ABSTRACT

JOHNSON, YARI BEN. Natural Variation of Hydrology in Nonrivierine Wet Hardwood Forests and the Implications for Restoration. (Under the direction of April James and Theodore Henry Shear).

Wetland restoration projects across the United States are failing. Restored sites commonly lack the species and hydrology of the targeted community being restored. A better understanding of natural wetlands would help restoration project designers achieve community composition and hydrologic regimes that more closely resemble natural conditions. I investigated two different methods to identify patterns in hydrologic regime useful to restoration design. The first method was based on success criteria commonly used by North Carolina wetland mitigation projects. The second method was based on The Nature Conservancy's Indicators of Hydrologic Alteration. In order to test these two methods, I collected hydrologic and compositional data across the natural variation of nonriverine wet hardwood forest stands, a rare wetland community type commonly restored in North Carolina. My results show that hydrologic parameters from the first method, based on current success criteria used in North Carolina, are not related to community composition. Hydrologic parameters from the second method, *e.g.* the maximum water table level over a 3-day span, explained much of the variation in nonriverine wet hardwood forest community composition. My results found that clear relationships do exist between hydrologic regime and community composition. Hydrologic parameters that are related to community composition need to be used as success criteria in future restoration designs. This will ensure that projects establish the appropriate hydrologic regime necessary to foster the desired wetland community type.

Natural Variation of Hydrology in Nonrivierine Wet Hardwood Forests and the Implications for Restoration

by
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DEDICATION

My life has been a journey molded and touched by countless people. Some provided the foundation, while others contributed the body and finishing touches. My mother brought me into the world in a natural environment, where I learned to love and respect our Earth. She taught me the importance of managing forests and protecting our natural resources. Foremost, she taught me to never give up, even when faced with life's toughest challenge. For these gifts, I humbly dedicate this work to her. My father taught me to love all learning and served as the motivation for me to leave and better myself through education. For these gifts, I humbly dedicate this work to him. My second mother gave me eyes to see things from another culture and the ability to speak a second language. She strongly supported and encouraged me to continue my quest for knowledge. For these gifts, I humbly dedicate this work to her. To my bride and companion, I graciously dedicate this work to you. Your strength, courage, wisdom, understanding, and interminable patience have never faltered on our journey. You have lovingly carried me while I finished this work. Finally, I dedicate this work to my children in hope that they may, too, be able to experience the joy and beauty of the world's natural wonders.

BIOGRAPHY

Yari Johnson was born at home in the foothills of the Sierra Nevada on a warm sunny day in December of 1980. He grew up wandering Ishi's land barefoot and swimming in the icy streams which flowed from Mount Lassen. The tall pines and red dirt were his tutors. Life changed when he moved to Taipei, Taiwan, at age ten. The treeless concrete jungle of northern Taipei was not crowded enough, so after three months his family moved to the city of Yung-ho, where 250,000 people packed into two square miles (1280 acres). The markets and alleys provided further education, until Yari realized that outside the cities lied a subtropical paradise filled with mountains, waterfalls, and deserted beaches.

Yari joined the family business of teaching at age twelve and moved up to helping future university students prepare for their college entrance exams at age sixteen. The next year, Yari joined the lucrative world of translating and consulting. Vacationing around East Asia, basking in the hot springs of Wulai, swimming near Turtle Island, and enjoying easy money while consulting for a division of Taylor Nelson Sofres, PLC, was getting boring for Yari. Therefore, he decided to leave for the US to learn about perseverance. He quickly learned that in America everyone has a chance to succeed but has to start at the bottom. Thus Yari began his journey in America by toiling in a restaurant full-time while attending university full-time. This was still not challenging enough, so Yari became an active participant in university activities, which eventually led to him becoming student body president of his campus. He helped to found the Chicago College Coalition, which gave a united voice to student government leaders in the Tri-state area.

Having had enough humiliation serving customers in a restaurant, Yari joined the Global Steel Exchange (GSX) and quickly moved his way into a Madison Street corner office in the Loop. By now, Yari's engineering dreams had morphed into a passion for environmental science. He graduated from Roosevelt University in 2001 with a major in International Studies and a minor in Environmental Science. Two weeks after graduating, GSX was cannibalized by its investors and a newly-married Yari soon found himself looking for a job in a market swamped with 5000 other highly educated survivors from Arthur Anderson, LLC. Yari continued receiving lessons in humility at a minimum-wage job, but found solace in knowing that he was the only worker without a masters degree.

After working two full-time jobs for six months to barely survive, Yari decided to leave the US once again and travel with his wife. This started "The Gap Year," the adventures of which will soon be available in a published book. The year included time on a self-sufficient farm in Piemonte, Italy, plugging away as a peasant, living in the deserts of Utah, and culminated with Yari's return to Taiwan, where he landed a job starting up a language school. He then worked for Taipei City Government's experimental elementary bilingual education program. It took a year for Yari to realize that the City Government could not and would not legally hire him. Yari then took a job teaching at the prestigious Taipei Kueishan Private School.

Yari was fascinated by Kueishan's mission, which included teaching ecology to all students starting from first grade. While Yari greatly enjoyed teaching at Kueishan, he yearned to further his education in the environmental field, preferably ecological engineering or restoration ecology. North Carolina seemed to be the best choice, so Yari, with his young family, moved across continents for the fifth time in 2006. He then joined the Restoration Ecology program at North Carolina State University in January, 2007.

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I would first like to thank Dr. Ted Shear for his “open-door” policy through which he provided me with countless hours of guidance and research support. Thanks also go to Dr. April James who helped me build a foundation in hydrology and always gave me articles to read, instead of answers. I would also like to thank Dr. Josh Heitman for helping me understand the inner workings of soil and providing moral support.

My field research would not have been possible without the hundreds of hours of help from Matt O’Driscoll, whose perseverance, plant ID skills, and good humor kept the research going. Thanks are also due for Joelle Laing who not only provided excellent field assistance, but also let all of the ticks bite her, so they did not bother me. Thanks are also due to Yang Lixin, Megan Malone, and Kim Shumate for their help and support. I am deeply indebted to the folks in the equipment room; thanks Matt and Lizzie.

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I would like to thank my Aunt and Uncle Piec for helping me become re-acclimated to living in the US and for supporting me through my undergraduate university career with their guidance and resources. I want to thank Jarrig Visser and Amybeth Maurer for believing in me and helping me to become an effective leader. I also want to thank Dr. Niall Michelsen for recommending North Carolina.

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INTRODUCTION

Failure of restoration efforts to establish appropriate hydrology has been documented for many wetland types in the United States (Kentula, et. al. 1992; Pfeifer and Kaiser 1995; National Research Council 2001). Part of this failure has been attributed to restored sites being wetter than natural wetlands. This is an unintended consequence of project designers attempting to ensure that restored wetlands meet hydrologic criteria required by regulations (National Research Council 2001), instead of hydrologic conditions found in natural wetland communities.

Forested wetlands are exceptionally difficult to restore since slight differences in hydrologic conditions cause tree composition to deviate from the targeted community being restored. In order to understand this problem, I focused on restoration done in North Carolina by the Ecosystem Enhancement Program, a division of the N.C. Department of Environment and Natural Resources which oversees much of the state's wetland mitigation. Based on a survey of Ecosystem Enhancement Program monitoring reports from 2005 to 2007, restoration success for wetland mitigation projects is usually contingent upon meeting wetland hydrology conditions as defined in the *Corps of Engineers Wetlands Delineation Manual* (Environmental Laboratory 1987). In order for forested communities to meet conditions for wetland hydrology, the soil must be inundated, or saturated within 30 cm of the surface, for one continuous period lasting more than 12.5% of the growing season. The growing season is approximated by the number of frost-free days (*i.e.*, days with minimum temperature above −2.2 ºC) (Environmental Laboratory 1987). By following the U.S. Army Corps of Engineers’ delineation guidelines, all forested wetland community types are judged by essentially the same hydrologic criterion. However, according to Schafale and Weakley’s *Classification of the Natural Communities of North Carolina: Third Approximation* (1990), there are twenty-four different forested wetland communities in North Carolina, ranging from wet pine flatwoods to several types of swamp forests. The diversity of wetland communities in this state raises some questions. For a particular wetland community, should restoration designers aim to have wetland hydrology for 12.5% of the growing season? Or would 25% be better? Would 99% be too wet? If one broad standard for hydrology is not suitable for all situations, what criteria should be used? How can designers be sure that restored hydrology is for one community type and not another?

There is a dearth of information on relationships between hydrologic regimes and plant community composition. Duration and frequency of soil inundation and saturation play an important role in forested wetland composition (Hewlett 1982; Leitman, et al. 1983; Day, et al. 1988; Beissel and Shear 1997; Bledsoe and Shear 2000). However, more investigations are needed to answer questions about water table depth, seasonal fluctuations, and to develop methods for quantifying these variations for different forested wetland types. Once these questions are answered, wetland restoration design can be improved to better reflect natural conditions.

Study Focus

For this study I focused on one community, nonriverine wet hardwood forests, but these methods can be used across different wetland community types. Based on my survey of wetland restoration projects done by the Ecosystem Enhancement Program, this is one of the most commonly restored forested wetland communities in North Carolina. A century ago it was estimated that this community occupied one-quarter of the wetland area, or about 260,000 hectares, in North Carolina’s coast plain (Pinchot and Ashe 1897). Once ditched and drained, the relatively flat mineral soils found in nonriverine wet hardwood forests were attractive to agriculture. As a result, less than two percent of this estimated area remains forested today (Rheinhardt and Rheinhardt 2000). Thus there is great potential for future restoration of nonriverine wet hardwood forests, given the current demand for wetland mitigation and the availability of sites suitable for this community type.

Nonriverine wet hardwood forest composition is well described (Cazier 1992; Cazier, et. al 2001; Morris 2004; Rheinhardt and Rheinhardt 2000; Schafale 1999), but the hydrologic regime has not been described in detail quantitative enough for use in restoration design. Little information is available on the relation of hydrologic regime to forest composition in these systems. Characterizing and comparing the relation of hydrologic regime to community composition across the natural variation of nonriverine wet hardwood forests would provide a reference dataset for restoration design. A reference dataset has been recommended (Westman 1991; Hobbs and Norton 1996) as a regional baseline for all elements that define success of a restoration project. Regional baselines describe the range of acceptable hydrologic variation characteristic of a particular wetland community. Since plant communities vary along moisture gradients, restorationists can use a regional baseline to decide which wetland community to restore for a particular hydrologic regime.

The goal of this study is to provide characteristics of the hydrologic regime that can be used as design criteria for restoration of nonriverine wet hardwood forests. I achieve this by: (1) describing the natural variation of hydrology and tree composition in nonriverine wet hardwood forests; (2) investigating novel ways to identify characteristics of the hydrologic regime that could be used for restoration design; and (3) translating results into restoration recommendations.

Ecohydrology of Nonriverine Wet Hardwood Forests

Nonriverine wet hardwood forests, historically called oak flats (Pinchot and Ashe 1897), are a precipitation-driven wetland community found on broad interstream divides of the Coastal Plain in North Carolina and Virginia. They occur on mineral soils and are composed primarily of hardwood species, *e.g. Liquidambar styraciflua* (sweetgum), *Acer rubrum* (red maple), and *Quercus* spp. (oak species), in contrast to pine flats, which are mainly composed of *Pinus* spp. (pine species) (Schafale and Weakley 1990). The soils of the Coastal Plain are typically sandy or mucky with depth to impermeable layer greater than 2 m. Parent material is generally unconsolidated coastal plain sediment deposited in the last

80,000 years (Tant 1981; Soil Survey Staff 2008). The lower Coastal Plain of North Carolina is flat, on average losing less than a meter in elevation every 20 km. The flat topography, broad interstream divides, and high precipitation (1140-1650 mm per year) result in large expanses of poorly drained areas (Lu 2003; Tant 1981). These interstream divides have a hydrologic gradient that progresses from well-drained streamside natural levees to poorly-drained interiors (Tant 1981). The wet interiors contain pocosins or nonriverine swamp forests, which are then surrounded by nonriverine wet hardwood forests (Schafale and Weakley 1990). Mesic mixed hardwood forests occur in areas that are less wet and have better drainage, such as slopes or levees. Thus, on a hydrologic gradient, nonriverine wet hardwood forests are between mesic mixed hardwood forests and nonriverine swamp forests (Figure 1). Species composition among these three communities is quite similar, with differences controlled by slight variation in microtopography and macrotopography. Since both communities can share some dominant species, distinguishing between mesic mixed hardwood forests and nonriverine wet hardwood forests can be difficult. When compared to nonriverine wet hardwood forests, mesic mixed hardwood forests have a major *Fagus grandifolia* (American beech) component, while nonriverine swamp forests contain *Taxodium distichum* (bald cypress) but lack *Quercus* species (Schafale and Weakley 1990; Schafale 1999).

METHODS

Site Selection

I selected study sites using (1) prior surveys and a list of suitable soil series for this community type from the North Carolina Natural Heritage Program (Schafale 1999) and (2) study site information from Morris (2004). I ground truthed potential study sites using indicator species for each community type (Schafale 1999) and these additional criteria:

1. Composition must be predominately hardwood;
2. Located in a continuous forest of at least 10 ha in size (to eliminate edge effects);
3. No evidence of logging in the past 50 years; and,
4. Minimal ditching (to ensure more natural hydrologic regimes).

Study sites were not free from disturbances, but these criteria ensured that ditching and other human influences were kept to a minimum.

Vegetation and hydrology data were collected at 10 selected study site locations (Figure 2). More than one community type, *i.e.*, either a nonriverine swamp forest or mesic mixed hardwood forest in addition to the nonriverine wet hardwood forest, were identified at three of the study site locations. In order to understand the hydrologic and compositional boundaries of nonriverine wet hardwood forests, these two additional community types were included in the study. This resulted in a total of 14 stands of different community types for the study (Table 1).

Vegetation

I quantitatively described community composition in each stand by setting up one 10 m x 100 m plot using the Carolina Vegetation Survey (CVS) protocol (Peet, *et. al.* 1998). Each plot was divided into 10 m x 10 m modules. In order to capture the full range of variation in each stand, I set up plots roughly perpendicular to hydrologic gradients identified through soil maps (Soil Survey Staff 2008). Plots were located at least 50 m from ditches and forest edges in areas that maximized their representation of a particular stand. I took coordinates at the ends of each plot using a handheld global positioning device. I recorded a size-class based on diameter at breast height (dbh) for all measurable woody stems and actual diameter for all woody stems >90 cm dbh, excluding lianas and shrubs. I focused on overstory composition because trees are the stable component planted during restoration of forested wetlands. Species' names follow those of the USDA PLANTS database (USDA 2009). *Nyssa sylvatica* (Blackgum) was only identified to species and not subspecies, thus *Nyssa sylvatica*, var. *biflora* (swamp tupelo) was not included as a separate tree species.

Hydrology

I characterized the hydrologic regime of each stand by monitoring the height of the water table using shallow wells. I installed each well in the midrange of the microtopographic relief, as defined by a visual scan of hummocks and hollows, at least 50 m from a forest edge or ditch. Previous studies into the hydrological effects of ditches on water tables in North Carolina show that ditch influence typically drops off significantly after 30 m and is usually negligible after 50 m (Philips, *et. al.* 2006). I installed wells to a 152 cm depth according to the U.S. Army Corp of Engineers technical standard for water table monitoring (U.S. Army Corps of Engineers 2005) (Figure 3). Data loggers (Infinities USA, Inc., Florida) attached to each well measured water table levels every 6 hours.

Despite protective efforts, *Ursus americanus* (American black bears) and vandals destroyed data at two nonriverine wet hardwood forests stands (N2 and N8) and one mesic mixed hardwood forest stand (M3). The final dataset contained 217 days of available water table data from July 29, 2008 to March 2, 2009 for ten stands (2 mesic mixed hardwood stands, 6 nonriverine wet hardwood stands, and 2 nonriverine swamp stands). I compared water table data from each well to daily precipitation records provided by the nearest weather station through the North Carolina State Climate Office CRONOS Database to identify anomalies or data logger errors. In order to get a general sense of the hydrologic regime for each stand, a groundwater hydrograph was created (for an example, see Figure 4).

I used two methods to search for patterns in the hydrographs. The first was a novel method based on the US Army Corps of Engineers' technical standard for wetland hydrology, the success criterion commonly used in North Carolina wetland restoration. A modification was necessary since the current standard does not provide any useful quantitative hydrologic information; it only determines whether or not a site has wetland hydrology for a certain number of days during the growing season. For this modified Corps method I chose to examine three parameters: (1) the total number of days the water table level was within at least 30 cm of the soil surface (the threshold for meeting the Corps' definition of wetland hydrology), (2) the total number of days the water table level was above the soil surface (a subset of 1), and (3) the total number of days the water table level was deeper than 61 cm below the soil surface (Figure 5). While current wetland hydrology standards only analyze growing season data, I included non-growing season measurements for these parameters because significant root growth still occurs in North Carolina trees during the winter (Perry 1971). The growing season for the Coastal Plain in North Carolina is roughly from the beginning of March to the end of November (USDA 2001). Parameters (1) and (2) measure soil saturation at depths where the majority of roots of interest are because of the impact that anaerobic conditions have on roots. Parameter (3) focuses on water table levels deeper than 61 cm below the soil surface because this was the depth after which few to no roots were found at each stand based on visual estimates from hand auguring. This parameter approximated when trees were free from the impacts of saturated soil on their roots. Thus the modified Corps method was composed of two measures of saturated root zone conditions, parameters (1) and (2), and one measure of roughly unsaturated root zone conditions, parameter (3).

The second method of quantitatively describing hydrologic regime was based on Indicators of Hydrologic Alteration (IHA) developed by The Nature Conservancy (Richter, *et. al.*1996). IHA provides a quick assessment of hydrologic conditions in either river discharge or water table monitoring wells, but it has been used primarily to quantify changes caused by dams on rivers (see Richter, et. al. 1996 for a detailed explanation of the method and parameters). The method calculates “32 ecologically relevant hydrologic parameters” across a time series (Richter, *et. al.*1996). Daily mean hydrologic conditions are used to estimate all attributes, *e.g.* for water table measurements the average level over a one-day period would be used, instead of smaller increments of time. IHA measures the magnitude, the timing of occurrence, the frequency of occurrence, the duration, and the rate of change in hydrologic conditions (Richter, *et. al.*1996).

I adapted this method for use below ground, *e.g.* I did not use "zero flow days," instead I quantified dry conditions by replacing this parameter with the number of days the water table level was below the sensor at each stand (approximately 150cm below the ground surface). I chose the 75th percentile of the water table level at each stand as the high pulse threshold and the 25th percentile as the low pulse threshold. "Pulse" is a unique hydrologic term used in IHA. It comes from the pulsing rise seen in a hydrograph when water levels increase and then decrease (such as during a storm event). Figure 6 provides examples of selected IHA parameters, as defined here for use with water table depths.

Data Analyses

I calculated an importance value (IV) ranging from 0 to 1 for individual species in each plot by dividing the sum of the relative basal area (dominance) and relative density by 2. The midpoint diameter was used to calculate basal area for each size class, and actual diameter was used for stems with dbh greater than 90 cm.

I analyzed tree composition, represented by species IV in each plot, by indirect ordination using the non-metric multidimensional scaling (NMS) function of PC-Ord multivariate analysis software (McCune and Medford 2006). NMS is an iterative optimization ordination technique that allows the reduction of multidimensional data structures into fewer dimensions for analytical purposes. It is used as an exploratory tool to indentify gradients and communities. Analyses were done based on guidelines by McCune and Grace (2002) using the autopilot function with the following options: (1) Sorenson (Bray-Curtis) distance scores were used as input coordinates, (2) ordination was run with up to six dimensions with reduction in dimensionality occurring one axis at a time, and (3) the instability criterion was set at 0.0000000. Stress from 250 runs with real data compared to 250 random Monte Carlo runs gave a p-value <=0.024 for two axes. Thus PC-Ord recommended two dimensions as the best choice for the final run, which consisted of the selected number of dimensions with no step-down in dimensionality. The configuration file from the preliminary run was used with one real run.

SAS version 9.1 (SAS Institute Inc., Cary, NC) was used to calculate Pearson's correlation coefficients between the ordination scores for both axes and species importance values. I also calculated correlations between the ordination scores for both axes and the two methods of characterizing hydrologic regime. Analysis of variance was done to determine how much variation in the ordination axes were described by either the modified Corps method or the IHA method.

RESULTS

Relationship between Communities and Hydrology

Based on my a priori community selection for each stand, there was some separation along axis 2 for the three community types (Figure 7). The separation is not perfect, but there is a clear ordination space for each of the three communities. A better separation might be done diagonally (see schematic "oval" in Figure 7). There is a statistical relation between the community composition and axis 1, but this axis does not explain community separation.

Parameter values for the modified Corps method and the IHA method are provided in Tables 2 and 3. Based on the ordination analysis, hydrologic parameters from the modified Corps method could not be used to explain variability in community composition ($p > 0.15$), however parameters from the IHA method could. Height of water table levels, as measured by the 1-day, 3-day, 7-day, and 30-day maximums, were correlated with community composition (axis 2 ordination scores) (Table 4). A single IHA parameter was able to explain 63% of the variation among communities (Figure 8). Duration of water table levels, *i.e.*, high pulse duration and November mean water table level, were correlated with axis 1 ordination scores (Table 4). The average duration of high pulses explained most of the variation among axis 1 ordination scores (Figure 9).

Relationship between Individual Species and Hydrology

There were 30 different canopy and subcanopy tree species across all stands. I found a gradient of species richness (S) from mesic mixed hardwood forest stands (S=15) to nonriverine swamp forest stands (*S*=10). Importance values (IV) for each species by stand are listed in Table 5. *Acer rubrum* and *Liquidambar styraciflua* were the dominant species in almost all stands, except two stands where an individual oak species had the highest IV. *Quercus michauxii* (swamp chestnut oak), *Quercus laurifolia* (swamp laurel oak), and *Quercus pagoda* (cherrybark oak) were the most common oak species. *Quercus* species as a total were dominant or co-dominant in most stands. When *Liriodendron tulipifera* (tulip poplar) occurred in a stand, it had importance, but this was usually from one or two large trees (>100cm dbh). This species mainly occurred in mesic mixed hardwood stands and did not occur in nonriverine swamp stands.

Species abundance varied along both ordination axes. *Liriodendron tulipifera*, *Acer rubrum*, and *Quercus michauxii* were strongly correlated with axis 2 ordination scores. *Persea palustris* (swamp bay), *Fraxinus pennsylvannica* (green ash), and *Quercus pagoda* were strongly correlated with axis 1 ordination scores (Table 6).

Some IHA parameters accounted for much of the variation among certain species (Figure 10). The daily maximums explained at least 65% of the variation among *Liriodendron tulipifera*, *Acer rubrum*, and *Quercus laurifolia*. The maximum water table level over a 3-day span was the best fit, but since these daily maximums are highly correlated with each other (r^2>0.90), 1-day and 7-day maximum water table levels also showed an almost identical relationship to these three species. Hydrologic regime explained 96% of the variation of *Q. michauxii* importance values; *Q. michauxii* importance decreased in stands with higher low pulse thresholds. As the minimum water table levels increased this species decreased in importance.

Other Important Ecohydrological Findings

During our monitoring period, there was a general decrease in water table levels from early May until about the end of August in all nonriverine wet hardwood forest stands, with exception due to storm events. Higher evapotranspiration rates cause water tables to sink during the summer months. Some stands remained dry with deep water table levels (>-100cm) until late December, while other stands exhibited higher water table levels starting in late summer (Figure 11). As I expected, there was a general hydrologic gradient from mesic mixed hardwood stands to nonriverine swamp stands. Mesic mixed hardwood stands had lower water table levels, while nonriverine wet hardwood forest stands had higher water table levels, and nonriverine swamps forest stands had the highest (Figure 5). Parameters from both methods showed differences among the three community types, but there was some overlapping for a few particular stands.

There were two outlying stands where vegetation composition did not seem to match the current hydrologic regime. In one instance a nonriverine wet hardwood forest stand (N7) had water table levels that deviated from the rest of the nonriverine wet hardwood forest stands and more closely resembled a mesic mixed hardwood forest (Figure 12). The other stand (S1), a nonriverine swamp forest, did not have surface ponding of water during the winter months as expected for this community type by Schafale and Weakley (1990) (Figure

13). This site has 3-day maximum water table levels closer to mesic mixed forests than nonriverine swamp forests. Both of these two stands have extensive ditching and possibly due to anthropogenic influences, the current species composition could be indicative of hydrologic conditions when the stand regenerated and not what conditions are today.

DISCUSSION

A single measure of hydrology, such as the maximum water table level over a 3-day span, can be a useful proxy for all of the complex characteristics that compose the hydrologic regimes of these three community types. Most of the variation in species composition for these communities can be explained by this single parameter via ordination. Research done in North Carolina bottomland forests has shown that similar parameters quantifying maximum water levels also accounted for much of the variation among plant species composition (Beissel and Shear 1997). Bottomland forests are wetlands that have similar species composition to nonriverine wet hardwood forests; the main difference being that bottomland forests have periods of soil inundation dominated by riverine flooding frequencies rather than the precipitation events that dominate soil saturation and inundation in nonriverine wet hardwood forests.

Since one or two stands do not accurately describe a population, the limited number of mesic mixed hardwood stands and nonriverine swamp forest stands in this research warrants caution when drawing conclusions about these two communities. Expanding research of these two communities would clarify whether the stands in this study are representative of their respective communities. However, since these stands fell outside of the nonriverine wet hardwood forest ordination space, they help to delineate the boundaries of nonriverine wet hardwood forests and provided useful information on the differences between these three communities.

The IHA method has been widely used in riverine systems (Nature Conservancy 2005), but I have shown that it has broader applications. My success using the IHA method has shown the importance of choosing characteristics of the hydrologic regime that are important to ecological functions of a particular system. I have shown that strong relationships do exist between hydrologic regime and species composition for nonriverine wet hardwood forests. However, the modified success criterion currently used for wetland restoration in North Carolina (*e.g.*, the number of days the water table is above -30 cm) was not related to community composition. This suggests that restoration designers need to choose more appropriate success criteria that are related to ecological functions and community composition.

The importance of *Quercus* species was higher in this study than in a previous study (Morris 2004). This most likely resulted from my method of choosing and defining nonriverine wet hardwood forest stands based on Schafale and Weakley's indicator species for this community type (1990). I only considered a particular stand to be a nonriverine wet hardwood forest if it had *Quercus* species and lacked *Taxodium disticum*. Morris included stands that lacked both *Quercus* species and *Taxodium disticum* in her study of nonriverine wet hardwood forest stands (2004). This difference likely accounts for the higher importance of *Quercus* species in my study.

The data used in this study did not cover a whole year or even an entire growing season, but since I was focusing on water table behavior, this short time span was enough to show relations between patterns in hydrologic regime and community composition. However, I would recommend further investigations of hydrologic regime over longer periods to confirm my findings. Multiple years of data could help indentify if any longer-term patterns influence community composition. The year before data collection (2007) was the driest on record for North Carolina out of 113 years (National Climatic Data Center, Annual Report January 20, 2009). All one hundred counties experienced severe drought conditions for most of the year. 2008 was also below normal, being the 30th driest year out of 114 for North Carolina. For the entire monitoring period, only one stand had above normal precipitation, while the others had precipitation varying from one-tenth to one-third below normal levels (see Table 7). It is possible that these climatic conditions could have influenced my results. However, there were periods when conditions closer to normal. For example, all stands did have above normal precipitation for the months of September and November. Since the hydrology of these systems is largely driven by precipitation and evapotranspiration, local conditions play an important role in hydrologic regime for a specific timeframe. This makes direct comparisons of hydrologic regimes between multiple sites difficult under differing local climatic conditions; in spite of this, I have shown that differences in community composition are clearly distinguished using characteristics of the hydrologic regime.

Implications for Restoration

The current criterion used for forested wetland restoration might answer whether or not a wetland was created, but it does not provide guidelines for restoring specific community types. Without clearer guidelines for particular communities, restoration designers could plant nonriverine wet hardwood forest species at a site with restored hydrologic conditions better suited for a nonriverine swamp forest community. In this study I show characteristics of the hydrologic regime that can be used as design criteria for restoration projects. Using one broad success criterion, such as 12.5% of the growing season, will probably result in communities that do not resemble natural wetlands since there is no distinction made for differences in community composition. Proper hydrologic regimes need to be established in order to foster the community desired by restoration designers. I hope that future design teams will use the concepts from this study to design more natural and functionally successful forested wetlands. Projects that are already designed can be corrected to better mimic some of the natural features and ranges found from the stands in this study.

Significant natural variation exists among nonriverine wet hardwood forests. Due to this natural variation it is challenging to identify the appropriate community composition to restore for a specific existing hydrologic regime. However, the dominant species in this study are all highly correlated with hydrologic parameters from the IHA method. These relationships can provide guidelines for targeting species to a particular hydrologic regime.

Restoration projects should use the dominant species, based on importance values from this study, as targets for species composition. Sites that are dryer during the late spring/ summer tended to have more oaks (regardless of winter ponding depths, as illustrated by stand N4). Projects that seek oak-dominance should aim for dryer conditions during this time. At the wettest stand (stand N1), oaks only occurred on the highest hummocks. This indicates that sites with similar hydrologic regimes could only support oaks with appropriate microtopography. Furthermore, since this stand seems to have a hydrologic regime that is the limit of oaks, restoration projects should aim for dryer conditions in order to support more oaks.

Restoring microtopography would be a good way to ensure success during nonriverine wet hardwood forest restoration projects. Since *Fagus grandifolia* trees grew on the hummocks of drier sites and oaks only grew on the hummocks of wetter nonriverine wet hardwood sites, re-creation of natural microtopography would provide more hydrologic variation (McKinney 1997; Scherrer 2000) and potentially increase the diversity of plant species by allowing a greater range of hydrologic regime. This would help mimic natural conditions where boundaries between communities are not as distinct as in project designs and patchiness of communities is common.

CONCLUSION

A simple proxy for hydrologic regime can be used to effectively separate hydrology-driven wetland communities. I have also shown that wetland hydrology, as measured by the combined number of days the water table is above -30 cm, is not a good indicator of plant community composition. Periods of maximum water table levels proved to be closely related to species composition and provide a better way of determining hydrologically important parameters for success criteria. These findings question the current practice of using wetland hydrology, as defined by the Army Corps of Engineers, as a success criterion for these community types when better methods that are closely related to community composition are available.

REFERENCES

Bedford, Barbara L. 1996. The Need to Define Hydrologic Equivalence at the Landscape Scale for Freshwater Wetland Mitigation. Ecological Applications **6:** 57-68.

Beissel, K.D., and T.H. Shear. 1997. Comparison of the vegetational, hydrologic, and edaphic characteristics of riverine forested wetlands on the North Carolina coastal plain. Transportation Research Record **1601:**42-48.

Bledsoe, B.P., and T.H. Shear. 2000. Vegetation along hydrologic and edaphic gradients in a North Carolina coastal plain creek bottom and implications for restoration. Wetlands **20:**126-147.

Brinson, M.M., and R. Rheinhardt. 1996. The role of reference wetlands in functional assessment and mitigation. Ecological Applications **6:**69-76.

Cazier, P.W. 1992. Hardwood Forests in the Coastal Plain of Virginia, east of the Suffolk Scarp. Thesis. The College of William and Mary, Williamsburg, Virginia.

Cazier, P.W., and S. Ware. 2001. Hardwood Forest Composition in the Undissected Lower Coastal Plain in Virginia. Journal of the Torrey Botanical Society **128:** 321-331.

Day, F. P., S. K. West, and E. G. Tupacz. 1988. The influence of groundwater dynamics in a periodically flooded ecosystem, the Great Dismal Swamp. Wetlands **8:**1–13.

Environmental Laboratory. 1987. Corps of Engineers wetlands delineation manual, Technical Report Y87-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. NTIS No. AD A176912

Hewlett, John D. 1982. Principles of Forest Hydrology. University of Georgia Press, Athens, Georgia.

Hobbs, R.J., Norton, D.A., 1996. Towards a conceptual framework for restoration ecology. Restoration Ecology **4:** 93-110.

Kentula, M.E., R.P. Brooks, S.E. Gwin, C.C. Holland, A. Sherman, and J.C. Sifneos. 1992. An Approach to Improving Decision Making in Wetland Restoration and Creation, Island Press, Washington, DC.

Leitman, H.M., J.E. Sohm, and.A. Franklin. 1983. Wetland Hydrology and Tree Distribution of the Apalachicola River Flood Plain, Florida. USGS Water Supply Paper 2196. U.S. Geological Survey.

McCune, B., and J.B. Grace. 2002. Analysis of Ecological Communities. MjM Software Design,Oregon.

McCune, B., and M. J. Mefford. 2006. PC-ORD. Multivariate Analysis of Ecological Data. Version 5.19 MjM Software, Gleneden Beach, Oregon, U.S.A.

McKinney, Jimmy Dwight. 1997. Effect of microtopography on the natural regeneration of prior converted wetlands. Thesis. North Carolina State University, Raleigh, NC.

Morris, T.C. 2004. Tree composition along edaphic and hydrologic gradients in nonriverine wet hardwood forests. Thesis. North Carolina State University, Raleigh, NC.

National Research Council, Committee on Mitigating Wetland Losses, Board on Environmental Studies and Toxicology, Water Science and Technology Board, Division on Earth and Life Studies. 2001. Compensating for Wetland Losses Under the Clean Water Act. National Academy Press, Washington, DC.

Nature Conservancy. 2005. IHA Applications (available from http://www.nature.org/initiatives/freshwater/files/iha_apps.pdf).

NatureServe. 2004. International Ecological Classification Standard: Terrestrial Ecological Classifications, Croatan National Forest Final Report. NatureServe Central Databases. Arlington, VA. U.S.A. Data current as of April 30, 2004.

O'Loughlin, David. 2007. A Statistical Approach To Evaluating The Performance Of Southern United States Forested Wetland Restoration. Thesis, North Carolina State University, Raleigh, NC.

Peet, R.K., T.R. Wentworth, and P.S. White. 1998. A flexible, multipurpose method for recording vegetation composition and structure. Castanea **63:**262-274.

Perry, T.O. 1971. Winter season photosynthesis and respiration by twigs and seedlings of deciduous and evergreen trees. Forest Science **17:**41-43.

Pfeifer, C. E. and E. J. Kaiser. 1995. An evaluation of wetlands permitting and mitigation practices in North Carolina. Water Resource Research Institute of the University of North Carolina, Raleigh, NC, USA. North Carolina State University Report No. 294.

Pinchot, G., and W.W. Ashe. 1897. Timber trees and forests of North Carolina. N.C. Geological Survey. Bull. 6.

Rheinhardt, M.C., and R.D. Rheinhardt. 2000. Canopy and woody subcanopy composition of wet hardwood flats in eastern North Carolina and southeastern Virginia. Journal of the Torrey Botanical Society **127:**33-43.

Rheinhardt, R.D., and M.M. Brinson. 2002. An Evaluation of North Carolina Department of Transportation Wetland Mitigation Sites: Selected Case Studies - Phase II Report. Report Number FHWA/NC/2002-009. U.S. Department of Transportation Research and Special Programs Administration, Washington, DC.

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology **10:**1163-1174.

Schafale, M.P. 1999. Nonriverine wet hardwood forests in North Carolina: status and trends. North Carolina Natural Heritage Program. Department of Environment, Health and Natural Resources, Raleigh, NC.

Schafale, M.P., and A.S. Weakley. 1990. Classification of the Natural Communities of North Carolina: third approximation. NC Natural Heritage Program, Department of Environment, Health and Natural Resources, Raleigh, NC.

Scherrer, Elizabeth. 2000. Using microtopography to restore wetland plant communities in eastern North Carolina. Thesis, North Carolina State University, Raleigh, NC.

Soil Survey Staff. 2008. Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey (available from http://websoilsurvey.nrcs.usda.gov).

Tant, P.L., et al. 1981. Soil Survey of Washington County, North Carolina. USDA Soil Conservation Service.

U.S. Army Corps of Engineers. 2005. “Technical Standard for Water-Table Monitoring of Potential Wetland Sites,” WRAP Technical Notes Collection (ERDC TN-WRAP-05-02), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

USDA, Natural Resources Conservation Service, National Water and Climate

Center. 2001. Climate Analysis for Wetlands by County (available from http://www.wcc.nrcs.usda.gov/climate/wetlands.html).

USDA, Natural Resources Conservation Service. 2009. The PLANTS Database. National Plant Data Center, Baton Rouge, LA (available from http://plants.usda.gov).

Westman, W.E. 1991. Ecological restoration projects: measuring their performance. Environmental Professional **13:**207-215.

Zedler, J.B. 2003. Wetlands at your service: reducing impacts of agriculture at the watershed scale. Front Ecol Environ **1:**65–72.

TABLES

Table 1. Stand locations and mapped soil series (Soil Survey Staff 2009). For each stand N denotes nonriverine wet hardwood forest, M denotes mesic mixed hardwood forest, and S denotes nonriverine swamp forest.

Stand	**County**	**Mapped Soil Series**	**Soils Series Description**
N1	Dare	Hyde	Very poorly drained soils (seasonal high water table 0 to 30cm). Fine-silty, mixed, active, thermic Typic Umbraquults
N2	Beaufort	Tomotley	Poorly drained soils (0 to 30cm). Fine-loamy, mixed, semiactive, thermic Typic Endoaquults
N3	Pitt	Pantego	Very poorly drained (0 to 30cm). Fine-loamy, siliceous, semiactive, thermic Umbric Paleaquults
		Byars	Very poorly drained (0 to 30cm). Fine, kaolinitic, thermic Umbric Paleaquults
M1 N4	Bertie	Leaf	Poorly drained soils (0 to 30cm). Fine, mixed, active, thermic Typic Albaquults
M2 N5	Craven	Leaf	Poorly drained soils (0 to 30cm). Fine, mixed, active, thermic Typic Albaquults
N6	Bertie	Leaf	Poorly drained soils (0 to 30cm). Fine, mixed, active, thermic Typic Albaquults
N7	Carteret	Deloss	Very poorly drained (0 to 30cm). Fine-loamy, mixed, semiactive, thermic Typic Umbraquults
M3 N8	Currituck	Tomotley	Poorly drained soils (0 to 30cm). Fine-loamy, mixed, semiactive, thermic Typic Endoaquults
N9	Washington	Portsmouth	Very poorly drained (0 to 30cm). Fine-loamy over sandy or sandy-skeletal, mixed, semiactive, thermic Typic Umbraquults
S1	Hyde	Gullrock	Very poorly drained (0 to 30cm). Coarse-silty, mixed, semiactive, nonacid, thermic Histic Humaquepts
S2	Craven	Bayboro	Very poorly drained (0 to 30cm). Fine, mixed, semiactive, thermic Umbric Paleaquults

Table 2. Modified Corps parameters for characterizing hydrologic regime. Parameters were calculated for 217 days (from July 29 to March 2, 2009) across ten stands. The percentage is calculated out of 217 days. For each stand N denotes nonriverine wet hardwood forest, M denotes mesic mixed hardwood forest, and S denotes nonriverine swamp forest.

Community Type	**Stand**	**Days Above Surface**	**%Time Above Surface**	**Days Above -30cm**	**%Time Above -30cm**	**Days Below Roots (-61cm)**	**%Time Below Roots (-61cm)**
	M1	0	0	8	4	187	86
	M2	0	0	12	6	117	54
Mesic Mixed Forest	**Average**	**0**	**0**	**10**	**5**	**152**	**70**
	N1	142	65	179	82	29	13
	N3	4	2	75	35	117	54
	N4	59	27	69	32	147	68
	N5	1	0.5	142	65	15	7
	N6	2	1	68	31	136	63
Nonriverine Wet Hardwood Forest	N7	0	0	1	0.5	111	51
	Average	**35**	**16**	**89**	**41**	**93**	**43**
	S1	0	0	88	41	3	1
Nonriverine Swamp Forest	S2	131	60	197	91	2	1
	Average	**66**	**30**	**143**	**66**	**3**	**1**

Table 3. IHA parameters for characterizing hydrologic regime. Parameters calculated for 217 days (from July 29 to March 2, 2009) across ten stands. M: mesic mixed; N: nonriverine wet; and S: nonriverine swamp forests.

	Stand Number										**Average by Community Type**		
IHA Parameter	**M1**	**M2**	**N1**	**N3**	**N4**	**N5**	**N6**	**N7**	**S1**	**S2**	**M**	**N**	**S**
July Mean (cm)	-113	-142	-67	-4	-145	-57	-51	-135	-68	-29	-128	-77	-49
August Mean (cm)	-145	-142	-98	-59	-145	-57	-140	-135	-44	-29	-144	-106	-37
September Mean (cm)	-145	-142	6	-132	-145	-43	-140	-134	-20	-15	-144	-98	-18
October Mean (cm)	-145	-113	3	-132	-143	-30	-140	-135	-35	-4	-129	-96	-20
November Mean (cm)	-116	-63	5	-132	-144	-21	-140	-54	-22	4	-90	-81	-9
December Mean (cm)	-100	-46	3	-39	-145	-15	-50	-46	-26	12	-73	-49	-7
January Mean (cm)	-39	-42	2	-10	6	-19	-7	-50	-40	10	-41	-13	-15
February Mean (cm)	-94	-50	-2	-6	4	-23	-11	-53	-41	8	-72	-15	-17
1-Day Minimum (cm)	-145	-142	-138	-132	-145	-98	-140	-135	-101	-71	-144	-131	-86
3-Day Minimum (cm)	-145	-142	-135	-132	-145	-97	-140	-135	-99	-70	-144	-131	-85
7-Day Minimum (cm)	-145	-142	-131	-132	-145	-92	-140	-135	-94	-57	-144	-129	-76
30-Day Minimum (cm)	-142	-142	-101	-132	-145	-79	-140	-135	-76	-37	-142	-122	-57
90-Day Minimum (cm)	-141	-142	-66	-132	-145	-66	-139	-134	-59	-27	-142	-114	-43
1-Day Maximum (cm)	-1	-11	19	26	12	1	36	-30	-5	18	-6	11	7
3-Day Maximum (cm)	-15	-18	15	26	11	-6	32	-34	-8	17	-17	7	5
7-Day Maximum (cm)	-26	-27	13	23	10	-10	30	-39	-16	15	-27	5	-1
30-Day Maximum (cm)	-39	-41	8	-2	7	-17	14	-45	-20	13	-40	-6	-4
90-Day Maximum (cm)	-64	-45	5	-18	4	-17	-22	-48	-28	11	-55	-16	-9
Low Pulse Threshold (cm)	-140	-140	-36	-114	-140	-54	-112	-132	-48	-16	-140	-98	-32
High Pulse Threshold (cm)	-81	-53	4	-12	4	-19	-11	-50	-29	11	-67	-14	-9
Low Pulse Count	9	3	3	2	2	5	4	6	3	4	6	4	4
Low Pulse Duration (days)	10	38	28	58	88	13	29	15	23	7	24	39	15
High Pulse Count	5	8	6	7	3	13	7	9	12	14	7	8	13

Table 3 continued.

	Stand Number										Average by Community Type		
IHA Parameter	**M1**	**M2**	**N1**	**N3**	**N4**	**N5**	**N6**	**N7**	**S1**	**S2**	**M**	**N**	**S**
High Pulse Duration (days)	16	9	9	11	23	5	11	6	5	3	13	11	4
Rise Rate (cm/day)	3.9	2.7	0.8	0.5	0.2	1.3	3.1	0.8	0.1	0.8	3.3	1.1	0.5
Fall Rate (cm/day)	-1.6	-1.1	-0.5	-0.8	-0.1	-0.7	-1.2	-0.4	-0.6	-0.6	-1.4	-0.7	-0.6
Days Below Sensor	69	113	0	90	126	0	110	102	0	0	91	71	0

Table 4. Pearson correlations among ordination axes and IHA parameters. Sorted by Axis 2.

	Axis 1		**Axis 2**	
IHA Parameters	**r**	**p**	**r**	**p**
3-Day Maximum (cm)	0.57	0.106	0.79	0.011
7-Day Maximum (cm)	0.55	0.128	0.77	0.015
30-Day Maximum (cm)	--	**	0.74	0.022
July Mean (cm)	--	**	0.73	0.027
1-Day Maximum (cm)	0.65	0.058	0.73	0.027
Low Pulse Count (days)	--	**	-0.67	0.047
High Pulse Threshold (cm)	--	**	0.67	0.049
February Mean (cm)	--	**	0.64	0.064
90-Day Maximum (cm)	--	**	0.58	0.102
August Mean (cm)	--	**	0.52	0.150
January Mean (cm)	0.54	0.137	0.52	0.150
Low Pulse Threshold (cm)	--	**	--	**
Rise Rate (cm/day)	--	**	--	**
September Mean (cm)	--	**	--	**
90-Day Minimum (cm)	--	**	--	**
Low Pulse Duration (days)	--	**	--	**
December Mean (cm)	-0.70	0.037	--	**
30-Day Minimum (cm)	--	**	--	**
October Mean (cm)	--	**	--	**
7-Day Minimum (cm)	--	**	--	**
3-Day Minimum (cm)	--	**	--	**
1-Day Minimum (cm)	--	**	--	**
Days Below Sensor	--	**	--	**
Fall Fate (cm/day)	--	**	--	**
High Pulse Duration (days)	0.82	0.007	--	**
November Mean (cm)	-0.79	0.011	--	**
High Pulse Count	-0.71	0.032	--	**

-- denotes |r| < 0.5

** denotes p-values > 0.150

Table 5. Species Importance Values (IVs), ranked from greatest to least by mean IV. M: mesic mixed; N: nonriverine wet; and S: nonriverine swamp forests.

	Stand											
Species	**M1**	**M2**	**M3**	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	**N8**	**S1**
Acer rubrum	0.10	0.13	0.08	0.32	0.05	0.35	0.24	0.16	0.46	0.05	0.30	0.22
Liquidambar styraciflua	0.19	0.14	0.23	0.20	0.04	0.50	0.13	0.18	0.15	0.04	0.12	0.32
Quercus michauxii	0.14	0.11		T	0.30	0.01	0.12	0.01		0.10		
Persea palustris		0.07	0.03	0.12	0.04			0.20		0.23	0.02	0.10
Nyssa sylvatica	0.01	0.02		0.05	0.03	0.07	0.01	0.05	0.02	0.14	0.33	
Liriodendron tulipifera	0.07	0.08	0.19		0.04			0.08		0.08		
Pinus taeda		0.09	0.07	0.17						0.03		0.12
Ilex opaca	0.01	0.11	0.10	0.01	0.01	0.02	0.02	0.09		0.08	0.02	
Quercus laurifolia		T	0.03	0.02	0.05	0.05	0.05		0.12		0.09	
Carpinus caroliniana		T	0.05	T	0.27			0.01			0.01	
Quercus pagoda	0.13		0.06				0.05	0.03	0.07			
Symplocos tinctoria		0.10	0.05					0.12		0.05	0.01	
Quercus nigra		0.07	0.02	0.07	0.04			0.01	0.03	0.08	0.01	
Quercus phellos							0.30					
Magnolia virginiana		0.01	0.05	0.01		0.01		0.05		0.04	0.06	
Fagus grandifolia	0.05	0.02	0.02		0.07						0.01	
Morella cerifera				T							0.01	0.15
Ulmus americana									0.11			0.02
Fraxinus pennsylvanica	0.04		T		0.03		0.04		0.01		0.01	
Carya alba	0.09											
Quercus alba	0.08											
Ulmus rubra	0.02				0.01		0.02					
Ostrya virginiana	0.03								0.02			T
Gordonia lasianthus				0.03								0.02
Quercus velutina		0.05										

Table 5 continued.

	Stand											
Species	**M1**	**M2**	**M3**	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	**N8**	**S1**
Taxodium disticum												0.04
Carya ovata	0.02						0.01					
Prunus serotina	0.02											
Crataegus spathulata												0.01
Platanus occidentalis									0.01			
Quercus lyrata			0.01									
Vibernum prunifolium			T								T	
Total no. of species	15	15	16	13	13	7	11	12	10	11	14	10

T denotes a trace (IV < 0.01)

Table 6. Pearson correlations among species abundance (IV) and ordination axes. Sorted by Axis 2.

	Axis 1		**Axis 2**	
Species	**r**	**p**	**r**	**p**
Liriodendron tulipifera	--	**	-0.89	0.001
Acer rubrum	--	**	0.86	0.003
Quercus michauxii	--	**	-0.79	0.012
Liquidamber styraciflua	--	**	0.67	0.049
Ilex opaca	-0.61	0.080	-0.64	0.065
Quercus laurifolia	0.59	0.095	0.57	0.105
Symplocos tinctoria	-0.57	0.111	-0.54	0.134
Magnolia virginiana	-0.66	0.053	-0.54	0.136
Fagus grandifolia	--	**	-0.52	0.149
Ulmus americana	--	**	--	**
Gordonia lasianthus	--	**	--	**
Carya alba	--	**	--	**
Prunus serotina	--	**	--	**
Quercus alba	--	**	--	**
Morella cerifera	--	**	--	**
Crataegus spathulata	--	**	--	**
Taxodium disticum	--	**	--	**
Carya ovata	0.70	0.036	--	**
Persea palustris	-0.86	0.003	--	**
Platanus occidentalis	--	**	--	**
Nyssa sylvatica	-0.62	0.073	--	**
Quercus nigra	--	**	--	**
Fraxinus pennsylvanica	0.80	0.011	--	**
Ulmus rubra	0.72	0.030	--	**
Quercus pagoda	0.77	0.016	--	**
Quercus velutina	--	**	--	**
Pinus taeda	--	**	--	**
Carpinus caroliniana	--	**	--	**
Ostrya virginiana	0.62	0.074	--	**
Quercus phellos	--	**	--	**

-- denotes |r| < 0.5

** denotes p-values > 0.150

Table 7. Precipitation measurements by stand during the study period from the nearest NC State Climate Office weather station. Normal precipitation is the 30-year average from 1971-2000. Stands are ranked in descending order from wettest to driest (compared to normal conditions). For each stand N denotes nonriverine wet hardwood forest, M denotes mesic mixed hardwood forest, and S denotes nonriverine swamp forest

Stand	Measured Precipitation (mm)	Normal Precipitation (mm)	Measured as Percent of Normal	Stand to Weather Station Distance (km)
N1	884	753	118%	18
M2	711	796	89%	5
N5	711	796	89%	6
S2	711	796	89%	6
N3	633	723	88%	13
N7	700	860	81%	16
S1	606	800	76%	15
M1	448	679	66%	5
N4	448	679	66%	4
N6	448	679	66%	2
N9	483	736	66%	15

FIGURES

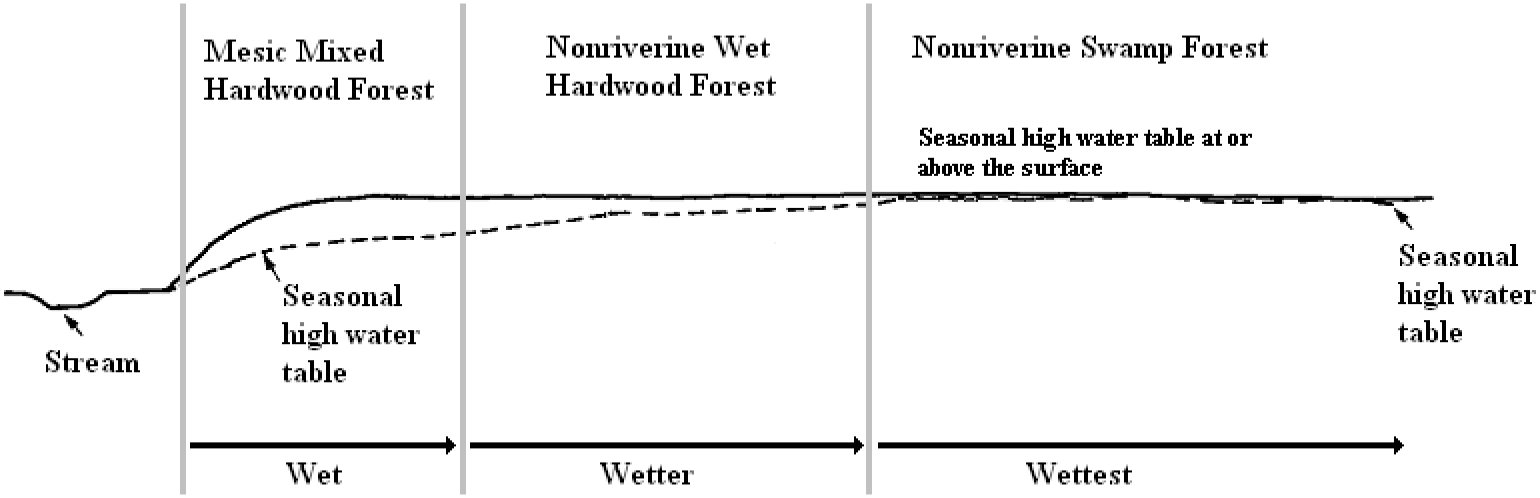

Figure 1. Hydrologic gradient for the three communities on an idealistic inter-stream divide.

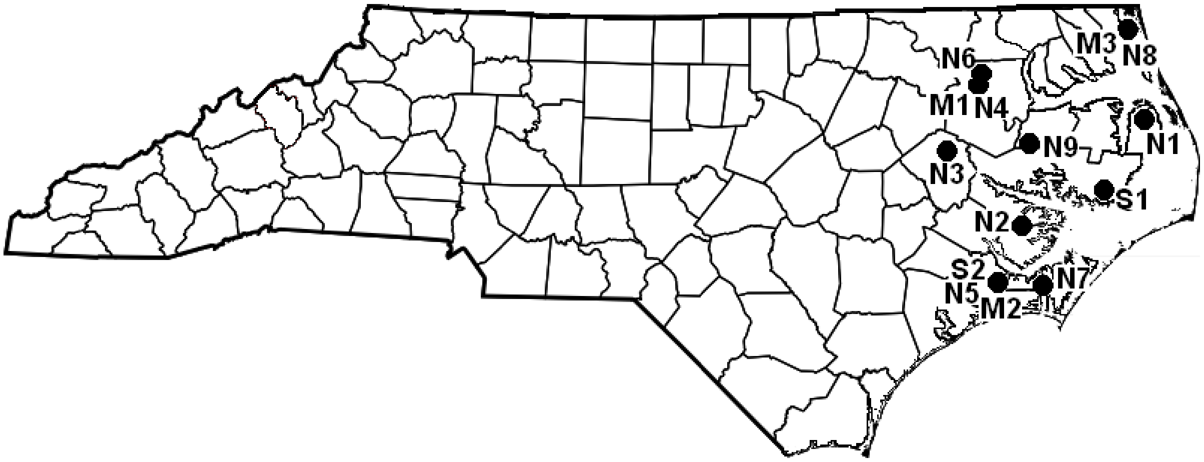

Figure 2. Study site locations. Each dot represents a study site location. Each alphanumeric represents an individual stand: N denotes nonriverine wet hardwood forest, M denotes mesic mixed hardwood forest, and S denotes nonriverine swamp forest.

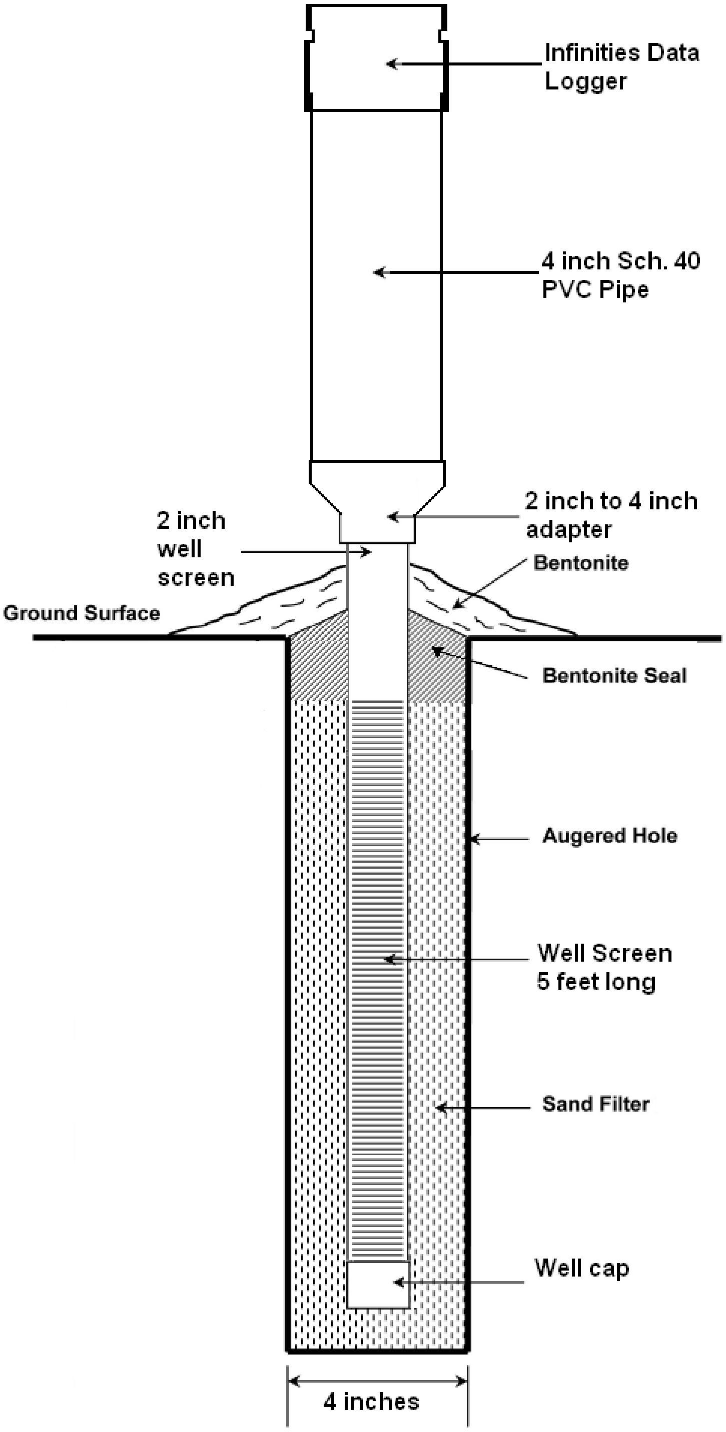

Figure 3. General diagram of well installation method. Figure based on an illustration by U.S. Army Corps of Engineers (2005).

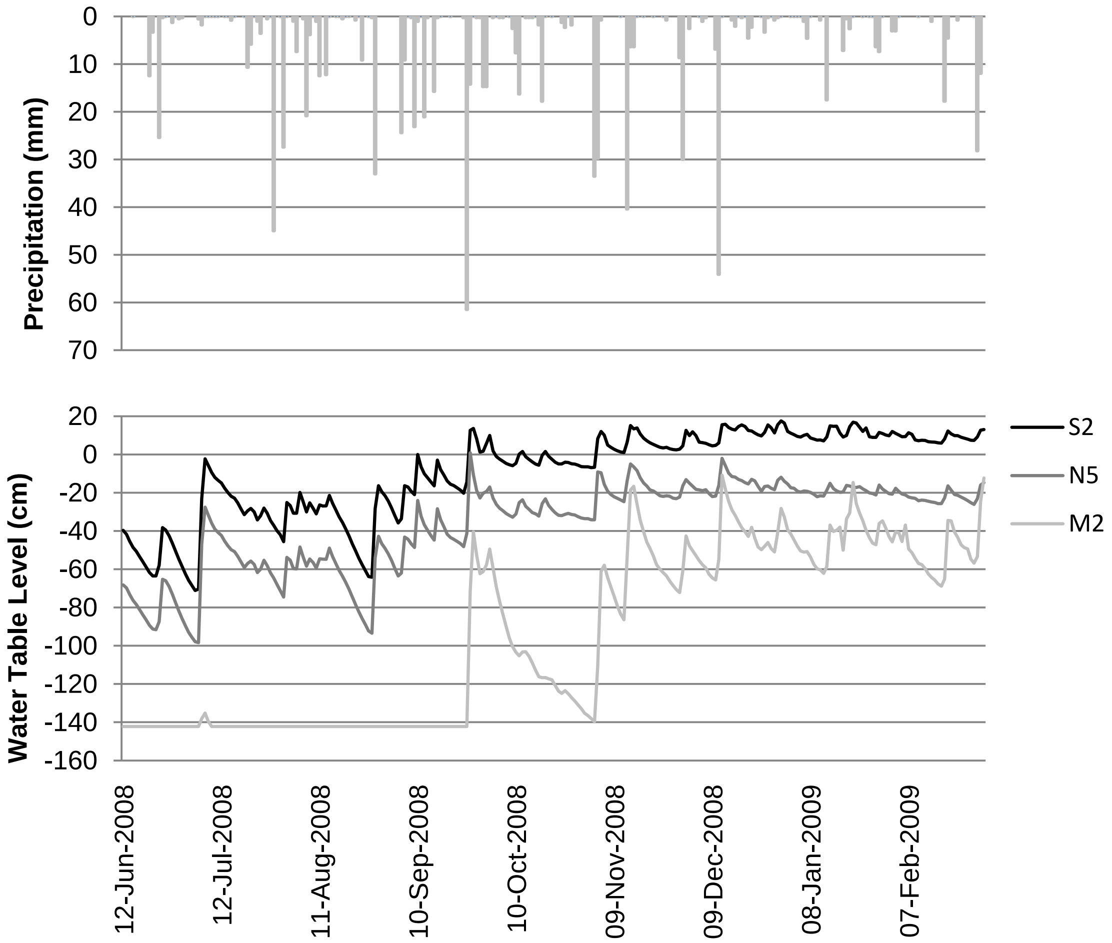

Figure 4. Sample hydrographs for the three plant communities (bottom). This graph shows separation of hydrologic regimes based on a priori community classification. Top: nonriverine swamp forest (stand S2), Middle: nonriverine wet hardwood forest (stand N5), and Bottom: mesic mixed hardwood forest (stand M2). These three stands are from the same study site location and have the same landscape position and precipitation patterns. Precipitation values for the hyetograph (top) are from the nearest NC State Climate Office weather station, approximately 10km away. For the water table level the ground surface is at 0 cm. The flat part of the hydrograph for the mesic stand (M2) results from the water table level being lower than the monitoring well.

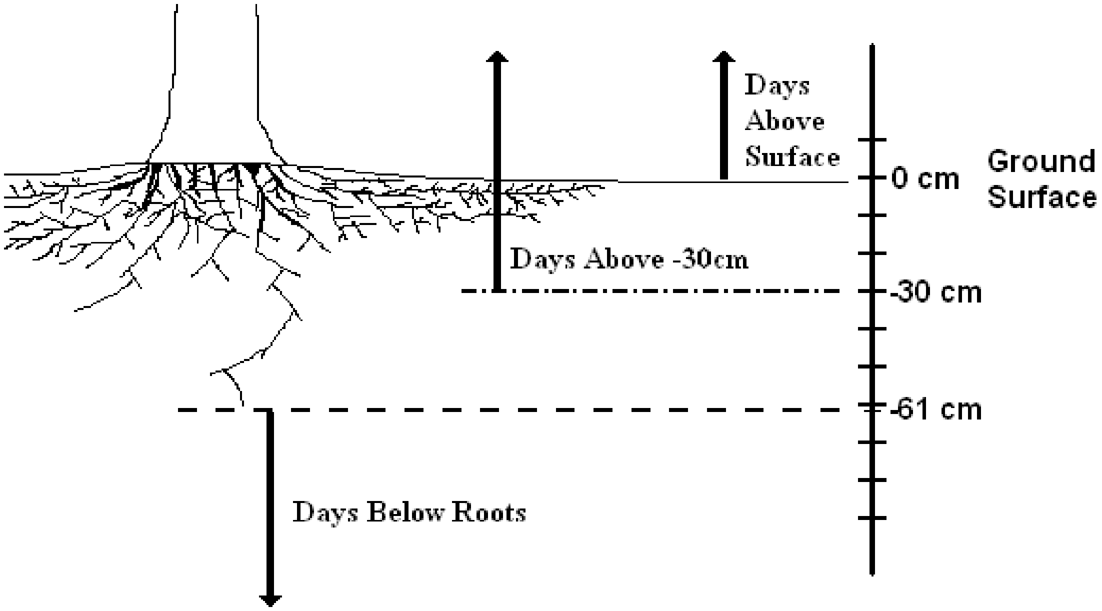

Figure 5. Parameters for the modified Corps method. (1) “Days Above -30 cm,” includes (2) “Days Above Surface,” and (3) “Day Below Roots.”

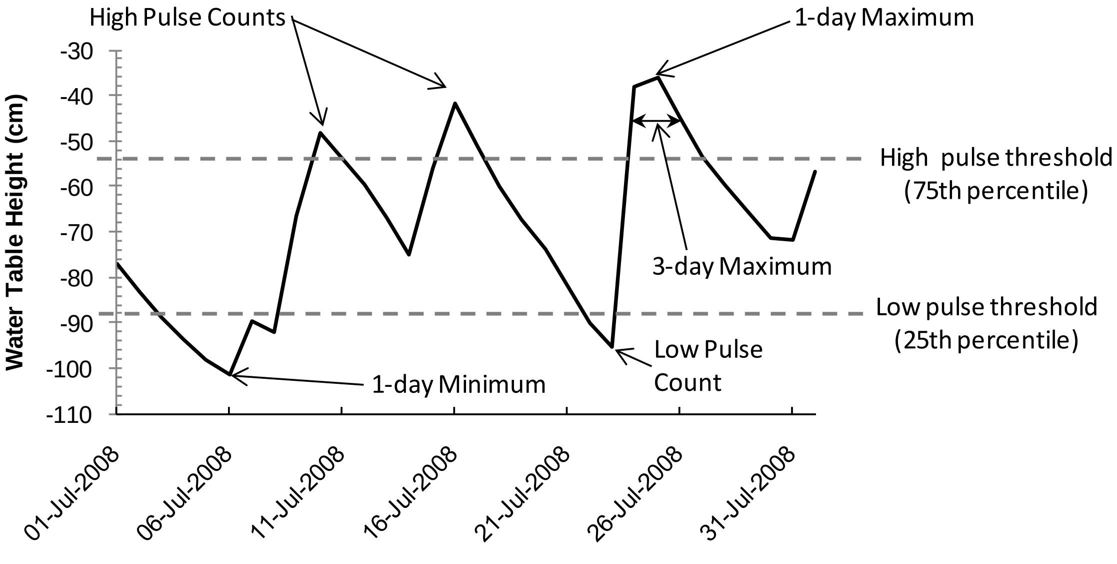

Figure 6. Examples of selected IHA parameters. A 1-day maximum occurs when the water table level is highest for a one-day span during the measurement period. A 3-day maximum occurs at the highest water table level over a three-day period. High pulse counts are the number of the times the water table peaks above the high pulse threshold. Low pulse counts are the number of the times the water table dips below the low pulse threshold.

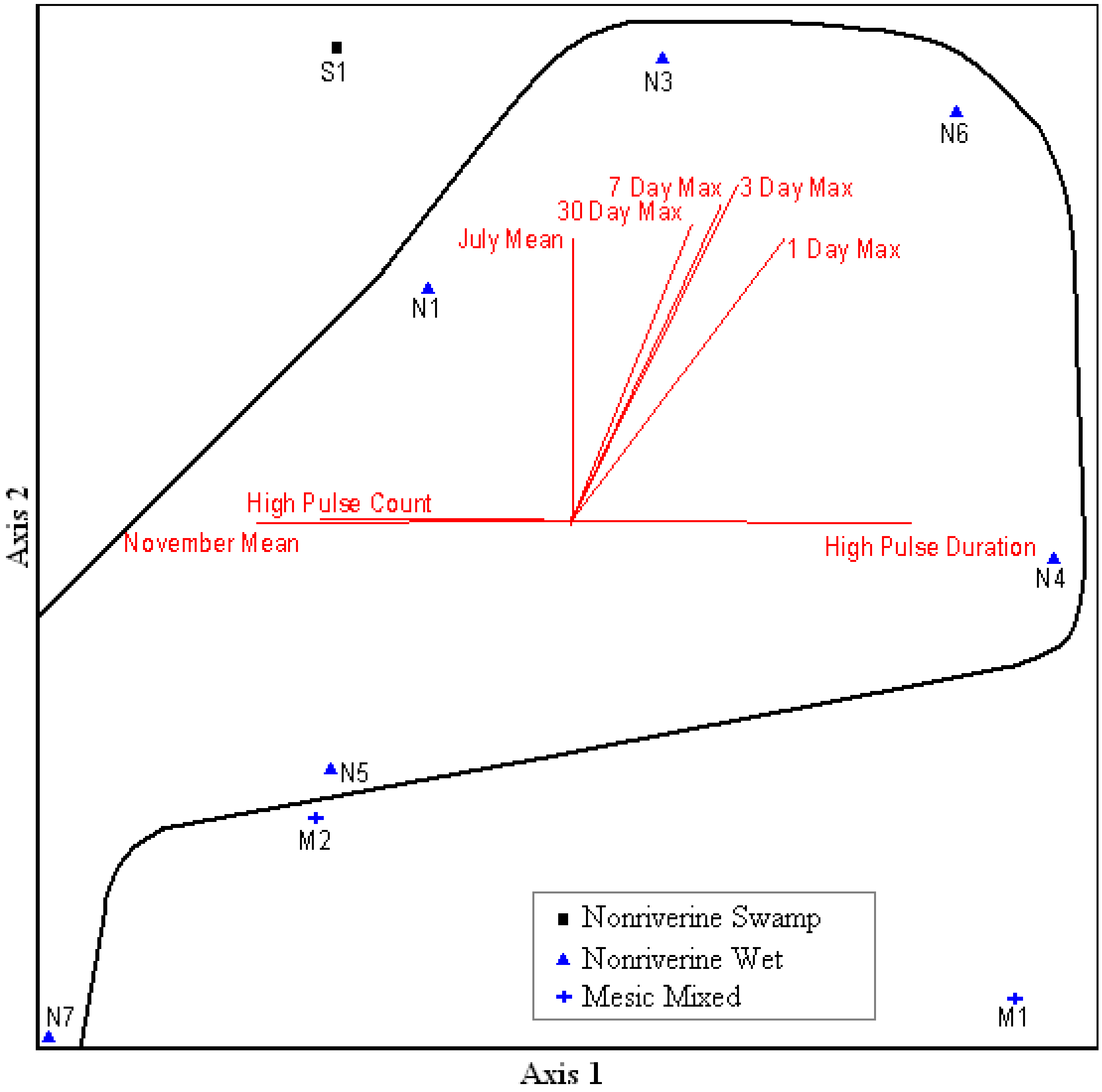

Figure 7. Ordination depicting stands sorted along two axes ($r^2 = 0.93$). IHA parameters with r^2 greater than 0.50 are overlaid on the ordination. See Table 7 for the correlation values for each IHA parameter. N denotes nonriverine wet hardwood forest, M denotes mesic mixed hardwood forest, and S denotes nonriverine swamp forest. The thick black line was added after the analysis to help differentiate the generalized ordination space for nonriverine wet hardwood forests.

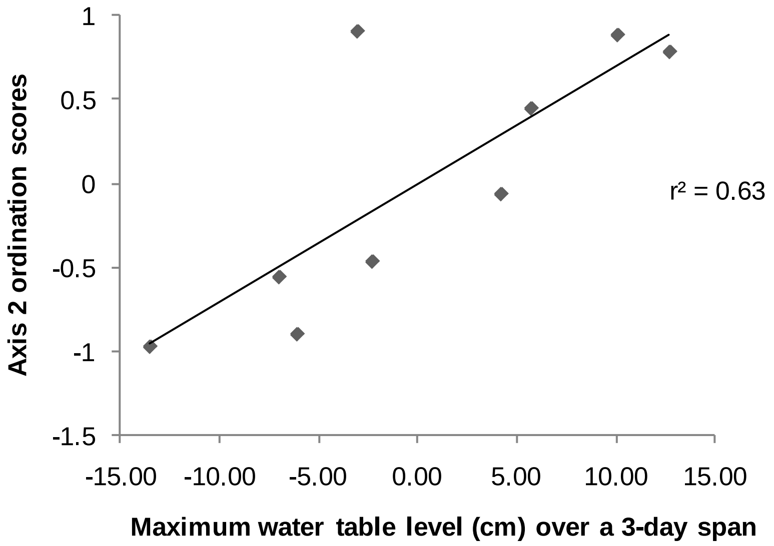

Figure 8. Relation between axis 2 ordination scores and the maximum water table level (cm) over a 3-day span. The outlier is a nonriverine swamp forest stand (S1). This stand would be expected to have water table levels higher than nonriverine wet hardwood forest stands, but it is more similar to the dryer mesic mixed hardwood stands.

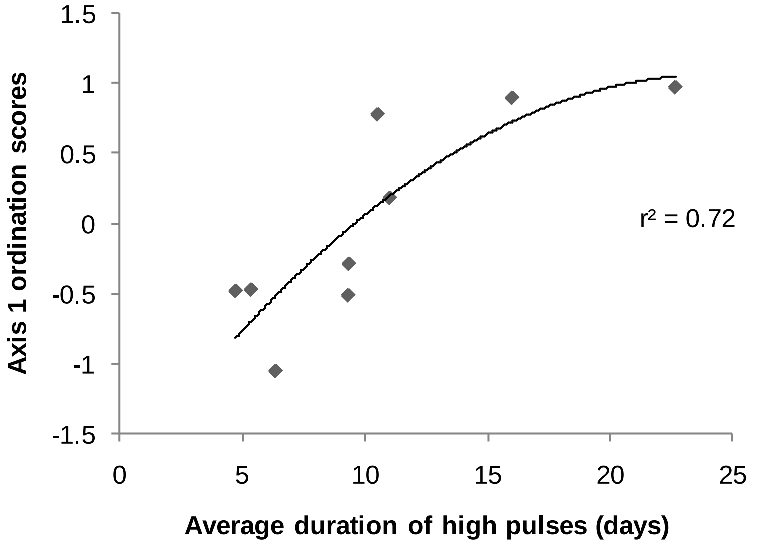

Figure 9. Relation between axis 1 ordination scores and the average duration of high pulses in days.

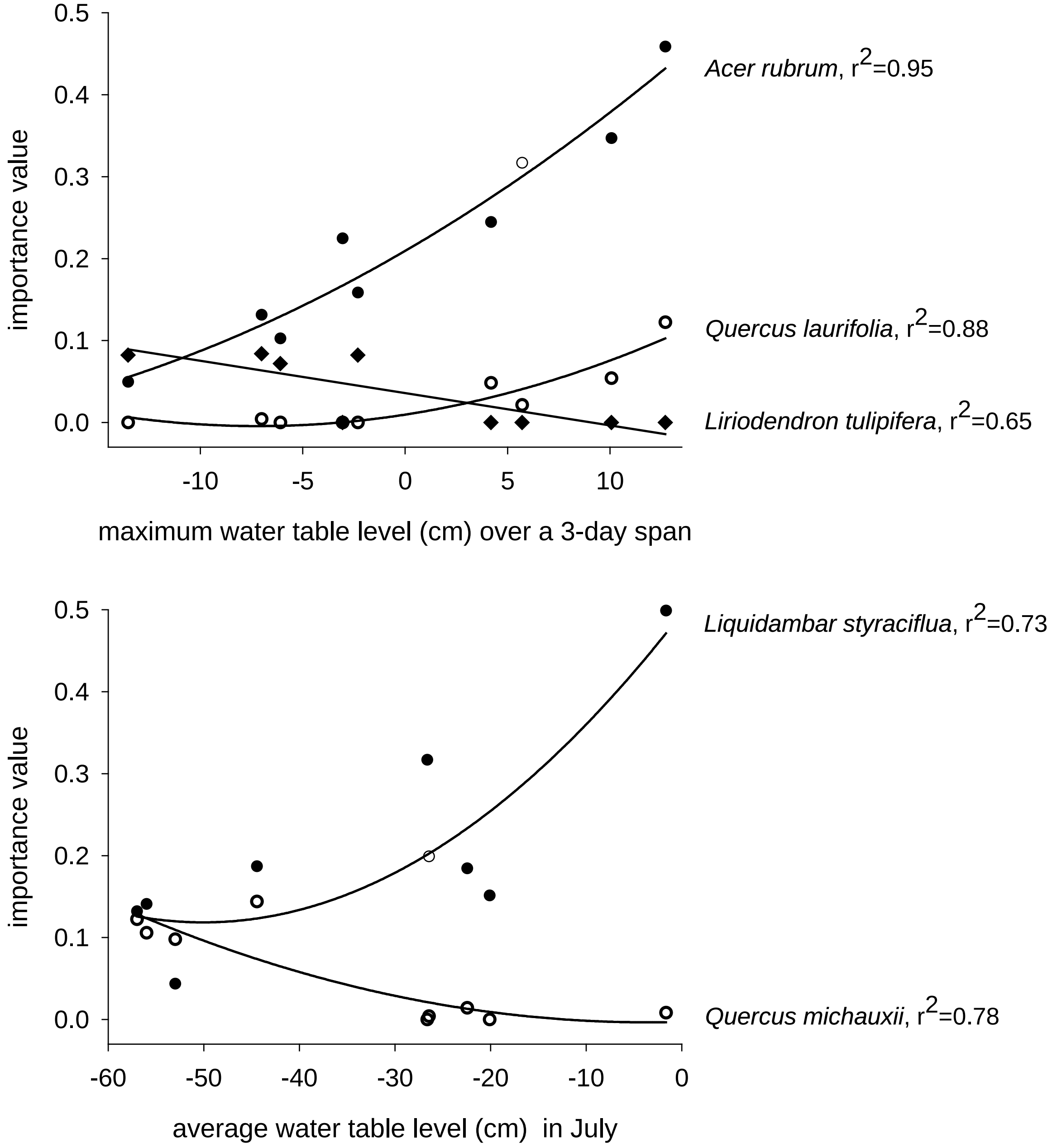

Figure 10. *Acer rubrum*, *Quercus laurifolia*, and *Liquidambar styraciflua* had higher importance values for stands higher water tables, while *Liriodendron tulipifera* and *Q. michauxii* had lower importance values at stands with higher water tables.

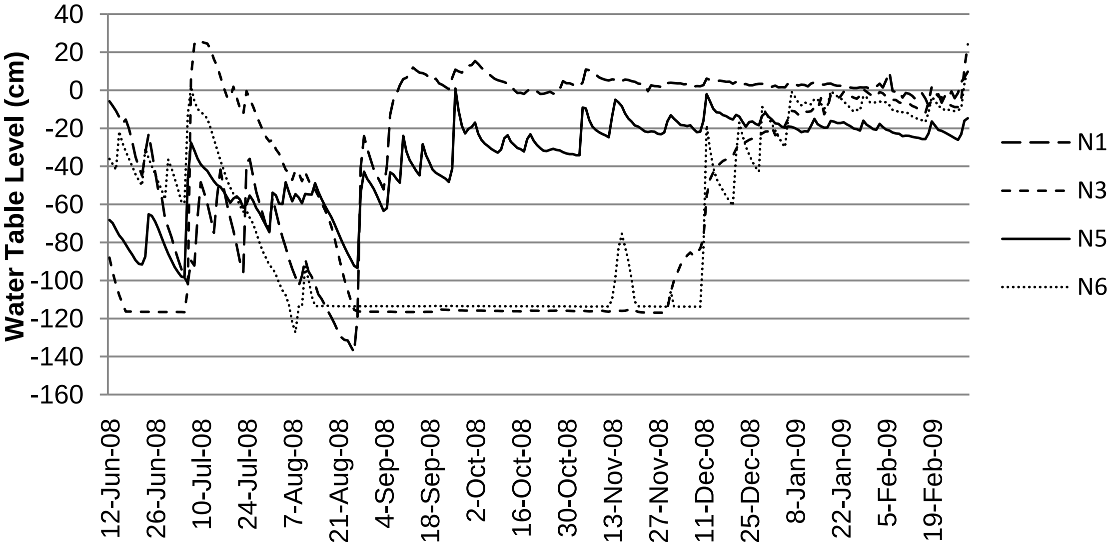

Figure 11. Water table depth for selected nonriverine wet hardwood forests (N1, N3, N5, and N6). Water table levels were lowest during the summer months and highest during the winter months when evaporation and transpiration rates are lower. Flat periods in the hydrographs indicate times when the water table level was below the monitoring wells.

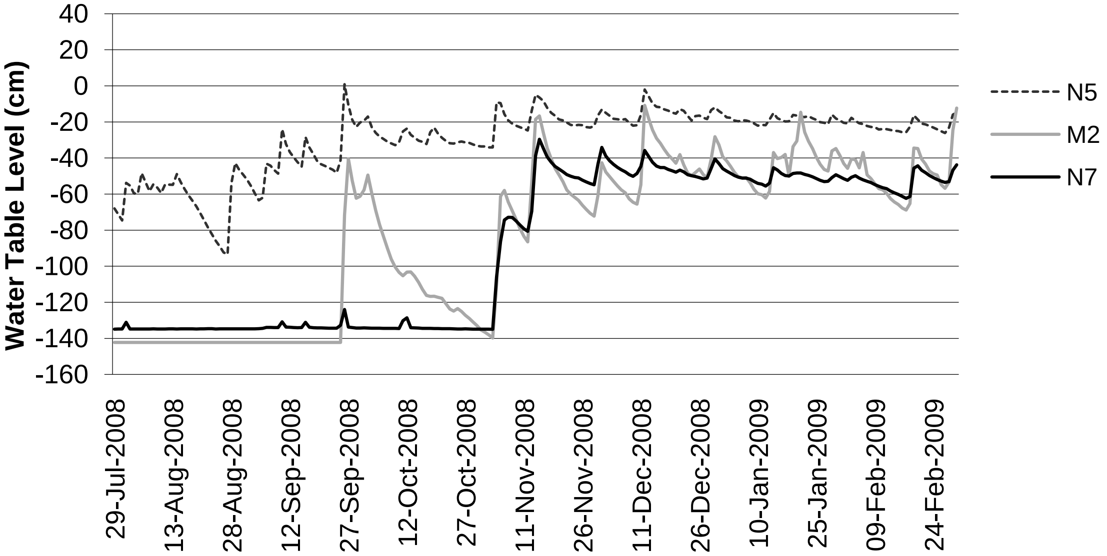

Figure 12. Hydrograph for stands N7, N5 and, M2. One of the nonriverine wet hardwood forest stands (N7) has a water table level similar to the mesic mixed hardwood forest stand (M2). Stand N7 had lower water table levels despite receiving more precipitation than the other nonriverine wet hardwood forest stand (N5) during the study period (Table 7). Flat periods in the hydrographs indicate times when the water table level was below the monitoring wells.

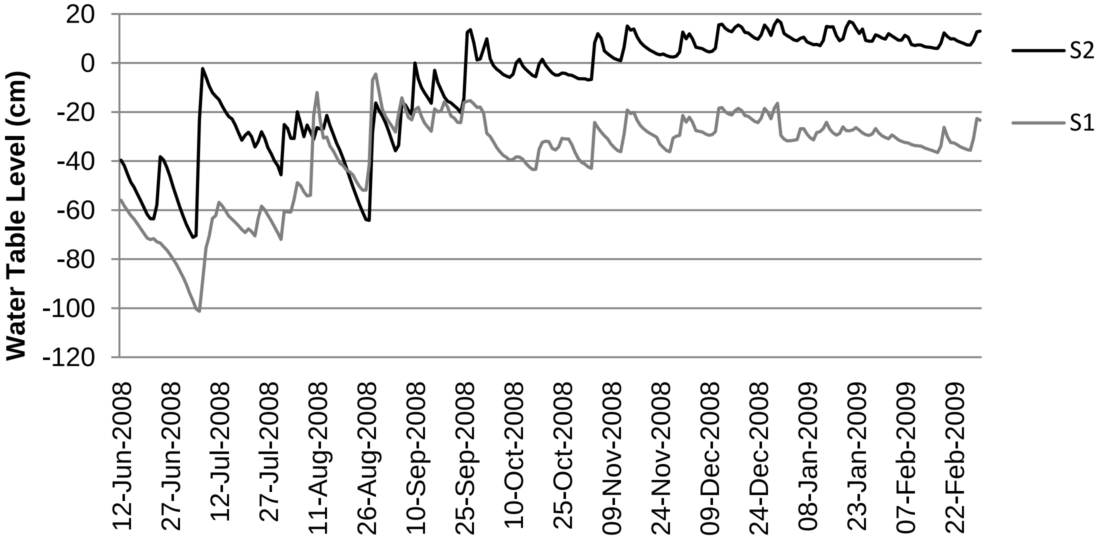

Figure 13. Hydrographs for both nonriverine swamp forest stands (S1 and S2). Despite receiving more precipitation than the wetter stand (S2) during the winter season, the dryer stand (S1) does not have ponding of water above the soil surface, while the wetter stand (S2) does.

APPENDIX

Table A-1. Stress in relation to dimentionality (number of axes). p = proportion of randomized runs with stress < or = observed stress, *i.e.*, p = (1 + no. permutations <= observed)/(1 + no. permutations)

	Stress in real data 250 runs			**Stress in randomized data Monte Carlo test, 250 runs**			
Axes	Minimum	Mean	Maximum	Minimum	Mean	Maximum	P
1	27.209	36.757	50.918	11.938	38.002	50.918	0.1952
2	**5.230**	**9.673**	**32.093**	**0.004**	**13.537**	**32.092**	**0.0239****
3	1.313	2.655	19.455	0.010	4.953	21.445	0.0478
4	0.000	0.738	13.250	0.000	1.336	9.936	0.0080
5	0.000	0.231	8.712	0.000	0.236	9.743	0.0279
6	0.000	0.103	5.944	0.000	0.047	6.505	0.0797

**This 2-dimensional solution was recommended by PC-Ord.

Table A-2. Pearson correlations among ordination scores for both axes and the modified Corps method. Sorted by Axis 2. All have |r| < 0.7.

Corps Method Parameter	**Axis 1 r**	**Axis 2 r**
Days Above -30cm	-0.08	0.51
Days Below Roots (-61cm)	0.64	-0.35
Days Above Ground	0.06	0.21

Table A-3. Pearson correlations among selected IHA parameters. Parameters with |r| < 0.7 are denoted by --.

	1-day Max	3-day Max	7-day Max	30-day Max	90-day Max
1-day Max	1				
3-day Max	0.98	1			
7-day Max	0.97	0.99	1		
30-day Max	0.88	0.93	0.95	1	
90-day Max	--	--	0.73	0.87	1

Table A-4. Pearson correlations among selected IHA parameters. Parameters with |r| < 0.7 are denoted by --.

	3-day Max	High Pulse Threshold	High Pulse Count	High Pulse Duration
3-day Max	1			
High Pulse Threshold	0.74	1		
High Pulse Count	--	--	1	
High Pulse Duration	--	--	-0.89	1

Table A-5. Measurements by stand from the nearest North Carolina State Climate Office weather station. Normal precipitation is the 30-year average from 1971-2000. Stands are ranked in descending order from wettest to driest (compared to normal conditions).

Precipitation (mm)

Stand		July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Total	Measured as % of Normal
N1	Measured	168	80	167	46	215	172	101	61	884	118%
	Normal	133	143	125	104	86	93	119	82	753	
M2	Measured	97	103	187	68	157	79	48	59	711	89%
	Normal	165	174	138	86	82	98	121	97	796	
N5	Measured	97	103	187	68	157	79	48	59	711	89%
	Normal	165	174	138	86	82	98	121	97	796	
S2	Measured	97	103	187	68	157	79	48	59	711	89%
	Normal	165	174	138	86	82	98	121	97	796	
N3	Measured	198	138	112	47	148	70	61	55	633	88%
	Normal	132	150	137	83	71	82	113	88	723	
N7	Measured	97	103	187	68	157	79	48	59	700	81%
	Normal	158	183	151	98	93	106	129	99	860	
S1	Measured	114	161	110	54	92	71	57	61	606	76%
	Normal	128	165	137	110	88	92	124	84	800	
M1	Measured	193	47	63	31	106	66	58	42	448	66%
	Normal	137	123	130	82	69	82	107	88	679	
N4	Measured	193	47	63	31	106	66	58	42	448	66%
	Normal	137	123	130	82	69	82	107	88	679	

Table A-5 continued.

Precipitation (mm)

Stand		**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Total**	**Measured as % of Normal**
N6	Measured	193	47	63	31	106	66	58	42	448	66%
	Normal	137	123	130	82	69	82	107	88	679	
N9	Measured	124	78	60	42	137	74	66	26	483	66%
	Normal	135	142	130	98	81	81	115	88	736	

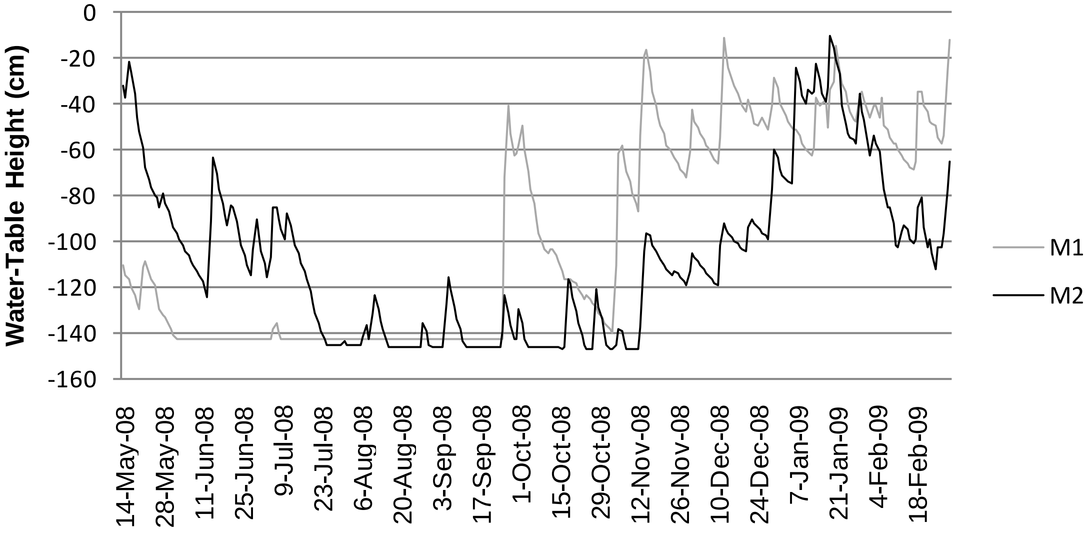

Figure A-1. Water-table depth for mesic mixed hardwood forests (stands M1 and M2). Mesic stands did not have water tables above the surface. The water table level generally stayed more than 40 cm below the surface for the study period. Flat periods in the hydrographs indicate times when the water table level was below the monitoring wells.

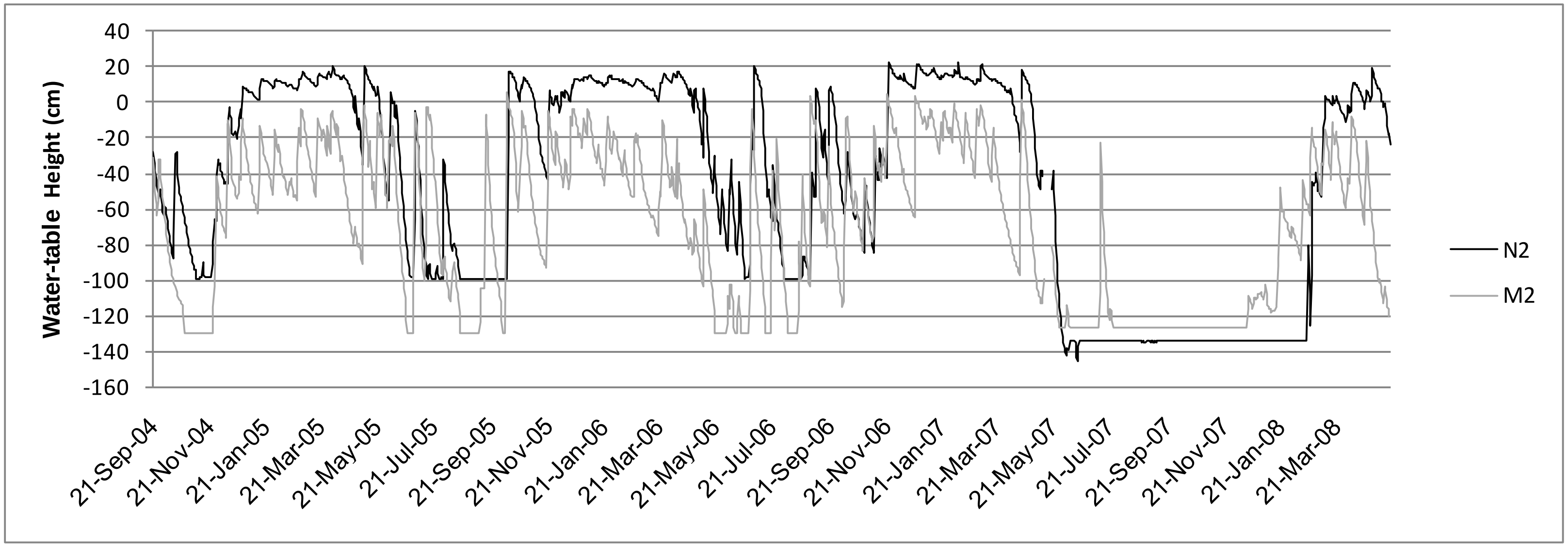

Figure A-2. Long-term water table depth for a mesic mixed hardwood (M2) and a nonriverine wet hardwood forest (N2). Notice the similar patterns between the two community types and the long dry period during the drought of 2007. Flat periods in the hydrographs indicate times when the water table level was below the monitoring wells.