CHANGES IN DIAMETER GROWTH OF *TAXODIUM DISTICHUM* (L.) RICH IN

RESPONSE TO FLOW ALTERATIONS IN THE SAVANNAH RIVER

by

MONICA MARIE PALTA

(Under the Direction of Judith L. Meyer)

ABSTRACT

The Savannah River was impounded in the 1950's near Augusta, Georgia (USA) by Thurmond Dam, a large hydroelectric facility. The objectives of this study were twofold: (1) Identify flooding patterns in areas of the Savannah River floodplain containing *Taxodium distichum* (L.) Rich, and how these patterns have been affected by dam operations; (2) Identify diameter growth responses of *Taxodium* to flooding patterns, and whether growth has changed in response to dam-induced hydrologic changes. River gage records revealed that higher elevation sites were significantly drier in the post-dam era. These sites also showed a significant post-dam increase in basal area increment growth. Low-elevation sites did not show significant hydrologic or growth differences between pre- and post-dam eras, but did show decreased sensitivity of growth to flooding in the post-dam era. This study is the first to quantitatively demonstrate an effect of Thurmond Dam on the hydrologic conditions and growth patterns of floodplain trees.

INDEX WORDS: Dam operations, Floodplain environments, *Taxodium distichum* (L.) Rich, Growth patterns, Dendroecology, Flooding

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MONICA MARIE PALTA

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MONICA MARIE PALTA

Major Professor: Judith L. Meyer

Committee: Rebecca Sharitz
C. Rhett Jackson
Thomas Doyle

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
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FOREWARD

The provisions of abundant water, high soil fertility, and removal of excessive nutrients have made floodplain systems lucrative areas for settlement of human populations, and river floodplains have often been at the epicenter of both agricultural and urban expansion. Historically, use of floodplain environments has been somewhat limited, due to the unpredictable and uncontrollable nature of large flood events. In the last century, however, large-scale hydrologic alterations such as ditching and damming of rivers and streams have facilitated more consistent anthropogenic use of floodplain environments. These alterations come with a cost: changes in flooding patterns can alter the composition, productivity, and structure of floodplain communities; the functions that make floodplains invaluable to humans are, therefore, often lost following dam construction. In recent decades, interest has increased worldwide in restoring ecologically beneficial flood regimes to dammed rivers. Due to the lack of long-term data sets and/or empirical studies examining the relationship between specific dam operations and floodplain processes, the potential ecological costs of hydrologic alterations in any given river system are often unexamined or poorly understood. The shortcomings in available data result in few predictive models and incomplete management plans.

This study is one of many being undertaken to examine the effect of hydroelectric damming of the Savannah River (bordering Georgia and South Carolina, USA) on downstream ecosystems. Specifically, numerous studies are being initiated by government and non-profit agencies to determine if an ecologically sound flow regime can be restored to the Savannah River through better regulation of existing dams. In my study, I use long-term data sets and empirical studies to investigate the effects of Thurmond Dam, the dam furthest downstream on the Savannah River, on growth of a floodplain forest canopy dominant, *Taxodium distichum* (L.) Rich. This research is the first to explicitly examine the growth response of a floodplain organism to operations of Thurmond Dam. It is also the first to empirically quantify changes in hydrologic conditions on the Savannah River floodplain due to dam operations.

The thesis is divided into two chapters. Chapter 1 gives the reader a general background on the relationship between *Taxodium* and flooding, synthesizing a wide range of greenhouse, mesocosm, and field studies on *Taxodium* seedlings and adult trees. Chapter 2 describes the design, methods, results, and conclusions of my study on *Taxodium* stands growing on the Savannah River floodplain, which utilized 100-year growth records recorded in the annual rings of the trees sampled.

Until now, the effect of dam operations on the hydrologic conditions and productivity of floodplain organisms on the Savannah River floodplain has not been empirically investigated. This study serves as a viable approach to examining the relationship between floodplain organisms and dam operations, and an important first step in designing a sustainable management plan for the Savannah River.

CHAPTER 1. Effects of Flooding on *Taxodium distichum* (L.) Rich Growing in River Riparian Environments

INTRODUCTION

Humans have extensively altered most aquatic ecosystems in the United States during the last century. The construction of dams and reservoirs in particular has had tremendous impacts on important ecological processes in rivers and associated wetlands, altering the flow of water and energy, and the movement of sediment, nutrients, and biota in these systems. Change in water flow, specifically changes in the magnitude, frequency, duration, timing, and flashiness of floods, has had arguably the greatest impact on the ecological integrity of rivers (Poff et al. 1997). In the southeastern United States, impoundments, constructed mostly in the mid-1900's, have affected the hydrologic conditions of numerous river systems. Approximately 90 hydroelectric dams and 120 impoundments are located along Coastal Plain rivers in the mid-Atlantic states alone (Schneider et al. 1989).

Predicting the ecological effects of changes in hydrology and river morphology downstream of a dam requires knowledge of the specific physical habitat requirements of key species or assemblages (Power et al. 1995). Using this approach requires evaluating the performance of a few important species and their dependence on the morphologic or hydraulic features of the river (Ligon et al. 1995). The close association between the physical character of the river corridor—in particular the distribution of hydrological processes and fluvial geomorphic features—and the distribution of river floodplain vegetation has been well-documented (Hupp & Osterkamp 1985, 1996; Cordes et al. 1997; Gurnell 1997; Robertson & Augspurger 1999; Hochman 2002).

Similarly, changes in the hydrologic conditions of rivers, particularly changes in the size and timing of annual maximum peak discharge, have been implicated in alterations of growth and regeneration patterns in riparian tree populations (Sharitz & Lee 1985, Kozlowski 2002). The goal of this study is to determine if a major change in the hydrology and morphology of a large river system—construction of a dam on the Savannah River—has affected the patterns of growth in a riparian tree species—bald cypress (*Taxodium distichum* L. Rich).

IMPORTANCE OF BALD CYPRESS IN SOUTHEASTERN FLOODPLAIN COMMUNITIES

Wetland habitats in general and alluvial river swamps in particular are necessary for the survival of a disproportionately high percentage of endangered and threatened species (Mitsch & Gosselink 2000). These areas are also valuable in flood mitigation, storm abatement, aquifer recharge, and maintenance of water quality (Mitsch & Gosselink 2000). Riparian forest communities that have *Taxodium distichum* as a canopy dominant are unique and particularly important components of floodplain ecosystems throughout the southeastern Coastal Plain of the United States (Conner & Toliver 1990). These highly productive communities support a variety of plants and animals, including invertebrates, birds, fish, and herpetofauna (Mitsch & Gosselink 2000). *Taxodium* itself is often an integral part of the life cycle of both plants and animals in southeastern floodplain systems. *Taxodium* knees trap seeds and provide a substrate for germination and growth of trees (Schneider & Sharitz 1988), herbs, and shrubs (such as *Carex decomposita*, or cypress knee sedge) (Meyer et al. 2003). The prothonotary warbler (*Protonataria citrea*) uses *Taxodium* knees for nesting (Petit 1999). *Taxodium* seeds and foliage are a food resource for several species of birds and mammals (Martin et al. 1961, Brown &

Montz 1986). The disappearance and presumed extinction of the ivory-billed woodpecker (*Campephilus principalis*) has been linked to the logging and draining throughout the southern United States of cypress swamps including trees 200-800 years old (Ewel & Odum 1984).

Energy production in *Taxodium*-dominated alluvial river swamps is almost exclusively due to primary productivity of the canopy trees; net primary productivity is almost twice that of net ecosystem productivity (Brown 1981). It is in large part the high productivity of the canopy trees that make *Taxodium*-dominated swamps so effective at nutrient removal; the trees both directly take up nutrients and indirectly contribute to nutrient uptake by providing large amounts of litter that house anaerobic bacteria (Ewel & Odum 1984).

BALD CYPRESS AND FLOODING

Mitsch & Gosselink (2000) classify *Taxodium distichum* (cypress) communities into five types: stillwater cypress domes, dwarf cypress domes, lake-edge swamps, slow-flowing cypress strands, and alluvial river swamps. Because this study was conducted in a floodplain environment, I focus on alluvial river swamps when discussing the relationship between *Taxodium* and flooding. Others have provided a more comprehensive review of the effect of flooding on *Taxodium* growth and survival in cypress domes and strands (Brown 1981, Ewel & Odum 1984, Mitsch & Gosselink 2000).

The effect of flooding on growth and survival of *Taxodium* ranges from ambiguous (e.g., Conner & Flynn 1989, Conner et al. 2001) to negative (e.g., Demaree 1932, Anderson & Pezeshki 2001) to relatively neutral (e.g., McLeod & Sherrod 1981, Donovan et al. 1988) to positive (e.g., Brown 1981, Cleveland 2000). The varied response of *Taxodium* to flooding in microcosm and field experiments is attributed to one of several factors: the wide variety of conditions that researchers consider “flooded” or “drained” (Megonigal & Day 1992); the relatively short duration of some studies (Megonigal & Day 1992, Young et al. 1995); and differences in sample collection and analysis (Young et al. 1995). Because variables such as water depth, tree age, and duration of flooding are not often standardized across *Taxodium* studies, the sections below take into account the potentially confounding effects of these variables in combination with flood tolerance of *Taxodium*.

Morphological responses to flooding. Floodplain systems are driven by disturbance, with flow as the “master variable” limiting the distribution and abundance of floodplain species (Junk et al. 1989, Poff et al. 1997). For species that are primarily terrestrial, such as most species of trees, flooding can limit oxygen and nutrient uptake (Shanklin & Kozlowski 1985), metabolism (Table 1), and growth (Table 1) (Kozlowski & Pallardy 1997). Flood waters are also necessary, however, for the delivery of sediment (Hodges 1997), oxygen (Junk et al. 1989), and essential nutrients such as phosphorus (Mitsch et al. 1979, Brown 1981). Floodplain tree species therefore utilize various strategies to survive, grow, and reproduce during flooding. Response time and type of strategy varies with species, genotype, age, life-history stage, and pre-conditioning to flooding; the type, timing, and duration of flooding also play major roles (Hochman 2002). The distribution of tree communities along ecological gradients that are oriented more or less perpendicular to river channels reflects the wide variation in degree of tolerance to flooding by different bottomland forest species.

Most important of these gradients are depth and duration of flooding, as well as geomorphology and soils (Townsend 2001, Kozlowski 2002). Communities of floodplain trees that include *Taxodium* are typically found on those sites with the longest hydroperiod (Hook 1984, Mitsch & Gosselink 2000, Townsend 2001). The dominance of *Taxodium* at these sites has been attributed to expression of particular life history characteristics when flooded, such as the ability to reduce root:shoot ratios (Shanklin & Kozlowski 1985, Anderson & Pezeshki 2001), open stomata while inundated (Anderson & Pezeshki 2001, but see Shanklin & Kozlowski 1985), and produce adventitious roots (studies cited in Mitsch & Gosselink 2000). These characteristics confer a high degree of flood tolerance (Anderson & Pezeshki 2001), but additionally may result in a low competitive ability under drier soil conditions (Mitsch & Ewel 1979) and a reduced ability to withstand drought (Shanklin & Kozlowski 1985, but see Elcan & Pezeshki 2002).

***Factors influencing the effects of flooding on* Taxodium.** The ambiguous nature of flood tolerance combined with the close association between flooding and sediment, nutrient, and oxygen delivery in river-floodplain systems results in a complex relationship between flooding and growth and survival of *Taxodium*. A few ecological factors in combination with flooding have, however, been independently identified as important in influencing growth of *Taxodium*. These factors are tree age; depth, duration, and timing of flooding; aeration of water; nutrient dynamics; and stand dynamics.

Age. Early field experiments demonstrated that foliage height needs to exceed flood level for *Taxodium* seedling survival (Demaree 1932). Since foliar submergence is rarely a problem for adult *Taxodium*, flooded conditions, especially in the short term, are probably not a primary determinant of adult survival. Additionally, responses in growth and mortality to flooding may differ with age due to the development of morphological adaptations to flooding as the tree matures. The advantage of age in submergence survival may be apparent within just one year of growth. In a greenhouse experiment using newly-germinated (< 2 weeks old) and one-year old seedlings, the newly-germinated seedlings showed signs of stress after one month of complete submergence and substantial mortality after 45 days of submergence (Souther & Shaffer 2000). The one-year old seedlings, on the other hand, experienced no mortality under complete submergence until day 60, and 75% survival after 90 and 100 days (Souther & Shaffer 2000).

The development of morphological characteristics minimizing root damage under flooded conditions appears to be a major advantage conferred by tree maturity. An experiment using one-year-old *Taxodium* seedlings in enclosures over a three-year period found higher root and shoot biomass in periodically flooded (PF) treatments than in continuously flooded (CF) treatments after one growing season (Megonigal & Day 1992). After three growing seasons, no significant differences in total plant biomass or shoot growth was observed between treatments, but a difference in carbon allocation was evident: PF plants had high root:shoot ratios and deep root systems, while CF plants had low root:shoot ratios and shallow root systems (Megonigal & Day 1992). Improved shoot growth in the CF treatment began in the second growing season and coincided with the production of adventitious roots, development of intercellular air spaces in phloem, and different root-system morphologies (Megonigal & Day 1992). The findings of this experiment are similar to those of a three-year field experiment on *Taxodium* seedlings, which documented better growth in PF areas than in CF areas during the first two growing seasons of planted one-year-old seedlings, but no difference during the third growing season (Conner & Flynn 1989). However, differences in stand dynamics may have played a role in growth differences between sites (Conner & Flynn 1989).

Depth, duration, and timing of flooding. Differences in the hydrologic characteristics of flood regime (deep vs. shallow, periodic vs. permanent, early vs. late growing season) can often determine the effect flooding has on *Taxodium* (Table 1a-b).

Table 1a. Effect of flooding on growth parameters of Taxodium distichum seedlings & saplings (modified from Megonigal & Day 1992). G = greenhouse study, M = mesocosm study, F = field study, RGR = relative growth rate, NAR = net assimilation rate, DM = dry mass, BM = biomass, LSA = leaf surface area, LA = leaf area, HG = height growth, DG = diameter growth, DWI = dry weight increment.

Study	Age of Seedlings	Type of Study	Driest treatment	Treatment for comparison	Seedlings						saplings (≥ 3 yrs)						growth parameter measured
					water depth[a]	water duration	water periodicity	water aeration	water nutrient levels	water + light level	water depth	water duration	water periodicity	water aeration	water nutrient levels	water + light level	
Nash & Graves (1993)	1 yr	G	- 353 cm*	- 170 cm*	+												RGR, NAR, shoot DM, estimated LSA, specific leaf mass
Nash & Graves (1993)	1 yr	G	- 170 cm*	- 46 cm*	0												RGR, NAR, shoot DM, root DM, estimated LSA
McLeod & Sherrod (1981)	1 yr	M	- 10 cm	- 5 cm	0												HG, DG, plant BM
McLeod & Sherrod (1981)	1 yr	M	- 10 cm	at surface	0												HG, DG, plant BM
Donovan et al. (1988)	< 1 yr	M	- 6 cm	at surface	0												HG, shoot BM
Dickson et al. (1972)	2-5 mo	G	drained, watered	saturated	+			+									leaf DM, stem DM
Dickson & Broyer (1972)	6 wks-11 mo	G	field capacity	1 cm	+			+	+								height, shoot DM
Nash & Graves (1993)	1 yr	G	- 46 cm*	~2 cm	-												shoot DM, root DM, estimated LSA
Shanklin & Kozlowski (1985)	8-14 wks	G	drained, watered	2 cm	-												RGR; HG; LA; DWI of whole seedlings, leaves, & roots; S uptake
Vann & Megonigal (2002)	~ 3 wks	G	- 10 cm	5 cm	-												HG, shoot BM, root BM, LA, # of branches, trunk diameter

Table 1a cont. Effect of flooding on growth parameters of Taxodium distichum seedlings & saplings (modified from Megonigal & Day 1992).

Study	Age of Seedlings	Type of Study	Driest treatment	Treatment for comparison	Seedlings						saplings ($\geq$ 3 yrs)						growth parameter measured
					water depth[a]	water duration	water periodicity	water aeration	water nutrient levels	water + light level	water depth	water duration	water periodicity	water aeration	water nutrient levels	water + light level	
Conner et al. (2001)	< 2 mo	G	drained, watered	5 cm	+/0												height, leaf mass, stem mass
Donovan et al. (1988)	NA	M	-6 cm	6 cm	0												HG, shoot BM
Donovan et al. (1989)	3 mo	G	drained, watered	6 cm	-												plant BM
Donovan et al. (1989)	3 mo	G	drained, watered	12 cm	-												stem HG, plant BM
Souther & Shaffer (2000)	< 2 wks & 1 yr	M	- 10 cm	100 cm	-	-			+/0	+/-							stem HG, DG
Loucks & Keen (1973)	0-1 yr	M	unflooded	submerged	-	-											mean terminal growth
Anderson & Pezeshki (2001)	< 5 mo - < 8 mo	G	drained, watered	flooded[b]	-	-											HG; leaf, stem, root, plant BM; # of leaves; LA per plant
Conner & Flynn (1989)	1-3 yrs	F	- 90 - 45 cm	- 75 - 55 cm	0	0	+				+	+	0				HG
Conner & Flynn (1989)	1-3 yrs	F	-90 - 45 cm	-50 - 65 cm	+	+	+				+	+	0				HG
McLeod et al. (2000)	0-3 yrs	F		up to 100 cm	+	+											HG

[a]effect relative to driest treatment; [b]depth not available; *converted from matric potential (kPa): 1 kPa = 0.01 bars = 10.13 cm

Table 1b. Effect of flooding on growth parameters of Taxodium distichum adult trees. RI = river riparian, DO = dome, GS = growing season, NA = not applicable. If only one box is filled under "Flood comparison", only that treatment is considered in the effect of various flood variables.

	Type of cypress system	Flood comparison		Flood variables					
		Continuous Flooding	Periodic Flooding	water depth	water duration	water periodicity	water aeration	water nutrient levels	water + light level
Conner & Day (1992)	impounded RI	year-round	Jan-Oct, Apr-Jul	-	-	-		+	-
Brown (1981)	DO, RI	year-round[b]	Nov-Apr			+		+	
Cleveland (2000)	RI		Dec-May	+	+				
Dicke & Toliver (1990)	RI	year-round	Dec-Jul	-	-				
Eggler & Moore (1961)	Impounded RI	year-round	spring flooding	-	-				
Harms et al. (1980)	impounded RI, RI	year-round	Jun-early fall	-					
Keeland & Sharitz (1995)	Stream/RI system	year-round	throughout year	+		-			
Keeland et al. (1997)	RI	full GS[c]	Variable	0/-		+			
Keeland & Young (1997)	impounded RI	year-round	not known			-			
Mitsch et al. (1979)	Impounded RI, RI	year-round	Feb-Apr	-	-			+	
Mitsch & Ewel (1979)	DO, RI	not known[d]	not known[d]	+/-				+	
Stahle et al. (1992)	impounded RI	year-round	not known	+/0	0	-/+			
Young et al. (1995)	impounded stream	NA	NA	-	-				

[a] part of the Mississippi River deltatic plain, but cut off at least in part by levees

[b] some drydown in summer

[c] GS = April-September

[d] hydrologic conditions inferred from community composition; see Figure 1 in Chapter 2

Depth. In greenhouse experiments, depth of water has a range of effects on *Taxodium* seedlings, depending on the exact depth of the experimental treatment and the depth of the control treatment to which it is compared (Table 1a). When under “severe” drought conditions, *Taxodium* appears to benefit from increased water levels up to 46 cm below the soil surface (Nash & Graves 1993). Under “moderate” drought conditions, however, a slight increase in soil water level has a neutral effect, and an increase in water levels to 2 cm above the soil surface has a negative effect (Nash & Graves 1993). Differences in soil water depth between -10 and 0 cm do not appear to have a significant effect on growth in *Taxodium* seedlings (McLeod & Sherrod 1981, Donovan et al. 1988). An increase from drained to saturated soil or from field capacity to 1 cm of surface water appears to benefit *Taxodium* growth (Dickson et al. 1972, Dickson & Broyer 1972). Increasing depth of water over 2 cm above soil surface generally results in a negative relationship with seedling growth in greenhouse experiments (Table 1a). However, studies which examine the effects of 5-6 cm of surface water on *Taxodium* growth show conflicting results, ranging from negative (Vann & Megonigal 2002) to neutral (Donovan et al. 1988, Conner et al. 2001) to positive (Conner et al. 2001, Elcan & Pezeshki 2002).

The inconsistency in growth response to 5-6 cm of surface water could be due to differences in study methodology. Duration of the studies differed: Donovan et al. (1988) had the longest study duration, followed by Conner et al. (2001) > Elcan & Pezeshki (2002) > Vann & Megonigal (2002). Donovan et al. (1988) and Conner et al. (2001) also had continuous flow-through mechanisms for changing the water flooding the seedlings; Vann & Megonigal (2002) replaced ET losses daily with tap water, but tubs were drained and refilled only every 3 weeks (Donovan et al. 1988, Conner et al. 2001, Vann & Megonigal 2002). The type of watering system utilized by Elcan & Pezeshki (2002) was not reported (Elcan & Pezeshki 2002). A longer study duration and/or continuous replacement of the soil water may have neutralized or greatly reduced any negative effects of flooding at the 5-6 cm level. The neutralizing effects of longer flooding durations on saplings has been demonstrated in at least two studies (Conner & Flynn 1989, Megonigal & Day 1992), but this response required three growing seasons; *Taxodium* plants were observed for only 1.5 growing seasons by Donovan et al. (1988) and 2 growing seasons by Conner et al. (2001). That a longer duration of flooding should lead to better growth of *Taxodium* seedlings is somewhat surprising, given findings of other studies on *Taxodium* seedlings within the same age range (Loucks & Keen 1973, Souther & Shaffer 2000); these latter studies did, however, test *Taxodium* in higher depths of water. Continuous replacement of soil water, which would likely lead to greater oxygen and nutrient availability to the plants' roots, may be expected to have positive effects on *Taxodium* growth (see below). Since design components were not uniform across studies, it is difficult to identify the cause(s) of the differences in study findings.

Periodicity. The dynamic hydrologic nature of floodplains makes comparison of field studies examining the effect of water depth on *Taxodium* difficult. Whereas field studies of *Taxodium* seedlings have not generally found any negative effects of water depth on growth, other hydrologic variables such as duration or periodicity of surface water can have an influence (Table 1a).

Flood periodicity has been proposed to have a beneficial effect on *Taxodium*, resulting in higher productivity at periodically flooded sites than at more continuously flooded sites. The findings of a three-year field planting experiment and a three-year mesocosm experiment on one-year old *Taxodium* seedlings are described above (see ***Age*** section, above). These studies indicate a greater benefit of periodic flooding (PF) to *Taxodium* growth than continuous flooding

(CF), but only up until the third growing season (Conner & Flynn 1989, Megonigal & Day 1992). The negative effects of continuous flooding are most likely due to the greater chance of root anoxia under these conditions; it is presumed that after some years, seedlings acclimate to their environment by developing flood tolerance features such as adventitious roots (Megonigal & Day 1992). Field studies of adult *Taxodium* trees also indicate, however, that duration and periodicity of flooding are important determinants of growth (Table 1b). As in seedlings, stagnant or continuous deep flooding during the growing season generally has a negative effect on adult *Taxodium* (Brown 1981, Lugo & Brown 1984) while PF episodes interspersed with drydown can often be less damaging or at times beneficial.

The difference caused by the periodicity of hydrologic regime is often dramatically demonstrated in riparian stands of *Taxodium* that are suddenly switched from periodic to continuous flooding after the impoundment of an adjacent stream or river (Table 1b). Prolonged, deep flooding due to impoundment had an adverse effect on radial growth of a riparian population of mature *Taxodium* trees in South Carolina (Young et al. 1995). Although flooding initially resulted in accelerated growth over a 5-year period following impoundment, an overall decline in growth was observed after this 5-year period for approximately 16 years (Young et al. 1995). The initial surge in radial growth of these trees was likely due to increases in nutrient levels or reductions in competition due to loss of less flood-tolerant species; it was surmised that root anoxia eventually led to a gradual long-term decline in growth (Young et al. 1995). Continuous flooding of a population of adult cypress tress above a reservoir 4 years after its construction showed a relationship between depth of flooding and mortality: as the prevailing water depth increased, mortality also increased (Harms et al. 1980). Almost complete mortality was observed in tree populations flooded to depths of 1.2 m or more after 7 years, whereas mortality ranged from 0-3% in water depths ranging from 0-65 cm (Harms et al. 1980). The proportion of trees exhibiting dead roots also decreased as water depth decreased (Harms et al. 1980).

Stands that naturally experience different flood regimes have also shown higher growth in periodically flooded stands. A CF 63-year-old stand of *Taxodium distichum* and *Nyssa sylvatica* in Louisiana was shown to have 27-46% less diameter growth in trees 25-35 cm in diameter as compared to a seasonally (Dec – Jul) flooded 63-year-old stand (Dicke & Toliver 1990). *Taxodium* basal area growth was also significantly less over 5 years in the CF stand (Dicke & Toliver 1990). A study of riparian areas in Louisiana and South Carolina, however, indicated that depth of flooding may outweigh the importance of periodicity of flooding (Keeland et al. 1997). Trees subjected to shallow flooding (either PF or CF) demonstrated greater growth and a longer growth phase than trees subjected to deep PF (Keeland et al. 1997). In a separate study, however, only diameter growth of trees at riverine sites experiencing shallow PF was correlated with changes in mean water levels (Keeland & Sharitz 1997). Variations in tree growth due to changes in water level at shallow PF sites were thought to be due to reduced function and frequent restructuring of the root systems due to alternately flooded and drained conditions at these sites (Keeland & Sharitz 1997).

Although continuous flooding has generally been shown to have negative effects on the growth of *Taxodium* trees, several studies have indicated positive effects. Due to their high degree of drought sensitivity, *Taxodium* has been shown to respond positively to continuous flooding when subjected to very dry or variable soil moisture conditions prior to flooding. At Reelfoot Lake in Tennessee, an enormous surge in diameter growth of adult *Taxodium* trees was observed following tectonic uplift and subsequent continuous flooding (Stahle et al. 1992). For a

3-year period after the trees were flooded to a depth of 1-2 meters, they grew lower density wood at a greatly accelerated rate, ostensibly because they were not as frequently affected by summer droughts (Stahle et al. 1992). Although 30 years of depressed growth followed this initial surge, a return to pre-flood growth levels was seen after 30 years (Stahle et al. 1992, Keeland & Young 1997). A study at Caddo Lake, another abruptly flooded area in Texas, revealed greater diameter growth in most mature *Taxodium* trees following inundation (Keeland & Young 1997). The authors speculated that the reduction in annual variation of water levels following flooding of the area may have been beneficial to *Taxodium* growth (Keeland & Young 1997).

It is interesting that these studies reveal a short-lived response in one direction (i.e. higher growth immediately following inundation), and a reversal in response over time (i.e. depression in growth following the initial surge). The additional finding at Reelfoot Lake that trees eventually returned to pre-impoundment growth levels implies that, at least in some cases, *Taxodium* may be affected more by abrupt changes in hydrologic regime than by a continuous vs. periodic hydrologic regime *per se*. At any rate, these studies certainly suggest that the effect of a particular flood regime on diameter growth of *Taxodium* may be dynamic over time.

Aeration of water. The difference in response of *Taxodium* to varying depths, durations, and frequencies of flooding is likely due to the relationship between these variables and the oxygen content of flood waters. Flooding that is deep and continuous is more likely to cause low oxygen content in the vicinity of the rooting zone of the tree. Oxygen deprivation in the rooting zone may in turn be responsible for decreased productivity in *Taxodium*. Under conditions meant to simulate soil oxygen conditions created by flooding, < 1-year-old *Taxodium* seedlings demonstrated stunted growth in response to root-zone oxygen deficiency, in turn limiting root capacity as a major sink for saccharides (Pezeshki et al. 1996, Pezeshki & Santos 1998). Low redox potential also stimulated ethylene production in leaves and roots (which enhances aerenchyma formation) (Pezeshki et al. 1996). Similarly, experiments on < 1-year-old seedlings revealed low growth in unsaturated soil, higher growth in saturated soil, and highest growth in saturated-aerated soil (Dickson & Broyer 1972, Dickson et al. 1972). This trend supports the idea of a trade-off between sensitivity of *Taxodium* to both drought and anaerobic conditions in the rooting zone (which decrease water absorption and increase internal moisture stress); the findings suggest, however, that drought stress may be more detrimental to growth than flood stress.

Nutrient dynamics. Nutrient content of floodwaters can be an important determinant of whether water depth and duration has a positive or negative relationship with *Taxodium* growth. Several field studies (Brown 1981, Mitsch et al. 1979) have indicated a positive response to flooding in *Taxodium* due to the high nutrient levels, phosphorous in particular, carried into floodplain forests by flood waters. High nutrient levels in flood waters (i.e. flooding with wastewater for treatment purposes) has been shown in some cases to compensate for the stress of continuously flooded conditions in studies on adult *Taxodium* in cypress domes (Mitsch & Ewel 1979, Brown 1981, Hesse et al. 1998, but see Straub 1984). Wastewater discharge was shown in one study to have an adverse effect on the growth and survival of *Taxodium distichum* seedlings, however, though this may have been related to nearly anaerobic conditions in the water column due to duckweed (Deghi 1984).

Stand dynamics. Degree of shading may also influence the flood tolerance of *Taxodium* trees (Hall & Harcombe 1998, Jones et al. 1994a, but see McLeod et al. 2000). At a constant water level, *Taxodium* has a positive relationship with light intensity. *Taxodium* seedlings watered weekly showed a significantly positive diameter growth relationship with light; growth increased as light increased from 5% to 75-100% full sunlight (Neufeld 1983). Height growth had a more complex relationship with light levels in this experiment, but in general, light levels higher than 5% resulted in more growth than height levels under 5% light (Neufeld 1983). Sensitivity to shading of *Taxodium* seedlings (i.e. lower growth in shaded areas) was found in willow canopy experiments, as well, but it was noted that seedlings in full sun did appear to be more subject to drought stress (McLeod et al. 2001).

Light intensity has various effects on *Taxodium* growth in combination with nutrient levels and age of seedlings. An interaction between light transmission, age and fertilizer indicated that fertilizer benefited newly-germinated seedlings only at 80% light transmission, whereas one-year old seedlings benefited from fertilization under all light levels except 100% (Souther & Shaffer 2000).

TAXODIUM ON THE SAVANNAH RIVER FLOODPLAIN

The Savannah River Basin drains 27,575 km^2 and flows through portions of North Carolina, South Carolina, and Georgia. Since the 1950's, the United States Army Corps of Engineers (USACE) has constructed three major impoundments in the Savannah River basin, primarily to reduce flood damage, generate hydropower, and supply water for the public (Meyer et al. 2003). The oldest and furthest downstream of these impoundments, Thurmond Dam, has significantly impacted the hydrology of the Coastal Plain portion of the Savannah River since its completion in 1954. Numerous studies done along the Savannah River over the last few decades have suggested an impact of these altered hydrologic regimes on populations of *Taxodium* (Birch & Cooley 1983, Schneider & Sharitz 1988, Sharitz et al. 1990). These studies suggest adverse affects of longer hydroperiods and large dam releases during the growing season on *Taxodium* regeneration and growth. Growth and regeneration measurements in the studies were limited, however, to short periods of time in the post-dam era. Additionally, the relationship between growth, germination, and survival of *Taxodium* and the hydrologic conditions of study sites was not directly quantified.

Dendrochronological techniques provide the possibility of generating a year-by-year verifiable long-term data set that spans both pre- and post-dam periods on the Savannah River. Several studies (Stahle et al. 1992, Young et al. 1995, Cleaveland 2000) have successfully reconstructed both long-term variation and alterations in the nature of river flow using *Taxodium*. According to the studies presented in this chapter, *Taxodium* seems to respond positively to flood waters that are well-aerated, nutrient-rich, and of fairly short duration. This study considers potential changes in the duration of floodplain inundation due to dam construction, and the effects these changes might have on diameter growth of *Taxodium* trees growing on the floodplain.

The largest percentage (40%) of total stock volume of *Taxodium distichum* found in the United States resides in Louisiana, but Georgia and South Carolina, where the Savannah River is located, also support high volumes of cypress (6% and 9% of total stock volume, respectively) (Mitsch & Gosselink 2000). *Taxodium* trees were heavily harvested around the turn of the 20^{th} century; it is estimated that only about 10 % of cypress swamps found in presettlement times still remain in the United States (Brandt & Ewel 1989, Conner & Toliver 1990). As a key component of swamp ecosystems and a potentially important solution to mitigation of pollution and storm water levels, *Taxodium distichum* is an organism that should be studied closely and prioritized highly in conservation and restoration efforts. The most important elements driving ecosystem structure and function in riparian communities dominated by *Taxodium* are flood dynamics (e.g., Ewel & Odum 1984, Visser & Sasser 1995, Middleton 2000, Mitsch & Gosselink 2000, Collins & Battaglia 2001, Townsend 2001). Design of conservation and restoration efforts in these systems must therefore take hydrologic characteristics into primary consideration.

CHAPTER 2. Changes in Growth of *Taxodium distichum* (L.) Rich on the Savannah River Floodplain in Response to an Upstream Dam

INTRODUCTION

The dynamic interaction between water and land is the principal process producing, maintaining, and affecting the biota living in river floodplain systems (Bayley 1995). Flood pulses have been shown to enhance biological productivity and maintain diversity in riverine systems; the principal agents associated with these functions are plants, nutrients, detritus, and sediments (Junk et al. 1989). Alterations in hydrology of river systems, whether caused by humans or other ecosystem engineers, can change the dynamic nature of floodplain ecosystems by prolonging or eliminating inundation of floodplain sites. The reduction or elimination of inundation events in floodplain areas below an impoundment is self-evident; impoundments are often built for this exact purpose. Impoundments can, however, additionally increase the duration and depth of inundation at some low-lying downstream sites by augmenting low flows in the main channel. The end result is a floodplain system that may resemble either a well-drained upland system or a poorly-drained deepwater swamp system; these are both less productive than the former floodplain (Mitsch & Ewel 1979, Conner and Day 1982) (Figure 1).

Taxodium distichum (L.) Rich is a canopy dominant in the wettest sites of floodplains in the Southeastern United States. This species has been highly valued for its important role in alluvial floodplain ecosystems, as well as its commercial value in the local timber industry. Studies on *Taxodium* seedlings and trees have indicated a quadratic relationship between growth variables and flooding, i.e. growth is maximal at intermediate levels of flooding (seedling studies cited in

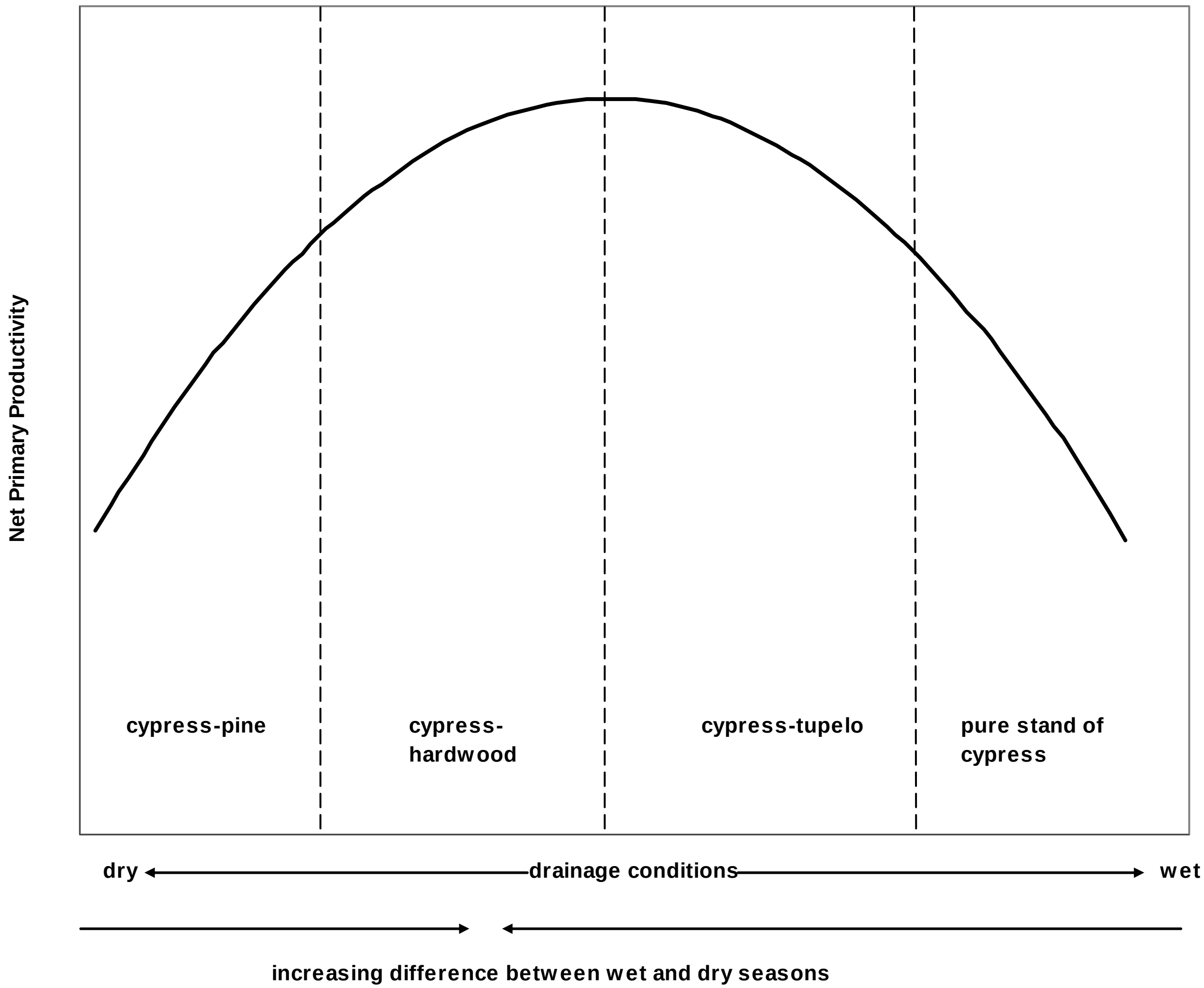


Figure 1. Relationship between net primary productivity of different types of cypress (*Taxodium distichum* (L.) Rich) swamps in Florida and their hydrologic conditions. Modified from Mitsch & Ewel (1979).

Chapter 1, Mitsch & Ewel 1979, Brown 1981, Conner & Day 1992). *Taxodium* is highly drought-sensitive, and not a good competitor under dry conditions (Mitsch & Ewel 1979, Shanklin & Kozlowski 1985). Flooding not only increases soil moisture, but can also supply *Taxodium* with nutrient-laden sediments that are beneficial to growth (Brown 1981, Mitsch et al. 1979). Oxygen deprivation in the rooting zone of the tree under flooded conditions is avoided through a number of physiological mechanisms, including production of adventitious roots and aerenchyma tissue, or air-filled spaces in the roots (studies cited in Mitsch & Gosselink 2000). When flood duration is too long or flood depths too deep, however, tolerance mechanisms are no longer effective in avoiding root hypoxia, and growth will respond negatively to increases in depth or duration of flooding (Eggler & Moore 1961, Mitsch et al. 1979, Harms et al. 1980, Donovan et al. 1989, Dicke & Toliver 1990, Conner & Day 1992, Young et al. 1995, Souther & Shaffer 2000).

The Savannah River was impounded in the 1950's near Augusta, Georgia by Thurmond Dam, a large hydroelectric facility. The Savannah River floodplain supports large populations of *Taxodium*, and a few studies done over the last few decades have suggested an impact of altered hydrologic regimes caused by Thurmond Dam on these populations (Birch & Cooley 1983, Schneider & Sharitz 1988, Sharitz et al. 1990). Specifically, the studies have indicated adverse affects of longer hydroperiods and large dam releases during the growing season on *Taxodium* regeneration and growth. Growth and regeneration measurements in the studies were limited, however, to short periods of time in the post-dam era. Additionally, the relationship between growth, germination, and survival of *Taxodium* and the hydrological conditions of study sites was not directly quantified. In this study, annual diameter growth of *Taxodium* on the Savannah River floodplain was measured using dendrochronological techniques; this technique allowed for reconstruction of diameter growth patterns over the last 103 years, spanning pre- and post-dam eras. Flooding patterns over the last 103 years were also reconstructed for the sites at which trees were sampled.

The objectives of this study were twofold. The first objective was to identify the flooding patterns (depth, duration, and periodicity of floodwaters) of different hydrogeomorphic areas of the Savannah River floodplain containing *Taxodium distichum*, and to determine whether and in which way flooding patterns in these areas have changed due to construction and operation of Thurmond Dam. The second objective was to identify responses of diameter growth in populations of *Taxodium* to flooding patterns, and to test whether diameter growth response has changed in response to changes in flooding patterns due to construction and operation of Thurmond Dam.

STUDY DESIGN

Three distinct hydrogeomorphic areas on the Savannah River floodplain supporting populations of *Taxodium* were identified: (1) in low-lying areas on the banks of the Savannah River mainstem; (2) on top of the levee next to the Savannah River mainstem; and (3) in low-lying areas behind the levee, further away from the Savannah River mainstem, i.e. in the backswamp. These sites are termed river (RI), levee (LE), and backswamp (BS), respectively.

Taxodium trees in the Savannah River basin have demonstrated a positive relationship with both regional Palmer drought severity index (PDSI, which decreases with increasing severity of drought) (Stahle et al. 1988) and regional precipitation (Stahle & Cleaveland 1992). These studies have suggested that the shallow root systems of *Taxodium* trees growing in this area are vulnerable to partial drydown during dry years, causing internal moisture stress and reduced growth (Stahle & Cleaveland 1992). Precipitation, PDSI, and surface flooding at floodplain sites are all highly correlated with one another. In order to isolate the effects of flooding and dam operations on *Taxodium* trees, I selected years with similar precipitation and PDSI for pre- and post-dam comparisons and for growth contrasts by site. Years in the pre- and post-dam period were assigned to one of three groups: dry, intermediate, or wet. Hypotheses concerning the response of trees at each site to the dam within each year type are summarized in Table 2.

At RI sites, I expected that, in both the pre-and post-dam era, trees were affected little by drought and that tree roots were saturated throughout the year. I anticipated that considerable surface flooding was taking place in both pre- and post-dam eras; however, I expected that more continuous surface flooding and fewer dry-down episodes were taking place in the post-dam era, particularly during drier years (Table 2). This expectation was based on studies anecdotally reporting more continuous flooding in lower-lying areas of the Savannah River floodplain (Birch & Cooley 1983, Schneider & Sharitz 1988, Sharitz et al. 1990) and a study documenting higher seven-day low flows and higher baseflow during dry months (August-October) in the Savannah River main channel as a result of dam operations (Hale & Jackson 2003). Given these changes in hydrologic conditions, I hypothesized that RI trees would have higher growth during drier years in the post-dam era (due to reduced drought stress). During wetter years, I hypothesized that RI trees would not show a change in response to flooding after dam construction, since fairly continuous inundation was expected for these low-lying areas in both pre- and post-dam periods (Table 2).

BS sites, low-lying like RI sites, were expected to experience more continuous periods of inundation and fewer dry-down episodes in the post-dam era than in the pre-dam era. Since BS sites are slightly higher in elevation relative to RI sites, however, inundation of BS sites was

Table 2. Hypotheses concerning the relationship between operation of Thurmond Dam and (a) inundation of floodplain sites, (b) diameter growth of *Taxodium distichum* (L.) Rich trees growing at floodplain sites during wet and dry years. For "Inundation", a + signifies longer periods of inundation in the post-dam period, and a - signifies shorter periods of inundation in the post-dam period.

Taxodium Population	Site description	Inundation		Diameter Growth		Growth response rationale
		Dry Years	Wet Years	Dry Years	Wet Years	
River (RI)	Low-lying, immediately adjacent to main channel.	+	0	+	0	**Dry Years:** More frequent and continuous flood inundation helps decrease drought stress. **Wet Years:** Poorly-drained conditions are similar during pre- and post-dam periods, so flood stress is high in both periods.
Levee (LE)	High elevation, immediately adjacent to main channel.	-	-	-	+	**Dry Years:** Less frequent and continuous flood inundation increases drought stress. **Wet Years:** Better-drained conditions reduce flood stress.
Backswamp (BS)	Low-lying, but intermediate in elevation to RI and LE sites. Further back from the main channel than LE or RI sites.	+	+	+	-	**Dry Years:** More frequent and continuous flood inundation helps decrease drought stress. **Wet Years:** Poorly-drained conditions increase in the post-dam period, so flood stress is higher.

expected to be slightly more infrequent and of shorter duration than inundation of RI sites (Table 2). As in RI sites, I hypothesized that the reduction in water level variability at BS sites would result in higher growth during dry years but lower growth during wet years in the post-dam era (Table 2). Inundation was expected to be of longer duration during the post-dam era at BS sites, resulting in greater levels of stress during wet years in the post-dam period.

At LE sites, which are higher in elevation than RI or BS sites, I expected that less flooding would take place after dam construction than before dam construction (Table 2). This expectation was based on documented changes in hydrologic patterns of the Savannah River main channel as a result of dam operations, i.e. a reduction in the magnitude of peak flows and lower flood recurrence in the main channel (Hale & Jackson 2003). In addition, a preliminary analysis of floodplain inundation using four cross-sections of the Savannah River channel downstream of Thurmond Dam indicated that, in the post-dam period, flows in the main channel have rarely been high enough to overtop the levee (Hale & Jackson 2003). I therefore hypothesized that LE trees would suffer more drought stress during dry years in the post-dam era than in the pre-dam era. I hypothesized that LE trees would experience greater growth during wet years in the post-dam era, since better-drained conditions at LE sites in the post-dam era should translate into less root anoxia for the trees (Table 2).

THE SAVANNAH RIVER BASIN

Physical Characteristics. The entire Savannah River Basin drains an area of 27,575 km^2 and flows through portions of North Carolina, South Carolina, and Georgia. Its headwaters originate in the Blue Ridge Mountains, and flow through the Piedmont Province and upper and lower Coastal Plains before reaching the Atlantic Ocean (USACE 1992). Thurmond Dam is located at the fall line dividing the Piedmont Province and Coastal Plain. Because the purpose of this study was to determine the impacts of Thurmond Dam on *Taxodium* growth in the Savannah River ecosystem, study sites were located exclusively on the stretch of river just below the dam, i.e. in the upper Coastal Plain section of the river (Figure 2). This section of the river is a low-gradient (mean slope = 0.1 m/km), alluvial, meandering fluvial system, varying from a width of 150-200 m for the first 50-60 km below the dam (USACE 1992). Mean annual precipitation occurs chiefly as rainfall, and ranges from 100-200 cm per year (USACE 1992). Rainfall distribution over the year is fairly even, but a distinct dry season occurs from mid-summer to late fall. Mean annual temperature is about 18ºC (USACE 1992).

Approximately 80% of the sediments on the Coastal Plain of the Savannah River are sands and clays. Soils are sandy or sandy over loamy; the sandy surface layer is of varying depth and overlies a red to yellow, loamy subsoil. Water table depths and soil textures in this part of the watershed are highly variable (Georgia DNR 2000).

Alterations to the Savannah River. Since the 1950's, the United States Army Corps of Engineers (USACE) has constructed several impoundments in the Savannah River basin, primarily to reduce flood damage, generate hydropower, and supply water for the public (Meyer et al. 2003). The largest impoundments are Hartwell Lake (227 km^2), Richard B. Russell Lake (105 km^2), and Strom Thurmond Lake (a.k.a. Clarks Hill Lake) (283 km^2), which is impounded by Thurmond Dam (Georgia DNR 2000). Thurmond Dam is the oldest and furthest downstream dam on the Savannah River, and has significantly impacted the hydrology of the Coastal Plain portion of the river since its construction was completed in 1954 (Hale & Jackson 2003).

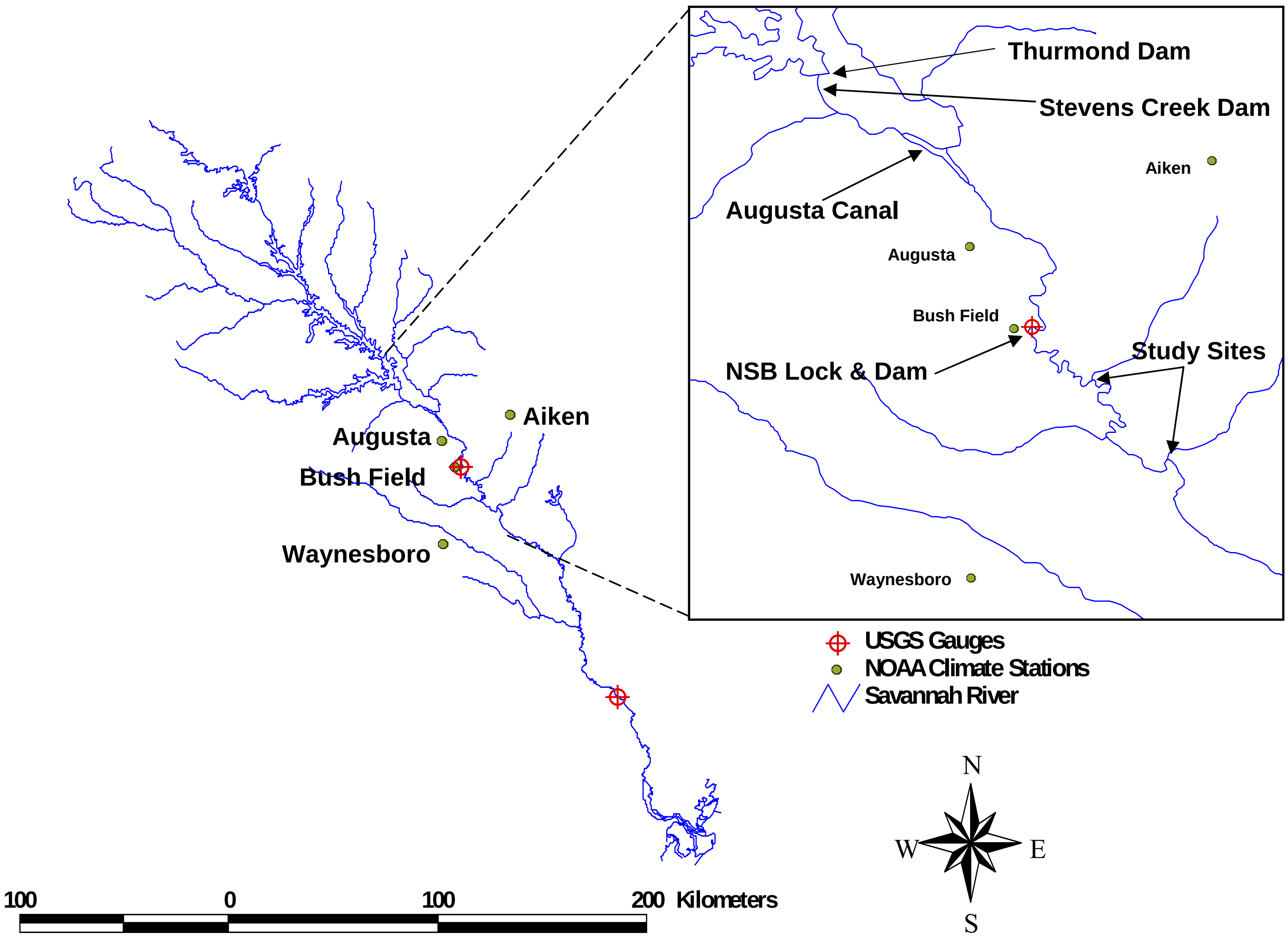


Figure 2. Map of the coastal plain section of the Savannah River system. (a) Large view. Names correspond to climate stations. Coastal plain begins downstream of Thurmond Dam. (b) Small view. Names with arrows correspond to hydrologic features on the river.

Situated near the fall line dividing the Piedmont and the Coastal Plain of Georgia, Thurmond Dam re-regulates the flows released from all dams located upstream of it. Management regimes of all other major dams on the Savannah River are therefore not directly relevant to flows on the Coastal Plain portion of the river (Meyer et al. 2003).

Smaller hydrologic regulation structures downstream of Thurmond Dam were constructed prior to construction of Thurmond Dam and likely modified flow regimes slightly in the Savannah River prior to 1954. Stevens Creek Dam, a small hydroelectric dam constructed in 1914, is located 21 river kilometers (RK) downstream of Thurmond Dam (Figure 2). New Savannah Bluff (NSB) lock and dam, a 4-meter overflow dam constructed in 1937, is located 53 RK downstream of Thurmond Dam (Figure 2). Both provide partial but relatively insignificant re-regulation of daily average releases from Thurmond Dam. The Stevens Creek Dam is capable of providing complete re-regulation of flows below 8,000 cfs (USACE 2000). Releases from Thurmond Dam greater than 20,000 cfs cannot be controlled by the NSB lock and dam (USACE 2000).

Between Stevens Creek Dam and NSB lock and dam is the Augusta Diversion Dam, which diverts between 1,500 and 3,000 cfs from the Savannah River into the Augusta Canal (USGS 02196485). Construction of the canal was completed in 1845 in order to provide a water supply and eventually, hydroelectric power to the city of Augusta (Mooneyhan & Leonard 2003). The diverted water eventually returns to the main channel after passing through Augusta (Mooneyhan & Leonard 2003). Thurmond Dam, Stevens Creek Dam, NSB lock and dam, and the Augusta Canal are all located upstream of the sites in this study (Figure 2).

To fulfill navigation requirements determined by USACE and authorized by Congress in 1957, USACE undertook a number of additional modifications to the Savannah River following construction of Thurmond Dam. These modifications occurred downstream of Thurmond Dam; they included dredging practices to widen and deepen the channel and construction of pile dikes and bend cutoffs. These practices ended in 1979, when commercial shipping on the Savannah River was discontinued. Although channel maintenance was discontinued in 1979, channel modifications have resulted in changes in sediment load, sediment composition, and channel structure in the Savannah (USACE 1992). The Army Corps of Engineers has identified 40 cut-off bends remaining largely disconnected from the Savannah main channel; the creation of these cuts has removed approximately 13% of the lower Savannah River's original 330 km (USACE 1992). Six of these cutoff bends are located upstream of the sites used in this study, and six are located in close proximity (within 8 RK) of sampling sites.

Records from two USGS gages on the Savannah River, both downstream of NSB lock and dam (Figure 2), indicate significant alteration in several hydrologic characteristics of flow within the channel following construction of Thurmond Dam in 1954 (Hale & Jackson 2003). The alterations can be summarized as follows: lower mean monthly flows in the months of December through April and July through September; higher mean monthly flows in the months of May, June, October, and November; reduction in magnitude of peak flows; higher seven-day low flows; and lower flood recurrence. The shape of the hydrograph also indicates a reduction in intra-annual variability (Hale & Jackson 2003).

The combined activities of dredging, straightening, and reservoir operation have resulted in discernable changes in channel configuration of the Savannah River. Thurmond Dam has likely contributed heavily to these changes, having decreased the magnitude and increased the return period of the pre-dam 1-2 year flood, which is the channel-forming flow (Hale & Jackson 2003). Sediment dynamics have also been affected by dam operations. Reservoirs trap sediment; the result is “sediment-deprived” waters downstream of the reservoir. Water flow below the dam will erode the bed of the river, thereby restoring the bedload appropriate for the river’s competence. This phenomenon leads to channel deepening and straightening downstream of a dam (Knighton 1998). The practices of straightening, dredging, and levee construction also result in both channel incision and narrowing (Knighton 1998, studies cited in Surian & Rinaldi 2002). These activities ultimately lead to less connection between the river and its adjacent floodplain.

Although a great deal of information exists on how the hydrology of the Savannah River’s main channel has changed over the last century, little is known about the hydrologic regime of the Savannah River floodplain. Preliminary analysis using a limited number of floodplain cross-sections suggests that in general, flooding has been greatly reduced on the floodplain (Meyer et al. 2003). It is not known how higher mean monthly flows in May and June in the main channel have affected water levels on the floodplain. Some studies suggest, however, that the lower-lying sloughs and backswamps adjacent to the channel have experienced greater magnitudes and longer durations of flooding during May and June following dam construction (Schneider & Sharitz 1986, Sharitz et al. 1990, McLeod et al. 2000).

SAMPLING SITES

Location of cypress trees on the Savannah River floodplain. *Taxodium* grows in three different types of geomorphic settings on the Savannah River floodplain. These areas are termed River (RI), Levee (LE), and Backswamp (BS) in this study. RI areas are located directly adjacent to the main channel, either on the face of a levee sloping toward the river or at a break in the levee, i.e. where a small side channel enters the main channel of the Savannah River (Figure 3a). The hydrology of these areas is the same as that of the main river channel, in that

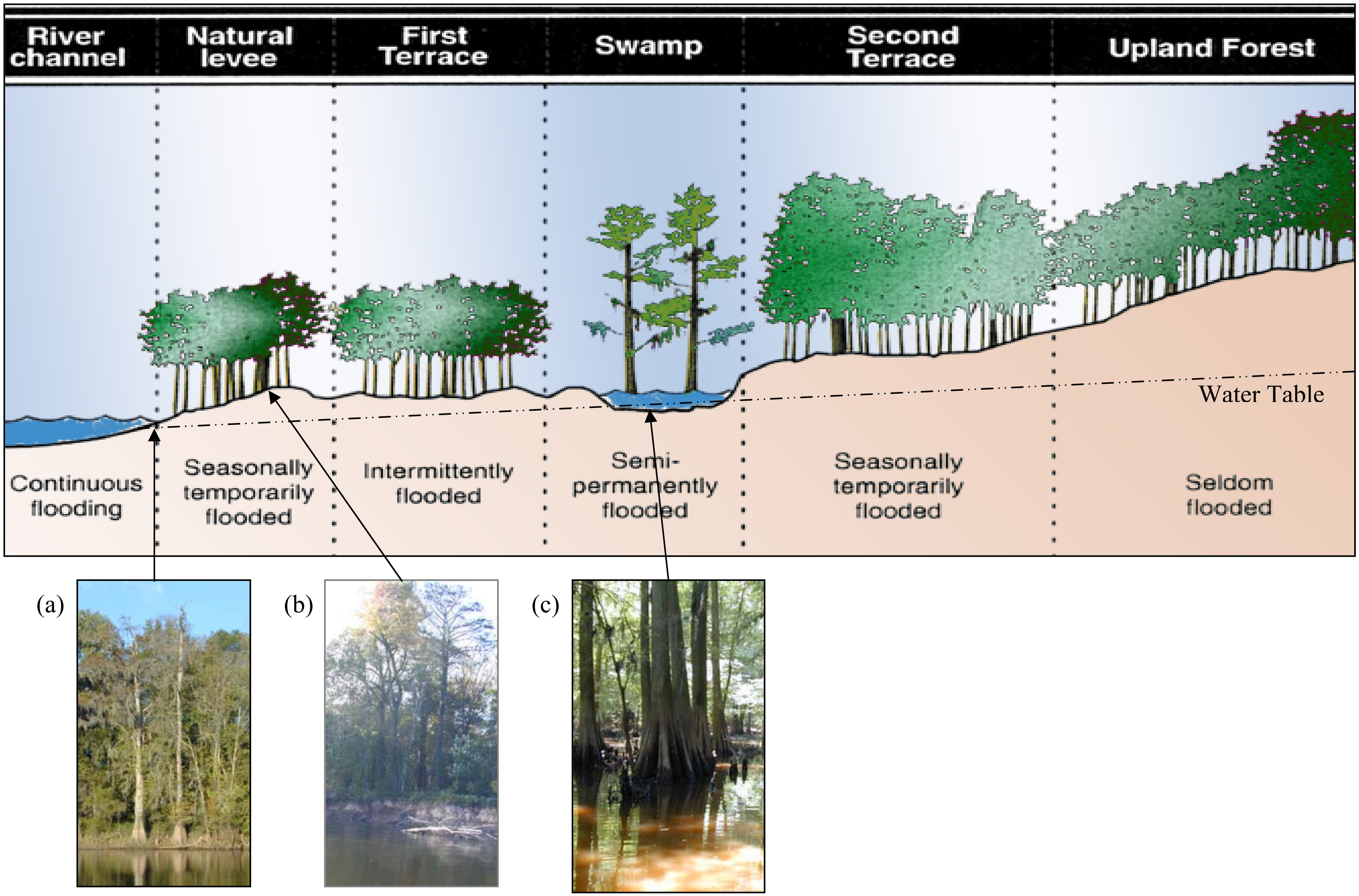


Figure 3. Relative locations of trees at (a) river, (b) levee, and (c) backswamp sites. Floodplain schematic taken from Mitsch & Gosselink (2000). Water table (‾ ·· ‾ ··) is based on schematic from Richardson & Vepraskas (2001).

the rise and fall of the river directly determines whether or not the trees in these areas are flooded. These sites likely have a great deal of hyporheic exchange in the rooting zone, since shallow groundwater is entering the stream in this area (Richardson & Vepraskas 2001). LE sites are located in drier areas on top of the levee next to the main channel (Figure 3b). These areas are flooded only when the water in the main channel is high enough to reach the top of the levee, and tend to have lower shallow groundwater tables (Richardson & Vepraskas 2001). BS areas, located further away from the river in the floodplain, have a less direct connection with the hydrology of the main channel. These areas are located in lower-lying areas behind the levee next to the main channel (Figure 3c). Backswamps are usually created by either an old meander bend (oxbow) of the main channel that has one or both of its entrances filled in with sediment or by a low-lying landscape behind the levee that is adjacent to a tributary to the main channel. Flooding occurs when the river reaches a level high enough to breach the entrance to the oxbow or when water backs up in the tributary and spills into the backswamp. Backswamps can also experience flooding due to rising groundwater, which is close to the soil surface in these areas (Richardson & Vepraskas 2001).

Species composition of floodplain areas. RI and BS forest canopies are largely dominated by *Taxodium*. RI areas have sparsely dispersed trees, but nearly all these trees are *Taxodium*; BS areas tend to have long stretches of nearly pure stands of *Taxodium*. LE areas, on the other hand, are usually characterized by 1-2 *Taxodium* trees surrounded by levee dominants such as sycamore, maple, and elm.

MATERIALS AND METHODS

Site selection. Thurmond Dam is located at river kilometer (RK) 355 (Figure 2). Study sites were located over a 32-kilometer stretch of the Savannah River from 72 to 104 RK below the dam (Figure 2). The site furthest upstream was Silver Bluff Plantation (SB), at RK 283; the furthest downstream site was at RK 251, on the Savannah River Site near Upper Three Runs (UTR) (Figure 4). Cowden Plantation (CP) is between these sites, around RK 270 (Figure 4). This stretch was chosen to maximize the signal of hydrologic change in the tree growth record; Meyer et al. (2003) demonstrated a diminishing influence of Thurmond Dam on the hydrology of the Savannah River as sites increased in distance downstream from the dam. I avoided areas adjacent to agriculture or areas extensively logged in the last century. Logging and agricultural practices add nutrients and/or decrease competition for light within a forest canopy, potentially confounding the effects of overbank flooding on tree growth rates. Appropriate sites were selected using GIS and topographic maps, historic aerial photographs, and ground and air reconnaissance trips on the Savannah River.

TREE SAMPLING PROTOCOLS

Tree selection. A set of pre-determined criteria was used to identify individual *Taxodium* trees for sampling. Trees with larger diameters were favored over those with smaller diameters, since trees at least 60 years or older were required for pre-dam analyses. Diameter is not always a good indication of the age of a particular *Taxodium* tree; exact age of individual trees was not determined until cores were analyzed. Numerous studies (Mitsch & Ewel 1979, Keeland & Conner 1999, Ewel & Wickenheiser 1988) have suggested that at least in the first few years of growth, competition can have a strong influence on growth of individual *Taxodium* trees. Of particular importance in competitive interactions are light and nutrient availability, which can

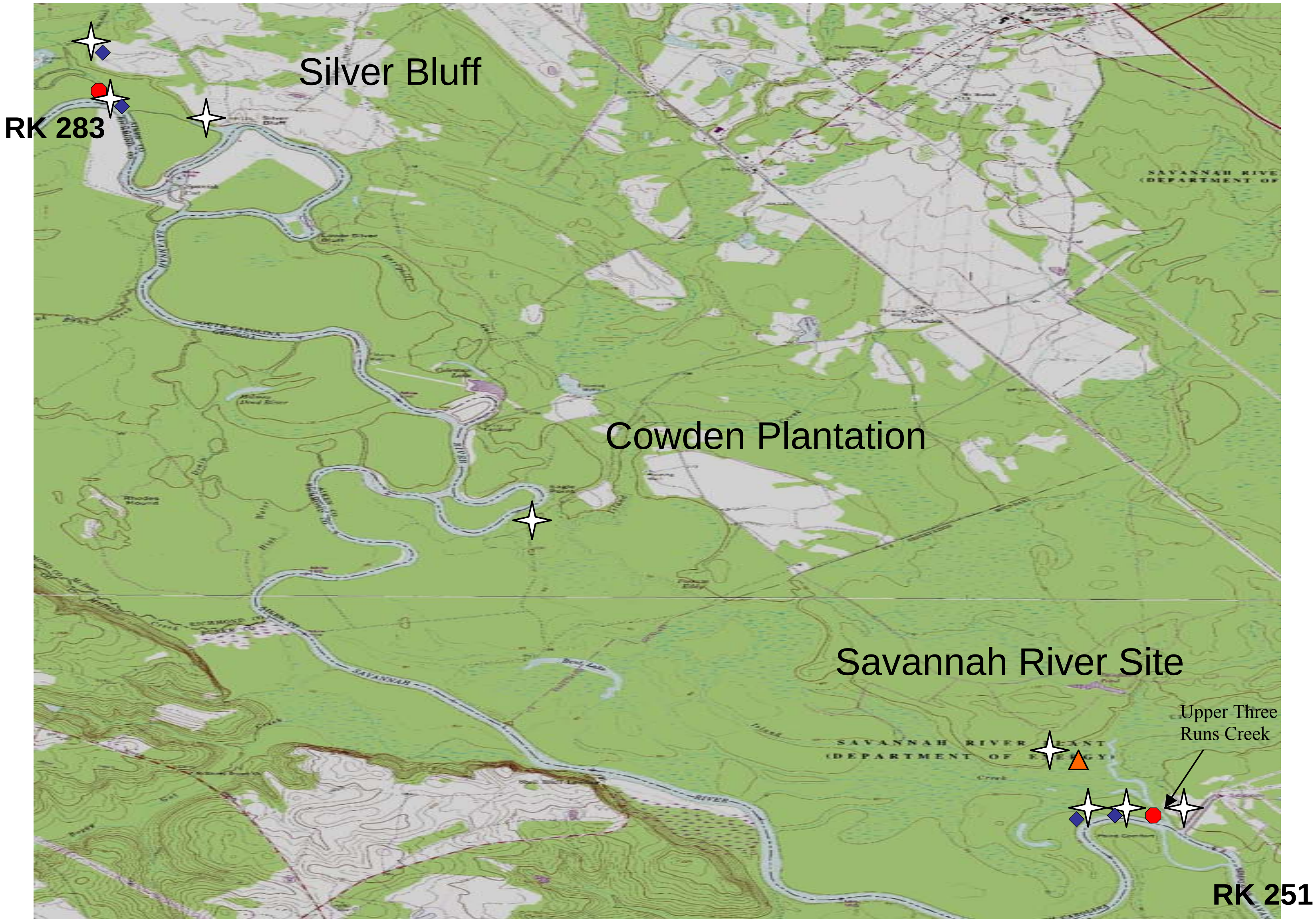


Figure 4. Map of Study Sites. Legend: star = tree sampling site; red circles = groundwater well, blue diamonds = groundwater well + HOBOs, orange triangle = Stevens Recorder

have an equal or stronger effect on tree growth than flooding (Conner & Day 1992, Conner & Flynn 1989, Mitsch & Ewel 1979, but see Visser & Sasser 1995). To minimize the potentially confounding effects of competition on individual tree growth, only *Taxodium* trees that appeared to be canopy dominants were sampled. To avoid surges in growth caused by release, or sudden availability of light due to death of nearby neighbors, trees located near large and/or obvious stumps were avoided. A total of 36 trees were cored: 13 RI trees, 10 LE trees, and 13 BS trees.

Core extraction. A minimum of two cores were extracted from each *Taxodium* tree using a 12" increment borer according to methods outlined in Jozsa (1988), Phipps (1985), and Stokes & Smiley (1968). Cores were taken above the butt-swell of the tree, at roughly 180^{o} from one another when possible. These procedures were used to prevent the common problem of missing rings or other anatomical features frequently occurring in *Taxodium* wood that can cause problems in analyzing tree-ring data (Bowers et al. 1990). The side of the tree to core was determined by the lean of the tree; cores were taken at a 90^{o} angle to the lean. A lean in a tree creates abnormal patterns in growth, called reaction wood, on the underside of the lean; this is the tree's attempt to "right itself," i.e. grow perpendicular to the ground, towards the light (Harlow 1970). The diameter of the tree was taken at the same height at which the cores were extracted for all trees, with the exception of some that were leaning out over the river ($n = 5$). In the case of these trees, cores could be taken from the side of the tree facing land, but the girth of the trunk was too wide to get the tape measure around the trunk from the land side of the tree.

Processing cores. Increment cores were placed in straws following collection and dried at 38°C for 2-3 days (B.D. Keeland, USGS, *personal communication*). Once dry, cores were affixed to wooden mounts with a water-based adhesive (Ford 1999) and sanded with the following grit sequence of sand paper: 200, 400, 600, then fine grit aluminum oxide 272L-5 mil sandpaper.

ANALYSIS OF TREE CORES

Cross-dating. A common pattern of inter-annual variability in growth across a population of trees is called a chronology. If the shared pattern of inter-annual variability in tree ring properties is strong enough, and if a long enough series of rings is available in each core, then it is possible to match the ring pattern of wood of unknown age against dated wood and thus attribute each growth ring in the former sample to a calendar year (Hughes 2003). This process is called cross-dating (Stokes & Smiley 1968).

In order to develop a chronology for RI, LE, and BS tree populations, calendar years were assigned to annual rings by carefully examining cores and noting missing or false rings on each core. Ring widths were measured to the nearest µm using a Henson stage recorder and optical reader. Few cores had missing rings; those rings identified as missing were assigned a value of 3 µm with the assumption that a small, undetectable amount of growth had occurred in that year, despite the fact that no ring was visible (T.W. Doyle, USGS, *personal communication*).

Although cores from 36 trees were originally collected, cores from about a third of the trees (8 RI, 3 LE, and 2 BS) demonstrated cross dating problems under examination. These trees were therefore excluded from further analysis.

Cross-dating for each series (core) was verified using the program COFECHA (Grissino-Mayer et al. 1997, Holmes 1983) (see Appendix 2). COFECHA removes low-frequency variance from individual series (cores) by (1) fitting a cubic smoothing spline, (2) removing persistence by autoregressive modeling, and (3) log-transforming the series of rings. These procedures are done, respectively, to (1) remove the influence of age on growth (trees grow faster when they are younger), (2) remove the influence of the previous year's growth, and (3) weigh proportional differences in ring measurement more equally.

A master chronology was compiled by averaging all series except the one to be tested. Correlation analysis between the test series and the master chronology was then used to check dating and measurement accuracy. This procedure was repeated for each core. If problems in dating (i.e. segments with low correlation to the master chronology) were flagged by COFECHA, increment cores were examined to correct the series if possible. Series that could not be corrected (one RI tree) were excluded from growth analyses to ascertain that potential dating errors were not influencing the outcome of the analysis.

Of the 36 trees cored for this study, 22 were successfully dated, cross-validated with COFECHA, and used for analysis: 5 RI trees, 7 LE trees, and 10 BS trees. Tree locations are shown in Figure 4.

HYDROLOGIC SAMPLING PROTOCOLS

Surface water. The hydrologic relationship between the Savannah River main channel and areas of SB and UTR was determined using a Type F Stevens recorder, HOBO temperature loggers, and field observations. Surface water levels were monitored at various sites for 6-9 months (Table 3, Figure 4). SB surface water levels were monitored at two points on the levee (sb_le1 and sb_le2) and one point in the backswamp (sb_bs1) using HOBO temperature loggers. Surface water levels were monitored at UTR at three points on the levee (utr_le1, utr_le2, and utr_le3) using HOBO temperature loggers and at one point in the backswamp (utr_bs1) using a Stevens recorder. I noted surface water levels at UTR at one point on the river (utr_ri1) during one flood episode.

Table 3. Location and period of record for hydrologic monitoring devices.

name	type of monitoring device	period of record	depth of piezometer below surface (cm)
utr_le1	piezometer HOBO gauge	1/29/04 - 9/30/04 9/30/04 - 5/18/05	209
utr_le2	HOBO gauge	11/11/04 - 5/18/05	
utr_le3	piezometer HOBO gauge	2/12/04 - 9/30/04 9/30/04 - 5/18/05	191
sb_le1	piezometer HOBO gauge	4/6/04 - 9/9/04 11/17/04 - 5/18/05	154
sb_le2	piezometer	4/6/04 – 9/9/04	155
utr_bs1	piezometer Stevens recorder	1/29/04 - 9/30/04 1/15/04 - 10/10/04	140
sb_bs1	piezometer HOBO gauge	4/6/04 - 9/9/04 9/9/04 - 5/18/05	34

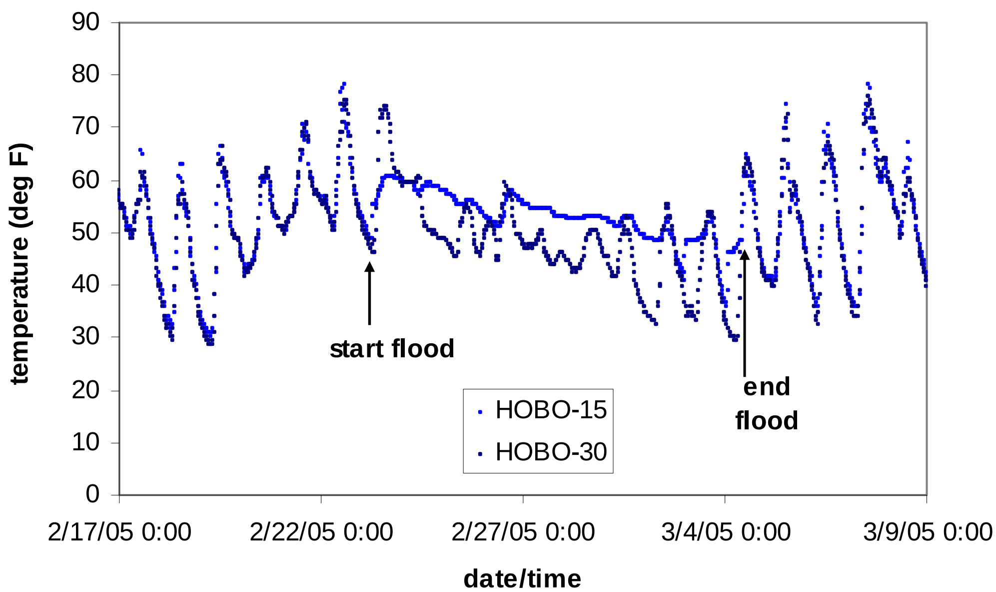


Figure 5. Example of a flood event recorded by two HOBO temperature loggers. HOBO-15 is located 15 cm above the ground surface, and HOBO-30 is located 30 inches above the ground surface. The damping in daily temperature fluctuations of HOBO-15 relative to HOBO-30 during the period 2/23/05 to 3/5/05 indicates that HOBO-15 is submerged in water during this period and HOBO-30 is not.

When a HOBO logger is submerged with water, the typical daily fluctuations in temperature recorded by the logger are severely dampened relative to a HOBO logger not submerged in water (e.g. Figure 5). Loggers were secured at ground level (HOBO-0), 15 cm above ground level (HOBO-15), and 30 cm above ground level (HOBO-30). The HOBO-0 loggers demonstrated damping patterns that appeared unrelated to flooding; the damping was likely due to disparities between soil and air temperatures. For this reason, flooding of a site was defined as the period when temperature fluctuations recorded by HOBO-15 were damped relative to HOBO-30. Flooding at the Stevens recorder was defined to be when the water level recording increased from zero to any higher level of water in a subsequent measurement.

Shallow groundwater. Shallow groundwater depths were monitored every other week using piezometers for 4-9 months at points located on SB and UTR. Two readings were taken each time a piezometer was checked: the maximum water level in the piezometer since the last visit, and the instantaneous water level in the piezometer at the time of the check. Maximum water level since the last visit to the piezometer was measured by leaving a small handful of cork shavings inside the piezometer. As water rises inside the piezometer and then falls, the cork sticks to a pvc pipe left inside the piezometer. The height of the cork shavings inside the piezometer was therefore indicative of maximum water level between instantaneous readings. The location and period of record for each piezometer is shown in Figure 4 and Table 3, respectively.

Soil characteristics. Soil organic matter and texture are important determinants of root conditions for floodplain plants (Sharitz & Mitsch 1993). Soils that are high in clay and have small pore sizes tend to hinder water drainage; they therefore tend to be more poorly aerated than sandy or loamy soils. High clay content of soils can also result, however, in higher concentrations of nutrients such as phosphorus, which has a higher affinity for clay particles than for sand or silt particles (Sharitz & Mitsch 1993). Depth from ground surface to the shallowest layer of exclusively clay soil particles was determined at each piezometer location when piezometers were installed.

HISTORIC DATA

Hydrologic data. Historic mean daily discharge (cfs) values were obtained from USGS gauge 02197000 (hereafter referred to as USGS 02197000) located in Augusta, Georgia. This gauge is located immediately downstream of NSB lock and dam, at RK 302 (Figure 2).

Climate data. Precipitation, temperature, and Palmer Drought Severity Index (PDSI) data were obtained from the National Oceanic and Atmospheric Administration (NOAA). Total monthly precipitation (inches) was obtained from a station in Aiken, South Carolina (NOAA Coop ID 380074). When precipitation data were missing from this station's record, data from Augusta, Georgia (NOAA Coop ID 090500), Augusta Bush Field Airport in Augusta, Georgia (NOAA Coop ID 090495), and Waynesboro, Georgia (NOAA Coop ID 099194) were used. These three stations are all in the same climatic division and within a 40 km radius of tree sampling sites.

The sites used in this study are at the border of climate division 6 in Georgia and climate division 5 in South Carolina. Mean monthly PDSI values were obtained for climate division 6 in Georgia.

ANALYSES

Growth calculations. Width measurements of rings were used to calculate diameter increment and basal area increment. Diameter increment (dinc) is the increase in diameter for a particular year on a given tree. Annual dinc is calculated using the following equation:

(1) $dinc_t = w_{1t} + w_{2t}$

where $dinc_t$ is the diameter increment of the tree in year (t), w_{1t} is the width of the ring assigned to year (t) on one side of the tree, and w_{2t} is the width of the ring assigned to year (t) on the other side of the tree.

Basal area increment (bai) is how much a tree has grown in a particular year relative to its size. Annual bai is calculated by first determining the diameter at core height (dch) of each tree, and then subtracting growth during the intervening years between the current year and a given year for every year in the record:

(2) $diam_t = dch_i - \sum_{j=t}^{i-1} dinc_{j+1}$

where $diam_t$ is the dch of a given tree at the beginning of year (t) and dch_i is the diameter at core height of the given tree at the end of the year the cores were extracted (2003). After calculating diameter at each time step, annual bai can be calculated by assuming the cross section of the tree every year is circular:

(3) $bai_t = ((diam_{t+1} / 2)^2 * \pi) - ((diam_t / 2)^2 * \pi)$

where bai_t is the basal area increment of a given tree in year (t), $diam_{t+1}$ is the dch of the given tree in year (t+1), and $diam_t$ is the dch of the given tree in year (t). Because of the difficulty in obtaining dch for certain trees, analyses involving bai have one fewer RI tree (sb04) and one fewer LE tree (sb07) than analyses involving dinc.

Diameter increment and basal area increment were calculated for each year for each sample tree. These measurements, and the average of these measurements for each year within a population (RI, BS, or LE), were used in all subsequent growth analyses.

Selection of pre- and post-dam years. Mean daily discharge levels in the Savannah River have been recorded by USGS 02197000 for over 100 years. The era preceding the construction of Thurmond Dam had, on average, less annual precipitation and lower PDSI values than the post-dam era (Figures 6-7). Additionally, USGS 02197000 was missing an 18-year period of record in the pre-dam era (1907-1924), excluding six years with relatively wet conditions from potential use in surface water and mixed model analyses (see relevant analysis sections below). To control for a potential bias toward more flooding in the post-dam era, 48 selected years (24 pre-dam and 24 post-dam) that were similar in climatic characteristics were used for hydrologic and growth analyses (Appendix 2). These years were characterized as "dry," "intermediate," and "wet" based on PDSI values (Figure 6, Table 4). Annual growth of *Taxodium* trees in the Savannah River basin demonstrates a positive relationship with both PDSI (Stahle et al. 1988) and precipitation (Stahle & Cleaveland 1992). PDSI is a regional value, and a good general indicator of surface and groundwater levels throughout most of the upper Coastal Plain section of the river basin. PDSI was thus favored over local precipitation for classification of individual years in this study. Since the Savannah River basin drains portions of several physiographic provinces, the precipitation driving particular flow events at study sites may have little correlation to the precipitation occurring within a 40 km radius of the sites (see Figure 7).

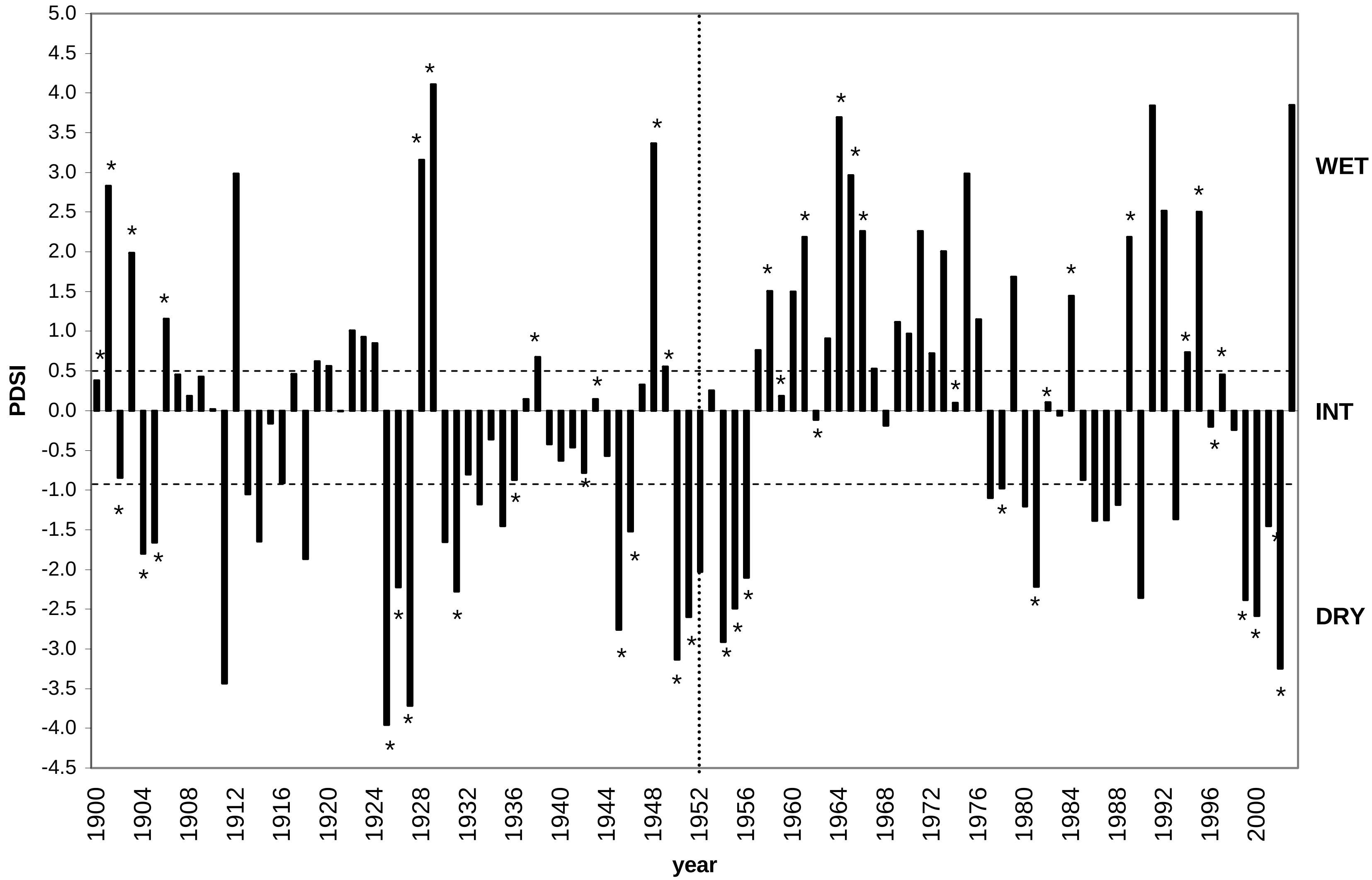


Figure 6. Average PDSI value during the growing season (Apr-Sept) for every year of tree growth record. Wet years: PDSI ≥ 0.5; Dry years: PDSI ≤ -1.0; Intermediate (INT) years: -1.0 < PDSI < 0.5. Dashed horizontal lines separate year types. Dashed vertical line separates pre-dam era from post-dam era. Asterisks indicate years used in this study.

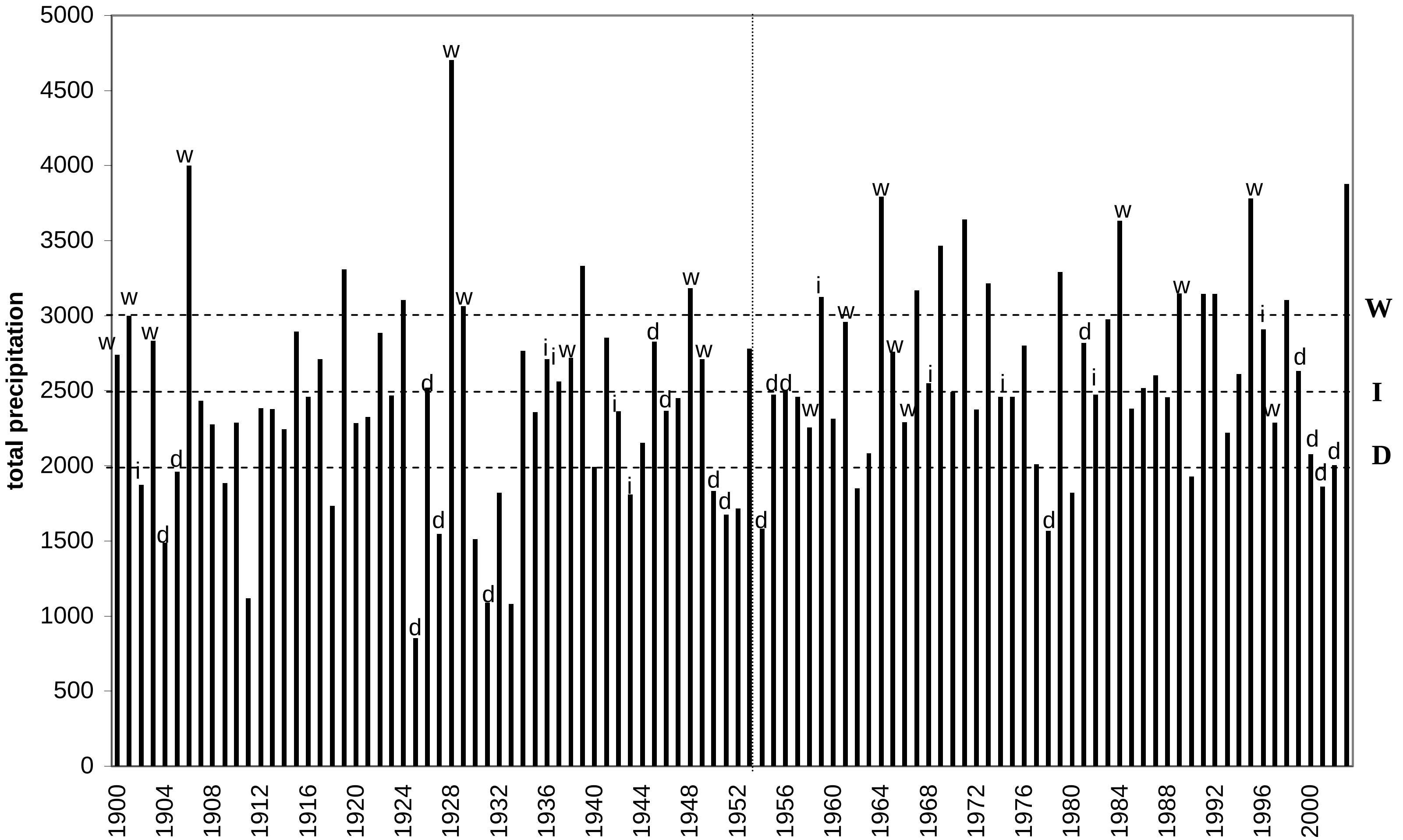


Figure 7. Total precipitation during the growing season (Apr-Sept) for every year of tree growth record. Dashed vertical line separates pre-dam era from post-dam era. Dashed horizontal lines indicate mean total GS precipitation values for dry (D), intermediate (I), and wet (W) years over the period of record. Letters at the end of each bar indicate year type based on PDSI (see Figure 6): dry (d), intermediate (i), and wet (w).

Table 4. Pre- and post-dam years comparison. Significance test was two-tail t-test with assumption of unequal variances. For precipitation ratios (GS / annual, late GS / GS), significance test was two-tail test with assumption of equal variance. Sample sizes for comparison: Dry (pre = 10, post = 9); Wet (pre = 9, post = 10); Intermediate (pre = 5, post = 5). * = marginally significant (p = 0.09) difference. In each case of significance, post-dam is significantly higher than pre-dam. NS = not significant (p > 0.14).

Parameter	Year Type	Pre-Dam Mean	Post-Dam Mean	Pre/Post Comparison
Total Annual Precipitation	Dry	3663.8 ± 241	3969.7 ± 204	NS
	Intermediate	4577.6 ± 328	4967 ± 308	NS
	Wet	5418.2 ± 336	5487.6 ± 297	NS
Total Annual GS Precipitation	Dry	1816.5 ± 197	2169.4 ± 153	NS
	Intermediate	2264.6 ± 182	2704.6 ± 134	*
	Wet	3218.2 ± 229	2951.7 ± 194	NS
Total Annual Apr-Jul Precipitation	Dry	1230.4 ± 152	1389.3 ± 164	NS
	Intermediate	1517.2 ± 99	1759.6 ± 133	NS
	Wet	2039.4 ± 154	2036.6 ± 153	NS
Mean Annual PDSI	Dry	-2.3 ± 0.2	-2.1 ± 0.2	NS
	Intermediate	-0.1 ± 0.2	0.2 ± 0.2	NS
	Wet	1.6 ± 0.6	1.8 ± 0.3	NS
Mean Annual GS PDSI	Dry	-2.6 ± 0.3	-2.3 ± 0.2	NS
	Intermediate	-0.4 ± 0.2	0.0 ± 0.1	NS
	Wet	2.0 ± 0.5	2.0 ± 0.3	NS
Mean Annual Apr-Jul PDSI	Dry	-2.5 ± 0.2	-2.3 ± 0.3	NS
	Intermediate	-0.3 ± 0.3	-0.1 ± 0.1	NS
	Wet	1.9 ± 0.4	1.9 ± 0.4	NS
GS/Annual Total Precipitation	Dry	0.49	0.54	NS
	Intermediate	0.50	0.55	NS
	Wet	0.60	0.55	NS
Late GS / GS Total Precipitation	Dry	0.32	0.37	NS
	Intermediate	0.32	0.34	NS
	Wet	0.36	0.33	NS

Average PDSI was determined for the entire year (Jan-Dec), the growing season (GS) (Apr-Sept), and the early GS (Apr-Jul). Early GS values were calculated separately from GS values for two reasons: (1) most growth in *Taxodium* occurs during the early GS, and growth starts to slow in August (Keeland et al. 1997), (2) hurricane-induced precipitation is fairly frequent during the late GS (Aug-Sept) in the Southeast, and could drastically increase the GS precipitation value in a given year. Annual, GS, and early GS PDSI were used to assign years to "dry" ($\text{PDSI} \leq -1.0$), "intermediate" ($-1.0 < \text{PDSI} < 0.5$), or "wet" ($0.5 \leq \text{PDSI}$) categories (Palmer 1965). In 6 cases (1 dry, 1 intermediate, 4 wet), either annual, GS, or early GS PDSI differed from the assigned category of a particular year. This discrepancy was largely due to the limited number of "wet" years available in the pre-dam era and the predominance of "wet" years in the post-dam era (see above). To ensure a balanced and maximal number of pre- and post-dam years within "dry," "intermediate," and "wet" categories, the average value of annual, GS, and early GS PDSI was favored in determining the classification of a given year in these 6 cases (see Appendix 2). This method appears to have been effective in classifying year type for the following reasons: (1) "Dry," "intermediate," and "wet" years had, on average, significantly ($p < 0.05$) different ($D < I < W$) annual, GS, and early GS PDSI and total precipitation during selected years (ANOVA, t-tests; results not shown); (2) Selected "dry," "intermediate," and "wet" years did not, on average, differ significantly ($p < 0.05$) in annual, GS, or early GS PDSI between pre- and post-dam eras (Table 4); (3) Later analyses using year type as a predictor of growth (see ***Analyses of dam impact on growth***, below) showed consistent significant differences between growth in "wet" and "dry" years (see Results section).

Total local precipitation was used to confirm that dry, intermediate, or wet conditions were relatively uniform over a selected year. The ratios of total GS / total annual precipitation and total late GS / total GS were examined; these ratios would indicate whether single large precipitation events were driving total precipitation values for the year or for the GS. A relatively even distribution of rainfall over the year was indicated by ~0.5 GS / annual precipitation (since GS was defined as 6 months of the year) and ~0.3 late GS / total GS precipitation (since late GS was defined as 2 months out of the 6-month GS). "Dry" and "wet" years did not, on average, differ significantly ($p < 0.05$) in total annual, GS, or early GS precipitation between pre- and post-dam eras (Table 4). "Intermediate" years were, in the case of GS precipitation, marginally ($p \leq 0.09$) significantly wetter in the post-dam period (Table 4). GS / annual and late GS / total GS precipitation ratios did not differ significantly between pre- and post-dam periods, and were close to 0.5 and 0.3, respectively (Table 4).

Surface water analyses. To determine what discharge at USGS 02197000 was required for flooding of LE and BS sites, flood episodes occurring during the monitoring period of this study were identified for each gauge using the criteria outlined in the "***Surface water***" section above. Linear regressions (proc REG; SAS Institute 2001) were subsequently built for each of these flood episodes relating height of water recorded at each floodplain site to discharge recorded at USGS 02197000.

The lag time between a rise in water level at USGS 02197000 and a rise in water level at each floodplain site was unknown. A lag of more than 24 hours may have led to difficulties in interpretation of dam effects, since mean daily discharges at USGS 02197000 were to be used in subsequent analyses of growth at floodplain sites. In order to ensure that the lag time was within a 24-hour period, regressions were designed in the following way: the "pre-flood" and "start" times of a flood episode at each floodplain site were identified (i.e. the time point immediately before water level increased above zero, and the point at which water level increased from zero to 15 cm, respectively). The time point at which water level increased from 15 to 30 cm (the "rise" time) was also identified for each floodplain site. Once the "pre-flood," "start," and "rise" time points were identified, the instantaneous discharge at USGS 02197000 at these three time points was identified. A regression was then run with these instantaneous discharges at USGS 02197000 as predictors of the 0, 15, and 30 cm water levels at each floodplain site. The instantaneous discharge at USGS 02197000 one hour before the "pre-flood," "start," and "rise" times, respectively, was identified next. A new regression was run using these latter discharges as predictors of the 0, 15, and 30 cm water levels at each floodplain site. This process was repeated, lagging the instantaneous discharge at USGS 02197000 one hour further behind for each subsequent regression, until the R-squared value of the regression began to decrease. A decrease in the R-squared value indicated that changes in water level at USGS 02197000 were no longer reflected in the changes in water level at floodplain sites.

The time lag between increases in discharge at USGS 02197000 and increases in water level at each floodplain site varied between sites and between flood events. All calculated time lags were, however, under 24 hours. For this reason, the average value of discharges recorded every 15 minutes at USGS 02197000 was determined for the 24-hour period preceding the "start" time of a flood event at a given recorder (Table 5). The mean discharge value for all flood events was calculated for each recorder; these mean values were then averaged again across all LE and all BS gauges (Table 5). These latter values were defined as the minimum discharge level at USGS 02197000 required to inundate LE and BS study sites over the entire period of record.

The minimum discharge level required to flood RI sites was determined by one field observation. The average value of discharges recorded at 15-minute intervals at USGS 02197000 was determined for a 24-hour period preceding a field observation of roughly 15 cm

Table 5. Determination of minimum daily discharge level required to inundate floodplain sites. Flood start date and time refers to when inundation was first observed at a particular gauge. Average discharge for flood refers to the average 24-hour discharge at USGS 02197000 prior to the observed start time of the flood. sb= Silver Bluff, utr = Upper Three Runs, le = Levee, bs = Backswamp, ri = River.

HOBO Gauge	Flood start date & time	Ave Flood Discharge	Ave Discharge for All Floods
sb_le1	12/17/2004 23:30	14,406	14,728
sb_le1	12/22/2004 2:00	14,432	
sb_le1	2/23/2005 19:00	14,608	
sb_le1	3/17/2005 20:30	14,029	
sb_le1	3/17/2005 20:30	16,167	
utr_le2	12/2/2004 13:00	12,433	12,561
utr_le2	12/14/2004 19:00	12,955	
utr_le2	1/15/2005 5:30	12,279	
utr_le2	2/18/2005 9:30	12,335	
utr_le2	2/23/2005 9:00	11,315	
utr_le2	3/17/2005 11:00	14,048	
utr_le3	10/2/2004 20:00	25,883	19,936
utr_le3	2/25/2005 19:00	20,606	
utr_le3	3/4/2005 11:30	13,319	
Levee Mean			**15,742**
utr_bs1	2/21/04 22:45	8,556	7,967
utr_bs1	3/4/04 20:30	8,774	
utr_bs1	3/9/04 20:30	7,772	
utr_bs1	3/15/04 20:30	9,185	
utr_bs1	6/8/04 18:30	4,680	
utr_bs1	6/9/04 18:30	7,492	
utr_bs1	6/13/04 2:30	5,407	
utr_bs1	9/4/04 16:00	12,042	
utr_bs1	9/28/04 8:30	7,793	
sb_bs1	11/24/04 15:45	7,241	13,158
sb_bs1	12/15/2004 2:15	13,770	
sb_bs1	2/15/2004 23:15	14,112	
sb_bs1	12/16/2004 20:15	14,048	
sb_bs1	12/17/2004 20:15	14,176	
sb_bs1	12/18/2004 22:45	14,070	
sb_bs1	12/20/2004 0:45	13,595	
sb_bs1	12/20/2004 19:15	14,337	
sb_bs1	12/21/2004 20:45	14,174	
sb_bs1	12/24/2004 3:45	12,950	
sb_bs1	12/24/2004 23:45	14,051	
sb_bs1	2/23/2005 6:45	10,614	
sb_bs1	3/3/2005 0:15	13,596	
sb_bs1	3/3/2005 22:45	13,474	
Backswamp Mean			**10,562**
utr_ri1	7/1/04 13:00	5,766	
River Value			**5,766**

of surface water at UTRRI1 (Table 5). This observation was considered sufficient for determining the relationship between RI sites and USGS 02197000 because RI sites were inundated during ~80% of field visits. It was therefore assumed that water level at RI sites was closely linked to water level in the main channel even at low flows, and that observations at multiple time points were not necessary.

The number of days during which mean daily discharge exceeded the minimum level required to flood RI, LE and BS trees was determined for each wet, normal, and dry year during the pre- and post-dam period. This value, or hydroperiod, was also determined for the growing season (GS) and early GS for the levee and backswamp. A t-test assuming unequal variance was run comparing pre- and post-dam hydroperiods during dry, intermediate, and wet years, respectively (Microsoft Excel version 2002). An ANOVA was used to compare hydroperiod between sites within dry, intermediate, and wet years (proc ANOVA; SAS institute 2001).

In order to determine potential changes in the duration of floodwaters between pre- and post-dam periods at a particular site, the number of floods occurring in each year, GS (April-September), and early GS (April-July) was also calculated. A flood was defined as a period of at least 1 day during which mean daily discharge exceeded the minimum level required to inundate river, levee, or backswamp sites. The average durations of these floods were also calculated for each year, GS, and early GS. A t-test assuming unequal variance was run comparing pre- and post-dam number of floods during dry, intermediate, and wet years, respectively (Microsoft Excel version 2002).

Analyses of dam impact on growth. To study the potential impact of dam construction on diameter growth of *Taxodium*, linear statistical mixed models were fit by SAS (proc MIXED, SAS Institute 2001). To account for year-to-year correlation in growth of a given tree, a repeated measures (see below) design was chosen to represent the data, with site (i.e., RI, LE, BS), year type (i.e., dry, intermediate, wet), dam (i.e., pre, post), GS hydroperiod, and GS hydroperiod-squared as predictors of growth. GS hydroperiod was used in these models because regression analysis indicated that this parameter was consistently a strong predictor of tree growth across sites (see Results section). GS hydroperiod-squared was added to the model because regression analysis indicated that the relationship between GS hydroperiod and growth was quadratic (see Results section).

Factor effects on growth in mixed models can be either random or fixed. Fixed effects represent the impact of measured factors of interest. Random effects represent the impact of unmeasured factors. In this case, one random effect captures unmeasured tree level characteristics (such as micro-climate or biological viability) that influence the growth of that specific tree and lead to the correlation of growth in different years within that tree (a random effect of this type is sometimes referred to as a block effect). Another random effect captures year-to-year growth fluctuations not explained by the fixed or random tree effects (a random effect of this type is referred to as residual regression error). Two models were constructed. In the first, the potential effects of the dam in combination with year types (dry, intermediate, wet) on diameter increment and basal area increment were tested. Fixed effects were site (which stayed constant for the duration of the study, and therefore affects the whole tree), dam (changing across study years and thus a within tree effect), and year type (changing across study years and thus a within tree effect). The model can be written mathematically as:

(5) $y_{ijkl} = \mu + \alpha_i + w_{im} + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\beta\delta)_{jl} + (\alpha\beta\gamma)_{ijk} + e_{ijkl}$

Where α_i is the site effect, β_j is the dam effect, and γ_k is the year type effect. w_{im} is the random tree effect, assumed iid $N(0, \sigma^2_1)$. Two-way interaction effects, $(\alpha\beta)_{ij}$, $(\alpha\gamma)_{ik}$, and $(\beta\gamma)_{jk}$, are site*dam, site*year type, and dam*year type, respectively. $(\alpha\beta\gamma)_{ijk}$ is the three-way interaction effect of site*dam*year type. e_{ijkl} is the residual error, also assumed iid $N(0, \sigma^2_2)$. e_{ijkl} and w_{im} are assumed to be independent of each other. y_{ijkl} is diameter or basal area increment of the l^{th} tree at the i^{th} site during the j^{th} dam period during the k^{th} year type.

This first model was run four times: once with all sites included in the model, and three additional times for each individual site (RI, LE, BS). For these latter three runs, site and all site interaction effects were taken out of the model.

In the second model, the potentially changing effect of hydroperiods in combination with dam construction on growth of trees was tested. Fixed effects were site (whole tree), dam (within tree), GS hydroperiod (within tree), and GS hydroperiod-squared (within tree). This model can be written as:

$$(6)\ y_{ijklm} = \mu + \alpha_i + w_{im} + \beta_j + \gamma_k + \delta_l + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\alpha\delta)_{il} + (\beta\gamma)_{jk} + (\beta\delta)_{jl} + (\alpha\beta\gamma)_{ijk} + (\alpha\beta\delta)_{ijl} + e_{ijklm}$$

Where α_i is the site effect, β_j is the dam effect, γ_k is the hydroperiod effect, and δ_l is the $(\text{hydroperiod})^2$ effect. w_{im} is the random tree effect, assumed iid $N(0, \sigma^2)$. Two-way interaction effects, $(\alpha\beta)_{ij}$, $(\alpha\gamma)_{ik}$, $(\alpha\delta)_{il}$, $(\beta\gamma)_{jk}$, and $(\beta\delta)_{jl}$, are site*dam, site*hydroperiod, site*$(\text{hydroperiod})^2$, dam*hydroperiod, and dam*$(\text{hydroperiod})^2$, respectively. Three-way interaction effects, $(\alpha\beta\gamma)_{ijk}$ and $(\alpha\beta\delta)_{ijl}$, are site*dam*hydroperiod and site*dam*$(\text{hydroperiod})^2$, respectively. e_{ijklm} is the residual error, also assumed iid $N(0, \sigma^2)$. e_{ijklm} and w_{im} are assumed to be independent of each other. y_{ijklm} is diameter or basal area increment of the m^{th} tree at the i^{th} site during the j^{th} dam period at the k^{th} hydroperiod and the l^{th} hydroperiod-squared.

Upon running the model using equation (6), it was found that GS hydroperiod-squared was not a significant predictor of growth in the pre- or post-dam era for RI tree growth. GS hydroperiod-squared and all interaction effects with GS hydroperiod-squared were therefore dropped from the model predicting growth of RI trees; GS hydroperiod, which was a significant predictor of growth, was left in the model.

When fixed effects consist of several levels or categories (as do “site” and “year type”) proc MIXED chooses one category to serve as the baseline for pairwise comparisons with the remaining categories. In the fitted model, this design results in the regression coefficient for that baseline level to be set to 0, and all p-values for specific levels are for comparison with the chosen baseline. By default, SAS proc MIXED chooses as baseline the category starting with the latest letter in the alphabet, e.g. “wet” year. When interactions are formed with such a categorical variable, the fitted effects of another variable interacting with it represent those at the baseline level. In models with interactions, proc MIXED was rerun several times, resetting the baselines to examine and test interacting effects at different sites and year types.

The necessity for a quadratic effect of hydroperiod introduced a further complication. In such a model, the linear term represents a tangent line fitted to the growth versus hydroperiod curve at the point where the quadratic term is 0. When hydroperiod is simply squared, this represents a hydroperiod of 0 days. Consequently, the significance of the linear variable and all the interaction effects with the linear variable (GS hydroperiod*dam, GS hydroperiod*site, GS hydroperiod*site*dam) only applied to a linear regression line with a y-intercept at zero days. In other words, the model drew a tangent line to the quadratic curve that crossed the y-axis and

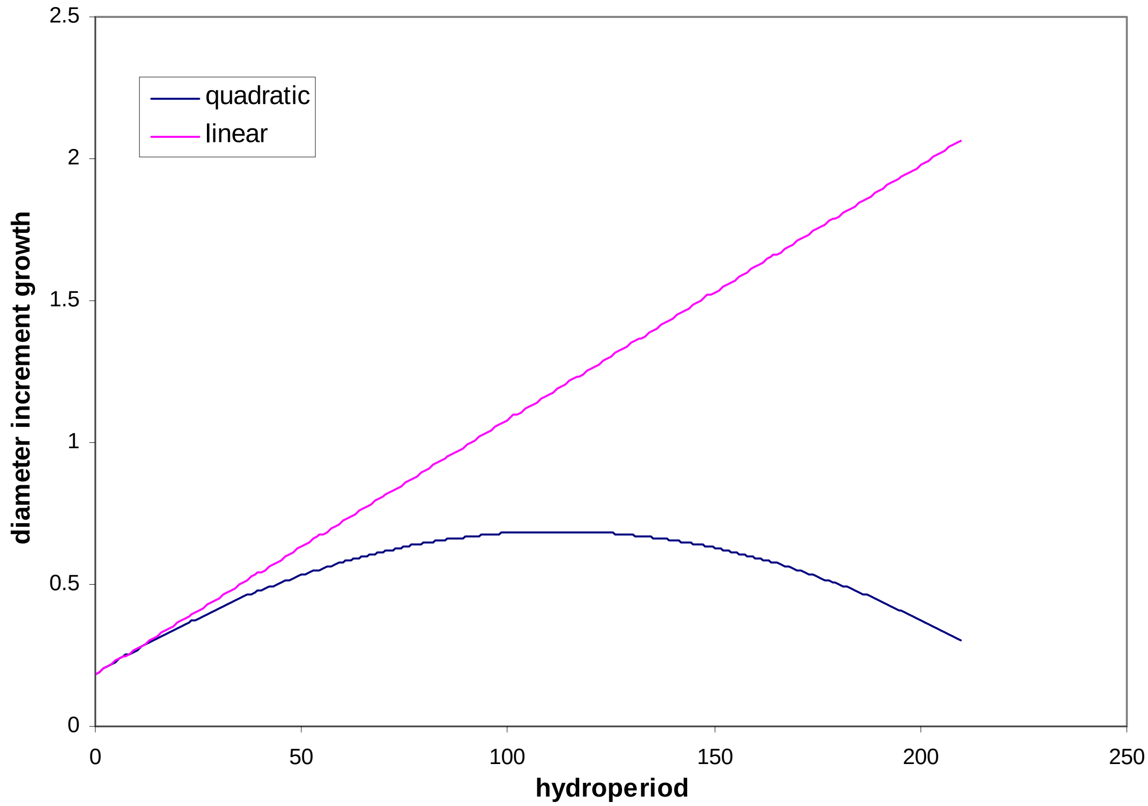


Figure 8. Illustration of comparison of growth at short and long hydroperiods as predicted by proc MIXED. In this particular case, in which there is a quadratic effect of hydroperiod on the predictand (growth), both hydroperiod and $(\text{hydroperiod})^2$ have been included in the model. The model therefore includes a linear effect and a quadratic effect of hydroperiod on growth. The linear effect is modeled by drawing a tangent line to the quadratic curve at the shortest hydroperiod given in the model (i.e. zero). Significance of the linear effect is then determined by comparing predicted growth at short and long hydroperiods along the tangent line.

compared predicted growth responses at high and low hydroperiod values along the tangent line (Figure 8).

To compare growth response between pre- and post-dam periods at longer hydroperiods, I "reset" the y-axis several times by subtracting the same value from all hydroperiod values used to construct the model. Values used for "re-setting" the model were chosen by examining regression curves and seeing where inflections in the quadratic curve occurred. LE trees demonstrated inflections in their growth response to hydroperiods around 10, 25, 35, 45, and 60 days (see Results section, Figure 11). BS trees demonstrated inflections in their growth response to hydroperiods around 45, 60, and 80 days (see Results section, Figure 10). I therefore re-ran the model with values of 10, 25, 35, 45, 60, and 80 days subtracted from each GS hydroperiod used in the model in order to compare growth response as represented by the linear term, in addition to running separate models for each site (RI, LE and BS).

RESULTS

Soil characteristics of study sites. The three LE sites showed variable depths between soil surface and buried clay layers, ranging from a clay layer > 2 m below soil surface, to a clay layer 68 cm below soil surface. The two BS sites had clay layers just below (< 15 cm) or at the soil surface (no A horizon) (see Appendix 3).

Hydrologic characteristics of study sites. Shallow groundwater levels were highly variable at LE sites during the year (Figure 9). BS sites showed a more consistent level of shallow groundwater that was closer to ground surface than LE sites; these sites were also flooded more often than LE sites during the sampling period (Figure 9). In the case of the BS site at SB, surface water was present during nearly every sampling date. At both LE and BS sites, shallow groundwater appeared to closely follow gauge height fluctuations in the mainstem of the Savannah River (Figure 9).

A higher level of discharge in the Savannah River mainstem was required to inundate LE sites than BS or RI sites, and RI sites were inundated at a lower discharge than BS sites (Table 5).

(a)

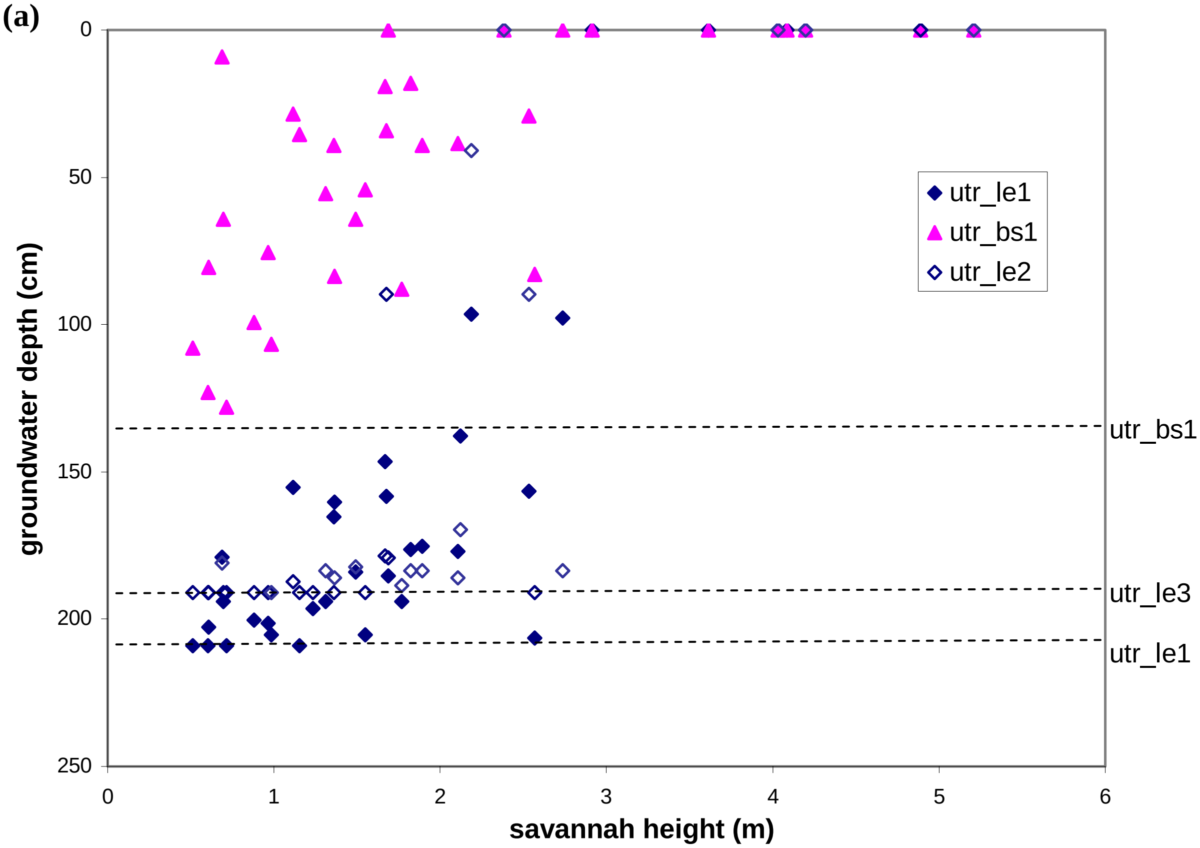


Figure 9. Depth of shallow groundwater and height of Savannah River main channel during the sampling period (1/29/2004 - 9/30/2004). Two types of groundwater (GW) readings are shown here: instantaneous readings and maximum value between instantaneous readings. Savannah River heights matching up to instantaneous GW readings are the average of USGS Augusta gage height readings over a 24-hour period prior to the instantaneous reading. Savannah River heights matching up to maximum GW readings are the maximum USGS Augusta gage height value between instantaneous readings. (a) Depths of Savannah River Site groundwater at levee (LE) and backswamp (BS) sites. (b) Height of Savannah River and depths of Silver Bluff groundwater at levee (LE) and backswamp (BS) sites. Depths of piezometers are indicated by dashed lines.

(b)

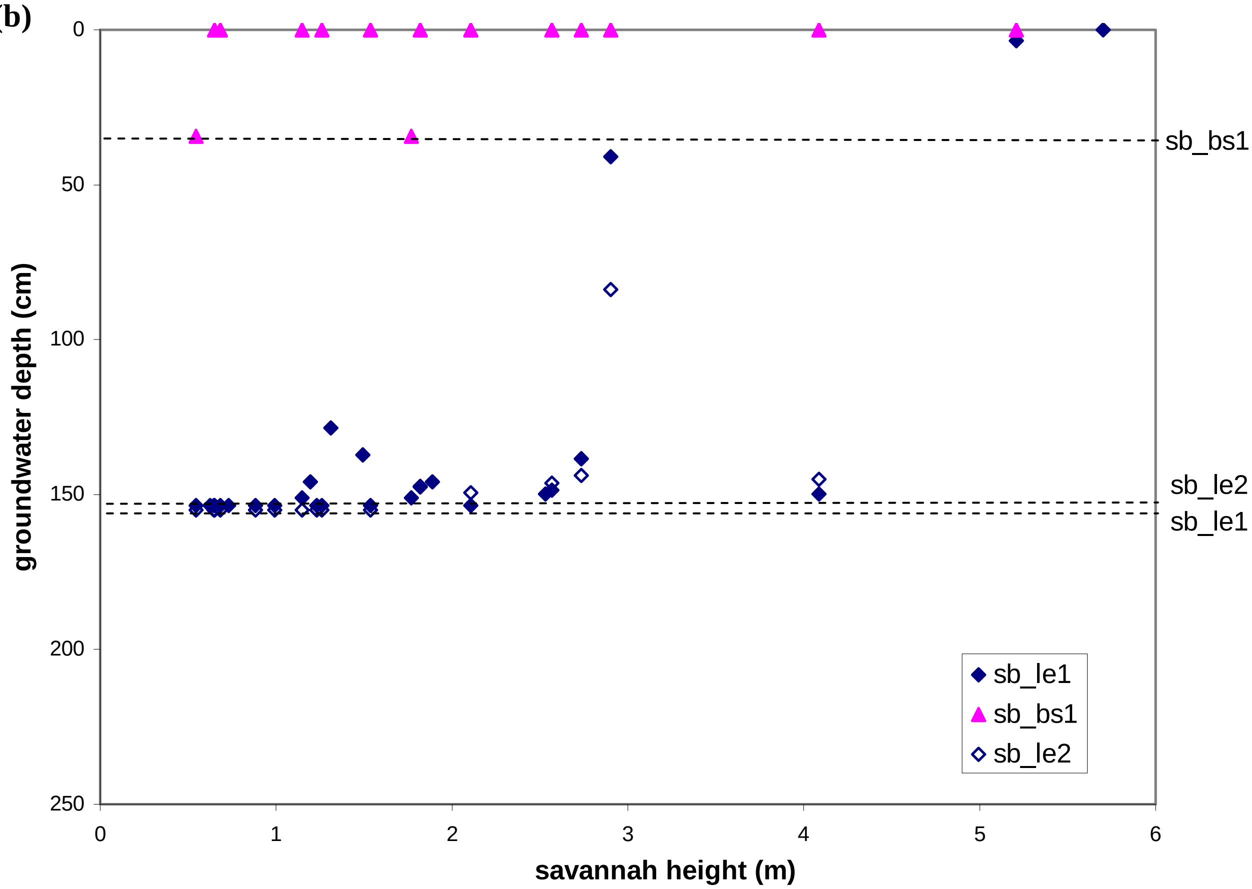


Figure 9 cont. Depth of shallow groundwater and height of Savannah River main channel during sampling period (1/29/2004 - 9/30/2004).

Pre- and post-dam hydrologic comparisons. Pre- and post-dam comparisons in the hydrologic characteristics between sites were all made using the selected 48 years described in the Methods section. During dry years, annual, GS, and early GS hydroperiod of LE and BS sites showed a highly significant ($p \leq 0.01$) post-dam decrease (Figure 10a, Table 6a). Post-dam hydroperiod at these sites was around 20% of that seen in the pre-dam era (Table 6a). A decrease in hydroperiod during the post-dam era was also significant ($p < 0.05$) in LE and BS during intermediate years, with the exception of the early GS hydroperiod on the levee ($p = 0.06$) (Figure 10b, Table 6a). Post-dam hydroperiods were 40-60% of pre-dam hydroperiods for these sites during intermediate years (Table 6a). RI sites did not show a significant difference in hydroperiod between pre- and post-dam periods during dry years (Figure 10a, Table 6a). During intermediate years, however, RI sites showed a significant ($p < 0.05$) increase in annual hydroperiod and a marginally significant ($p < 0.1$) increase in GS hydroperiod; post-dam hydroperiods were 130-140% of pre-dam hydroperiods. During wet years, annual, GS, and early GS hydroperiod were not significantly different ($p > 0.15$) between pre- and post-dam periods at LE and RI sites (Figure 10c, Table 6a). This was also the case for annual hydroperiod at BS sites, but GS and early GS hydroperiod in the backswamp was significantly ($p < 0.05$) lower in post-dam wet years than in pre-dam wet years (Figure 10c, Table 6a).

The number of annual, GS, and early GS floods was significantly ($p \leq 0.06$) lower during dry, intermediate, and wet years at LE sites (Table 7). Number of floods at LE sites was 10-20%, 20-50%, and 40-60% of pre-dam values during the post-dam era in dry, intermediate, and wet years, respectively (Table 7). At BS sites, annual, GS, and early GS number of floods decreased significantly ($p < 0.06$) during wet and dry years (Table 7). BS number of floods during the post-dam period was 30% and 60% of pre-dam values in dry and wet years, respectively (Table 7). The number of floods at RI sites did not change significantly between pre- and post-dam periods in any year type (Table 7).

On average, RI sites had significantly ($p \leq 0.05$) longer annual, GS, and early GS hydroperiods than both LE and BS sites during all year types in both pre- and post-dam periods (Table 6b). LE and BS sites did not have significantly ($p \leq 0.05$) different GS or early GS hydroperiods during dry or intermediate years in the pre-dam era, but LE sites did have significantly shorter annual hydroperiods than BS or RI sites during these years (Table 6b).

(a)

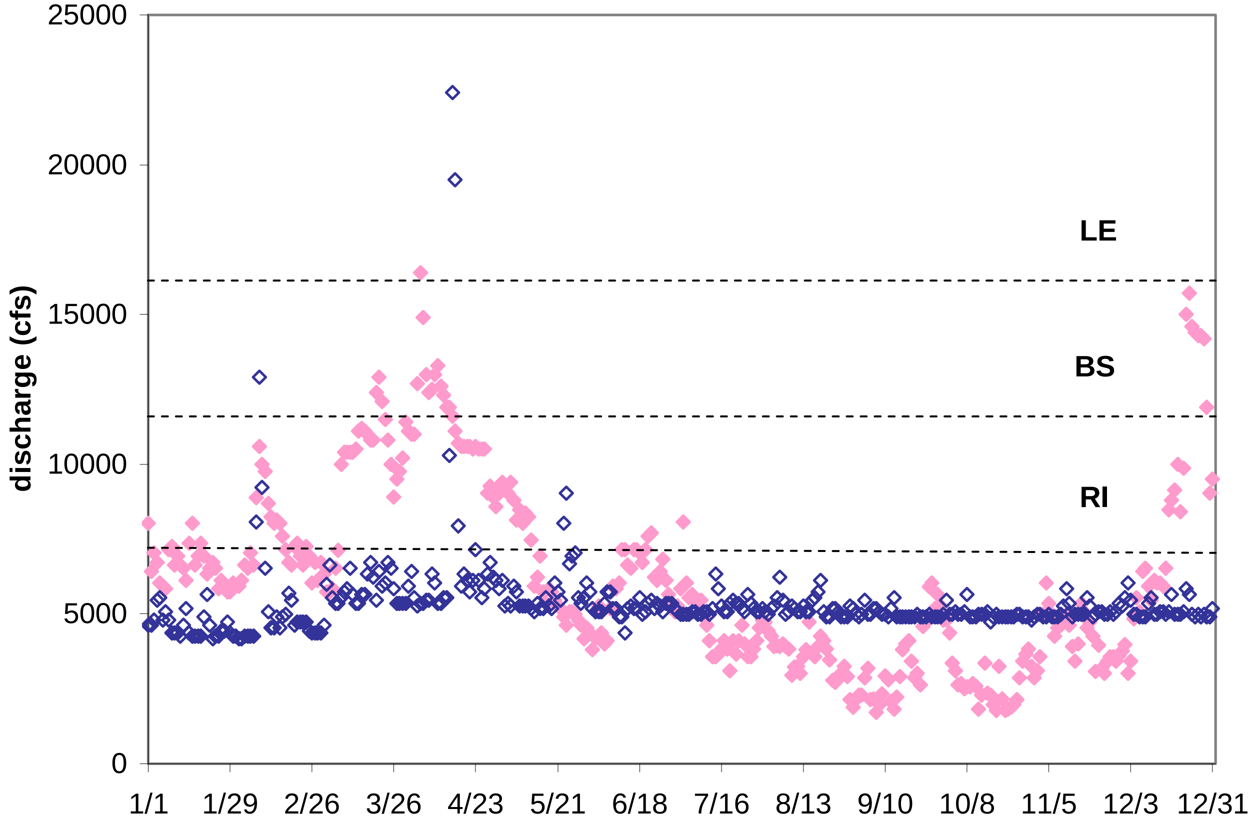
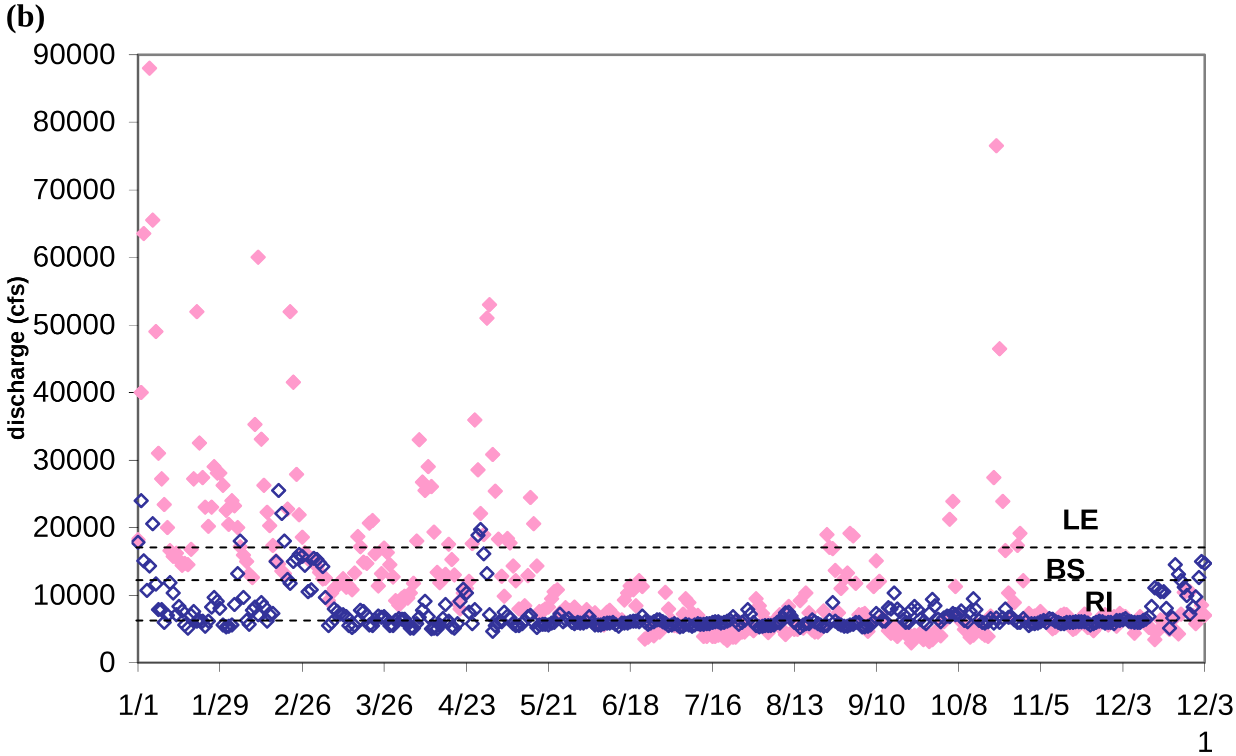


Figure 10. Annual hydrograph in Savannah River main channel for representative (a) dry (pre-dam: 1951, post-dam: 1955); (b) intermediate (pre-dam: 1937, post-dam: 1982); and (c) wet (pre-dam: 1901, post-dam: 1961) years in the pre- and post-dam era. Day of the year is on the x-axis. Mean daily discharge in on the y-axis. Filled pink points = pre-dam, unfilled blue points = post-dam. Dashed lines indicate minimum discharge required to flood river (RI), backswamp (BS), and levee (LE) sites. Note difference in y-axis scale in each figure. See Appendix 2 for precipitation and PDSI data for individual years.



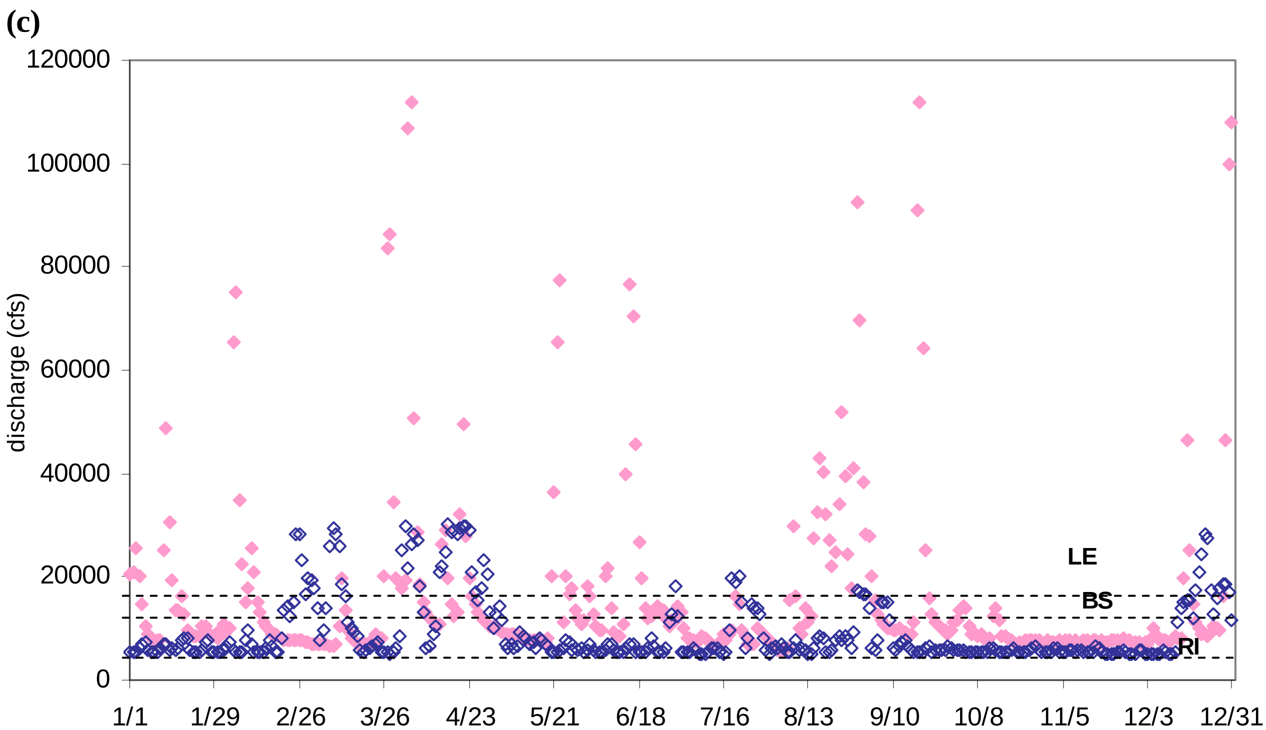


Figure 10 cont. Annual hydrograph in Savannah River main channel for representative (a) dry (pre-dam: 1951, post-dam: 1955); (b) intermediate (pre-dam: 1937, post-dam: 1982); and (c) wet (pre-dam: 1901, post-dam: 1961) years in the pre- and post-dam era.

Table 6a. Comparison of hydroperiod in pre- and post-dam periods. Hydroperiod refers to total number of days that a location experienced surface water. Discharge refers to the minimum mean daily discharge at USGS 020190000 required to flood a location. P-values based on one-tail t-test assuming unequal variances. NS = not significant (p > 0.15).

Location	Discharge (cfs)	Year Type	Hydroperiod	Pre-Dam Mean ± SE	Post-Dam Mean ± SE	Post Mean/Pre Mean	p-value
River	> 5,800	Dry	Annual	167 ± 11	120 ± 39	0.7	NS
			GS	67 ± 7	60 ± 20	0.9	NS
			early GS	54 ± 7	42 ± 16	0.8	NS
River	> 5,800	Intermediate	Annual	237 ± 15	311 ± 22	1.3	0.03
			GS	108 ± 8	146 ± 16	1.4	0.07
			early GS	87 ± 7	94 ± 11	1.1	NS
River	> 5,800	Wet	Annual	293 ± 23	293 ± 23	1.0	NS
			GS	152 ± 9	146 ± 13	1.0	NS
			early GS	111 ± 5	96 ± 10	0.9	NS
Backswamp	> 10,500	Dry	Annual	60 ± 9	13 ± 7	0.2	< 0.001
			GS	20 ± 4	4 ± 2	0.2	0.002
			early GS	17 ± 4	4 ± 2	0.2	0.01
Backswamp	> 10,500	Intermediate	Annual	116 ± 14	68 ± 11	0.6	0.03
			GS	39 ± 6	17 ± 4	0.4	0.02
			early GS	32 ± 5	14 ± 4	0.4	0.02
Backswamp	> 10,500	Wet	Annual	149 ± 18	117 ± 17	0.8	NS
			GS	75 ± 8	43 ± 8	0.6	0.02
			early GS	54 ± 5	32 ± 6	0.6	0.01

Table 6a cont. Comparison of hydroperiod in pre- and post-dam periods.

Location	Discharge (cfs)	Year Type	Hydroperiod	Pre-Dam Mean ± SE	Post-Dam Mean ± SE	Post Mean/Pre Mean	p-value
Levee	> 15,700	Dry	Annual	28 ± 6	5 ± 4	0.2	0.002
			GS	7 ± 2	1 ± 0.5	0.1	0.003
			early GS	6 ± 2	1 ± 0.5	0.2	0.01
Levee	> 15,700	Intermediate	Annual	64 ± 8	38 ± 9	0.6	0.03
			GS	18 ± 3	9 ± 4	0.5	0.04
			early GS	15 ± 3	8 ± 3	0.5	0.06
Levee	> 15,700	Wet	Annual	72 ± 10	69 ± 14	1.0	NS
			GS	34 ± 5	26 ± 7	0.8	NS
			early GS	24 ± 2	23 ± 6	1.0	NS

Table 6b. Comparison of hydroperiod betweeen sites in pre- and post-dam periods. Hydroperiod refers to total number of days that a location experienced surface water. Discharge refers to the minimum mean daily discharge at USGS 020190000 required to flood a location. Same letter(s) within a year type/hydroperiod/dam group indicates no significant difference ($p > 0.05$) as determined by an ANOVA with pairwise Tukey's test. Same letter(s) within a year type/hydroperiod group indicates no significant difference ($p > 0.05$) as determined by a t-test assuming unequal variance. Early GS hydroperiod differences were the same as GS hydroperiod differences, and are therefore not shown here.

Location	Discharge (cfs)	Year Type	Hydroperiod	Pre-Dam Mean ± SE	Post-Dam Mean ± SE
River	> 5,800	Dry	Annual	167 ± 11^{A}	120 ± 39^{A}
Backswamp	> 10,500	Dry	Annual	60 ± 9^{B}	13 ± 7^{F}
Levee	> 15,700	Dry	Annual	28 ± 6^{C}	5 ± 4^{G}
River	> 5,800	Dry	GS	67 ± 7^{A}	60 ± 20^{A}
Backswamp	> 10,500	Dry	GS	20 ± 4^{B}	4 ± 2^{F}
Levee	> 15,700	Dry	GS	7 ± 2^{B}	1 ± 0.5^{F}
River	> 5,800	Intermediate	Annual	237 ± 15^{A}	311 ± 22^{E}
Backswamp	> 10,500	Intermediate	Annual	116 ± 14^{B}	68 ± 11^{F}
Levee	> 15,700	Intermediate	Annual	64 ± 8^{C}	38 ± 9^{G}
River	> 5,800	Intermediate	GS	108 ± 8^{A}	146 ± 16^{A}
Backswamp	> 10,500	Intermediate	GS	39 ± 6^{B}	17 ± 4^{F}
Levee	> 15,700	Intermediate	GS	18 ± 3^{B}	9 ± 4^{F}
River	> 5,800	Wet	Annual	293 ± 23^{A}	293 ± 23^{A}
Backswamp	> 10,500	Wet	Annual	149 ± 18^{B}	117 ± 17^{BC}
Levee	> 15,700	Wet	Annual	72 ± 10^{C}	69 ± 14^{BC}
River	> 5,800	Wet	GS	152 ± 9^{A}	146 ± 13^{A}
Backswamp	> 10,500	Wet	GS	75 ± 8^{B}	43 ± 8^{C}
Levee	> 15,700	Wet	GS	34 ± 5^{C}	26 ± 7^{C}

Table 7. Number of floods in pre- and post-dam periods. Flood refers to presence of surface water at a site during consecutive days. A flood may, however, last one day. P-values result from a two-tail t-test. P values are only reported when they are > 0.15.

Location	Discharge (cfs)	Year Type	Period	Pre-Dam Mean Number of Floods ± SE	Post-Dam Mean Number of Floods ± SE	Post / Pre Number of Floods	Number of Floods p-value
River	> 5,800	Dry	Annual	18 ± 2	18 ± 3	1.0	NS
			GS	9 ± 1	9 ± 2	1.0	NS
			early GS	6 ± 1	5 ± 2	0.8	NS
River	> 5,800	Intermediate	Annual	19 ± 3	17 ± 7	0.9	NS
			GS	11 ± 0.8	11 ± 4	1.0	NS
			early GS	6 ± 1	8 ± 3	1.3	NS
River	> 5,800	Wet	Annual	13 ± 3	17 ± 4	1.3	NS
			GS	7 ± 2	9 ± 2	1.3	NS
			early GS	4 ± 1	6 ± 2	1.5	NS
Backswamp	> 10,500	Dry	Annual	12 ± 1	3 ± 0.8	0.3	0.00002
			GS	4 ± 0.8	1 ± 0.4	0.3	0.005
			early GS	3 ± 0.6	0.9 ± 0.4	0.3	0.01
Backswamp	> 10,500	Intermediate	Annual	13 ± 1	8 ± 3	0.6	NS
			GS	5 ± 0.9	2 ± 1	0.4	0.14
			early GS	4 ± 0.9	2 ± 0.6	0.5	0.13
Backswamp	> 10,500	Wet	Annual	16 ± 2	11 ± 1	0.7	0.06
			GS	8 ± 1	4 ± 0.7	0.5	0.03
			early GS	5 ± 1	3 ± 0.6	0.6	0.03

Table 7 cont. Number of floods in pre- and post-dam periods.

Location	Discharge (cfs)	Year Type	Period	Pre-Dam Mean Number of Floods ± SE	Post-Dam Mean Number of Floods ± SE	Post / Pre Number of Floods	Number of Floods p-value
Levee	> 15,700	Dry	Annual	9 ± 1	0.7 ± 0.4	0.1	0.0003
			GS	3 ± 0.6	0.3 ± 0.2	0.1	0.002
			early GS	2 ± 0.6	0.3 ± 0.2	0.2	0.007
Levee	> 15,700	Intermediate	Annual	13 ± 1	6 ± 0.7	0.5	0.009
			GS	5 ± 0.9	1 ± 0.2	0.2	0.02
			early GS	4 ± 0.9	1 ± 0.2	0.3	0.06
Levee	> 15,700	Wet	Annual	16 ± 2	10 ± 1	0.6	0.04
			GS	7 ± 1	3 ± 0.6	0.4	0.02
			early GS	5 ± 0.9	3 ± 0.6	0.6	0.04

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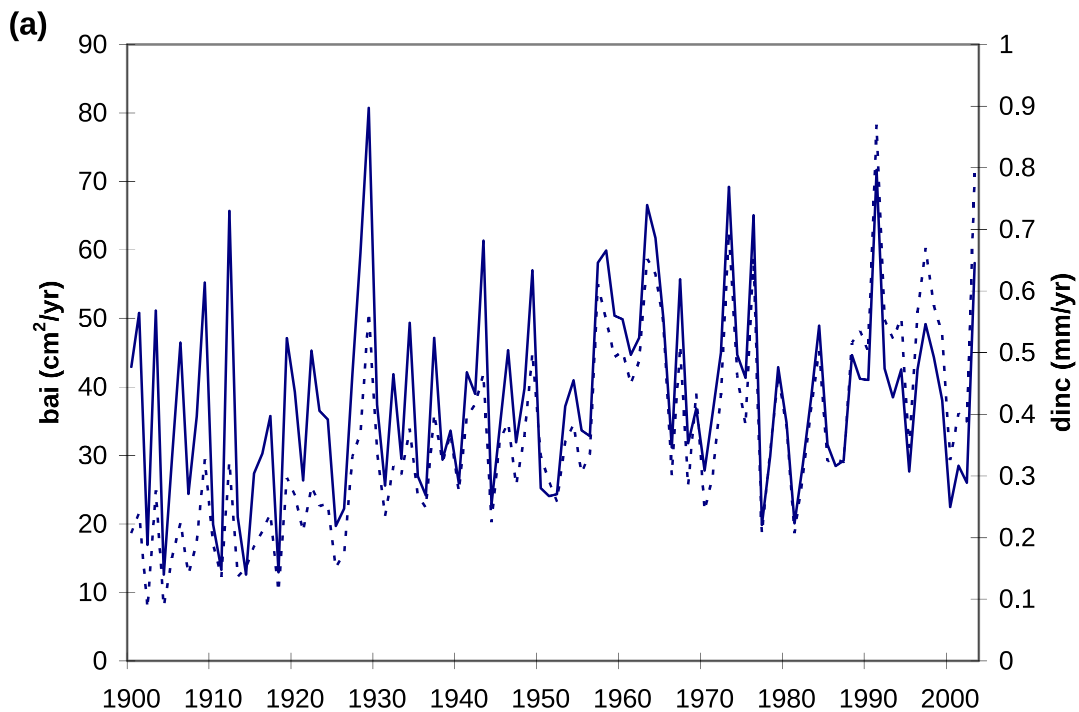
During wet years in the pre-dam era, all sites had significantly different annual, GS, and early GS hydroperiods, in the order LE < BS < RI (Table 6b). The post-dam era showed a pattern identical to the pre-dam era during dry and intermediate years, but during wet years, LE and BS sites did not have significantly different annual, GS, or early GS hydroperiods (Table 6b).

Patterns in growth over period of record. Diameter increment (dinc) and basal area increment (bai) chronologies are shown for the period of record in Figure 11. BS, LE, and RI sites showed similar inter-annual variability over the period of record. Growth trend differences are apparent between the dinc and bai chronologies at each site; dinc declines slightly with age (Figure 11).

Growth responses to hydrology. Diameter increment growth (dinc) and basal area increment growth (bai) of LE and BS trees demonstrated a significant quadratic relationship with GS hydroperiod; growth was highest at intermediate hydroperiods at both sites (Figures 12-13, Table 9). Dinc had a much better fit than bai in this model, as evidenced by the 1000-fold lower residual error (Table 9). Dinc and bai of RI trees did not demonstrate a significant quadratic relationship with GS hydroperiod, and this variable, along with its interactions, was dropped from the model; RI bai and dinc did, however, demonstrate significant positive linear relationships with GS hydroperiod (Figure 14, Table 9).

According to values predicted by the second mixed model (equation (6)), dinc and bai were highest at LE sites at a GS hydroperiod of 17-18 days in the pre-dam era and at a GS hydroperiod of 29-32 days in the post-dam era (Figure 13). At BS sites, dinc and bai were highest at a GS hydroperiod of 54-59 days in the pre and post-dam era (Figure 12). RI trees had lower dinc and bai than BS or LE trees at comparable GS hydroperiods in both pre- and post-



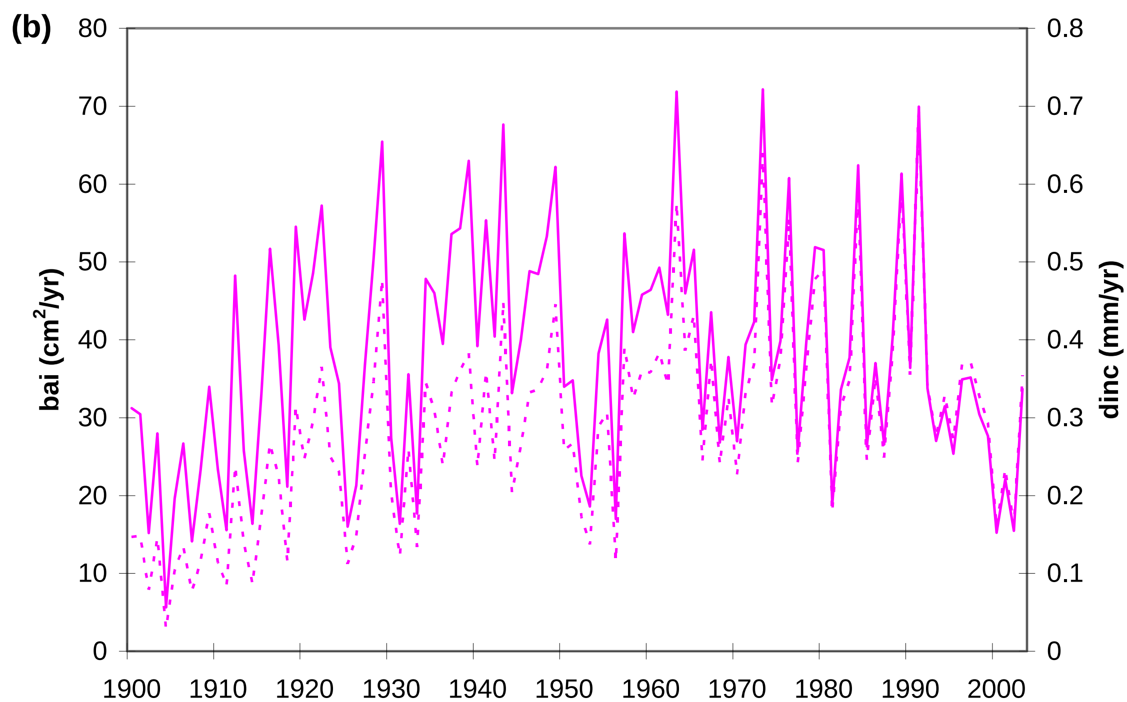


Figure 11. Diameter increment (solid line) and basal area increment (dashed line) over the period of record (1900-2003) for (a) backswamp, (b) levee, and (c) river sites. Thurmond Dam was installed between 1952 and 1954.

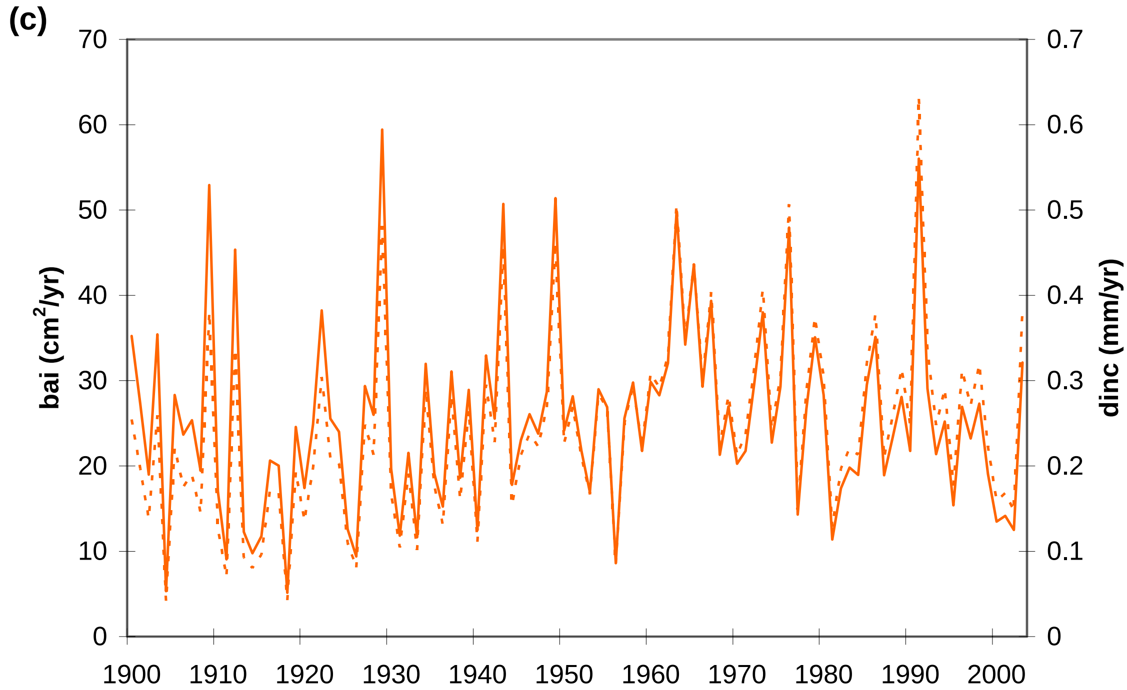
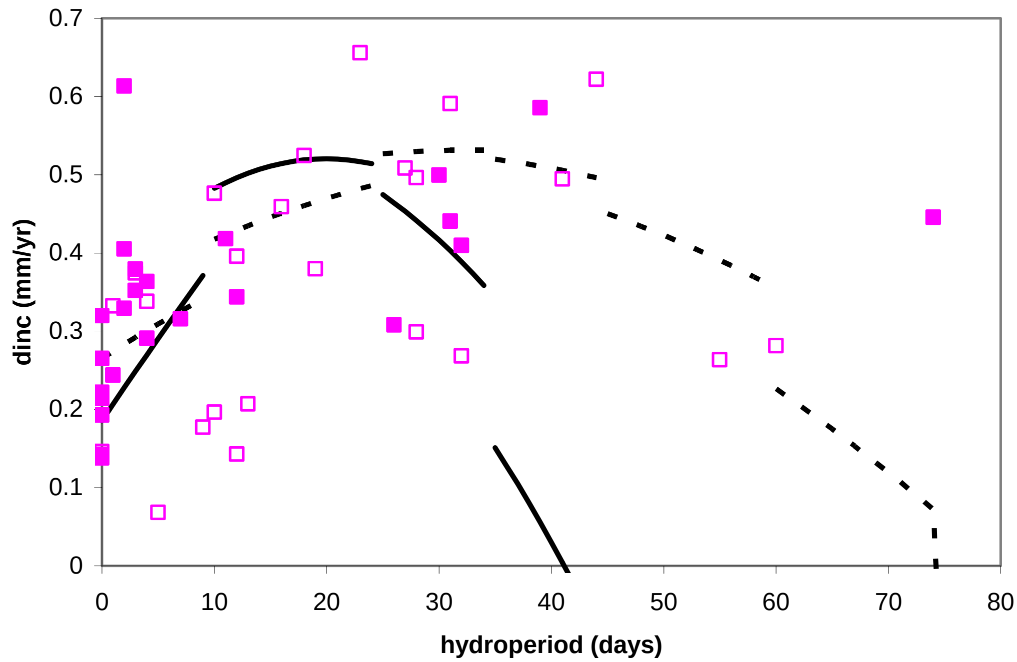


Figure 11 cont. Diameter increment (solid line) and basal area increment (dashed line) over the period of record (1900-2003)

(a)



(b)

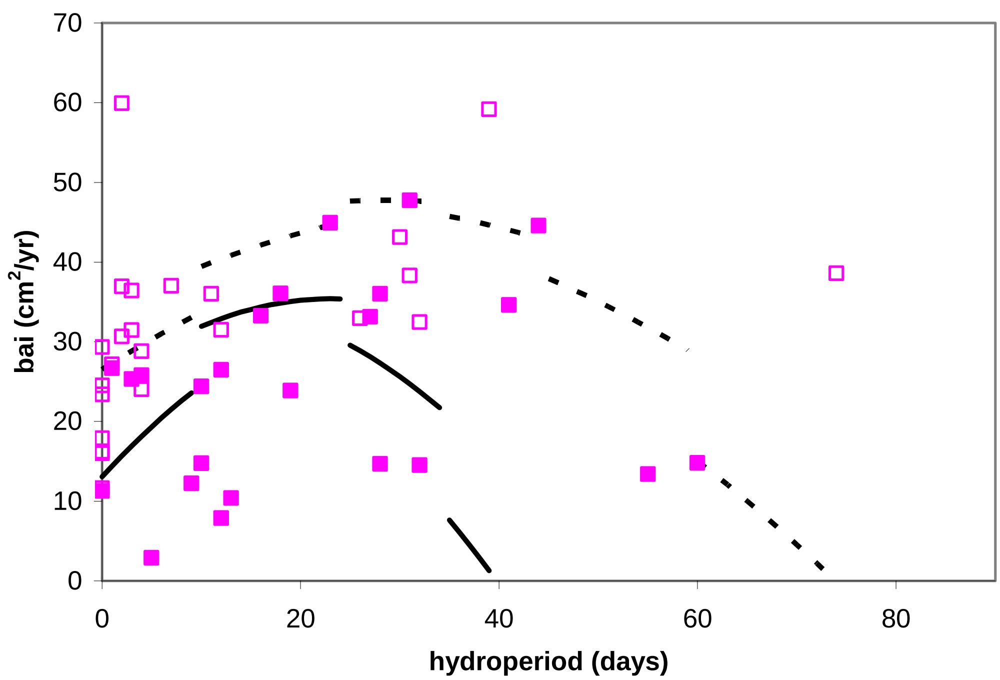
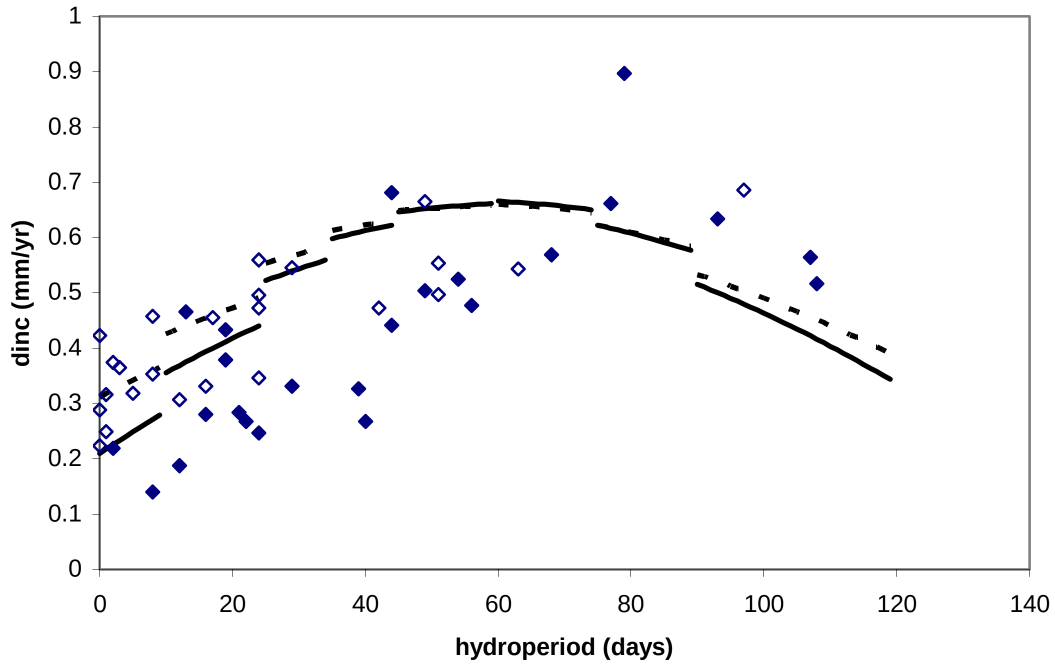


Figure 12. GS hydroperiod as a predictor of (a) mean diameter increment and (b) mean basal area increment at LE sites. Filled data points = pre-dam, no-fill data points = post-dam, solid line = pre-dam relationship as predicted by proc MIXED, dashed line = post-dam relationship as predicted by proc MIXED. See also Table 9.

(a)



(b)

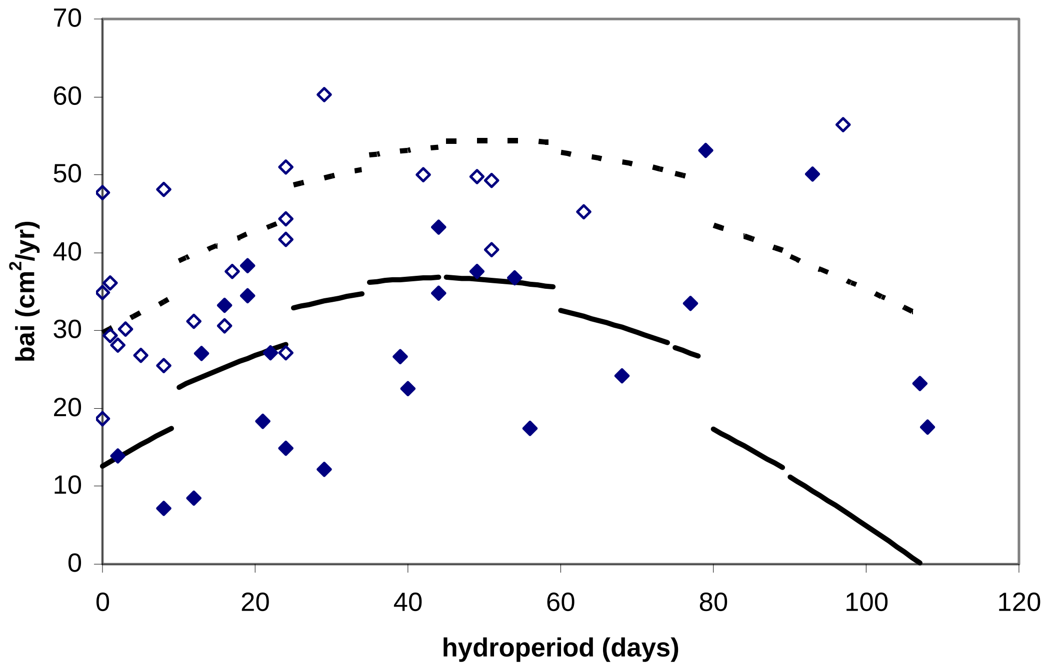


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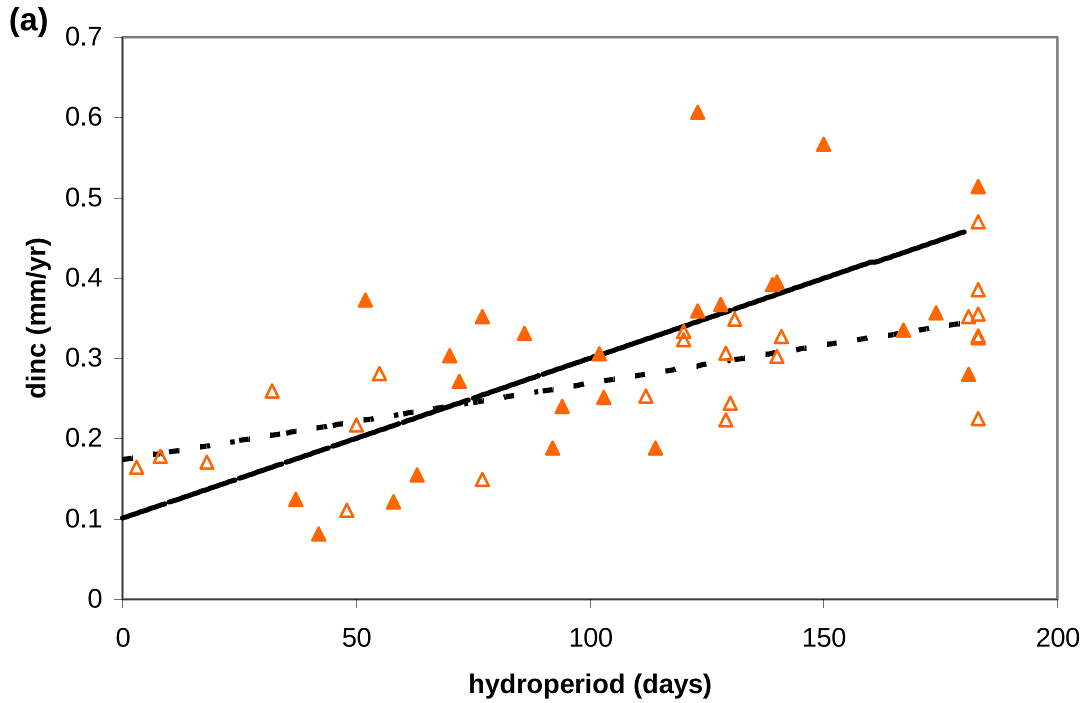
Figure 13. GS hydroperiod as a predictor of (a) mean diameter increment and (b) mean basal area increment at BS sites. Filled data points = pre-dam, no-fill data points = post-dam, solid line = pre-dam relationship as predicted by proc MIXED, dashed line = post-dam relationship as predicted by proc MIXED. See also Table 9.



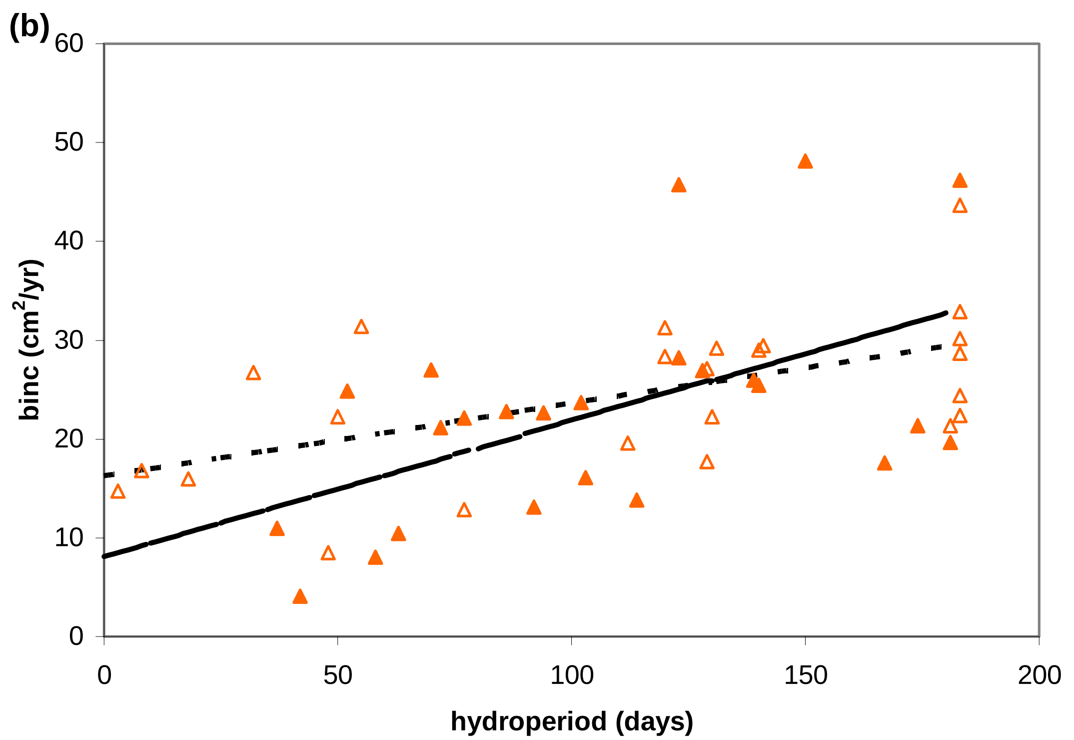


Figure 14. GS hydroperiod as a predictor of (a) mean diameter increment and (b) mean basal area increment at RI sites. Filled data points = pre-dam, no-fill data points = post-dam, solid line = pre-dam regression relationship, dashed line = post-dam regression relationship. Because neither hydroperiod-squared nor dam were significant predictors in the model, they were taken out of the equation to generate the trendlines depicted on the graph.

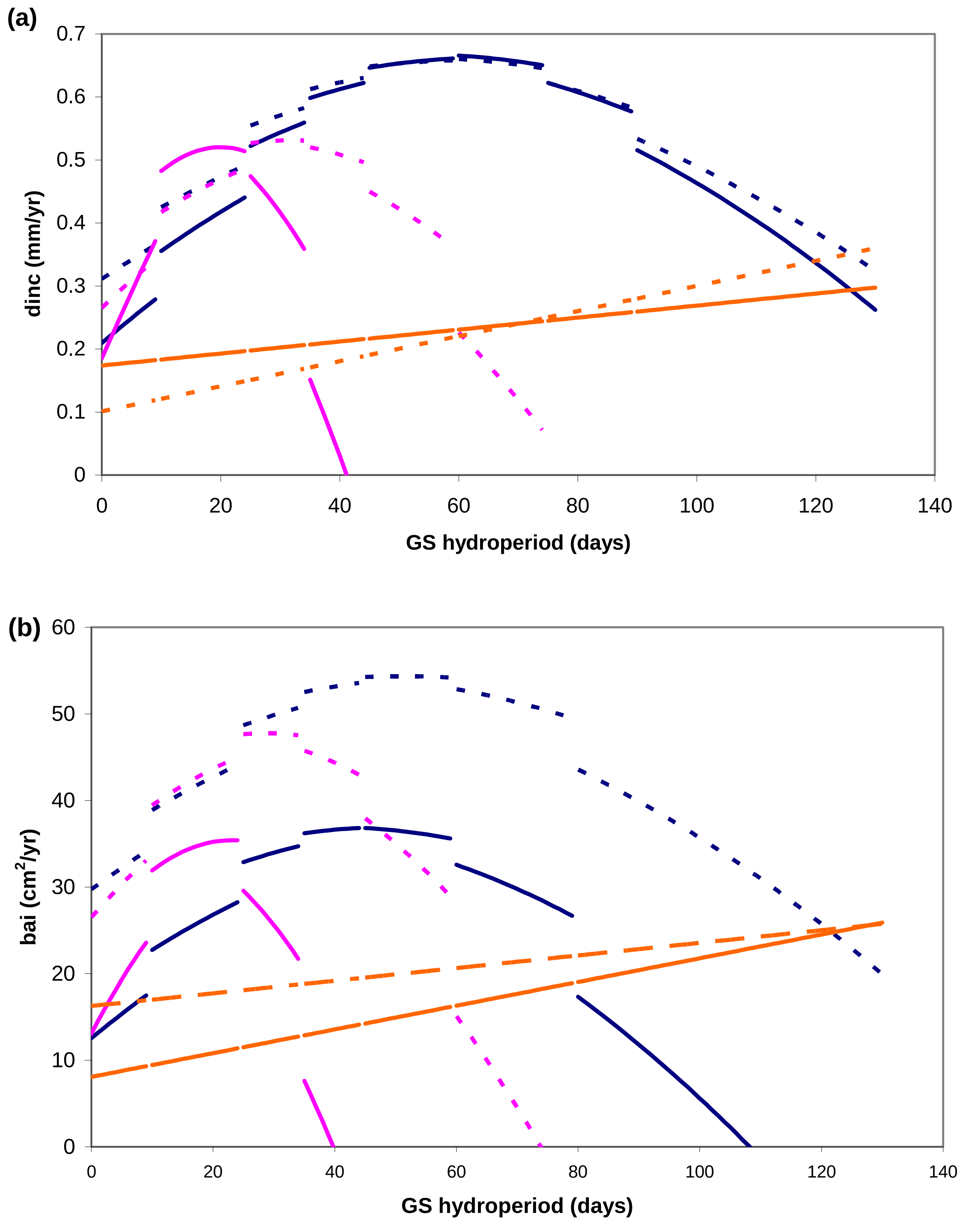


Figure 15. (a) Dinc and (b) bai as a function of hydroperiod at each site as modeled by equation (6). Blue = backswamp, pink = levee, and orange = river. Solid lines = pre-dam, dashed lines = post-dam.

Table 8. Proc MIXED results for the first model with year type as a predictor; the model has been run separately for each sampling site to determine specific effects of dam on each site. The predictand is either diameter increment or basal area increment growth; each column is a predictor. Values in each column represent p-values for each predictor at a given hydroperiod range. Asterisks indicate highly significant effects ($p < 0.01$); p values are only reported when < 0.15. NA = not applicable. In the case of a significant year type effect, models were re-run, re-setting the baseline, to determine which year types were significantly different from one another. D = dry years, I = intermediate years, and W = wet years. RI = river, LE = levee, BS = backswamp.

Model	Site value	μ Intercept	δ_l site	γ_k year type	β_j dam	$(\beta\gamma)_{jk}$ year type*dam	$(\delta\gamma)_{kl}$ site*year type	$(\beta\delta)_{jl}$ site*dam	e_{ijkl} residual error	year type differences
1; dinc	All	< 0.0001	0.13	< 0.0001*	0.0003*	NS	NS	NS	0.04	
1; bai	All	< 0.0001	NS	< 0.0001*	0.0005*	NS	NS	0.02	245.22	
1; dinc	RI	0.006	NA	0.0005*	0.12	NS			0.02	
1; bai	RI	0.005	NA	0.006*	NS	NS			143.67	D < W
1; dinc	LE	< 0.0001	NA	0.0003*	0.008*	NS			0.04	
1; bai	LE	0.0001	NA	0.0002*	0.07	NS			254.84	D < I; D < W
1; dinc	BS	< 0.0001	NA	< 0.0001*	0.02	NS			0.04	
1; bai	BS	< 0.0001	NA	< 0.0001*	0.0007*	NS			285.88	D < I < W

Table 9. Proc MIXED results for the second model; the model has been run multiple times for each sampling site at a new hydroperiod range each time to determine the significance of GS hydroperiod, dam and dam*GS hydroperiod effects. The predictand is either diameter increment or basal area increment growth; each column is a predictor. Values in each column represent p-values for each predictor at a given hydroperiod range, with the exception of the last column, which is the residual error value. Asterisks indicate significant dam effect. NA indicates that the effect was not significant, and therefore not used in the final model.

			μ	δ_l	γ_k	β_j	$(\beta\delta)_{jl}$	$(\beta\gamma)_{jk}$	e_{ijkl}
Model	Site	GS hydroperiod value (days)	Intercept	(GS hydroperiod)^2	GS hydroperiod	Dam	(GS hydroperiod)^2 * dam	GS hydroperiod * dam	residual error
2; dinc	RI	All values	0.08	0.18^{NA}	< 0.0001	0.2	0.17^{NA}	0.007*	0.02
2; bai	RI	All values	0.04	0.15^{NA}	< 0.0001	0.1	0.14^{NA}	0.06	134.01
2; dinc	LE	0-10	0.003	< 0.0001	< 0.0001	0.1	0.0006	0.006	0.04
		10-25	0.0005	< 0.0001	< 0.0001	0.5	0.0006	0.14	
		25-35	0.0002	< 0.0001	< 0.0001	0.07	0.0006	0.7	
		35-45	0.0002	< 0.0001	0.05	0.2	0.0006	0.02	
		45-60	0.0001	< 0.0001	0.09	0.07	0.0006	0.001	
		> 60	< 0.0001	< 0.0001	0.0004	0.06	0.0006	0.0006	
2; bai	LE	0-10	0.0007	< 0.0001	< 0.0001	0.01*	0.02	0.1	249.41
		10-25	0.0002	< 0.0001	< 0.0001	0.009*	0.02	0.2	
		25-35	0.0001	< 0.0001	< 0.0001	0.06	0.02	0.43	
		35-45	0.0001	< 0.0001	0.16	0.04*	0.02	0.01	
		45-60	0.0001	< 0.0001	0.11	0.01*	0.02	0.007	
		> 60	0.0002	< 0.0001	0.002	0.009*	0.02	0.009	

Table 9 cont. Proc MIXED results for the second model.

Model	Site	GS hydroperiod value (days)	μ Intercept	δ_l (GS hydroperiod)^2	γ_k GS hydroperiod	β_j Dam	$(\beta\delta)_{jl}$ (GS hydroperiod)^2 * dam	$(\beta\gamma)_{jk}$ GS hydroperiod * dam	e_{ijkl} residual error
2; dinc	BS	0-10	<0.0001	0.01	< 0.0001	0.06	0.8	0.5	0.04
		10-25	<0.0001	0.01	< 0.0001	0.03*	0.8	0.4	
		25-35	<0.0001	0.01	< 0.0001	0.04*	0.8	0.3	
		35-45	<0.0001	0.01	< 0.0001	0.11	0.8	0.2	
		45-60	<0.0001	0.01	< 0.0001	0.3	0.8	0.2	
		> 60	<0.0001	0.01	< 0.0001	0.5	0.8	0.4	
2; bai	BS	0-10	< 0.0001	0.002	< 0.0001	0.002*	0.7	0.7	270.58
		10-25	< 0.0001	0.002	< 0.0001	0.0002*	0.7	0.7	
		25-35	< 0.0001	0.002	< 0.0001	< 0.0001*	0.7	0.8	
		35-45	< 0.0001	0.002	< 0.0001	0.0001*	0.7	0.9	
		45-60	< 0.0001	0.002	< 0.0001	0.0003*	0.7	1	
		60-80	< 0.0001	0.002	< 0.0001	0.0005*	0.7	0.8	
		> 80	< 0.0001	0.002	0.4	0.002*	0.7	0.7	

dam periods (Figure 15). BS trees had the highest growth in both pre- and post-dam periods at hydroperiods exceeding 30-40 days (Figure 15).

Dam effect models. In the first mixed model (equation (5)), with all sites included, both year type and dam were significant ($p \leq 0.0005$) predictors of basal area increment (bai) and diameter area increment (dinc) (Table 8). Dinc again had a much better model fit than bai, as evidenced by the 1000-fold lower residual error (Table 9). Separate analyses of each site using the same model confirmed that year type was a significant predictor of growth at each site, but differences in growth between year types varied across sites. At RI sites, dry years resulted in significantly less growth than that in wet years; at BS and LE sites, dry years resulted in significantly less growth than that in intermediate or wet years (Table 8). Growth during intermediate and wet years was not significantly different except at BS sites (Table 8). The differences in growth response to year type between sites were not picked up by a site*year type interaction (Table 8).

A site*dam interaction was a significant predictor of bai, but not of dinc (Table 8). Separate analyses of each site showed a fairly consistent pattern in both bai and dinc: growth was significantly higher in the post-dam era at BS and LE sites (the difference in bai was marginally significant at LE sites), and not significantly different between pre- and post-dam eras at RI sites (Table 8). Site did not have a significant effect on growth, nor did a dam*year type interaction (Table 8).

The second mixed model (equation (6)) generally indicated significant dam effects on bai BS and LE sites due to higher growth at all hydroperiods in the post-dam era (Figures 12-13, Table 9). RI sites did not exhibit a significant dam effect on bai (Table 9, Figure 14). No significant dam effects were apparent at any site in the case of dinc, with the exception of hydroperiods between 10 and 35 days in length on BS sites (Table 9). This latter range of hydroperiods resulted in significantly higher growth in the post-dam period at BS sites (Figure 13). LE sites did have marginally ($p < 0.1$) higher dinc in the post-dam era at hydroperiods longer than 45 days in length (Table 9, Figure 12).

BS sites did not exhibit any significant dam interaction effects on bai or dinc (Table 9). LE sites, on the other hand, demonstrated interaction effects on bai and dinc of both hydroperiod-squared (over all hydroperiod lengths), and hydroperiod (at hydroperiods longer than 35 days) (Table 9). These interaction effects were due to much steeper curvature in the regression line between growth and hydroperiod; growth was more sensitive to changes in hydroperiod in the post-dam era (Figure 13). This trend was consistent for both bai and dinc (Table 9). Similarly, RI trees exhibited a significant ($p = 0.007$) dam*GS hydroperiod effect on dinc and a marginally significant ($p = 0.06$) dam*GS hydroperiod effect on bai; these effects were due to higher growth response to incremental increases in hydroperiod (Figure 14).

DISCUSSION

The hydrology of floodplain sites in the backswamp and on the levee has changed significantly since dam construction – these sites have become drier. The drier conditions appear to have had a positive effect on trees growing in these areas of the floodplain; they are experiencing higher growth during dry, wet, and intermediate years. That drier conditions should decrease flood stress during wet years in not surprising, but given the quadratic relationship found in this study between growth and flooding, it would be expected that drier conditions in the post-dam period during dry years would increase drought stress at these sites, leading to lower growth. The findings of this study suggest that LE and BS trees may have been inhibited in growth during all year types in the pre-dam period by stress due to root anoxia. This interpretation is supported by the low growth of RI trees relative to LE and BS trees during all year types and hydroperiods during pre- and post-dam periods. RI trees, located in low-lying, nearly continuously flooded areas of the floodplain, grow in consistently wetter conditions than BS or LE trees. The hydrologic conditions at RI sites have not changed drastically as a result of dam operations, and growth of trees at these sites in turn does not appear to have changed between the pre- and post-dam periods. Shallow groundwater dynamics in the post-dam era may be playing a role in higher post-dam growth at LE and BS sites; higher low flows in the main channel due to dam operations may be resulting in more available groundwater to tree roots at LE and BS sites during the late GS. The late GS does not typically support high tree growth levels, since it is characterized by high temperatures (and thus high evapotranspiration and drought stress).

Productivity at floodplain sites in response to pre- and post-dam inundation patterns. The trees on the Savannah River floodplain sampled for this study appear to be slowing in growth due to age, but are putting on more diameter growth relative to their size in the post-dam period. Because comparisons of diameter increment and basal area increment revealed an age trend in the data, only basal area increment, which indirectly accounts for age by adjusting for size, will be discussed in terms of growth response of *Taxodium* populations to Thurmond Dam.

BS sites were expected to be wetter in the post-dam period during wet and dry years (Table 2), but the opposite was true. That BS sites are drier in the post-dam era was surprising, given the anecdotal observations in several SRS and SB studies (Birch & Cooley 1983, Schneider & Sharitz 1988, Sharitz et al. 1990) of deep, continuous flooding in the backswamp attributed to dam operations. It is possible that these studies were conducted in backswamp areas even more low-lying or more poorly drained than the areas observed in this study of the Savannah River floodplain. This possibility is supported in part by the observation that low-lying RI sites in this study were significantly wetter on average during intermediate years in the post-dam period. Though hydroperiods have been shorter in the post-dam era at BS sites, the number of floods at this site type has not changed between pre- and post-dam eras. This indicates that flooding at BS sites is flashier: the same number of floods is occurring after dam installation, but the floods are of shorter duration.

BS sites were expected to have higher growth during dry years and lower growth during wet years in the post-dam period; this hypothesis was based, however, on the expectation that BS sites would be wetter in the post-dam period (Table 2). Given the shorter hydroperiods during wet and dry years at these sites, I would have expected similar responses at BS sites as were anticipated for LE sites (Table 2), i.e. lower growth during dry years and higher growth during wet years. Instead, growth of BS trees was significantly higher during all year types and across all hydroperiods in the post-dam era. That shorter hydroperiods and fewer floods at BS sites in the post-dam era would lead to higher growth in wet years is not surprising, since several other studies on *Taxodium* have revealed higher growth under more periodic vs. more continuous flooding (Brown 1981, Lugo & Brown 1984, Conner & Flynn 1989, Megonigal & Day 1992). During dry years in the post-dam era, however, growth would be expected to be lower, due to higher drought stress (Mitsch & Ewel 1979, Shanklin & Kozlowski 1985). It is possible that, though surface water is more infrequent during dry years, higher low flows in the post-dam era due to dam operations (Hale & Jackson 2003) have led to higher shallow groundwater levels at floodplain sites. Higher groundwater levels may be preventing roots from drying out completely during the late GS, when temperatures and drought stress should typically be highest (USACE 1992), leading to more growth during dry years in the post-dam era. The presence of shallow groundwater and high clay content just below the soil surface at BS sites further suggests that, though BS sites are experiencing less surface flooding in the post-dam era, belowground water may still be available to these trees. Since shallow groundwater was monitored at BS sites during an "intermediate" year (in 2004, annual PDSI = 0.5, GS PDSI = -0.3, early GS = -0.4), further monitoring during dry years would be necessary to confirm that groundwater availability is compensating for drought stress in the rooting zone.

As expected (Table 2), LE sites were drier on average in the post-dam period during dry years. During wet years, however, LE sites did not show a significant difference in hydroperiod between pre- and post-dam eras. LE sites did have significantly fewer floods during wet years in the post-dam period, implying that LE sites are experiencing longer floods during wet years in the post-dam period. The drier conditions during dry years would be expected to decrease growth in LE trees during dry years (Table 2). However, LE trees had higher growth during all year types and across all hydroperiods in the post-dam era. Higher growth at LE sites during dry years may, as in the case of BS sites, be due to higher shallow groundwater levels in the post-dam era.

A large body of literature supports the idea that long periods of deep, continuous flooding have an adverse effect on *Taxodium* growth (Mitsch & Ewel 1979, Harms et al. 1980, Keeland et al. 1997). Other studies considering the impacts of impoundment on diameter growth and survival of *Taxodium* have primarily looked at populations of trees upstream of impoundment (Harms et al. 1980, Stahle et al. 1992, Young et al. 1995, Keeland & Young 1997). These studies have at times found conflicting results, in that responses to flood regime change through time and according to pre-conditioning; in general and over time, however, more continuous, deep flooding does seem to have an adverse affect on diameter growth in *Taxodium*. My study controlled for differences in growth due to more periodic vs. more continuous flooding by looking at hydroperiod, but did not explicitly consider depth of flooding. A study of riparian areas in Louisiana and South Carolina indicated that depth of flooding may outweigh the importance of periodicity of flooding (Keeland et al. 1997). Trees subjected to shallow flooding, irrespective of whether the flooding was periodic or continuous, demonstrated greater growth and a longer growth phase than trees subjected to deep periodic flooding (Keeland et al. 1997). Previous studies on the hydrologic effects of Thurmond Dam on the Savannah River main channel have shown a sharp decrease in flood magnitude between the pre- and post-dam era (Hale & Jackson 2003). This study found higher growth in the post-dam period at LE and BS sites when making a comparison at a given hydroperiod length. In addition, the growth response curve of LE trees indicated less flood stress at long hydroperiod lengths in the post-dam period (i.e. an increase in hydroperiod length during the pre-dam era caused a greater reduction in growth than a similar increase in hydroperiod during the post-dam era). These findings support the idea that characteristics of flooding other than hydroperiod length, such as flood magnitude, are driving the growth response of *Taxodium* to inundation at floodplain sites.

RI sites were not wetter in the post-dam period during dry years as expected (Table 2); RI sites were, however, significantly wetter during intermediate years in the post-dam period. This result, combined with the fact that average number of floods at RI sites during intermediate years was not significantly different in the post-dam, indicates that RI sites are less flashy with more continuous flooding in the post-dam era during intermediate years.

Nearly continuous flooding at RI sites during wet and intermediate years means that these trees must invest more of their energy into morphological structures that allow the tree to avoid root anoxia. Trees at RI sites did exhibit a positive relationship with hydroperiod, but their lower growth in relation to LE and BS trees at comparable hydroperiods again suggests that soil characteristics, shallow groundwater dynamics, or other aspects of flood regime (such as depth) may play a role in determining the nature of the relationship between flooding and diameter growth.

Floodplain-main channel relationships were built using data from an "intermediate" and part of a "wet" year (2004 and 2005, respectively). Although the period of monitoring encompassed a relatively dry period as well as several large flood events during the growing season, additional monitoring during a "dry" year may be necessary to confirm floodplain-main channel flooding relationships. A storm on a dry watershed will typically have a delayed peak that is lower than average (McCuen 1998). It is possible, therefore, that hydroperiods during dry years were slightly overestimated in this study.

Flood regime and competition. Studies conducted on the Roanoke, a river in North Carolina similar in size to the Savannah and hydroelectrically regulated in similar ways, demonstrated through forest composition analysis that inundation during extremely wet years is the primary determinant of species composition on the floodplain (Townsend 2001). In post-dam wet years on the Roanoke, communities with *Taxodium distichum* as a canopy dominant were flooded 125-275 days annually (Townsend 2001). At annual hydroperiods below 125 days, the relative dominance of *Taxodium* decreased to zero (Townsend 2001). This change in dominance is attributed to reduced seedling recruitment and survival, as well reduced productivity of mature *Taxodium* relative to other species (Townsend 2001). The average annual hydroperiod at LE sites in this study was well below this range in both pre- and post-dam periods; *Taxodium* was not, however, a very dominant species at these sites relative to other species such as sycamore, maple, and elm. In BS areas, on the other hand, annual hydroperiod was within the range of 125-

275 days prior to dam construction during wet years. Though a t-test indicated that wet year annual hydroperiod did not change significantly at BS sites in the post-dam era, an ANOVA did indicate that significant differences between BS and LE annual hydroperiods in the pre-dam era disappeared in the post-dam era.

Recent studies on the Savannah River looking at recruitment in bottomland hardwood areas (similar to the LE sites used in this study) do indicate low levels of *Taxodium* germination and recruitment in the post-dam era. A study examining recruitment between 1979 and 1989 in hardwood swamps on the Savannah River Site found that *Taxodium* trees $\geq$ 4.5 cm dbh showed low or negative net changes in basal area and stem density, and high mortality relative to ingrowth (Jones et al. 1994b). In a four-year (1987-1990) seedling plot study on a UTR creek floodplain site, basal area of overstory *Taxodium* stems at the site in 1987 is 3.3 m^2/ha (on five 25x25 m plots), but there are no *Taxodium* seedlings to be found (on 35 1 m^2 plots) in the same year (Jones et al.1994a). Further, though mean annual seedfall of *Taxodium* is relatively high throughout the study (around 10^4-10^5 seeds/yr/m^2 basal area), the mean annual percentage of these seeds germinating is 0% (Jones et al. 1994a). According to their PDSI values, the years during which the recruitment and germination studies took place are mostly "dry" years by my classification scheme; a few are "intermediate" or "wet" years. The lack of germination and/or high mortality of saplings during all year types suggests that recruitment of *Taxodium* to LE sites in my study is likely very low; whether this is due to dam operations is unclear.

The decrease in relative dominance of *Taxodium* at drier sites in the Roanoke River basin (Townsend 2000) and the sensitivity of *Taxodium* to drought (Mitsch & Ewel 1979, Shanklin & Kozlowski 1985) suggest that backswamp areas on the Savannah River, previously dominated by cypress, should be experiencing some invasion by less flood-tolerant species. Competition dynamics not seen in adult trees in this study may be occurring in *Taxodium* seedlings; drier conditions may be having a negative effect on recruitment and growth of *Taxodium* seedlings. *Taxodium* seedlings often show higher sensitivity to flood regime and water depth than *Taxodium* saplings (Conner & Flynn 1989, Megonigal & Day 1992). A study of forest stands dominated (> 50%) by *Taxodium* in areas of UTR and the Savannah River Site does not, however, support this idea. Basal area and stem density both increased over a twelve-year (1987-1999) period at these sites, though it is not known which species predominantly accounted for this increase (Conner et al. 2002).

Conclusions. The hypothesized response of tree growth at floodplain sites to hydrologic conditions and changes therein was based on principles of the subsidy-stress hypothesis (Megonigal et al. 1997): the assumption was that the benefits of water and nutrient subsidies provided by flood waters are negated by the physiological stresses imposed by either anaerobic soils (during wet years) or drought (during dry years) (Megonigal et al. 1997, Mitsch & Rust 1984). In the absence of flooding, it would therefore be expected that physiological stress due to drought would increase (during dry years), and physiological stress due to anaerobic soils would decrease (during wet years). Results from this study support this expectation in part; the quadratic relationship in both pre- and post-dam periods between hydroperiod and diameter and basal area increment at BS and LE sites confirms findings of other studies suggesting that growth of *Taxodium* is inhibited by stress under conditions that are too wet or too dry (Mitsch & Ewel 1979, Conner & Day 1992). The growth response of LE and BS trees to dam installation, however, suggests that stress due to excessively wet conditions outweighs the stress of dry conditions at these sites; i.e. flood pulses on the Savannah River floodplain prior to dam installation were primarily a stressor, not a subsidy, for *Taxodium* populations on LE and BS sites. Another possibility is that higher low flows in the post-dam era due to dam operations (Hale & Jackson 2003) have also increased shallow groundwater levels, preventing roots from drying out completely during the late growing season, when temperatures and drought stress should typically be highest.

Several government agencies and non-profit organizations, including the U.S. Army Corps of Engineers, the U.S. Fish and Wildlife Service, and The Nature Conservancy, are in the process of designing and implementing plans to restore and maintain a flow regime on the Savannah River that more closely mimics pre-dam conditions. Until now, the precise effects of Thurmond Dam on the hydrologic characteristics of the Savannah River floodplain have not been known, and the effects of dam operations on forest productivity have not been explicitly studied. Results indicate that hydroperiod is an important determinant of adult tree growth, and that the flooding-growth relationship differs between hydrogeologic areas and year types. These parameters should therefore be incorporated into future research of and management designs for forest species on the Savannah River floodplain. This study, along with productivity studies targeting other forest canopy dominants on the Savannah River floodplain, is a needed contribution to development of management schemes that encompass a broader ecosystem context. One species alone cannot be used to make management decisions, but by synthesizing productivity studies of many species over a range of habitats and life stages, one can design management schemes that facilitate healthier floodplain ecosystems.

Floodplain areas are often at the epicenter of human population development and expansion. As urban areas have expanded in the United States in recent decades, the importance of integrating the needs of human society with ecological system function has also increased. Issues concerning the hydrology and productivity of floodplains are pertinent to the well-being of both humans and floodplain environments; informed policy that targets these issues can promote more sustainable and mutually beneficial relationships between the two.

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APPENDIX A. Cores used for analysis. NO = not obtained.

Core ID	Direction	Date Collected	Location	Site Type	dch (cm)	height of buttswell (m)	period of record
SB04	NW	9/25/2003	SB	RI	NO	NO	1900-2003
	SE						1900-2003
UTR01	N	10/9/2003	UTR	RI	75.7	2.4	1900-2003
	NE						1900-2003
UTR04	NW	10/19/2003	UTR	RI	80.2	2.7	1900-2003
	SE						1900-2003
UTR05	NW	10/23/2003	UTR	RI	71.7	3	1900-2003
	SE						1900-2003
UTR07	N	10/23/2003	UTR	RI	80.3	4.5	1900-2003
	SE						1900-2003
UTR14	E	11/20/2003	UTR	BS	64.6	3.6	1900-2003
	W						1900-2003
UTR15	SE	11/20/2003	UTR	BS	67.2	3	1900-2003
	SW						1900-2003
UTR16	N	11/20/2003	UTR	BS	68.6	3.3	1900-2003
	S						1900-2003
UTR17	SE	11/20/2003	UTR	BS	67.6	3.3	1900-2003
	NW						1900-2003
UTR18	N	11/20/2003	UTR	BS	78	3	1900-2003
	W						1900-2003
UTR19	S	11/20/2003	UTR	BS	85.5	3.6	1909-2003
	N						1900-2003
CP03	N	10/14/2003	CP	BS	70.5	2.1	1934-2003
	E						1938-2003
CP04	N	10/14/2003	CP	BS	78	1.5	1955-2003
	NW						1933-2003
HC03	N	11/23/2003	SB	BS	54.9	2.4	1900-2003
	S						1900-2003

APPENDIX A. Cores used for analysis. NO = not obtained.

Core ID	Direction	Date Collected	Location	Site Type	dch (cm)	height of buttswell (m)	period of record
SB05	E	11/23/2003	SB	BS	64.4	2.4	1900-2003
	SW						1900-2003
SB07	N	12/6/2003	SB	LE	NO	3	1900-2003
	E						1900-2003
SB08	SE	12/6/2003	SB	LE	71.5	2.7	1900-2003
	NE						1900-2003
UTR08	SE	10/23/2003	UTR	LE	61.3	2.4	1900-2003
	E						1900-2003
UTR09	NNE	11/6/2003	UTR	LE	71.2	1.8	1900-2003
	SW						1900-2003
UTR10	NW	11/6/2003	UTR	LE	64.3	1.8	1900-2003
	NNE						1900-2003
UTR13	SE	11/6/2003	UTR	LE	67.9	1.8	1908-2003
	NW						1900-2003
SRS01	SW	11/6/2003	UTR	LE	80.6	1.8	1900-2003
	NE						1900-2003

APPENDIX B. COFECHA output

```
[]  Dendrochronology Program Library
[]  P R O G R A M      C O F E C H A
Version 6.06P    25781
-----------------------------------------------------------------------------
QUALITY CONTROL AND DATING CHECK OF TREE-RING MEASUREMENTS

 File of DATED series:   c:\rings\savanall.txt

 CONTENTS:
    Part 1:  Title page, options selected, summary, absent rings by series
    Part 2:  Histogram of time spans
    Part 3:  Master series with sample depth and absent rings by year
    Part 4:  Bar plot of Master Dating Series
    Part 5:  Correlation by segment of each series with Master
    Part 6:  Potential problems: low correlation, divergent year-to-year
     changes, absent rings, outliers
    Part 7:  Descriptive statistics

 RUN CONTROL OPTIONS SELECTED                             VALUE

 1  Cubic smoothing spline 50% wavelength cutoff for filtering
                                  32 years
 2  Segments examined are         20 years lagged successively by  10 years
 3  Autoregressive model applied  A  Residuals are used in master dating
series and testing
 4  Series transformed to logarithms  Y  Each series log-transformed for
master dating series and testing
 5  CORRELATION is Pearson (parametric, quantitative)
Critical correlation, 99% confidence level        .5155
 6  Master dating series saved                      N
 7  Ring measurements listed                        N
 8  Parts printed                                 1234567
 9  Absent rings are omitted from master series and segment correlations

Time span of Master dating series is  1900 to  2003   104 years
Continuous time span is               1900 to  2003   104 years
Portion with two or more series is    1900 to  2003   104 years
Portion with two or more series is    1900 to  2003   104 years
                                     ****************************************
                                     *C* Number of dated series        46 *C*
                                     *O* Master series 1900 2003  104 yrs *O*
                                     *F* Total rings in all series   4601 *F*
                                     *E* Total dated rings checked   4601 *E*
                                     *C* Series intercorrelation     .650 *C*
                                     *H* Average mean sensitivity    .518 *H*
                                     *A* Segments, possible problems   91 *A*
                                     *** Mean length of series     100.0 ***
                                     ****************************************
```

```
PART 2:  TIME PLOT OF TREE-RING SERIES: appen
00:14  Sun 31 Jul 2005  Page   2
-----------------------------------------------------------------------------
-------------------------------------------------------
 1800 1850 1900 1950 2000 2050 Ident   Seq Time-span  Yrs
:    :    :    :    :    :  -------- --- ---- ---- ----
.    .    .  <======>    . CPL03E     1 1934 2003   70
.    .    .  <======>    . CPL03N     2 1938 2003   66
.    .    .    <====>    . CPL04N     3 1955 2003   49
.    .    .  <======>    . CPL04W     4 1933 2003   71
.    .    <=========>    . HCR03N     5 1900 2003  104
.    .    <=========>    . HCR03S     6 1900 2003  104
.    .    <=========>    . SBL04W     7 1900 2003  104
.    .    <=========>    . SBL04E     8 1900 2003  104
.    .    <=========>    . SBL05E     9 1900 2003  104
.    .    <=========>    . SBL05W    10 1900 2003  104
.    .    <=========>    . SBL07E    11 1900 2003  104
.    .    <=========>    . SBL07N    12 1900 2003  104
.    .    <=========>    . SBL08N    13 1900 2003  104
.    .    <=========>    . SBL08S    14 1900 2003  104
.    .    <=========>    . SRS01E    15 1900 2003  104
.    .    <=========>    . SRS01W    16 1900 2003  104
.    .    <=========>    . UTR01N    17 1900 2003  104
.    .    <=========>    . UTR01E    18 1900 2003  104
.    .    <=========>    . UTR04W    19 1900 2003  104
.    .    <=========>    . UTR04E    20 1900 2003  104
.    .    <=========>    . UTR05W    21 1900 2003  104
.    .    <=========>    . UTR05E    22 1900 2003  104
.    .    <=========>    . UTR07N    23 1900 2003  104
.    .    <=========>    . UTR07S    24 1900 2003  104
.    .    <=========>    . UTR08E    25 1900 2003  104
.    .    <=========>    . UTR08S    26 1900 2003  104
.    .    <=========>    . UTR09N    27 1900 2003  104
.    .    <=========>    . UTR09S    28 1900 2003  104
.    .    <=========>    . UTR10E    29 1900 2003  104
.    .    <=========>    . UTR10W    30 1900 2003  104
.    .    <=========>    . UTR13N    31 1908 2003   96
.    .    <=========>    . UTR13N    32 1900 2003  104
.    .    <=========>    . UTR13S    33 1900 2003  104
.    .    <=========>    . UTR13W    34 1900 2003  104
.    .    <=========>    . UTR14E    35 1900 2003  104
.    .    <=========>    . UTR14W    36 1900 2003  104
.    .    <=========>    . UTR15E    37 1900 2003  104
.    .    <=========>    . UTR15W    38 1900 2003  104
.    .    <=========>    . UTR16N    39 1900 2003  104
.    .    <=========>    . UTR16S    40 1900 2003  104
.    .    <=========>    . UTR17W    41 1900 2003  104
.    .    <=========>    . UTR17E    42 1906 2003   98
.    .    <=========>    . UTR18N    43 1900 2003  104
.    .    <=========>    . UTR18W    44 1900 2003  104
.    .    <=========>    . UTR19N    45 1900 2003  104
.    .    <=========>    . UTR19S    46 1909 2003   95
1800 1850 1900 1950 2000 2050
```

```
PART 3:  Master Dating Series: appen
00:14  Sun 31 Jul 2005  Page   3
-----------------------------------------------------------------------------
---  Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab
  ------------------    ------------------    ------------------
  1900  1.004  39       1950  -.965  45       2000 -1.556  46
  1901   .676  39       1951  -.798  45       2001  -.472  46
  1902 -1.157  39       1952 -1.509  45       2002 -1.080  46
  1903  1.096  39       1953  -.740  45       2003  1.543  46
  1904 -2.330  39       1954   .241  45
  1905   .170  39       1955  -.322  46
  1906   .569  40       1956 -2.379  46
  1907  -.349  40       1957   .737  46
  1908   .329  41       1958   .749  46
  1909  1.533  42       1959   .201  46
  1910  -.662  42       1960   .226  46
  1911 -1.459  42       1961   .007  46
  1912  1.678  42       1962   .094  46
  1913  -.484  42       1963  1.652  46
  1914 -1.217  42       1964   .778  46
  1915  -.022  42       1965   .813  46
  1916   .404  42       1966  -.789  46
  1917   .421  42       1967   .867  46
  1918 -1.581  42       1968 -1.009  46
  1919  1.063  42       1969  -.244  46
  1920   .112  42       1970 -1.524  46
  1921  -.019  42       1971  -.636  46
  1922  1.162  42       1972   .253  46
  1923   .339  42       1973  1.755  46
  1924  -.016  42       1974   .089  46
  1925 -1.636  42       1975   .015  46
  1926 -1.275  42       1976  1.771  46
  1927   .576  42       1977 -2.021  46
  1928  1.078  42       1978  -.181  46
  1929  1.865  42       1979   .601  46
  1930  -.188  42       1980   .260  46
  1931 -1.411  42       1981 -2.239  46
  1932   .174  42       1982  -.560  46
  1933 -1.040  43       1983   .170  46
  1934   .902  44       1984   .853  46
  1935  -.454  44       1985  -.865  46
  1936  -.670  44       1986  -.410  46
  1937   .824  44       1987 -1.075  46
  1938   .051  45       1988   .003  46
  1939   .393  45       1989   .404  46
  1940  -.747  45       1990   .276  46
  1941   .868  45       1991  2.363  46
  1942   .220  45       1992   .449  46
  1943  1.834  45       1993   .013  46
  1944 -1.297  45       1994   .316  46
  1945  -.249  45       1995 -1.318  46
  1946   .373  45       1996   .650  46
  1947  -.219  45       1997   .627  46
  1948   .489  45       1998   .546  46
  1949  1.652  45       1999   .000  46
-----------------------------------------------------------------------------
-------------------------------------------------------
```

```
PART 4:  Master Bar Plot: appen
00:14  Sun 31 Jul 2005  Page   4
-----------------------------------------------------------------------------
-------------------------------------------------------
   Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel
value  Year Rel value  Year Rel value  Year Rel value
   1900---------D  1950--d         2000f
   1901--------C   1951--c         2001---b
   1902-e          1952f           2002-d
   1903---------D  1953--c         2003----------F
   1904i           1954------A
   1905-----A      1955---a
   1906-------B    1956j
   1907---a        1957--------C
   1908------A     1958--------C
   1909----------F 1959------A
   1910--c         1960------A
   1911f           1961----@
   1912----------G 1962-----@
   1913---b        1963----------G
   1914-e          1964--------C
   1915----@       1965--------C
   1916-------B    1966--c
   1917-------B    1967--------C
   1918f           1968-d
   1919---------D  1969---a
   1920-----@      1970f
   1921----@       1971--c
   1922---------E  1972------A
   1923------A     1973----------G
   1924----@       1974-----@
   1925g           1975----@
   1926-e          1976----------G
   1927-------B    1977h
   1928---------D  1978----a
   1929----------G 1979--------B
   1930----a       1980------A
   1931f           1981i
   1932-----A      1982---b
   1933-d          1983-----A
   1934---------D  1984--------C
   1935---b        1985--c
   1936--c         1986---b
   1937--------C   1987-d
   1938-----@      1988----@
   1939-------B    1989-------B
   1940--c         1990------A
   1941--------C   1991----------I
   1942------A     1992-------B
   1943----------G 1993----@
   1944-e          1994------A
   1945---a        1995-e
   1946-------A    1996--------C
   1947---a        1997--------C
   1948-------B    1998-------B
   1949----------G 1999----@
```

PART 5: CORRELATION OF SERIES BY SEGMENTS: appen
00:14 Sun 31 Jul 2005 Page 5

--- Correlations of 20-year dated segments, lagged 10 years
Flags: A = correlation under .5155 but highest as dated; B = correlation higher at other than dated position

Seq	Series	Time_span		1900 1919	1910 1929	1920 1939	1930 1949	1940 1959	1950 1969	1960 1979	1970 1989	1980 1999	1990 2009
1	CPL03E	1934	2003				.19B	.14B	.33A	.57	.36B	.14B	.26B
2	CPL03N	1938	2003				.06B	.08B	.02B	.44B	.36B	.35A	.43A
3	CPL04N	1955	2003						.62	.75	.68	.52B	.54
4	CPL04W	1933	2003				.62	.58B	.58	.76	.75	.64	.75
5	HCR03N	1900	2003	.78	.61	.51A	.69	.56	.58	.49A	.54	.76	.76
6	HCR03S	1900	2003	.71	.59	.66	.80	.76	.66	.57	.63	.60	.61
7	SBL04W	1900	2003	.87	.77	.70	.80	.82	.58	.56	.58	.65	.66
8	SBL04E	1900	2003	.89	.84	.73	.92	.69	.58	.62	.72	.70	.69
9	SBL05E	1900	2003	.75	.67	.39A	.39B	.27B	-.16B	.46B	.45A	.19B	.24A
10	SBL05W	1900	2003	.85	.67	.57	.54	.33B	.20B	.40B	.38B	.32B	.57
11	SBL07E	1900	2003	.88	.70	.54	.70	.83	.73	.66	.78	.70	.71
12	SBL07N	1900	2003	.70	.63	.68	.58	.75	.88	.85	.82	.70	.63
13	SBL08N	1900	2003	.66	.77	.75	.80	.58	.43A	.74	.79	.63	.64
14	SBL08S	1900	2003	.72	.86	.74	.67	.69	.44A	.37A	.55	.45A	.45A
15	SRS01E	1900	2003	.80	.63	.62	.55	.55	.60	.56	.52	.49B	.49A
16	SRS01W	1900	2003	.74	.76	.81	.79	.70	.68	.87	.82	.67	.75
17	UTR01N	1900	2003	.83	.78	.64	.69	.57	.44B	.64	.66	.73	.66
18	UTR01E	1900	2003	.86	.83	.81	.71	.77	.85	.67	.52	.46A	.52
19	UTR04W	1900	2003	.56	.52B	.58	.78	.62	.63	.88	.87	.76	.73
20	UTR04E	1900	2003	.66	.61	.54	.71	.59	.61	.87	.75	.65	.68
21	UTR05W	1900	2003	.85	.89	.81	.69	.83	.87	.81	.55	.50A	.52
22	UTR05E	1900	2003	.85	.88	.83	.79	.59	.45A	.49B	.53	.78	.76
23	UTR07N	1900	2003	.88	.88	.83	.80	.79	.74	.74	.47A	.24B	.51A
24	UTR07S	1900	2003	.77	.86	.79	.78	.55	.37B	.65	.46A	.28B	.58
25	UTR08E	1900	2003	.69	.50A	.38A	.42A	.56B	.72	.57	.61	.76	.72
26	UTR08S	1900	2003	.76	.58	.41A	.52	.75	.78	.63	.71	.71	.60
27	UTR09N	1900	2003	.63	.67	.72	.63	.58	.52	.46A	.38A	.39B	.32B
28	UTR09S	1900	2003	.31B	.37B	.71	.58	.63	.59	.70	.74	.71	.61
29	UTR10E	1900	2003	.80	.77	.71	.55	.60	.68	.91	.82	.68	.80
30	UTR10W	1900	2003	.84	.62	.52	.50A	.39A	.50A	.85	.78	.72	.56
31	UTR13N	1908	2003	.67	.68B	.63	.67	.62	.48A	.51A	.45A	.58	.67
32	UTR13N	1900	2003	.42B	.53	.51B	.33B	.16B	.04B	.35B	.50A	.51A	.62
33	UTR13S	1900	2003	.65	.61	.58	.37B	.22B	.39B	.74	.58	.38A	.56
34	UTR13W	1900	2003	.64	.55	.52	.50A	.64	.62	.48A	.48A	.48A	.57
35	UTR14E	1900	2003	.81	.77	.56	.69	.87	.74	.80	.63	.60	.73
36	UTR14W	1900	2003	.81	.40B	.28B	.73	.88	.78	.75	.60	.61	.61
37	UTR15E	1900	2003	.83	.83	.70	.71	.82	.55	.76	.84	.79	.86
38	UTR15W	1900	2003	.83	.78	.59	.44A	.57	.73	.90	.88	.81	.80
39	UTR16N	1900	2003	.78	.85	.79	.86	.65	.61	.88	.67	.52	.69
40	UTR16S	1900	2003	.73	.82	.74	.77	.73	.72	.78	.60	.51A	.48A
41	UTR17W	1900	2003	.83	.87	.83	.82	.72	.65	.92	.92	.76	.69
42	UTR17E	1906	2003	.70	.85	.69	.74	.80	.68	.87	.76	.62	.58
43	UTR18N	1900	2003	.88	.85	.77	.66	.71	.64	.76	.73	.71	.62
44	UTR18W	1900	2003	.80	.69	.59	.69	.76	.65	.74	.63	.25B	-.07B
45	UTR19N	1900	2003	.86	.87	.84	.70	.81	.78	.73	.74	.75	.77
46	UTR19S	1909	2003	.90	.91	.80	.65	.66	.66	.82	.85	.69	.50A
Av segment correlation				.76	.72	.65	.63	.62	.57	.68	.64	.58	.60

```
PART 6:  POTENTIAL PROBLEMS: appen
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-----------------------------------------------------------------------------
For each series with potential problems the following diagnostics may appear:

 [A] Correlations with master dating series of flagged  20-year segments of
series filtered with  32-year spline,
     at every point from ten years earlier (-10) to ten years later (+10)
than dated

 [B] Effect of those data values which most lower or raise correlation with
master series
     Symbol following year indicates value in series is greater (>) or lesser
(<) than master series value

 [C] Year-to-year changes very different from the mean change in other series

 [D] Absent rings (zero values)

 [E] Values which are statistical outliers from mean for the year
=============================================================================

CPL03E    1934 to 2003      70 years
Series   1

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                +2   +3   +4   +5   +6   +7   +8   +9   +10
                ---  ---  ---  ---  ---  ---  ---  ---  ---
1934 1953   -7   -.27 -.26 -.03 .47* -.06 .03  -.32 -.03 -.06 .08  .19| -.14
                -.21 .02  .39  .44  .12  -.07 .06  .15  -.18
1940 1959    5   -.13 -.03 -.13 .28  -.32 -.15  -.22 -.02 -.17 .06  .14| -.03
                -.24 .02  .43  .65* .16  .03  -.01 .21  -.09
1950 1969    0   -.01 .02  -.30 .20  -.01 -.25  .22  -.12 -.26 .16  .33* .33
                .02  -.08 .22  .27  .07  -.15 -.22 .21  -.11
    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
1970 1989   -8   -.09 .13  .39* -.16 -.02 -.29 .17  -.08 .14  -.08 .36| -.07
                -.52 -.02 .10  -.13 .04  -.01 -.07 -.11 -.15
1980 1999   -8   -.13 -.11 .41* -.01 .04  -.11 .22  -.25 .18  -.01 .14| .03
                -.61 -.05 -.07  -    -    -    -    -    -
1984 2003   -8   -.10 -.14 .35* .10  -.01  .02  .14  -.36 .25  -.08 .26| -
                -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .312) is:
Lower 1989< -.075 1947< -.026 1944> -.018 1956> -.018 1965< -.018 1949< -.013
Higher 1976  .026 1977  .025
1934 to 1953 segment:
Lower 1944> -.099 1935> -.052 1953> -.041 1950> -.036 1947< -.030 1948< -.021
Higher 1943  .082 1934  .063
1940 to 1959 segment:
Lower 1956> -.087 1944> -.085 1947< -.040 1953> -.034 1950> -.031 1948< -.022
Higher 1943  .094 1952  .059
1950 to 1969 segment:
Lower 1965< -.105 1956> -.078 1953> -.030 1966> -.022 1962< -.011 1950> -.011
Higher 1952  .087 1967  .057

1970 to 1989 segment:
```

```
Lower 1989< -.429 1985> -.021 1971> -.010 1975> -.008 1983< -.003 1978< -.003
Higher 1976  .080 1977  .070
1980 to 1999 segment:
Lower 1989< -.338 1985> -.028 1995> -.006 1982> -.004 1997< -.004 1992< -.002
Higher 1981  .066 1984  .052
1984 to 2003 segment:
Lower 1989< -.332 1985> -.031 1995> -.012 2001> -.009 1997< -.005 1988> -.003
Higher 2003  .092 2002  .043

[E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1947 -4.9 SD;    1989 -4.9 SD
==============================================================================

CPL03N    1938 to 2003      66 years
Series   2

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1938 1957    5   .09  -.41 -.10 .18  .06  -.20 .14  -.01 -.28 .35  .06| .09
                 -.07 -.19 .02  .54* .00  -.02 .16  .04  -.24
1940 1959    5   .12  -.42 -.16 .20  .00  -.18 .13  -.02 -.27 .35  .08| .07
                 -.03 -.21 .05  .57* .07  .00  .13  .07  -.28
1950 1969   -4   .43  .15  -.17 .16  .08  .13  .48* -.45 -.18 -.19 .02| -.06
                 -.02 -.50 .31  .26  .11  .08  -.31 .35  .08
1960 1979   -9   .30  .58* .24  .07  .25  -.14 .07  -.17 -.18 -.49 .44| -.27
                 -.18 .09  .22  -.07 .00  -.02 -.17 .28  -.04
1970 1989   -8   .06  .12  .41* .01  .03  -.29 .11  -.01 -.05 -.17 .36| -.08
                 -.45 .07  .05  -.03 .14  .01  .01  -.16 -.21
1980 1999    0   -.15 -.13 .29  .02  -.01 -.04 .20  .00  .12  -.07 .35* .04
                 -.57 -.13 -.25 -    -    -    -    -    -
1984 2003    0   -.26 -.15 .28  .15  .02  .07  .11  -.19 .29  -.08 .43*  -
                 -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .340) is:
Lower 1989< -.087 1956> -.025 1965< -.023 1940> -.023 1970> -.022 1953> -.022
Higher 1977  .045 1991  .042
1938 to 1957 segment:
Lower 1940> -.060 1953> -.054 1956> -.051 1948< -.047 1957< -.045 1954< -.017
Higher 1949  .123 1943  .072
1940 to 1959 segment:
Lower 1940> -.062 1953> -.057 1956> -.052 1948< -.047 1957< -.046 1954< -.018
Higher 1949  .115 1943  .065
1950 to 1969 segment:
Lower 1956> -.087 1965< -.076 1953> -.068 1960< -.039 1957< -.034 1969> -.014
Higher 1963  .102 1967  .098
1960 to 1979 segment:
Lower 1970> -.092 1965< -.081 1969> -.052 1971> -.048 1960< -.043 1964< -.014
Higher 1977  .166 1976  .070
1970 to 1989 segment:
Lower 1989< -.321 1970> -.062 1971> -.023 1985> -.020 1980< -.018 1978< -.006
Higher 1977  .107 1976  .074
1980 to 1999 segment:
Lower 1989< -.370 1995> -.037 1985> -.031 1980< -.016 1992< -.005 1993> -.001
Higher 1991  .158 1981  .073
1984 to 2003 segment:
```

```
Lower 1989< -.363 1995> -.039 1985> -.032 1992< -.004 1993> -.002 1988< -.001
Higher 1991  .114 2003  .064

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1989 -5.1 SD
=============================================================================

 CPL04N    1955 to 2003      49 years
Series   3

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------  ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1980 1999   -4   -.04 -.17 .16  .01  -.05 -.14 .56* .08  -.40 -.17 .52| .17
                 .30  -.38 -.10   -    -    -    -    -    -

[B] Entire series, effect on correlation (  .626) is:
Lower 1995> -.036 1985< -.022 1982> -.017 1955< -.014 1987> -.013 1991< -.013
Higher 1981  .047 1977  .029
1980 to 1999 segment:
Lower 1995> -.098 1991< -.050 1982> -.037 1987> -.036 1980< -.008 1990< -.007
Higher 1981  .179 1985  .032

=============================================================================

 CPL04W    1933 to 2003      71 years
Series   4

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1940 1959    6   -.22 -.17 .27  -.48 .41  -.15 -.13 -.14 .03  -.45 .58| .14
                 -.09 .26  -.07 -.09 .77* -.20 -.02 .06  -.13

[B] Entire series, effect on correlation (  .639) is:
Lower 1956> -.035 1940> -.029 1934< -.026 1995> -.010 1970> -.009 1946< -.009
Higher 1944  .022 1943  .021
1940 to 1959 segment:
Lower 1956> -.118 1940> -.077 1941< -.026 1946< -.025 1958< -.013 1945> -.004
Higher 1943  .097 1944  .089

=============================================================================

 HCR03N    1900 to 2003     104 years
Series   5

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1920 1939    0   .37  -.14 .14  .12  -.32 .21  -.29 .06  .31 -.17 .51* -.34
                 -.25 -.10 .03  .39  -.03 -.11 -.51 .25  -.07
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - -
```

```
1960 1979    0   .42  .01  -.14 -.34 -.33 -.37 .04  -.29 .08  .34  .49* .17
                .09  -.07 -.30 -.06 -.17 -.31 -.12 .28  -.08

[B] Entire series, effect on correlation (  .634) is:
Lower 1977> -.027 1925> -.025 1942< -.014 1905< -.009 1958< -.009 1974> -.007
Higher 1904  .022 1991  .018
1920 to 1939 segment:
Lower 1925> -.146 1924> -.031 1928< -.029 1935< -.029 1938< -.009 1923> -.008
Higher 1929  .098 1933  .045
1960 to 1979 segment:
Lower 1977> -.137 1974> -.050 1975> -.031 1969< -.018 1960< -.016 1962> -.013
Higher 1973  .087 1970  .071

=============================================================================

 HCR03S    1900 to 2003     104 years
Series   6

[B] Entire series, effect on correlation (  .677) is:
Lower 1987> -.012 1928< -.010 1910> -.010 1969< -.010 1925> -.009 1971> -.007
Higher 1981  .018 1956  .011

=============================================================================

 SBL04W    1900 to 2003     104 years
Series   7

[B] Entire series, effect on correlation (  .704) is:
Lower 1987< -.023 1962< -.021 1975> -.009 1901< -.007 1931> -.005 1995> -.005
Higher 1991  .016 1904  .013

=============================================================================

 SBL04E    1900 to 2003     104 years
Series   8

[B] Entire series, effect on correlation (  .726) is:
Lower 1955< -.018 1924< -.013 1977> -.010 1974> -.009 1961> -.009 1929< -.008
Higher 1981  .013 1991  .010

=============================================================================

 SBL05E    1900 to 2003     104 years
Series   9

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                +2   +3   +4   +5   +6   +7   +8   +9   +10
                ---  ---  ---  ---  ---  ---  ---  ---  ---
1920 1939    0   .19  .17  -.12 .37  -.31 .08  -.14 -.17 .28  -.24 .39* .13
                -.23 .08  -.35 -.01 .19  -.23 .04  -.06 .01
1930 1949   -2   -.10 .05  .08  .05  -.28  -.13 -.11 .31  .42* -.32 .39| -.21
                -.31 .11  -.06 .10  .22  -.14 -.07 .19  -.32
1940 1959    6   -.41 .02  .31  .07  .07  -.32 -.38 .23  -.01 -.44 .27| .01
                -.14 .15  .06  .14  .45* .09  .17  .21  -.10
1950 1969   -8   -.12 .11  .57* .07  .01  -.17 -.33 -.02 -.11 -.58 -.16|-.02
                .03  -.05 -.05 -.05 .46  .47  .21  .11  .16
```

```
1960 1979   -9   -.12 .50* .31  .31  -.16 -.13 -.20 -.12 .12  -.31 .46| -.28
                 .17  -.25 .26  -.14 -.08 .12  .23  -.17 .06
1970 1989    0   -.32 .34  .22  -.05 -.33 -.20 .17  -.21 -.03 -.25 .45* -.15
                 .08  .14  .45  -.07 -.03 -.16 .11  -.05 .07
1980 1999    3   -.34 -.23 .18  -.23 -.13 -.10 .35  -.17 -.29 -.28 .19| .14
                 .03  .41* .16   -    -    -    -    -    -
1984 2003    0   -.19 .00  .02  .09  -.16 -.14 .12  -.17 .09  -.25 .24*  -
                  -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .418) is:
Lower 1956> -.050 1931> -.027 2000> -.024 1926> -.019 1987> -.019 1963< -.015
Higher 1977  .033 2003  .018
1920 to 1939 segment:
Lower 1931> -.218 1926> -.153 1937< -.012 1922< -.008 1934< -.007 1924> -.007
Higher   1929  .135   1925  .113
1930 to 1949 segment:
Lower 1931> -.222 1947< -.018 1940> -.016 1942> -.014 1945> -.011 1937< -.010
Higher 1943  .082 1949  .071
1940 to 1959 segment:
Lower 1956> -.258 1958< -.031 1959< -.028 1947< -.027 1946< -.018 1948< -.014
Higher 1957  .065 1950  .064
1950 to 1969 segment:
Lower 1956> -.272 1964< -.062 1963< -.059 1960< -.018 1966> -.015 1958< -.011
Higher 1957  .207 1950  .094
1960 to 1979 segment:
Lower 1971> -.072 1963< -.069 1964< -.062 1966> -.049 1974> -.043 1979< -.032
Higher 1977  .282 1976  .089
1970 to 1989 segment:
Lower 1987> -.090 1988> -.064 1989< -.052 1979< -.049 1971> -.024 1974> -.010
Higher 1977  .190 1976  .061
1980 to 1999 segment:
Lower 1987> -.121 1988> -.059 1989< -.045 1998< -.025 1992< -.012 1993< -.009
Higher 1981  .133 1991  .076
1984 to 2003 segment:
Lower 2000> -.106 1987> -.077 1988> -.029 1989< -.024 1998< -.015 1995> -.010
Higher 2002  .135 2003  .116

[E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1931 +3.2 SD;    1956 +4.4 SD;    1988 +3.3 SD
=============================================================================

 SBL05W    1900 to 2003     104 years
Series  10

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1940 1959    5   -.17 .30  -.09 .04  -.18 -.13 -.18 .12  -.36 -.37 .33| -.22
                 -.23 .10  .23  .38* .36  -.02 .08  .30  -.08
1950 1969    6   .03  .08  .04  -.08 -.19 -.31 -.04 .08  -.51 -.17 .20| .15
                 .18  -.24 -.25 .18  .57* -.18 .31  .23  -.14
1960 1979   -3   -.01 .15  -.12 -.04 -.42 -.14 -.24 .42* -.01 .29  .40| .06
                 -.15 -.18 .01  -.51 .38  -.17 .20  -.14 .16
1970 1989   10   .06  .13  -.17 .02  -.25 .34  -.23 -.12 -.12 .38  .38| -.13
                 -.14 .01  .06  -.49 -.02 .07  .10  -.26 .43*
```

```
1980 1999   -5   -.11 -.12 -.12 .10  .02  .50* .16  -.10 -.09 .32  .32| -.18
                 .18  .05  -.36   -    -    -    -    -    -

[B] Entire series, effect on correlation (  .492) is:
Lower 1981> -.025 1947< -.025 1956> -.022 1995> -.016 1971< -.014 1926> -.014
Higher 1904  .023 1918  .011
1940 to 1959 segment:
Lower 1956> -.096 1947< -.089 1952> -.041 1953> -.025 1948< -.021 1941< -.011
Higher 1944  .054 1950  .039
1950 to 1969 segment:
Lower 1956> -.087 1969< -.060 1964< -.046 1952> -.037 1963< -.036 1953> -.026
Higher 1950  .081 1958  .058
1960 to 1979 segment:
Lower 1966> -.044 1971< -.036 1969< -.030 1974> -.020 1964< -.015 1961> -.011
Higher 1977  .046 1976  .037
1970 to 1989 segment:
Lower 1981> -.131 1971< -.069 1979< -.008 1974> -.007 1978< -.007 1988< -.005
Higher 1977  .052 1976  .034
1980 to 1999 segment:
Lower 1981> -.144 1995> -.089 1990< -.015 1988< -.009 1998< -.003 1992< -.003
Higher 1991  .091 1987  .064

[E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1956 +3.1 SD;    1971 -5.0 SD;    1981 +3.2 SD
==============================================================================

 SBL07E    1900 to 2003     104 years
Series  11

[B] Entire series, effect on correlation (  .734) is:
Lower 1940> -.014 1995> -.013 1966> -.011 1960< -.011 1969> -.007 1931> -.006
Higher 1981  .014 1956  .013

==============================================================================

 SBL07N    1900 to 2003     104 years
Series  12

[B] Entire series, effect on correlation (  .731) is:
Lower 1940> -.012 1995> -.012 1911> -.012 1931> -.010 1916< -.010 1922< -.008
Higher 1956  .013 1904  .013

==============================================================================

 SBL08N    1900 to 2003     104 years
Series  13

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1950 1969    0   -.19 .14  -.29 -.31 .38  .17  .15  .27  .08  .31  .43* -.37
                 -.18 .09  -.14 -.17 -.05 -.42 -.06 .08  -.08

[B] Entire series, effect on correlation (  .654) is:
Lower 1957< -.027 1995> -.015 1952> -.012 1909< -.012 1935> -.012 1950> -.011
Higher 1981  .011 1944  .011
```

```
1950 to 1969 segment:
Lower 1957< -.118 1952> -.063 1950> -.057 1951> -.035 1966> -.024 1968> -.012
Higher 1956  .357 1967  .025

=============================================================================

 SBL08S    1900 to 2003     104 years
Series  14

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1950 1969    0   -.04 .34  -.07 -.46 .31  .32  -.29 -.09 -.11 -.06 .44* -.18
                 -.25 .17  -.10 -.04 -.11 -.07 .02  .38  .14
1960 1979    0   .10  .11  -.04 -.26 .31  .31  -.05 -.15 -.10 -.28 .37* .01
                 -.26 .06  -.05 -.08 -.42 .20  -.03 .20  -.04
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
                 - - - - - - - - - - - - - - - - - - - - - - - - - - -
1980 1999    0   -.04 -.06 .09  -.07 .37  -.01 .06  -.46 -.17 .08  .45* -.34
                 .16  -.19 -.10   -    -    -    -    -    -
1984 2003    0   .10  .00  .09  .17  .19  .05  -.20 -.42 -.07 -.04 .45*  -
                 -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .575) is:
Lower 1961< -.050 1977> -.013 1935> -.011 1993< -.010 1952> -.010 1903< -.008
Higher 1956  .018 1943  .013
1950 to 1969 segment:
Lower 1961< -.211 1952> -.057 1967< -.037 1951> -.028 1955> -.014 1950> -.010
Higher 1956  .118 1963  .072
1960 to 1979 segment:
Lower 1961< -.166 1977> -.065 1971> -.037 1967< -.024 1978> -.008 1974< -.003
Higher 1963  .062 1976  .038
1980 to 1999 segment:
Lower 1993< -.063 1983< -.046 1994< -.023 1986> -.020 1990< -.019 1996< -.015
Higher 1981  .126 1987  .034
1984 to 2003 segment:
Lower 1993< -.053 2000> -.021 1994< -.021 1986> -.018 1990< -.017 1996< -.015
Higher 2002  .065 2003  .037

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1961 -5.3 SD
=============================================================================

 SRS01E    1900 to 2003     104 years
Series  15

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1980 1999   -4   -.02 -.51 .33  .07  -.11 .06  .59* -.03 -.14 -.16 .49| -.01
                 .21  -.05 -.14   -    -    -    -    -    -
1984 2003    0   .00  -.56 .37  .03  -.11 .22  .44  .03  -.02 -.23 .49*  -
                 -    -    -    -    -    -    -    -    -
```

```
[B] Entire series, effect on correlation (  .597) is:
Lower 1985< -.035 1995> -.016 1950> -.016 1977> -.015 1910> -.010 1929< -.010
Higher 1904  .025 1956  .020
1980 to 1999 segment:
Lower 1985< -.136 1995> -.088 1991< -.040 1992< -.003 1986> -.001 1999>  .000
Higher 1981  .043 1996  .017
1984 to 2003 segment:
Lower 1995> -.095 1985< -.064 2003< -.033 1991< -.019 2001> -.010 1987> -.005
Higher 2000  .063 2002  .021

=============================================================================

 SRS01W    1900 to 2003     104 years
Series  16

[B] Entire series, effect on correlation (  .761) is:
Lower 1995> -.013 1950> -.012 1902> -.010 1968> -.008 1918> -.008 1910> -.007
Higher 1904  .016 1977  .009

=============================================================================

 UTR01N    1900 to 2003     104 years
Series  17

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1950 1969    9   -.21 .15  .06  -.10 .37  -.47 -.32 .09  -.15 -.30 .44| -.25
                 .33  .07  .03  -.22 .44  .05  -.02 .48* -.14

[B] Entire series, effect on correlation (  .690) is:
Lower 1956> -.024 1988< -.020 1970> -.016 1959< -.012 1971> -.011 1955> -.011
Higher 1904  .023 1977  .021
1950 to 1969 segment:
Lower 1956> -.143 1959< -.062 1962< -.056 1955> -.048 1964< -.032 1966> -.008
Higher 1968  .068 1950  .061

=============================================================================

 UTR01E    1900 to 2003     104 years
Series  18

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1980 1999    0   -.13 -.19 -.27 .36  -.01 .02  .36  .22  .10  .25  .46* .17
                 -.15 -.13 -.19   -    -    -    -    -    -

[B] Entire series, effect on correlation (  .742) is:
Lower 1995> -.021 1984< -.014 1975> -.012 1944> -.012 1917< -.008 1988< -.008
Higher 1904  .020 1956  .009
1980 to 1999 segment:
Lower 1995> -.144 1984< -.085 1988< -.043 1993> -.018 1986< -.010 1989< -.009
Higher 1981  .135 1991  .118
```

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===============================================================================

 UTR04W    1900 to 2003     104 years
Series  19

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1910 1929    5   -.09 .02  .18  .11  -.02 .18  -.15 -.04 -.09 .10  .52| -.37
                 -.37 -.05 -.03 .56* -.01 .31  -.23 -.58 .09

[B] Entire series, effect on correlation (  .667) is:
Lower 1919< -.025 1957< -.020 1925> -.017 1992> -.009 1906< -.009 1904> -.008
Higher 1991  .015 1981  .015
1910 to 1929 segment:
Lower 1919< -.152 1925> -.083 1928< -.034 1924> -.026 1920< -.024 1915< -.002
Higher 1929  .083 1918  .052

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1956 -4.5 SD
===============================================================================

 UTR04E    1900 to 2003     104 years
Series  20

[B] Entire series, effect on correlation (  .663) is:
Lower 1985> -.024 1928< -.013 1906< -.011 1983< -.010 1935> -.010 1957< -.009
Higher 1977  .018 1991  .016

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1956 -4.5 SD
===============================================================================

 UTR05W    1900 to 2003     104 years
Series  21

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1980 1999    0   .05  -.22 -.22 .23  .01  -.15 -.22 -.05 .02  -.06 .50* -.23
                 .00  .12  -.03   -    -    -    -    -    -

[B] Entire series, effect on correlation (  .763) is:
Lower 1985> -.024 1986> -.014 1944> -.013 1984< -.011 1907> -.007 1993< -.005
Higher 1904  .017 1956  .010
1980 to 1999 segment:
Lower 1985> -.140 1986> -.074 1984< -.069 1993< -.023 1983< -.019 1997< -.010
Higher 1981  .161 1991  .151

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```
 UTR05E    1900 to 2003     104 years
Series  22

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1950 1969    0   -.21 .13  .11  -.16 .19  .36  .37  .40  .27  .05  .45* -.22
                 -.14 -.33 -.30 -.44 -.13 -.18 -.10 .26  .08
1960 1979   -3   -.19 -.17 -.25 -.19 .03  .23  .09  .50* .14  -.07 .49| -.22
                 -.42 -.26 .10  -.45 .09  .03  .13  .14  .28

[B] Entire series, effect on correlation (  .718) is:
Lower 1973< -.018 1950> -.016 1977> -.011 1952> -.011 1971< -.010 1951> -.007
Higher 1904  .022 1991  .015
1950 to 1969 segment:
Lower 1950> -.084 1952> -.052 1957< -.045 1959< -.043 1951> -.036 1960< -.029
Higher 1956  .206 1963  .089
1960 to 1979 segment:
Lower 1973< -.103 1971< -.042 1960< -.021 1966> -.009 1978> -.009 1975> -.008
Higher 1976  .072 1963  .043

=============================================================================

 UTR07N    1900 to 2003     104 years
Series  23

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1970 1989    0   -.13 .00  .03  .38  .03  -.16 .22  .13  -.13 -.36 .47* -.24
                 -.18 -.27 -.07 -.18 -.16 .12  .15  -.21 .15
1980 1999   -7   -.13 -.23 .05  .51* -.14 -.07 .36  .10  .13  -.08 .24| .17
                 -.18 -.14 -.47   -    -    -    -    -    -
1984 2003    0   -.22 -.31 -.09 .47  -.07 .05  .22  .03  .40  -.03 .51*  -
                 -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .715) is:
Lower 1981> -.021 1995> -.017 1953> -.010 1984< -.009 1989< -.008 1952> -.008
Higher 1904  .021 1929  .008
1970 to 1989 segment:
Lower 1981> -.098 1984< -.044 1989< -.042 1988< -.038 1982> -.026 1975< -.026
Higher 1977  .085 1976  .078
1980 to 1999 segment:
Lower 1995> -.077 1984< -.062 1981> -.058 1989< -.049 1988< -.034 1982> -.024
Higher 1991  .180 1985  .078
1984 to 2003 segment:
Lower 1995> -.123 1984< -.052 1989< -.045 1988< -.038 1992> -.014 1999< -.013
Higher 1991  .120 2003  .078

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```
 UTR07S    1900 to 2003     104 years
Series  24

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1950 1969   -4   -.18 -.13 -.15 -.31 .28  .34  .38* .21  .17  .12  .37| -.14
                 -.17 -.06 -.02 -.08 -.21 -.41 -.19 -.23 .23
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
                 - - - - - - - - - - - - - - - - - - - - - - -
1970 1989    0   -.05 .42  -.09 .00  .28  -.10 -.40 .15  -.12 -.45 .46* -.10
                 .17  -.05 .06  .03  -.02  .18  .03  -.10 .26
1980 1999    1   -.24 .06  .03  -.11 .28  -.08 -.38 .25  .07  .01  .28| .37*
                 .30  -.29 -.49   -    -    -    -    -    -

[B] Entire series, effect on correlation (  .593) is:
Lower 1981> -.026 1950> -.014 1980< -.014 1968> -.013 1975< -.012 1958< -.012
Higher 1977  .029 1991  .019
1950 to 1969 segment:
Lower 1958< -.062 1957< -.062 1950> -.058 1968> -.053 1952> -.029 1966> -.018
Higher 1956  .526 1963  .039
1970 to 1989 segment:
Lower 1981> -.157 1980< -.061 1975< -.053 1982> -.031 1985> -.024 1983< -.012
Higher 1977  .235 1973  .070
1980 to 1999 segment:
Lower 1981> -.135 1980< -.101 1982> -.029 1983< -.026 1994< -.026 1984< -.019
Higher 1991  .365 1987  .024

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1956 -4.5 SD
==============================================================================

 UTR08E    1900 to 2003     104 years
Series  25

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1910 1929    0   .08  -.03 -.40 .50  -.15 -.59 .34  .25  -.48 -.10 .50* .01
                 -.21 .00  .03  -.24 -.06 .38  .07  .00  -.03
1920 1939    0   -.08 -.07  .21  .12  -.18 .07  -.22 -.14 -.19 -.04 .38* .16
                 .21  -.23 -.11 -.09 .24  .14  -.09 .05  -.07
1930 1949    0   -.12 .03  .09  .33  .03  .03  -.32 .00  -.01 -.24 .42* -.03
                 .16  .04  -.16 .08  .07  -.31 -.20 .03  -.15
1940 1959   -6   -.28 -.13 .03  -.24 .57* -.07 -.17 .12  .09  -.18 .56| -.07
                 .07  .21  -.10 .03  .18  -.63 -.01 -.17 .04

[B] Entire series, effect on correlation (  .601) is:
Lower 1975< -.042 1929< -.024 1944> -.022 1958< -.014 1970> -.011 1992< -.010
Higher 1981  .022 1977  .017
1910 to 1929 segment:
Lower 1929< -.154 1917< -.051 1927< -.028 1920> -.026 1916> -.024 1910> -.015
Higher 1912  .088 1911  .061
1920 to 1939 segment:
```

```
Lower 1929< -.144 1936> -.065 1934< -.041 1920> -.040 1935> -.021 1927< -.018
Higher 1931  .101 1925  .063
1930 to 1949 segment:
Lower 1944> -.131 1934< -.065 1936> -.043 1940> -.041 1932< -.016 1945> -.012
Higher 1931  .114 1933  .058
1940 to 1959 segment:
Lower 1944> -.123 1958< -.106 1940> -.038 1955> -.017 1945> -.009 1942< -.004
Higher 1956  .127 1950  .050

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 UTR08S    1900 to 2003     104 years
Series  26

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1920 1939    0   .04  -.11 -.07 .28  -.12 .02  -.30 -.31 .09  .04  .41* .10
                 .13  -.21 -.23 -.17 .25  .36  .07  -.06 -.05

[B] Entire series, effect on correlation (  .656) is:
Lower 1970> -.012 1929< -.009 1928< -.009 1936> -.009 1971> -.008 1998< -.007
Higher 1981  .017 1956  .014
1920 to 1939 segment:
Lower 1936> -.074 1928< -.053 1927< -.036 1935> -.031 1921> -.031 1929< -.030
Higher 1925  .126 1931  .080

=============================================================================

 UTR09N    1900 to 2003     104 years
Series  27

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1960 1979    0   -.08 -.21 -.43 -.32 .05  -.32 -.02 .36  -.01 .10  .46* -.29
                 -.01 .11  -.04 -.16 .36  -.35 -.30 .09  .29
1970 1989    0   -.11 -.06 -.23 -.09 .06  .23  .08  -.24 -.10 .36  .38* -.52
                 -.15 .01  -.18 -.18 .08  .06  -.07 .14  .32
1980 1999   -5   -.25 .01  -.02 .15  -.13 .40* .13  -.64 -.10 .25  .39| -.22
                 .08  -.03 -.35   -    -    -    -    -    -
1984 2003   -5   -.17 .15  -.05 -.12 .06  .43* -.08 -.46 -.20 .11 .32|  -
                 -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .520) is:
Lower 1912< -.024 2002> -.016 1972< -.014 1902> -.013 1981> -.012 1948< -.011
Higher 1904  .019 1929  .018
1960 to 1979 segment:
Lower 1972< -.077 1961> -.068 1970> -.029 1971< -.026 1964< -.021 1965< -.018
Higher 1963  .064 1973  .052
1970 to 1989 segment:
Lower 1972< -.077 1981> -.045 1971< -.028 1980> -.015 1986< -.012 1970> -.011
Higher 1973  .043 1984  .039
1980 to 1999 segment:
Lower 1981> -.061 1997< -.054 1980> -.038 1994< -.025 1995> -.013 1993< -.009
```

```
Higher 1991  .103 1987  .038
1984 to 2003 segment:
Lower 2002> -.099 1997< -.051 2000> -.044 1994< -.022 2003< -.015 1995> -.009
Higher 1991  .148 1987  .047

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 UTR09S    1900 to 2003     104 years
Series  28

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1900 1919    3    -    -    -    -    -    -    -    -    -    -  .31| -.47
                 -.13 .40* -.46 -.09 .23  -.16 -.08 .19  .19
1910 1929   10   .14  -.34 .14  .22  -.32 .36  .11  -.44 -.01 .31  .37| -.18
                 -.10 .15  -.47 .08  .01  -.04 .03  -.07 .41*

[B] Entire series, effect on correlation (  .557) is:
Lower 1915< -.068 1912< -.016 1913> -.012 1940> -.009 1937< -.009 1999> -.008
Higher 1929  .017 1981  .016
1900 to 1919 segment:
Lower 1915< -.197 1913> -.048 1912< -.030 1902> -.019 1905< -.015 1916< -.008
Higher 1909  .078 1903  .067
1910 to 1929 segment:
Lower 1915< -.228 1913> -.053 1912< -.047 1916< -.011 1910> -.008 1926> -.006
Higher 1929  .134 1918  .070

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 UTR10E    1900 to 2003     104 years
Series  29

[B] Entire series, effect on correlation (  .738) is:
Lower 1952< -.021 1938> -.013 1964< -.010 1981> -.009 1942< -.007 1920< -.007
Higher 1977  .017 1991  .009

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1952 -4.7 SD
=============================================================================

 UTR10W    1900 to 2003     104 years
Series  30

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1930 1949    0   .10  .42  -.22 .14  .00  .19  -.25 -.17 -.08 -.14 .50* -.27
                 .09  -.13 -.11 .21  -.08 -.31 .08  .10  .06
1940 1959    0   -.23 .17  .08  .26  -.09 -.09 -.30 -.22 -.04 -.01 .39* -.03
                 .12  -.05 .08  .07  -.02 -.06 -.02 .07  .04
1950 1969    0   -.12 -.12 .08  -.04 -.14 -.17 -.31 -.28 -.02 .07  .50* .22
                 .19  .20  .31  -.06 -.14 -.05 -.08 .35  -.12
```

```
[B] Entire series, effect on correlation (  .657) is:
Lower 1956> -.035 1911> -.017 1920< -.014 1942< -.011 1938> -.009 1987> -.008
Higher 1904  .021 1981  .019
1930 to 1949 segment:
Lower 1942< -.092 1938> -.056 1943< -.019 1944> -.012 1945< -.011 1932< -.007
Higher 1937  .035 1940  .031
1940 to 1959 segment:
Lower 1956> -.168 1942< -.042 1944> -.022 1959< -.016 1950> -.010 1955> -.007
Higher 1952  .075 1957  .034
1950 to 1969 segment:
Lower 1956> -.240 1950> -.021 1959< -.021 1967< -.011 1955> -.010 1961< -.004
Higher 1963  .067 1952  .056

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1956 +3.3 SD
==============================================================================

 UTR13N    1908 to 2003      96 years
Series  31

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1910 1929   -7   .08  .25  -.45 .69* -.24 -.30 -.04 .01  -.29 .13  .68| -.27
                 -.03 -.02 -.14 .06  -.03 .31  -.17 -.12 .13
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
               - - - - - - - - - - - - - - - - - - - - - - - - -
1950 1969    0   -.17 -.09 -.27 .00  -.17 .09  .25  .05  -.01 .34  .48* .20
                 .22  .03  .10  -.02 -.49 -.56 -.18 -.03 -.08
1960 1979    0   .16  -.01 -.07 -.26 -.15 -.17 .26  -.03 -.32 .13  .51* -.25
                 .14  .49  -.04 -.36 -.15 .06  -.06 -.12 -.07
1970 1989    0   .05  -.08 -.02 .14  -.20 -.13 .36  .10  -.42 .21  .45* -.35
                 .01  .45  -.10 -.37 -.22 .28  -.08 -.36 -.16

[B] Entire series, effect on correlation (  .610) is:
Lower 1977> -.032 1950> -.021 1910> -.014 1984< -.010 1927< -.010 1934< -.010
Higher 1991  .015 1976  .014
1910 to 1929 segment:
Lower 1910> -.061 1927< -.034 1926> -.033 1918> -.031 1911< -.007 1920> -.007
Higher 1925  .045 1922  .022
1950 to 1969 segment:
Lower 1950> -.155 1968> -.035 1957< -.024 1962> -.022 1959< -.015 1954< -.014
Higher 1963  .126 1956  .078
1960 to 1979 segment:
Lower 1977> -.147 1978< -.043 1962> -.019 1974< -.018 1968> -.015 1967< -.015
Higher 1976  .098 1973  .057
1970 to 1989 segment:
Lower 1977> -.147 1984< -.060 1978< -.045 1974< -.024 1988< -.016 1987> -.014
Higher 1976  .156 1973  .098

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1977 +3.0 SD
==============================================================================
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```
 UTR13N    1900 to 2003     104 years
Series  32

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1900 1919    7   -    -    -    -    -    -    -    -    -    -   .42| -.26
                 -.25 .27  .21  -.39 .00  .46* -.05 -.03 -.10
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
                 - - - - - - - - - - - - - - - - - - - - - - -
1920 1939    5   .09  .06  -.06 .16  .21  .06  -.21 -.12 -.11 -.17 .51| .24
                 -.26 -.36 -.47 .61* .30  .06  -.13 -.39 -.07
1930 1949    5   -.02 .08  .21  -.08 .30  -.05 -.08 -.04 -.29 .09  .33| -.17
                 -.19 -.12 -.26 .70* .05  -.20 -.06 -.08 -.16
1940 1959    5   .07  .17  .15  .21  -.05 -.27 .04  .14  -.13 .16  .16| -.18
                 -.12 -.37 -.09 .26* .03  .07  -.22 -.02 .19
1950 1969   -4   .25  .26  .36  .23  -.05 .10  .54* .09  -.03 -.19 .04| -.21
                 -.11 -.66 -.11 -.10 .15  .23  .13  .24  .07
1960 1979   -4   .26  .25  .16  -.10 -.06 .08  .43* -.09 .41  -.07 .35| -.42
                 -.11 -.44 -.02 -.14 .10  .08  .26  .17  .07
1970 1989    0   .02  -.04 .16  -.15 -.37 -.37 .34  -.14 .04  -.16 .50* -.23
                 .02  -.29 .11  -.01 -.14 .40  .17  .09  .09
1980 1999    0   .08  -.19 .36  .12  -.14 .00  .20  -.06 -.30 -.42 .51* -.13
                 -.08 -.41 -.04   -    -    -    -    -    -

[B] Entire series, effect on correlation (  .417) is:
Lower 1907< -.024 1944> -.021 1960< -.016 1950> -.015 1956> -.014 1939< -.014
Higher 1911  .019 1925  .017
1900 to 1919 segment:
Lower 1907< -.144 1914> -.052 1918> -.033 1906< -.021 1912< -.017 1902> -.011
Higher 1911  .079 1904  .029
1920 to 1939 segment:
Lower 1939< -.079 1920< -.075 1929< -.042 1935> -.039 1938> -.034 1936> -.021
Higher 1925  .105 1922  .058
1930 to 1949 segment:
Lower 1944> -.136 1939< -.108 1935> -.034 1938> -.032 1941< -.032 1946< -.026
Higher 1949  .105 1943  .073
1940 to 1959 segment:
Lower 1944> -.099 1950> -.072 1959< -.070 1956> -.044 1941< -.030 1946< -.029
Higher 1949  .150 1943  .110
1950 to 1969 segment:
Lower 1960< -.087 1950> -.063 1968> -.043 1959< -.039 1956> -.033 1953> -.022
Higher 1967  .105 1957  .055
1960 to 1979 segment:
Lower 1960< -.090 1968> -.082 1979< -.057 1969> -.025 1972< -.019 1966> -.014
Higher 1970  .076 1976  .068
1970 to 1989 segment:
Lower 1979< -.089 1987> -.062 1972< -.038 1982> -.027 1988< -.015 1973< -.010
Higher 1981  .069 1976  .049
1980 to 1999 segment:
Lower 1987> -.071 1991< -.071 1992< -.039 1982> -.031 1988< -.019 1999> -.011
Higher 1981  .117 1985  .058

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```
 UTR13S    1900 to 2003     104 years
Series  33

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                +2   +3   +4   +5   +6   +7   +8   +9   +10
                ---  ---  ---  ---  ---  ---  ---  ---  ---
1930 1949    7   -.05 -.26 -.08 .05  .08  .25  .12  -.39 -.19 -.08 .37| .16
                .30  -.18 .01  -.31 -.05 .38* .08  -.25 -.24
1940 1959    7   -.11 -.16 .20  -.05 .04  -.17 .11  -.38 -.15 -.11 .22| .25
                .35  -.05 .14  -.08 .19  .40* .30  -.31 -.12
1950 1969    2   -.12 -.22 .13  .05  .22  -.50 -.24 -.16 .23  -.24 .39| -.13
                .47* .04  .25  -.18 .37  .05  -.05 .26  -.19
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
                - - - - - - - - - - - - - - - - - - - - - -
1980 1999    0   .12  -.19 .13  .18  -.15 -.36 -.16 .18  -.34 -.46 .38* -.24
                .26  -.23 .02   -    -    -    -    -    -

[B] Entire series, effect on correlation (  .529) is:
Lower 1956> -.030 1972< -.017 1987> -.016 1982> -.014 1949< -.013 1926> -.009
Higher 1977  .033 1991  .013
1930 to 1949 segment:
Lower 1949< -.080 1947> -.069 1942> -.040 1943< -.038 1937< -.026 1940> -.023
Higher 1931  .128 1944  .089
1940 to 1959 segment:
Lower 1956> -.141 1949< -.086 1943< -.043 1947> -.030 1948< -.029 1955> -.029
Higher 1944  .109 1952  .080
1950 to 1969 segment:
Lower 1956> -.198 1964< -.050 1955> -.039 1966> -.022 1958< -.019 1962< -.015
Higher 1968  .083 1952  .071
1980 to 1999 segment:
Lower 1987> -.095 1982> -.079 1993< -.044 1986> -.040 1997< -.038 1998< -.017
Higher 1991  .132 1995  .106

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1956 +3.7 SD
=============================================================================

 UTR13W    1900 to 2003     104 years
Series  34

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                +2   +3   +4   +5   +6   +7   +8   +9   +10
                ---  ---  ---  ---  ---  ---  ---  ---  ---
1930 1949    0   .10  -.03 -.16 .12  .16  .13  -.09 -.38 .11  .06  .50* -.29
                -.09 -.30 -.16 .25  .04  -.12 -.26 .33  -.09
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
                - - - - - - - - - - - - - - - - - - - - - -
1960 1979    0   .24  -.11 -.30 -.49 -.10 -.27 .15  -.26 .17  .27  .48* -.17
                .06  -.02 -.10 -.16 -.30 .22  -.07 -.12 -.13
1970 1989    0   -.16 .07  .07  -.48 -.16 -.12 .38  -.35 .14  .31  .48* -.24
                -.08 -.15 -.09 -.25 -.19 .46  -.39 -.20 -.17
1980 1999    0   -.63 -.15 -.03 -.14 -.02 .17  .39  -.29 .02  .17  .48* .11
                -.02 .05  -.07  -    -    -    -    -    -
```

```
[B] Entire series, effect on correlation (  .561) is:
Lower 1977> -.042 1995> -.021 1905< -.018 1950> -.018 1929< -.014 1944> -.013
Higher 1904  .021 1956  .018
1930 to 1949 segment:
Lower 1944> -.074 1930> -.038 1933> -.035 1936> -.029 1945< -.020 1946< -.020
Higher 1943  .085 1949  .077
1960 to 1979 segment:
Lower 1977> -.236 1968> -.041 1967< -.019 1979< -.012 1972< -.006 1961> -.004
Higher 1970  .106 1973  .065
1970 to 1989 segment:
Lower 1977> -.226 1983< -.026 1987> -.021 1989< -.015 1986< -.014 1979< -.006
Higher 1973  .090 1976  .082
1980 to 1999 segment:
Lower 1995> -.156 1983< -.037 1987> -.030 1998< -.024 1989< -.022 1999< -.019
Higher 1991  .203 1981  .096

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1977 +3.3 SD
=============================================================================

 UTR14E    1900 to 2003     104 years
Series  35

[B] Entire series, effect on correlation (  .701) is:
Lower 1995< -.030 1981> -.019 1931> -.012 1957< -.007 1977> -.006 1910> -.005
Higher 1904  .014 1991  .011

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1995 -5.3 SD
=============================================================================

 UTR14W    1900 to 2003     104 years
Series  36

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1910 1929    5   .17  .00  -.11 .33  -.35 -.33 -.06 .35  .12  -.04 .40| -.45
                 -.36 .26  .18  .44* -.38 .02  -.03 -.22 .24
1920 1939   -5   .38  -.31 -.13 -.24 -.31 .44* -.05 .12  .18  -.01 .28| -.52
                 -.27 .05  .21  .29  -.28 -.13 -.09 .42  -.05

[B] Entire series, effect on correlation (  .663) is:
Lower 1928< -.023 1925> -.015 1935< -.012 1977> -.011 1985> -.010 1956> -.009
Higher 1981  .017 1976  .011
1910 to 1929 segment:
Lower 1928< -.131 1925> -.070 1924> -.046 1927< -.040 1910> -.016 1920> -.008
Higher 1929  .061 1919  .049
1920 to 1939 segment:
Lower 1928< -.100 1925> -.095 1924> -.040 1927< -.027 1933> -.026 1920> -.010
Higher 1929  .087 1934  .062

=============================================================================
```

```
 UTR15E    1900 to 2003     104 years
Series  37

[B] Entire series, effect on correlation (  .775) is:
Lower 1939< -.010 1965< -.009 1931> -.007 2002> -.007 1916< -.005 1980< -.005
Higher 1991  .011 1977  .009

=============================================================================

 UTR15W    1900 to 2003     104 years
Series  38

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1930 1949    0   -.11 -.10 .15  .12  .29  .20  -.16 -.04 -.15 -.44 .44* -.21
                 -.17 .13  -.16 .06  .17  -.49 .02  .32  -.21

[B] Entire series, effect on correlation (  .747) is:
Lower 1941< -.018 1939< -.007 1983< -.006 1953> -.006 1935> -.005 1966< -.005
Higher 1977  .017 1991  .013
1930 to 1949 segment:
Lower 1941< -.115 1939< -.042 1942< -.028 1935> -.026 1945> -.016 1936> -.007
Higher 1949  .092 1934  .052

=============================================================================

 UTR16N    1900 to 2003     104 years
Series  39

[B] Entire series, effect on correlation (  .730) is:
Lower 1956> -.021 1955< -.016 1981> -.015 1904> -.011 1984< -.007 1986< -.006
Higher 1944  .010 1976  .007

=============================================================================

 UTR16S    1900 to 2003     104 years
Series  40

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1980 1999    0   -.05 .05  .11  .18  -.19 .00  -.24 -.21 -.37 -.21 .51* -.05
                 -.22 -.08 -.20   -    -    -    -    -    -
1984 2003    0   -.36 -.02 .15  .15  .04  .11  -.47 -.42 -.29 -.09 .48*  -
                 -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .690) is:
Lower 1987> -.015 1985> -.014 1904> -.014 1955< -.014 1901< -.010 2002> -.009
Higher 1977  .020 1944  .011
1980 to 1999 segment:
Lower 1987> -.087 1985> -.079 1993< -.032 1992< -.029 1994< -.025 1980< -.019
Higher 1991  .140 1995  .090
1984 to 2003 segment:
Lower 1987> -.083 1985> -.075 2002> -.043 1993< -.023 1992< -.022 1994< -.020
```

```
Higher 1991  .129 1995  .092

==============================================================================

 UTR17W    1900 to 2003     104 years
Series  41

[B] Entire series, effect on correlation (  .792) is:
Lower 1956> -.021 2002> -.013 1998< -.009 1955> -.008 1936> -.008 1992> -.007
Higher 1977  .013 1991  .010

==============================================================================

 UTR17E    1906 to 2003      98 years
Series  42

[B] Entire series, effect on correlation (  .731) is:
Lower 1989< -.020 1909< -.016 1931> -.014 2002> -.010 1956> -.010 1916< -.007
Higher 1977  .017 1944  .011

==============================================================================

 UTR18N    1900 to 2003     104 years
Series  43

[B] Entire series, effect on correlation (  .714) is:
Lower 2003< -.019 1962< -.016 2002> -.012 2001> -.009 1951> -.008 1930> -.007
Higher 1904  .015 1991  .012

==============================================================================

 UTR18W    1900 to 2003     104 years
Series  44

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1980 1999    4   .23  -.10 -.25 -.30 -.38 -.10 -.07 .09  .14  -.08 .25| -.16
                 -.04  .41  .43*   -    -    -    -    -    -
1984 2003  -10   .38* -.04 -.09 -.38 -.47 .01  -.30 .20  .12  -.34 -.07|  -
                 -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .607) is:
Lower 1997< -.018 2002> -.017 1985> -.015 1991< -.013 2003< -.012 1928< -.011
Higher 1904  .031 1977  .024
1980 to 1999 segment:
Lower 1985> -.082 1997< -.073 1987> -.056 1998< -.037 1988> -.020 1991< -.019
Higher 1981  .244 1995  .119
1984 to 2003 segment:
Lower 1997< -.059 2002> -.058 1985> -.047 2003< -.037 1998< -.033 1987> -.030
Higher 1995  .230 2000  .093

==============================================================================
```

```
 UTR19N    1900 to 2003     104 years
Series  45

[B] Entire series, effect on correlation (  .793) is:
Lower 1966> -.017 2000> -.006 1914> -.005 1949< -.005 1998< -.005 1975< -.005
Higher 1977  .012 1956  .009

=============================================================================

 UTR19S    1909 to 2003      95 years
Series  46

[A] Segment High -10  -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1
    ------- ---- ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
                 +2   +3   +4   +5   +6   +7   +8   +9   +10
                 ---  ---  ---  ---  ---  ---  ---  ---  ---
1984 2003    0   .11  .08  .20  -.09 .05  .11  -.52 -.15 .18  -.03  .50*  -
                 -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .687) is:
Lower 1995< -.047 2000> -.031 1950> -.013 1953> -.008 1942< -.006 1911> -.006
Higher 1977  .021 1981  .017
1984 to 2003 segment:
Lower 2000> -.138 2002> -.020 1985> -.013 1997< -.010 1999> -.004 1993> -.003
Higher 1995  .028 1987  .027

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1995 -5.5 SD
=============================================================================
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PART 7: DESCRIPTIVE STATISTICS: appen
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						Corr	//-------- Unfiltered	--------\\			//---- Filtered	-----\\			
			No.	No.	No.	with	Mean	Max	Std	Auto	Mean	Max	Std	Auto	AR
Seq	Series	Interval	Years	Segmt	Flags	Master	msmt	msmt	dev	corr	sens	value	dev	corr	()
1	CPL03E	1934 2003	70	7	6	.312	3.37	9.01	2.042	.596	.398	2.53	.466	.040	2
2	CPL03N	1938 2003	66	7	7	.340	2.78	7.27	1.675	.535	.425	2.65	.461	.061	2
3	CPL04N	1955 2003	49	5	1	.626	3.49	7.07	1.611	.554	.389	2.53	.525	.002	1
4	CPL04W	1933 2003	71	7	1	.639	1.98	4.76	1.048	.343	.395	3.14	.560	-.039	2
5	HCR03N	1900 2003	104	10	2	.634	1.64	6.28	1.073	.487	.508	2.94	.522	-.013	1
6	HCR03S	1900 2003	104	10	0	.677	1.62	4.47	.988	.540	.460	2.76	.471	-.013	4
7	SBL04W	1900 2003	104	10	0	.704	2.11	6.62	1.091	.105	.491	3.06	.498	-.037	2
8	SBL04E	1900 2003	104	10	0	.726	2.97	8.42	1.586	.436	.409	2.94	.615	.082	1
9	SBL05E	1900 2003	104	10	8	.418	1.85	8.73	1.549	.681	.424	2.90	.452	-.120	1
10	SBL05W	1900 2003	104	10	5	.492	2.25	7.72	1.687	.671	.463	2.81	.537	.040	1
11	SBL07E	1900 2003	104	10	0	.734	1.36	3.75	.900	.661	.472	2.95	.612	-.035	1
12	SBL07N	1900 2003	104	10	0	.731	.96	2.97	.614	.538	.570	2.79	.520	-.090	1
13	SBL08N	1900 2003	104	10	1	.654	1.94	6.59	1.272	.325	.649	2.60	.422	.048	1
14	SBL08S	1900 2003	104	10	4	.575	1.70	5.29	1.102	.142	.733	2.81	.487	-.030	1
15	SRS01E	1900 2003	104	10	2	.597	2.82	7.44	1.295	.633	.331	2.43	.391	-.018	1
16	SRS01W	1900 2003	104	10	0	.761	2.23	6.24	1.297	.663	.435	2.63	.521	-.004	1
17	UTR01N	1900 2003	104	10	1	.690	1.35	2.60	.543	.187	.425	2.86	.582	-.028	1
18	UTR01E	1900 2003	104	10	1	.742	1.40	3.18	.582	.289	.373	2.78	.505	-.044	1
19	UTR04W	1900 2003	104	10	1	.667	1.06	3.19	.655	-.180	.752	2.66	.380	.025	1
20	UTR04E	1900 2003	104	10	0	.663	1.56	3.82	.910	.046	.710	2.70	.399	-.032	1
21	UTR05W	1900 2003	104	10	1	.763	1.85	7.82	1.321	.290	.530	3.17	.581	.018	1
22	UTR05E	1900 2003	104	10	2	.718	1.81	7.15	1.427	.238	.642	3.06	.506	.054	1

23	UTR07N	1900	2003	104	10	3	.715	.41	1.17	.247	.437	.550	2.64	.464	-.020	1
24	UTR07S	1900	2003	104	10	3	.593	.71	1.60	.342	.668	.366	2.72	.401	-.026	1
25	UTR08E	1900	2003	104	10	4	.601	2.39	7.01	1.607	.608	.547	2.77	.524	-.010	2
26	UTR08S	1900	2003	104	10	1	.656	2.47	7.04	1.778	.647	.593	2.66	.471	-.001	2
27	UTR09N	1900	2003	104	10	4	.520	1.02	4.26	.824	.053	.839	2.88	.444	.016	2
28	UTR09S	1900	2003	104	10	2	.557	1.03	5.29	.789	.026	.899	2.95	.433	.023	2
29	UTR10E	1900	2003	104	10	0	.738	1.40	4.90	.823	.331	.551	3.09	.470	.036	1
30	UTR10W	1900	2003	104	10	3	.657	1.85	5.05	1.136	.622	.433	3.20	.552	.037	1
31	UTR13N	1908	2003	96	10	4	.610	3.14	10.27	1.863	.643	.392	2.70	.451	-.099	1
32	UTR13N	1900	2003	104	10	8	.417	2.21	5.61	.917	.646	.320	2.74	.467	.017	1
33	UTR13S	1900	2003	104	10	4	.529	1.75	4.44	.900	.711	.360	2.52	.366	-.106	1
34	UTR13W	1900	2003	104	10	4	.561	3.09	7.43	1.475	.315	.441	2.79	.544	.047	1
35	UTR14E	1900	2003	104	10	0	.701	2.31	5.73	1.172	.099	.543	2.65	.411	-.022	2
36	UTR14W	1900	2003	104	10	2	.663	2.51	7.42	1.294	.288	.503	2.77	.510	.034	2
37	UTR15E	1900	2003	104	10	0	.775	2.63	10.43	1.951	.421	.617	2.84	.462	-.049	1
38	UTR15W	1900	2003	104	10	1	.747	1.48	4.56	.941	.183	.664	3.03	.570	.006	2
39	UTR16N	1900	2003	104	10	0	.730	1.98	6.57	1.120	.208	.507	2.82	.566	-.004	1
40	UTR16S	1900	2003	104	10	2	.690	2.26	5.76	1.213	.231	.513	2.78	.556	.021	1
41	UTR17W	1900	2003	104	10	0	.792	2.30	6.29	1.224	.120	.555	2.99	.588	-.020	1
42	UTR17E	1906	2003	98	10	0	.731	2.90	8.57	1.677	.446	.486	2.77	.600	-.121	2
43	UTR18N	1900	2003	104	10	0	.714	1.11	5.41	.842	.091	.679	3.09	.590	-.027	1
44	UTR18W	1900	2003	104	10	2	.607	1.26	4.06	.741	.209	.547	2.83	.589	-.006	1
45	UTR19N	1900	2003	104	10	0	.793	2.26	5.39	.893	.346	.386	2.71	.534	-.051	1
46	UTR19S	1909	2003	95	10	1	.687	2.60	6.63	1.066	.479	.346	2.54	.378	-.062	1
Total or mean:				4601	446	91	.650	1.94	10.43	1.137	.377	.518	3.20	.499	-.012	

- = [COFECHA APPENCOF] = -

APPENDIX C. Select years used in pre- and post-dam comparisons. PDSI rank is reflective of ranges used by Palmer (1965) to indicate drought. 1 = extreme drought (< +4.0), 2 = severe drought (-4.0 to -3.0), 3 = moderate drought (-2.0 to -3.0), 4 = mild drought (-1.0 to -2.0), 5 = incipient drought (-1.0 to -0.5), 6 = normal (-0.5 to +0.5), 7 = incipient wet (+0.5 to +1.0), 8 = mild wet (+1.0 to +2.0), 9 = moderate wet (+2.0 to +3.0), 10 = severe wet (+3.0 to +4.0), 11 = extreme wet (> +4.0).

	YEAR	Total Annual Precip	Total GS Precip	Total Early GS Precip	Total GS/ annual Precip	Total late GS/GS Precip	Annual Ave PDSI	Annual PDSI Rank	GS Ave PDSI	GS PDSI Rank	Early GS Ave PDSI	Early GS PDSI Rank	Ave Annual, GS, and Early GS PDSI Rank
	DRY												
Pre-Dam	1904	2954	1489	563	0.50	0.62	-1.5	4	-1.8	4	-2.0	3	4
	1905	4062	1961	1396	0.48	0.29	-1.5	4	-1.7	4	-1.6	4	4
	1925	3452	853	734	0.25	0.14	-3.0	2	-4.0	1	-3.2	2	2
	1926	4604	2521	1967	0.55	0.22	-2.2	3	-2.2	3	-2.3	3	3
	1927	3523	1549	1424	0.44	0.08	-3.6	2	-3.7	2	-3.9	2	2
	1931	2238	1087	660	0.49	0.39	-2.5	3	-2.3	3	-2.1	3	3
	1945	4536	2827	1555	0.62	0.45	-2.4	3	-2.8	3	-2.8	3	3
	1946	4435	2367	1796	0.53	0.24	-1.5	4	-1.5	4	-1.5	4	4
	1950	3662	1834	1159	0.50	0.37	-2.8	2	-3.1	2	-3.4	2	2
	1951	3172	1677	1050	0.53	0.37	-2.4	3	-2.6	3	-2.4	3	3
Post-Dam	1954	2863	1581	1148	0.55	0.27	-2.8	3	-2.9	3	-2.3	3	3
	1955	3910	2474	1709	0.63	0.31	-2.7	3	-2.5	3	-2.5	3	3
	1956	4550	2504	1514	0.55	0.40	-2.2	3	-2.1	3	-2.0	3	3
	1978	3374	1567	925	0.46	0.41	-0.93	5	-1.0	4	-0.8	5	5
	1981	4701	2818	2284	0.60	0.19	-1.98	4	-2.2	3	-2.5	3	3
	1999	4394	2633	1778	0.60	0.32	-2.2	3	-2.4	3	-2.7	3	3
	2000	4049	2079	686	0.51	0.67	-2.1	3	-2.6	3	-2.7	3	3
	2001	3527	1864	1369	0.53	0.27	-1.8	4	-1.5	4	-1.4	4	4
	2002	4359	2005	1091	0.46	0.46	-2.2	2	-3.2	2	-4.0	1	2

APPENDIX C cont. Select years used in pre- and post-dam comparisons.

	YEAR	Total Annual Precip	Total GS Precip	Total Early GS Precip	Total GS/ annual Precip	Total late GS/GS Precip	Annual Ave PDSI	Annual PDSI Rank	GS Ave PDSI	GS PDSI Rank	Early GS Ave PDSI	Early GS PDSI Rank	Ave Annual, GS, and Early GS PDSI Rank
	WET												
Pre-Dam	1900	5134	2743	2068	0.53	0.25	0.26	6	0.4	6	1.1	8	7
	1901	5094	3001	1627	0.59	0.46	2.46	9	2.8	9	2.1	9	9
	1903	5183	2835	1464	0.55	0.48	1.24	8	2.0	9	1.8	8	8
	1906	5391	4002	2688	0.74	0.33	0.84	7	1.2	8	0.3	6	7
	1928	6388	4706	2670	0.74	0.43	2.5	9	3.2	10	2.0	8	9
	1929	6711	3064	2145	0.46	0.30	4.3	11	4.1	11	4.2	11	11
	1938	4027	2717	2312	0.67	0.15	-0.48	6	0.7	7	1.2	8	7
	1948	6713	3184	1874	0.47	0.41	3.73	10	3.4	10	3.8	10	10
	1949	4123	2712	1507	0.66	0.44	-0.16	6	0.6	7	0.6	7	7
Post-Dam	1958	4072	2254	1624	0.66	0.44	1.0	8	1.5	8	2.8	8	7
	1961	5210	2957	1931	0.57	0.35	1.2	8	2.2	9	2.1	9	9
	1964	7136	3791	2523	0.53	0.33	3.9	10	3.7	10	3.0	10	10
	1965	4885	2761	1945	0.57	0.30	3.0	10	3.0	10	3.3	10	10
	1966	4638	2294	1609	0.49	0.30	1.5	8	2.3	9	2.1	9	9
	1984	5986	3630	2726	0.61	0.25	0.68	7	1.4	8	2.5	9	8
	1989	5228	3147	2612	0.60	0.17	1.70	8	2.2	9	1.5	8	8
	1994	5843	2611	1562	0.45	0.40	1.1	8	0.7	7	-0.1	6	7
	1995	6720	3782	2389	0.56	0.37	3.1	10	2.5	9	2.0	9	9
	1997	5158	2290	1445	0.44	0.37	1.1	8	0.5	7	0.0	6	7

APPENDIX C cont. Select years used in pre- and post-dam comparisons.

	YEAR	Total Annual Precip	Total GS Precip	Total Early GS Precip	Total GS/ annual Precip	Total late GS/GS Precip	Annual Ave PDSI	Annual PDSI Rank	GS Ave PDSI	GS PDSI Rank	Early GS Ave PDSI	Early GS PDSI Rank	Ave Annual, GS, and Early GS PDSI Rank
	INTERMEDIATE												
Pre-Dam	1902	4175	1873	1280	0.45	0.32	0.38	6	-0.8	5	-0.9	5	5
	1936	5592	2713	1884	0.49	0.31	-0.45	6	-0.9	5	-0.5	5	5
	1937	4157	2563	1504	0.62	0.41	0.02	6	0.1	6	0.2	6	6
	1942	5100	2364	1464	0.46	0.38	-0.42	6	-0.8	5	-0.7	5	5
	1943	3864	1810	1454	0.47	0.20	-0.19	6	0.1	6	0.4	6	6
Post-Dam	1959	6052	3127	1608	0.52	0.49	0.81	7	0.2	6	-0.1	6	6
	1968	4306	2551	2271	0.59	0.11	-0.46	6	-0.2	6	0.0	6	6
	1974	4443	2461	1605	0.55	0.35	0.12	6	0.1	6	-0.2	6	6
	1982	4963	2474	1773	0.50	0.28	0.26	6	0.1	6	0.4	6	6
	1996	5071	2910	1541	0.57	0.47	0.21	6	-0.2	6	-0.4	6	6

APPENDIX D. Depth to the shallowest layer of pure clay at each piezometer.

Piezometer	Depth to clay layer
utr_le1	2 m
utr_le3	68 cm
sb_le1	> 2 m
utr_bs1	< 15 cm
sb_bs1	0 cm (at soil surface)