are less correlated below this value. At extremely low link magnitudes, there is not a very strong correlation, and downstream links can range from close to the link magnitude to much larger.


1400
1200
1000
800
600
400
200
0
Downstream link
y = 0.9355x + 40.074
0
200
400
600
800
1000
1200
Link magnitude


1000
900
800
700
600
500
400
300
200
100
0
Downstream link
y = 0.6316x + 59.512
0
20
40
60
80
100
120
Link magnitude

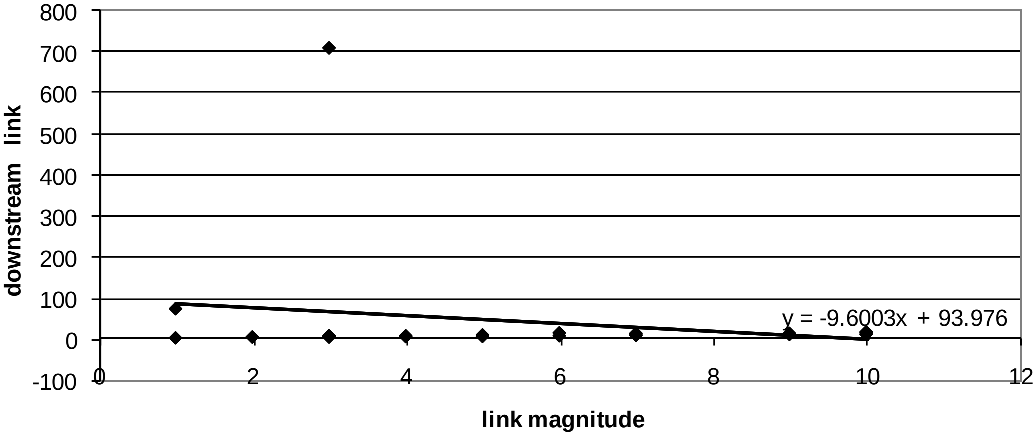

800
700
600
500
400
300
200
100
0
-100
downstream link
y = -9.6003x + 93.976
0
2
4
6
8
10
12
link magnitude

Figure 4.6: Hydrologic alteration by major basin. 1:100,000 scale stream cover map of Georgia above the fall line with major drainages outlined. Each basin is color coded with respect to its percentage of USGS gages that indicated altered hydrology from water extractions or impoundments.

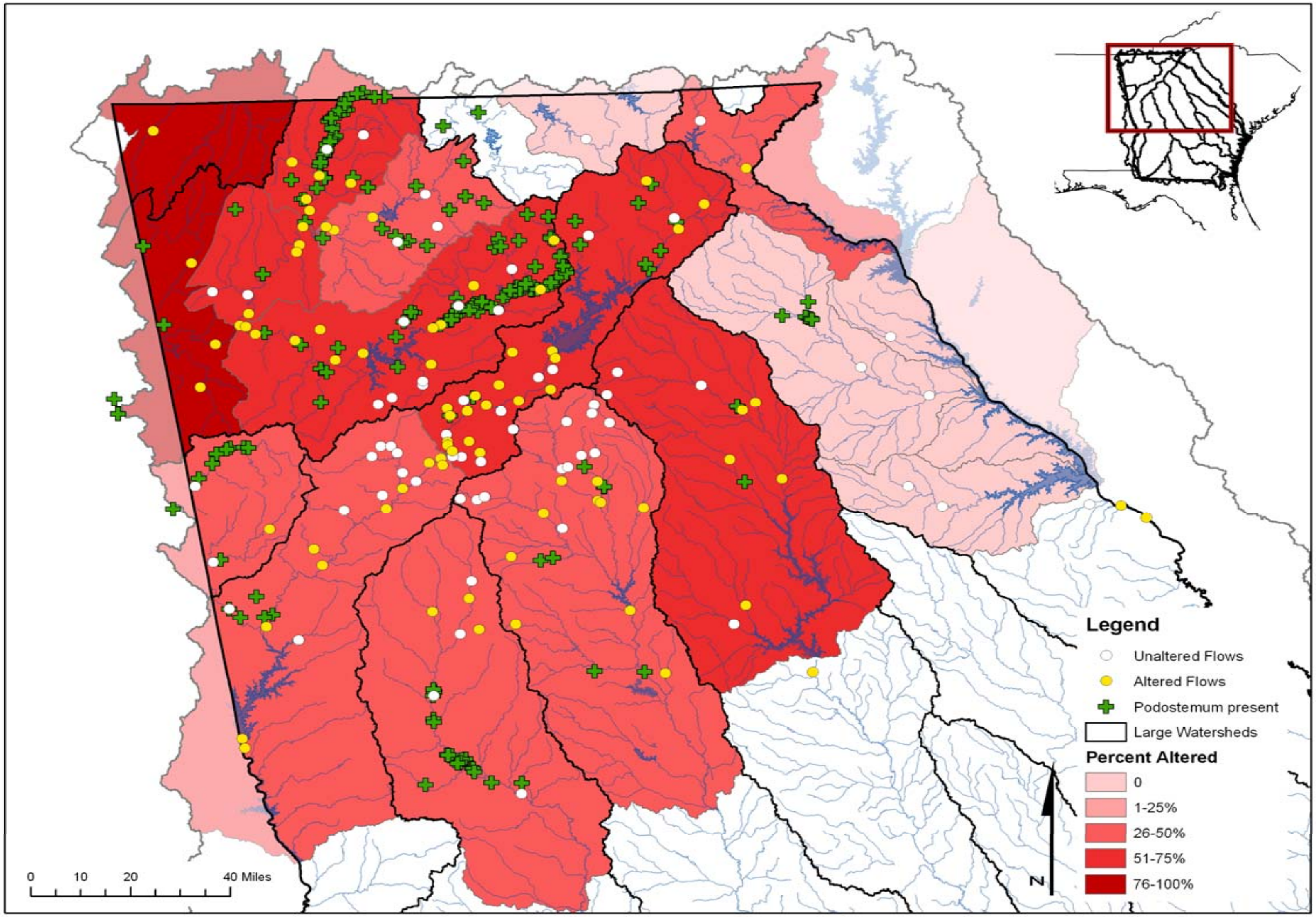

Legend
Unaltered Flows
Altered Flows
Podostemum present
Large Watersheds
Percent Altered
0
1-25%
26-50%
51-75%
76-100%
0
10
20
40 Miles
N

Image 3.1: Study shoal in the Middle Oconee River, at Ben Burton Park, Athens, GA. This image highlights the variability in substrate elevation and the large area of exposed sediments under drought conditions.

Image 3.2: Photograph of *P. ceratophyllum* holdfast (raphe) markings on a boulder. This type of marking was used as evidence of past colonization for boulders that were used in the isolated substrate study.

APPENDIX A

RAW DATA: RIVERWEED BIOMASS AND OTHER VARIABLES

P. ceratophyllum (Riverweed) biomass is expressed in g-AFDM/m^2, velocity is in m/s, substrate code 1 = bedrock/boulder, 0 = gravel/cobble, Location code 1 = edge, 0 = center.

Date	Riverweed	Substrate	Location	Velocity
12/13/2007	24.9254	1	1	0.11
12/13/2007	61.1149	1	1	0.04
12/13/2007	4.8137	0	0	0.08
12/13/2007	38.9237	1	0	0.34
12/13/2007	32.1267	0	0	0.04
12/13/2007	32.8006	1	0	0.59
12/13/2007	19.9576	0	0	0.75
12/13/2007	1.0494	0	0	-0.04
12/13/2007	1.2131	0	1	-0.06
12/13/2007	0.2696	1	1	0.15
2/11/2008	12.1979	1	0	0.51
2/11/2008	6.8066	0	0	0.52
2/11/2008	58.0630	1	0	0.51
2/11/2008	35.2941	1	0	0.59
2/11/2008	7.0184	1	1	0.85
2/11/2008	55.2999	1	0	0.79
2/11/2008	1.2516	1	1	0.42
2/11/2008	2.0892	1	1	0.41
3/25/2008	69.3174	1	0	0.66
3/25/2008	0.1059	1	0	0.75
3/25/2008	0.5776	1	0	0.25
3/25/2008	120.4776	1	0	0.23
3/25/2008	116.2126	1	0	0.29
3/25/2008	21.5751	0	0	0.61
3/25/2008	0.0000	1	1	0.29
3/25/2008	6.1423	1	1	0.37
4/21/2008	69.3848	1	0	0.71
4/21/2008	11.2545	1	0	0.82
4/21/2008	371.2815	1	0	0.52
4/21/2008	155.1459	1	0	0.48
4/21/2008	27.0145	1	1	-0.01
4/21/2008	161.5193	0	0	0.40
4/21/2008	41.8023	1	1	0.73
4/21/2008	23.0192	1	1	0.49
5/27/2008	16.7132	1	1	1.17
5/27/2008	5.6513	1	1	0.43

5/27/2008	81.7849	1	1	0.38
5/27/2008	18.5232	1	0	-0.02
5/27/2008	48.0697	0	0	0.37
5/27/2008	11.6203	0	0	0.24
5/27/2008	197.4199	1	0	0.67
5/27/2008	31.2987	0	0	0.52
5/27/2008	4.7752	1	1	0.27
5/27/2008	70.5209	1	1	0.53
6/19/2008	1.8100	1	1	0.65
6/19/2008	9.7911	0	1	0.14
6/19/2008	25.9266	1	0	0.20
6/19/2008	215.7987	1	0	0.49
6/19/2008	276.3936	1	0	0.42
6/19/2008	146.7700	1	0	0.25
6/19/2008	141.9371	1	0	0.03
6/19/2008	208.5492	1	0	0.47
6/19/2008	20.5545	1	1	0.52
6/19/2008	29.2000	1	1	0.47
7/14/2008	9.0209	1	1	0.18
7/14/2008	13.2184	1	1	0.06
7/14/2008	75.8737	1	0	0.12
7/14/2008	156.0316	1	0	0.02
7/14/2008	36.1606	1	0	0.08
7/14/2008	355.7525	0	0	0.19
7/14/2008	207.6442	1	0	0.13
7/14/2008	44.9408	1	0	0.09
7/14/2008	27.5441	1	1	0.05
7/14/2008	84.0378	1	1	0.07
8/18/2008	54.0676	1	0	0.01
8/18/2008	87.5999	0	0	0.10
8/18/2008	154.3372	1	0	0.34
8/18/2008	1.8388	0	0	0.24
8/18/2008	28.8726	1	0	-0.04
8/18/2008	19.3126	1	0	0.11
8/18/2008	4.0050	1	1	0.09
8/18/2008	15.1632	1	1	0.07
9/19/2008	36.0836	1	1	0.28
9/19/2008	14.6433	1	1	0.00
9/19/2008	11.2545	1	0	0.16
9/19/2008	28.8052	1	0	0.02
9/19/2008	212.6794	1	0	0.34
9/19/2008	4.2264	0	0	0.25
9/19/2008	27.8714	1	0	0.10
9/19/2008	19.1586	1	0	0.00
9/19/2008	18.8890	1	1	0.19
9/19/2008	17.8877	1	1	0.16
10/15/2008	7.5960	1	1	0.04
10/15/2008	39.8960	0	1	0.09
10/15/2008	15.6349	1	0	0.16
10/15/2008	54.2409	1	0	0.22
10/15/2008	23.5198	0	0	0.41

10/15/2008	110.2532	1	0	0.36
10/15/2008	7.8945	1	0	0.18
10/15/2008	42.6880	1	0	0.11
10/15/2008	39.9923	1	1	0.37
10/15/2008	35.3808	1	1	0.23