TREE-RING ANATOMICAL VARIABILITY AND FLOODING NEAR THE WHITE RIVER-MISSISSIPPI RIVER CONFLUENCE

by

MATTHEW DOBBYN MEKO

MATTHEW THERRELL, COMMITTEE CHAIR

SAGY COHEN
GLENN TOOTLE

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ABSTRACT

I explored the relationship between inter-annual tree-ring anatomical variability of overcup oak (*Quercus lyrata*) and river flooding at a floodplain forest site near the confluence of the White River and Mississippi River, developing chronologies of anatomical variability from quantitative measurement series and also from the visual identification of presence or absence of “flood-ring” anatomical anomalies. A chronology developed from measured widths of the first rank of earlywood vessels (VR₁W) in each growth increment displayed a strong signal related to spring river levels, and a VR₁W-based model of spring river levels explains 37 percent of the variance of the 67 years of mean March-April-May stage height with which it was calibrated. The flood-related signal present in the VR₁W chronology provides quantitative evidence supporting the continued study of past floods using tree rings, but does not capture relative magnitude of floods better than a chronology of flood response based on visual identification of flood-ring anatomical anomalies. Further investigation of the tree-ring flood record necessitates the development of chronologies from carefully selected sites, as well as continued exploration of methods of quantifying anatomical variability.
## LIST OF ABBREVIATIONS AND SYMBOLS

**BOT**  
Big Oak Tree State Park

$c_{\text{eff}}$  
The effective number of cores per tree, when a chronology is averaged from an unequal number of cores per tree

$c_i$  
Number of cores in the $i^{\text{th}}$ tree

**EPS**  
Estimated signal strength of a sample chronology as a fraction of a hypothetical perfect population chronology signal

**LW**  
Latewood width

**MAM**  
March, April and May

$n$  
sample size

$n_t$  
Number of trees

$n_T$  
The average number of trees contributing to each year of a chronology

$p$  
Probability value as determined by a test of statistical significance

$r$  
Pearson product-moment correlation

$r_1$  
First-order autocorrelation

$R^2$  
Coefficient of determination

$\bar{r}_{bt}$  
The mean interseries correlation between all series from different trees

**RE**  
relative predictive skill of a model compared to that of the mean of the calibration data

$\bar{r}_{\text{eff}}$  
An estimate of chronology signal that accounts for both within- and between-tree correlations

**RI**  
Proportion of analyzed trees exhibiting flood-ring anatomical anomalies

$r_s$  
Spearman rank correlation
RW  Total ring width

$\bar{r}_{wt}$  mean of correlations between series from the same tree over all trees

SSM  The sum of the squared differences of the validation data from the mean of the calibration data

SSR  The sum of the squared residuals for validation data

VR\_W Width of the first rank of earlywood vessels in an annual increment of xylem growth

WRR  Dale Bumpers White River National Wildlife Refuge

<  Less than

=  Equal to
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1. INTRODUCTION

River floods affect human populations via direct damage to natural and cultural bodies upon which economic systems depend, including but not limited to agricultural ecosystems, infrastructure, properties private and public, and human life. The United States suffered an estimated $50 billion in flood damages in the 1990s [Downton et al., 2005]. In that same decade, floods killed about 100,000 people worldwide, affecting an estimated 1.4 billion people [Jonkman, 2005]. These threats to human environments and society make floods an important topic in hydrological and atmospheric research [e.g., Changnon and Kunkel, 1995; Knox, 2000; Pinter et al., 2008], and studies of human vulnerability to, preparedness for, and perception of natural hazards [e.g., Messner and Meyer, 2006].

Floods occur as part of hydrologic systems that are linked globally and driven primarily by atmospheric circulation, yet because global circulation models focus on average conditions, event-scale atmospheric and hydrologic phenomena related to flood forcing remain inadequately understood [Knox, 2000]. Statistical models used to predict the magnitude and frequency of future floods primarily rely on instrumental and to some extent historical measurements of flood stage and discharge, however instrumental records prior to mid-nineteenth century are rare and lack adequate temporal and spatial resolution, hindering quantification of the potential range of severity and temporal pattern of floods [Costa, 1987; Klemeš, 1989; Benito et al., 2004; Brázdil et al., 2006]. Studies of paleofloods, those floods that occurred before the instrumental record, can augment temporal and spatial coverage of current flood records, and shed light on the
variable frequency and magnitude of extreme events [Knox, 2000]. Indirect evidence of floods that occurred before the hydrologic record includes sediment deposits, landforms, and vegetation [Costa, 1987]. Paleoflood hydrological studies into pre-instrumental flood frequency and magnitude, can supplement knowledge of past flooding and associated climatic variability [Costa, 1987]. Such studies often employ methods of geochronology and geomorphology, such as Quaternary stratigraphy and sedimentology to interpret slack-water deposits and paleostage indicators [Baker, 2006; Kochel et al., 1982].

Botanical archives can also provide data for the study of paleoflood hydrology, because riparian trees record evidence of past streamflow variability in a variety of ways, and that evidence can be accurately located in time using dendrochronological dating methods. The formation of scar tissue after local cambial death caused by impact or abrasion by flood-borne debris can date past floods with annual or sometimes sub-annual precision, and the height of scarring along the tree stem can serve as a minimum estimate of past flood stage [Sigafoos, 1964; Harrison and Reid, 1967; McCord, 1996]. The ages of stems sprouting vertically from flood-tilted trees, and the ages of trees growing on surfaces stripped bare by catastrophic flooding can indicate dates of floods [Sigafoos, 1964; Gottesfeld and Gottesfeld, 1990]. Defoliation of the crown or prolonged inundation of roots and stem can interfere with physiological processes controlling xylem formation and result in distinct flood-related anatomical anomalies within the annual growth increment, termed “flood rings,” which mark the year and possibly the season of flood occurrence [Yanosky, 1983; Astrade and Bégin, 1997; St. George and Nielsen, 2000; Therrell and Bialecki, 2014].

Overcup oak (Quercus lyrata) increment core samples collected by Stahle [1980] from Scrubgrass Bayou, Arkansas exhibit anatomical variability including features associated with
those of flood rings, often in growth formed in years of major Mississippi River floods, e.g., 1844, 1913, 1927, 1945 (Figure 1) [Therrell and Bialecki, 2014]. Annual growth increments of ring-porous hardwood trees such as *Q. lyrata* typically feature a porous earlywood zone consisting of very large conductive vessel-member cells, and a latewood zone featuring dense fibers and much smaller vessels [Yanosky and Jarret, 2002]. *Quercus* flood rings differ from typical *Quercus* growth increments primarily in the size and arrangement of earlywood vessels, which often appear diminished and occupying a greater portion of the growth increment relative to adjacent and surrounding rings [Astrade and Bégin, 1997; St. George and Nielsen, 2000; Therrell and Bialecki, 2014]. I hypothesized that a chronology of quantified vessel variability in trees growing at the Scrubgrass Bayou site would yield an ecophysiological signal related to flooding, and I conducted the present study with the following objectives: 1) to develop new site chronologies of anatomical variability as well as ring width, for trees likely to carry flood-related anatomical signals; and 2) to determine how the new chronologies respond to flooding at nearby river gauges. I developed chronologies of anatomical variability from measurement series of earlywood vessel size, and from visually identified flood ring presence/absence. I compared these chronologies to hydrologic data representative of nearby river flooding, and discuss their respective strengths and weaknesses with respect to potential contribution to the paleoflood record.
Figure 1. Tree-ring anatomical anomaly examples. Increment-core photomicrographs show *Q. lyrata* anatomical anomalies within growth increments formed in years of major Mississippi River floods (highlighted), apparent in samples collected along Scrubgrass Bayou, Arkansas. Anomalous features include diminished earlywood vessels relative to normal rings, especially those vessels in the first rank, adjacent to the ring boundary (b), (c), and (d); and an extended porous zone of earlywood vessels (a), (b), and (d).
2. LITERATURE REVIEW

2.1. Foundations of dendrochronology

The central dendrochronological principle of crossdating – assigning dates to annual growth in trees by comparing internal markers across multiple individuals – has been practiced since at least 1737, however dendrochronology did not gain a lasting foothold in the sciences until the early twentieth century when A. E. Douglass developed extensive tree-ring chronologies for applications in astronomy and archaeology [Studhalter, 1956]. Application of methods of dendrochronology has since grown over the course of the past century to become important to climatological, hydrological, and ecological research [Fritts and Swetnam, 1989; Cook and Kairiukstis, 1990]. Douglass famously dated the occupation of twelfth-century structures in Chaco Canyon, New Mexico, and other archaeological sites throughout the American Southwest with the discovery of charcoal remains of a single beam that cemented the dates of a floating prehistoric tree-ring chronology against a centuries-long chronology extending from the present [Haury, 1962]. Douglass’s work to develop the field of dendrochronology grew out of his interest in tree rings as they related to his work as an astronomer. He hypothesized that solar variability could be represented by the growth patterns of trees, reasoning that certain trees would record climate, and climate variations could be driven by solar variations, e.g., sunspot cycles [Webb, 1983; Cook and Kairiukstis, 1990]. Douglass continued his inquiry into the relationship of tree rings and climate in parallel with his archaeological work, and served as the first director of the University of Arizona’s Laboratory of Tree-Ring Research from its
establishment in 1937 until his death in 1962 [Cook and Kairiukstis, 1990]. Schulman [1945] further advanced the field of dendroclimatology, reconstructing runoff in the upper Colorado River basin, identifying wet and dry periods reaching back over 600 years into the past; as well as describing the important considerations of site selection and species selection.

Dendroclimatological studies generally use chronologies of tree-ring growth indices to reconstruct a climate variable for the pre-instrumental period covered by the chronology. The reconstruction is typically achieved using a regression model, where the mean index chronology is the predictor for the climate-variable that most influences tree growth at a given site [Fritts, 1976]. The use of dendrochronological methods for problems in ecology grew substantially in the late twentieth century; in their review of dedroecology, Fritts and Swetnam [1989] place such applications into one of four basic categories: 1) dating specific ecological events based on associated ring structures or injuries e.g., fire scars; 2) dating and evaluating forest disturbances based on distinctive changes in ring widths or other ring features e.g., insect outbreaks; 3) applying climatic or hydrologic reconstructions to problems in ecology; and 4) inferring variations in animal populations from closely-related variations in climate as reflected in the tree-ring record. Fritts and Swetnam [1989] note the development of flood records from mechanical scaring of floodplain trees by Sigafos [1964] as an example of the first dendroecological application.

2.2. Anatomical response to floods and other environmental factors

Although dendrochronological records of past flood events first used tree rings to date mechanical scars and other flood damage caused to trees, as well as flood-related depositional events, trees also record evidence of past flooding as anatomical responses to flood conditions
that are then preserved in the structure of xylem cells within the annual growth increment 
[Yanosky, 1983; Astrade and Bégin, 1997; St. George and Nielsen, 2000]. Under normal growing conditions, ring-porous trees e.g. Quercus and Fraxinus species form distinct tissues during early and later parts of the growing season, which investigators refer to as earlywood and latewood, respectively [St. George et al., 2003]. Earlywood tissue in ring-porous species is characterized by single or multiple ranks of large conductive vessels formed before and during leaf expansion and twig elongation in spring; latewood tissue exhibits much smaller vessels, and is characterized by dense fiber and flame parenchyma cells [Yanosky and Jarrett, 2002]. Inundation of roots and stem of ring-porous tree species can lead to a variety of abnormalities in annual ring tissues. Yanosky [1983, 1984] found trees that experienced defoliation during summer floods developed latewood tissues that exhibited some characteristics of earlywood, such as enlarged vessels and abnormally thin fiber-cell walls. Astrade and Bégin [1997] found that Q. robur trees developed abnormally small and disorganized earlywood vessels in response to root inundation during spring flooding. St. George and Nielsen [2003] used Q. macrocarpa flood rings exhibiting similar anatomical anomalies to construct a proxy record of extreme floods in the lower Red River, Manitoba. The flood response evident in variability of vessel size and arrangement is thought to be related to a disruption in the normal downward flow of auxin in the inundated tree [St. George, 2010]. Concentrations of auxin, specifically indole-3-acetic acid (IAA) control the rate of vessel cell differentiation from the vascular cambium, with high IAA concentrations resulting in rapidly differentiated and thus smaller-diameter vessels, and low IAA concentrations resulting in slowly differentiated, wide-diameter vessels [Aloni and Zimmerman, 1983].
At present, paleoflood chronologies developed from anatomical anomalies within tree rings primarily rely on visual identification of flood rings, resulting in categorical presence/absence data [e.g., St. George and Nielsen, 2003; Wertz et al., 2013; Therrell and Bialecki, 2014]. However, measurement of cell-structure parameters within the ring can provide continuous data that may contain information about magnitude and duration of flood events that occurred during cell formation. Such measurements e.g., mean vessel area can contain environmental information not present in the signal of other tree-ring metrics such as ring width [Fonti and García-González, 2004]. Woodcock [1989] measured anatomical variables in bur oak (Q. macrocarpa) growing in southeastern Nebraska, including diameter and density of both earlywood and latewood vessels, and developed a reconstruction of October-June precipitation from latewood vessel diameter. Fonti and García-González [2008] built chronologies of mean vessel area, earlywood width, latewood width, and total ring width of oak (Q. petraea and Q. pubescens) growing in a range of climatic contexts in Switzerland, and compared the applicability of the anatomical variable as a potential climate proxy with that of standard variables. That study found mean vessel area to have a different and stronger response to climate compared to that of ring-width variables, especially at mesic sites, where mean vessel area correlated strongly with spring precipitation. García-González and Eckstein [2003] used an automatic image analysis system to measure vessel lumen areas of Q. robur growing on a maritime Mediterranean site and found vessel area correlated to March and April temperature and precipitation. García-González and Fonti [2006] highlight the importance of selecting the appropriate anatomical elements within the annual increment to include in an analysis of interannual variability, as they found chronologies of chestnut (Castanea sativa) vessel area incorporating different size classes of vessels contained different signals, and that vessel area
chronologies incorporating all sizes of vessels yielded weaker climate-growth relationships. 

*Fonti et al.* [2006] found *C. sativa* mean vessel area chronologies contained both a negative February-March temperature signal, and a positive April temperature signal. *Kames et al.* [2011] suggested use of earlywood vessel area measurements to refine temporal and spatial resolution of forest fire reconstruction. *Sass-Klaassen et al.* [2011] found that the timing and duration of earlywood-vessel formation can vary between species and between individuals within species. *Lopez et al.* [2014] reconstructed water levels of the Atrato River in the Darien Gap in Panama from a chronology built from series of measured number of vessels in the annual growth of the tropical floodplain-forest tree *Prioria copaifera*. *Astrade and Bégin* [1997] describe flood-related anatomical variability in *Q. robur* trees growing in floodplain forests of the Saone River, France, including a marked reduction in mean and standard deviation of vessel lumen area in rings formed in 1983 when the Saone experienced severe late spring flooding. *St. George et al.* [2002] found that *Q. macrocarpa* rings bearing vessels with areas roughly two standard deviations below the mean coincided with major floods, but could not account for more subtle variations. Nonetheless, that study concluded that vessel area series were useful for the reconstruction of extreme flood frequency.

2.3. *Overcup oak and flooding*

Overcup oak is considered a flood-tolerant species, and can be found growing on sites subject to lengthy inundation [*Parker*, 1950; *Broadfoot and Williston*, 1973; *Hook*, 1984]. In a study of flood-related root injury by *Parker* [1950], all oaks studied exhibited a decline in transpiration after flooding, but only overcup oak showed a rebound in transpiration after 29 days of inundation, accompanied by production of a second crop of leaves. Other oaks in that
study showed a persistent decline in transpiration throughout the period of inundation. Kozlowski [1997, 2002] described a variety of possible direct and indirect effects of flooding on Quercus and other woody plant species, including reduction of root growth as a result of soil inundation, flood-induced reduction of photosynthesis, and anatomical abnormalities attributed to hormonal dysfunction or adaptive strategies. One example of adaptive plasticity is the formation of aerenchyma tissue wherein intercellular spaces are enlarged, sometimes resulting in cell collapse. Aerenchyma tissues facilitate the basipetal transport of oxygen from aerial tissues to oxygen-starved inundated roots [Kozlowski, 1997]. Hook [1984] noted that in the Mississippi Delta, overcup oak and associates green ash (Fraxinus americana) and water hickory (Carya aquatica) leaf out nearly a month later into the year than do surrounding upland hardwoods. Filer [1975] found that mycorrhizal fungi populations associating with Mississippi Delta overcup oak were reduced and inhibited during flooding, but recovered from flood effects within the growing season of flood recession, which suggests possible disruption of normal nutrient transport.
3. MATERIALS AND METHODS

3.1. Study area

Scrubgrass Bayou lies within the Dale Bumpers White River National Wildlife Refuge (WRR), Arkansas (34° 21’ N, 91° 06’ W; Figure 2). Located along the White River, just upstream of its confluence with the Mississippi River, the 65,000 ha WRR comprises 62,300 ha of forests, 2,000 ha permanent water, 360 ha cropland, and 400 ha grassland [Clark and Eastridge, 2006]. Bailey [1995] places the refuge within the Lower Mississippi Riverine Forest Province, subject to a humid subtropical climate including precipitation averaging around 1,400 mm annually with an August minimum; warm winters with average temperatures 10°-16°C and hot summers with average temperatures 21°-27°C. Soils of the Lower Mississippi Riverine Forest Province comprise a mosaic of Inceptisols formed in alluvium, Alfisols formed in loess, and Mollisols formed in areas dominated by swampy vegetation [Bailey, 1995]. The forests of the WRR make up the largest publicly owned tract of bottomland hardwood forest in the lower Mississippi alluvial valley [Oli et al., 1997]. Elevation ranges between 41-49 m, with the lower 75 percent of the refuge experiencing prolonged inundation from winter and spring flooding [Oli et al., 1997; Clark and Eastridge, 2006]. Bedinger [1971] states that flooding is the dominant environmental factor in bottomland forests of the lower White River. The White River drains a 72,520-km² basin spanning northern Arkansas and southern Missouri, its principle headwaters originating in the Boston Mountains of northern Arkansas [Gordon, 1982]. Discharge averages 741 m³s⁻¹, or about 65 percent of the average discharge of the Arkansas River, and four percent
of the average discharge of the Mississippi River [Schrader et al., 2006]. We observed *Q. lyrata* growing on the natural levees and floodplains adjacent to Scrubgrass Bayou, in association with water hickory (*Carya aquatica*) and southern hackberry (*Celtis laevigata*). Bedinger [1971] determined that similarly composed forests of the lower White River valley experienced inundation averaging 29-40 percent of the year.

Flooding depth and duration in the lower White River valley system can be influenced to varying degrees independently or collectively by the Mississippi River, White River, Arkansas River, and local rainfall patterns [United States Fish and Wildlife Service, 2012]. The geology of the involved river basins partly explains the complex hydrology of the area, in that the relatively high sediment load of the Mississippi and Arkansas rivers as compared to that of the White has resulted in a rise in base level of the White River without a concomitant equal rise in flood plain by deposition [Bedinger, 1971]. As a result of this situation, the level of the Mississippi River exerts a strong effect on the behavior of the flood waters in the lower White River valley, allowing quick and unhindered drainage of White River waters in times of low Mississippi River levels, and slowing or halting drainage of White River waters in times of higher Mississippi River levels, exacerbating flood depth and duration [United States Fish and Wildlife Service, 2012]. The 1939 construction of the White River Levee constricted the floodplain of the lower White River; lower flows result in higher elevations of flooding than was the case under pre-settlement hydrology [United States Fish and Wildlife Service, 2012]. Other twentieth-century hydrologic modifications affecting the study site include the Kerr/McClellan Navigation project connecting the Arkansas River and mile 10 of the White River, the construction of dams on the upper White River and its tributaries beginning in 1943, the conversion of bottomland hardwood forest to agricultural land, the withdrawal of surface and subsurface water for agricultural
irrigation, the entrainment of the Mississippi River, and other alterations to the hydrology of the Mississippi River associated with the federal flood control projects that began after the major Mississippi River flood of 1927 [United States Fish and Wildlife Service, 2012].

Figure 2. Study area. Sources of data used in the study include the tree-ring collection site at Scrubgrass Bayou; the White River gauges at St. Charles and Clarendon, AR; the Mississippi River gauge at Helena, AR; and the Dumas, AR weather station.

3.2. Data collection and analysis

I collected increment-core samples from living Q. lyrata trees and cross-sections from dead trees in the WRR in August and November 2014. I collected multiple increment core samples from each tree sampled when possible, to aid in crossdating and to reduce noise introduced from within-tree variation of ring width and other measured parameters [Fritts, 1976]. I collected increment-core samples using a 5-mm Swedish increment borer, as near to ground level as possible, as St. George et al. [2002] found that the anatomical response to flooding may
decrease with height along the trunk of the tree. Along the east bank of Scrubgrass Bayou, *Q. lyrata* individuals dominated the riverside slopes and crowns of the natural levees, and sampling targeted trees representative of the entire spectra of age classes and topographical positions. Samples taken from the west bank of Scrubgrass Bayou consisted of cross sections from dead and down trees further inland on the floodplain flat. I also included in this study 24 increment cores from 15 trees sampled by *Stahle* [1980] on the west bank of Scrubgrass bayou.

After allowing the samples to dry, I mounted the increment cores, prepared transverse surfaces of all samples using progressively finer-grit sand paper, and assigned exact annual dates to growth increments using the method of cross-dating patterns of relative ring width [*Stokes and Smiley*, 1968]. I measured the width of the first rank of earlywood vessels (VR₁W) and the total ring width (RW) of each dated growth ring to 0.001 mm precision using the earlywood/latewood measurement function of Measure J2X computer software (VoorTech Consulting, Holderness, NH, 2007) and a sliding measurement stage (Figure 3). I used the computer program COFECHA to statistically verify accurate sample dating. COFECHA filters measurement series with a smoothing spline, applies an autoregressive model and log transformation, and computes correlation coefficients for 25-year-lagged, 50-year series segments with a master mean-value chronology, flagging segments that do not meet a critical correlation value and providing correlation coefficients for alternative dating solutions [*Holmes*, 1983; *Grissino-Mayer*, 2001].
Figure 3. Measurement of *Q. lyrata* growth increment. I used the earlywood/latewood measurement configuration of MeasureJ2X to record measurement series of the radial width of first rank of earlywood vessels (VR\textsubscript{1}W) and total wing width (RW = VR\textsubscript{1}W + LW).

I developed a response-index (RI) chronology based on visual identification of the presence or absence of flood-ring anatomical anomalies [e.g., *Therrell and Bialecki*, 2014]. The RI value for each year in the chronology gives the proportion of analyzed trees exhibiting anatomical anomalies in the growth increment formed that year. Diagnostic features identifying flood rings include reduced-sized earlywood vessels, and earlywood vessels extending into latewood. I included only years represented by two or more trees in the response-index analysis. To examine the sensitivity of response index values to flood magnitude and timing, I compared response index values with height and date of historic crests recorded at the White River gauges.
at Clarendon, Arkansas and St. Charles, Arkansas, available from the National Weather Service (http://water.weather.gov/). 45 ranked historic crests are listed for the gauge at Clarendon, and 15 ranked historic crests are listed for the gauge at St. Charles. I computed Spearman’s rank correlation values for response index values and historic crests at each gauge. I removed redundant instances of same-year historic crest observations from this analysis, e.g., I removed the thirteenth-ranked 2011 historic crest at St. Charles because 2011 appears in higher in the ranking for the third-ranked historic crest at St. Charles.

I developed mean-value index chronologies from VR,1W and RW measurement series using the package dplR (A. Bunn et al., dplR: Dendrochronology Program Library in R, 2015, http://CRAN.R-project.org/package=dplR) in the R statistical computing environment (R Core Team, R: a language and environment for statistical computing, 2014, http://www.R-project.org) [Bunn, 2008]. I standardized all measurement series using a smoothing spline with a frequency response of 0.5 at a wavelength of two-thirds series length to model low-frequency variability and age-related trend in growth. Dividing each series by the spline curve results in a dimensionless index series with a mean value of 1. I then averaged the standardized VR,1W and RW index series into mean VR,1W and RW index chronologies, respectively.

I computed commonly used chronology statistics using dplR, including EPS and first-order autocorrelation. The Expressed Population Signal (EPS) statistic provides a metric for estimating the signal strength of a sample chronology as fraction of a hypothetical perfect population chronology signal:

\[
EPS(n_t) = \frac{n_T r_{e_{eff}}}{n_T r_{e_{eff}} + (1 - r_{e_{eff}})}
\]  

(1)
where \( n_T \) is the average number of trees contributing to each year of the chronology, and \( \bar{r}_{\text{eff}} \) is an estimate of chronology signal that accounts for both within- and between-tree correlations:

\[
\bar{r}_{\text{eff}} = \frac{\bar{r}_{\text{wt}}}{\bar{r}_{\text{wt}} + \frac{1 - \bar{r}_{\text{wt}}}{c_{\text{eff}}}}
\]  

(2)

where \( \bar{r}_{\text{wt}} \) is the mean of the correlations between series from the same tree over all trees and \( \bar{r}_{\text{bt}} \) is the mean interseries correlation between all series from different trees and \( c_{\text{eff}} \) is the effective number of cores per tree, when a chronology is averaged from an unequal number of cores per tree:

\[
\frac{1}{c_{\text{eff}}} = \frac{1}{n_T} \sum^{n_T}_{i=1} \frac{1}{c_i}
\]  

(3)

where \( n_T \) is the number of trees and \( c \) is the number of cores in the \( i \)th tree [Cook and Kairiukstis, 1990].

I computed Pearson correlation coefficients for relationships of chronologies VR, W and RW with temperature, precipitation, and river-stage variables representing each month of the water year, which includes October, November, and December of the year preceding growth as well as January through September of the year contemporaneous with growth. This analysis quantifies the linear response of a given chronology to the annual variability of environmental conditions in each month of the water year of tree-ring growth. For variables representative of flood conditions I computed annually resolved monthly averages from daily stage-height data measured at a nearby river gauge at St. Charles, AR, available from the United States Army Corps of Engineers (http://rivergages.mvr.usace.army.mil/). I chose to focus on the St. Charles gauge because its location on the lower White River most closely approximates the hydrologic situation of the tree-ring sample site along Scrubgrass Bayou, subject to headwater flooding.
originating in the White River basin and backwater flooding influenced by the levels of the Mississippi River, including Mississippi River floods. For climate variables I used 64 years of monthly mean temperature and monthly precipitation totals spanning the period 1948-2011, recorded at the nearby weather station at Dumas, AR [Menne, et al. 2012].

Temporal coverage of the St. Charles gauge data is intermittent, with complete daily coverage for only 53 of the 82 calendar years in the observational period 1932-2013. For the correlation analysis of mean stage heights for months October-September of the water year I included the 38 complete-coverage years in the St. Charles gauge record consecutively succeeding another year with complete coverage, limiting the number of observations in that analysis to 38 (Figure 4). I also computed correlation coefficients for relationships of $VR_1W$ with stage height means for months March, April and May individually and seasonalized into a MAM stage height mean, using all available years with complete daily coverage of those months. Complete data coverage of individual months varies from 67 years of complete daily stage-height measurements for June, to 71 years of complete coverage for March, April and July. 67 years feature complete coverage of MAM daily stage.
Figure 4. White River daily stage heights for 38 water years. These data were recorded at the gauge at St. Charles, Arkansas, for which there is no official flood stage. The dotted horizontal line indicates 7.9-meter stage, the criterion for closure of flood-prone areas of the WRR to deer hunting, according to the Arkansas Game and Fish Commission Hunting Guidebook 2014-2015 (http://www.agfc.com/). The majority of severe floods crest in the spring months, but the most severe flood represented in the data (1937) crested in winter. Both years with flood crests in late June reached higher stages earlier in their respective years of occurrence.

I reconstructed spring (March through May; MAM) mean daily White River stage heights for the period 1800-2013 using a simple linear regression of the Scrubgrass Bayou VR1W chronology. I used the split-sample method of model validation to evaluate the reconstruction [Snee, 1977]. In the split-sample method, the final reconstruction regression model utilizes the full available predictand data for calibration; validation is accomplished by splitting the predictand data into two subsets used to calibrate and validate two separate models. One model uses the first subset as calibration data and the second subset as validation data, and the
respective roles of the subsets reverse in the other model. The full available predictand data for my reconstruction comprise 67 years of MAM mean daily stage heights, computed from St. Charles gauge data for years with complete daily MAM coverage within the 1932-2013 instrumental period. For the split-sample validation I used two 33-year subsets of the MAM mean-stage data, one comprising years within the period 1932-1969, and the other comprising years within the period 1970-2012. I excluded 2013 data from the analysis to allow an even split of observations and maximize comparability of the two subsets and respective validation statistics. I computed Pearson’s $r$ correlation coefficients, and reduction of error (RE) statistics for validation of each split-sample model. The RE statistic gives a measure of the predictive skill of the model relative to that of the mean of the calibration data, and is computed as follows:

$$RE = 1 - \frac{SSR}{SSM}$$

(4)

where SSR is the sum of the squared residuals for the withheld validation years, and SSM is the sum of the squared differences of the validation data from the mean of the calibration data. The statistic can theoretically vary from negative infinity to 1, with any value less than zero indicating no agreement between estimates and observed data, and positive values reflecting some degree of agreement, up to perfect agreement indicated by $RE = 1$ [Fritts, 1976].
4. RESULTS

4.1. Dating and measurement

The 14,772 dated growth increments analyzed in this study formed within the 250-year period 1764-2013. Only one sample included growth increments formed in the years 1764 through 1775. Dated VR₁W and RW measurement series ranged in length from 34 to 217 years. Measured VR₁W mean ± sd was 0.287 ± .085 mm. Measured RW mean ± standard deviation was 2.014 ± 1.34 mm (Figures 5 and 6). 50-year segments of dated ring-width measurement series ranged in correlation with a COFECHA-generated master chronology from as strong as 0.87 to as weak as -0.08, with a mean series intercorrelation of 0.58. 50-year segments of dated VR₁W measurement series ranged in correlation with the COFECHA-generated master chronology nearly as widely, from 0.82 to -0.08, and had a mean series intercorrelation of 0.54. Low correlation of segments with the master chronology indicate possible dating or measurement errors, which I investigated and corrected if necessary; however in many instances, confidence in dating of segments having low correlation of RW was bolstered by higher correlations for the same segments of series of VR₁W, and vice versa.

Many characteristics of tree growth in the sample collection necessitated great care be taken in the crossdating process. These features include the presence of wedging or locally absent rings, indistinct and questionable ring boundaries in suppressed growth, as well as “false” rings and other sources of confusion resulting from inter- and intra-annual anatomical variability present in the samples. Patterns of both interannual ring-width and anatomical variability aided
the visual crossdating process, and annotating skeleton plots for anatomical anomalies proved a useful crossdating tool. Particularly reliable anatomical marker years or patterns include the exemplary flood ring of 1844; a distinct 1898-1899-1900 pattern where the 1898 and 1899 rings each exhibit a single rank of very small vessels and the 1900 ring exhibits consistently large earlywood vessels; a 1915-1916 pattern where earlywood vessels appear in the 1915 latewood and the 1916 growth exhibits an extended zone of reduced-size earlywood vessels; a 1927-1928 pattern where 1927 growth exhibits very small, disorganized and extended earlywood vessels and a latewood zone often devoid of fibers, and 1928 growth features two zones of earlywood vessels separated by a band of fibers, with the first rank of vessels often appearing “collapsed.”

Figure 5. Plotted raw VR₁W measurement series. An age-related positive trend in individual VR₁W series is apparent in the form of “hanging tails” representing small vessel size in juvenile growth.
Figure 6. Plotted raw ring-width measurement series.

4.2. Visual identification of flood rings and response index

The response-index chronology of flood-ring formation covers the period 1779-2013 (Figure 7). 118 of 235 years in the period covered by my RI analysis reflect RI values of 0.1 or greater, indicating that at least 10 percent of analyzed trees show anatomical anomalies in growth formed in those years. The highest response index value reflected in the record is .906 for the year 1928, the only year in which over 90 percent of trees formed growth increments with anatomical anomalies. The White River gauge at Clarendon recorded two flood crests in 1928, 9.6 meters on 3 May and 10.6 m on 1 July (Clarendon daily stage data are available from the United States Army Corps of Engineers, http://rivergages.mvr.usace.army.mil/). Both of these crests would rank among the top 15 historic crests recorded at Clarendon, but are absent from the NWS ranked historic crest data. 1928 growth rings formed following the 1927 historic flood of
record on the lower white; the very high proportion of trees showing anatomical anomalies in 1928 suggests the possibility of a lagged response to the 1927 flood. 87 percent of analyzed trees exhibited anomalies in growth rings formed in 1927, which tied with 1916 for second highest RI value. Rank correlations of RI values and historic crests at St. Charles and Clarendon were significant ($r_s = 0.60$, $p < 0.05$, $n = 14$, St. Charles; $r_s = 0.45$, $p < 0.01$, $n = 39$, Clarendon;).

Seven of the eight St. Charles historic crests above 9.4 meters occurred in years when 60 or greater percent of trees exhibited flood rings (Table 1). Each of those seven floods crested in the months of April or May; and the major flood not captured by the flood-ring record, the 12.2-meter crest in 1937 (< 10% trees injured), occurred in mid February when trees lie dormant. Five of the six St. Charles historic floods which crested below the 9.4-meter stage crested in winter months, with the sixth flood crested in late April; trees injured in those flood years range from 0 to 58 percent. All of the St. Charles historic crests that occurred in years with RI values of 0 occurred in winter months. Both the 8.5-meter April 1994 crest and the 9-meter January 1991 crest correspond to RI values indicating flood response in 30 percent of trees. 58 percent of trees exhibited a response in 1993 growth, when waters crested at 7.92 meters in late January.
Figure 7. Flood-ring response index chronology. Sample depth (a) indicates the number of trees analyzed for year $t$. Bar height indicates RI, the proportion of trees exhibiting anomalous anatomy in a given year (b).
Table 1. St. Charles historic crests and corresponding response index values.

<table>
<thead>
<tr>
<th>Year</th>
<th>Historic crest date</th>
<th>Historic crest rank</th>
<th>Crest height (m)</th>
<th>RI value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1927&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1-Apr</td>
<td>1</td>
<td>13.59</td>
<td>0.868</td>
</tr>
<tr>
<td>1937</td>
<td>13-Feb</td>
<td>2</td>
<td>12.22</td>
<td>0.096</td>
</tr>
<tr>
<td>2011</td>
<td>15-May</td>
<td>3</td>
<td>12.19</td>
<td>0.655</td>
</tr>
<tr>
<td>1945</td>
<td>26-Apr</td>
<td>4</td>
<td>11.95</td>
<td>0.704</td>
</tr>
<tr>
<td>1973</td>
<td>7-May</td>
<td>5</td>
<td>11.13</td>
<td>0.769</td>
</tr>
<tr>
<td>2008</td>
<td>20-Apr</td>
<td>6</td>
<td>10.54</td>
<td>0.750</td>
</tr>
<tr>
<td>1975</td>
<td>10-Apr</td>
<td>7</td>
<td>10.33</td>
<td>0.600</td>
</tr>
<tr>
<td>1983</td>
<td>22-May</td>
<td>8</td>
<td>9.91</td>
<td>0.636</td>
</tr>
<tr>
<td>1982</td>
<td>17-Dec</td>
<td>9</td>
<td>9.33</td>
<td>0.000</td>
</tr>
<tr>
<td>1989&lt;sup&gt;a&lt;/sup&gt;</td>
<td>28-Feb</td>
<td>10</td>
<td>9.24</td>
<td>0.212</td>
</tr>
<tr>
<td>1991</td>
<td>15-Jan</td>
<td>11</td>
<td>8.99</td>
<td>0.303</td>
</tr>
<tr>
<td>1994</td>
<td>28-Apr</td>
<td>12</td>
<td>8.50</td>
<td>0.303</td>
</tr>
<tr>
<td>1993</td>
<td>24-Jan</td>
<td>14</td>
<td>7.92</td>
<td>0.576</td>
</tr>
<tr>
<td>1992</td>
<td>1-Jan</td>
<td>15</td>
<td>7.73</td>
<td>0.000</td>
</tr>
</tbody>
</table>

<sup>a</sup> Years lacking daily stage measurements.

4.3. Chronology development and environmental signal correlation analysis

111 standardized index series of each VR<sub>1</sub>W and RW contributed to mean-value chronologies (Figures 8 and 9). Signal estimate statistics (e.g., $\bar{r}_b$, $\bar{r}_w$, $\bar{r}_{eff}$) for both RW and VR<sub>1</sub>W chronologies are similar, and both RW and VR<sub>1</sub>W chronologies yield a strong EPS, expressing 95 percent of the hypothetical common signal shared by the sampled population (Table 2). EPS values exceeding 0.85 are commonly accepted as indicating adequate statistical quality of a chronology [Cook and Kairiukstis, 1990]. A 50-year moving-window calculation of EPS indicates that the VR<sub>1</sub>W chronology EPS rises above 0.85 beginning with the year 1800 with a sample depth of 9, and the RW chronology EPS rises above 0.85 beginning with the year 1805, also with a sample depth of 9. The VR<sub>1</sub>W chronology does not show significant autocorrelation, but the RW chronology shows significant first-order autocorrelation ($r_1 = 0.392$, $p < 0.05$). Growth suppression in the period 1958-1964, noted in many samples, is evident as
persistence the RW chronology. Both VR\textsubscript{1}W and RW chronologies exhibit a trend in variance associated with change in sample depth, although this trend is more apparent in RW.

Figure 8. VR\textsubscript{1}W chronology. Expressed population signal of the chronology calculated from 50-year interval beginning at year $t$, plotted with dotted horizontal line at EPS = 0.85, (a); (b) sample depth, or number of standardized measurement series contributing to chronology index value of year $t$; and (c) mean VR\textsubscript{1}W indices.
Figure 9. Ring-width chronology. Expressed population signal of chronology calculated from 50-year interval beginning at year $t$, plotted with dotted horizontal line at EPS = 0.85, (a); (b) sample depth, or number of standardized measurement series contributing to chronology index value of year $t$; and (c) mean ring-width indices.
Table 2. Chronology statistics for RW and VR₁W indices

<table>
<thead>
<tr>
<th></th>
<th>n_t</th>
<th>n₇</th>
<th>c_eff</th>
<th>rₑₑₑ</th>
<th>rₑₑₑ</th>
<th>EPS</th>
<th>r₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW</td>
<td>58</td>
<td>32.7</td>
<td>1.74</td>
<td>0.75</td>
<td>0.33</td>
<td>0.37</td>
<td>0.95</td>
</tr>
<tr>
<td>VR₁W</td>
<td>58</td>
<td>32.7</td>
<td>1.74</td>
<td>0.66</td>
<td>0.32</td>
<td>0.38</td>
<td>0.95</td>
</tr>
</tbody>
</table>

¹Total number of trees (n_t), average number of trees contributing to each year of the chronology (n₇), effective number of cores per tree (c_eff), mean correlation within trees (rₑₑₑ), mean correlation between trees (rₑₑₑ), effective mean correlation (rₑₑₑ), and effective population signal (EPS) of 111 standardized series each of RW and VR₁W measurements contributing to RW and VR₁W mean-index chronologies; and first-order autocorrelation (r₁) of RW and VR₁W mean-index chronologies.

Analysis of VR₁W and RW chronology correlation with monthly climate (n = 64 years) and flood variables (n = 38 years) revealed a strong signal related to spring river levels in the VR₁W chronology (Figure 10). My analysis revealed only one potentially significant relationship reflected in the RW chronology, a positive correlation of ring width with January precipitation (r = 0.28, p < 0.05). I found no significant relationships of RW with temperature or river levels. April mean river-stage height and VR₁W showed the strongest relationship (r = -0.71, p < 0.01). VR₁W was also significantly correlated with March, May, June, July, August and September mean river-stage heights (p < 0.01), as well as with stage height in the December preceding growth (p < 0.05). The vessels that constitute the VR₁W measurement likely form concurrently with or before spring bud break, leaf expansion, and twig elongation; the relationship of VR₁W with summer river levels may be attributed to intra-annual persistence of river levels. VR₁W also shows a significant (though likely not meaningful) relationship with August precipitation (r = -0.36, p < 0.01), as well as mean temperature of the previous October (r = -0.25, p < 0.05).

Correlation coefficients for relationships of VR₁W with mean daily stage for months March, April, and May increase in significance when computed for all available years with
complete coverage of those months (n = 67; \( r = -0.43, p < 0.001 \), March; \( r = -0.62, p < 0.000001 \), April; \( r = -0.47, p < 0.0001 \), May). Correlation of VR\(_1\)W with a seasonalized flood variable of mean MAM stage heights indicated a relationship of the same significance level as that of VR\(_1\)W and April stage (\( r = -0.62, p < 0.0000001 \)), indicating that the VR\(_1\)W signal may have significant power to model past spring river levels.
Figure 10. Monthly correlation analysis. Bar heights indicate correlation (Pearson’s $r$) of index chronologies ($VR_1$, left column; $RW$, right column) with climate (mean temperature, first row; precipitation, center row) and flood variables (mean stage height, bottom row) for months of the water year (October of year preceding the calendar year of tree-ring growth through September of the calendar year of tree-ring growth).
4.4. Reconstruction

A linear-regression reconstruction of mean MAM stage from the VR\textsubscript{1}W index chronology reveals some degree of temporal nonstationarity in the linear relationship between my measures of vessel variability and spring flooding. Split-sample model 1, calibrated on data for the 33 years in the period 1932-1969 and validated against data for the 33 years in the period 1970-2012, explains a significant proportion of the variance of its calibration data (\(R^2 = 0.22, p < 0.01\)), but is a poorer fit than split-sample model 2, calibrated on 33 the years in the period 1970-2012 and validated against the 33 years in the period 1932-1969 (\(R^2 = 0.53, p < 0.000001\); figure 11). Split-sample model 1 yields more favorable validation statistics (\(r = 0.74, RE = 0.43\)) than split-sample model 2 (\(r = 0.49, RE = 0.08\)), indicating that although the strength of the linear relationship of VR\textsubscript{1}W to MAM stage may be weaker in the early period of the gauge record, the slope of that relationship better models years in the later period. Regression coefficients for the two split-sample models are not significantly different (\(p > 0.05\)), which indicates that calibrating a final model on the full available data is not inappropriate; however graphical analysis of both split-sample models reveals frequent over- and under-estimation of above-average MAM stage, as well as consistent over-estimation of below-average MAM stage. The final mean MAM stage height reconstruction extends back in time to 1800, as EPS values of the VR\textsubscript{1}W chronology indicated inadequate signal strength before 1800 (figure 12). The final model explains 37 percent of the variance of the 67 years of mean MAM stage with which it was calibrated.

Data from other nearby river gauges can further illuminate strengths and weaknesses in the flood-anatomical relationship modeled by the VR\textsubscript{1}W reconstruction of river stage. Daily
stage data records for both the Mississippi River gauge at Helena, Arkansas, and the White River
gauge at Clarendon, Arkansas (available from the U. S. Army Corps of Engineers,
http://rivergages.mvr.usace.army.mil/) include coverage for the years 1898 and 1899, years for
which consistently undersized VR\textsubscript{1}W measurements resulted in the fifth- and first-highest
modeled MAM-stage values, respectively, in the reconstruction. Flooding occurred on both the
Mississippi River and White River in both 1898 and 1899, however floodwaters crested higher in
1898 at both Clarendon and Helena. 1899 flooding on the Mississippi River occurred earlier in
the season than flooding on White River indicated by the Clarendon gauge record. The WRR site
may have experienced inundation by Mississippi River floodwaters, followed by inundation by
White River floodwaters, and such prolonged inundation may explain the extreme VR\textsubscript{1}W signal
for 1899. The 1899 signal may also represent some interannual persistence of flood effect on
VR\textsubscript{1}W. Although I found no significant autocorrelation in the VR\textsubscript{1}W chronology, that does not
discount the possibility of the effect of extreme events carrying over to subsequent years’
growth. The relative strength of the 1899 signal may also be the result of effects of one or more
other factors exerting control on earlywood vessel formation.

All but one of the 27 years corresponding to visually identified flood-ring response in 60
percent or greater of WRR trees analyzed for the RI chronology also correspond to above-
average reconstructed MAM mean daily stage values, indicating general agreement in the record
of flood response captured by RI and VR\textsubscript{1}W chronologies. The 1893 below-average
reconstructed value exemplifies the inability of the VR\textsubscript{1}W chronology to capture important
anatomical variability that visual analysis would identify as flood-ring response, because VR\textsubscript{1}W
only measures variability of first-formed vessels. In that year, Mississippi River floodwaters
crested in late May at Helena, AR (Figure 14); which suggests WRR trees may not have
experienced inundation until after formation of the first earlywood vessels, and recorded any flood damage as anatomical anomalies in the remainder of the growth increment.

Figure 11. Split-sample model calibration and validation. Observed and VR1W-modeled MAM daily stage mean heights for the two split-sample validation models are plotted in time series; one model (a) calibrated on 33 annual observations in the period 1932-1969 and validated on 33 annual observations in the period 1970-2012, the other model (b) calibrated on 33 annual observations in the period 1970-2012 and validated against 33 annual observations in the period 1932-1969. Horizontal lines indicate series means, computed from the entire available data for the observed variable, and from the calibration-period values of the model data.
Figure 12. VR$_1$W-modeled MAM stage reconstruction. March-April-May mean daily stage height reconstructed from simple linear regression of VR$_1$W index values (black line), and observed MAM mean daily stage heights (diamonds, solid gray line) for 67 years in the period 1932-2013 recorded at the White River gauge at St. Charles, AR are plotted the period 1800-2013. Dotted horizontal line indicates 8.8-meter MAM daily stage mean for 1945, 1973, 1975, 1983, and 2008; the five years when historic crests occurred in March, April, or May, and for which daily stage data coverage exists in the St. Charles gauge record. Years corresponding to flooding response in 60 percent or greater of WRR trees (RI > 0.6) indicated within plot area.
Figure 13. Daily stage for water years 1898 and 1899. Solid (1898) and dashed (1899) black lines indicate daily stage heights recorded at (a) the White River gauge at Clarendon, AR; and (b) the Mississippi River gauge at Helena, AR. Dotted horizontal gray line indicates flood stage, 7.9 meters at Clarendon and 13.4 meters at Helena.
Figure 14. Daily stage for water years 1892 and 1893. Solid (1892) and dashed (1893) black lines indicate daily stage heights recorded at the Mississippi River gauge at Helena, AR. Dotted horizontal gray line indicates 13.4-m flood stage at Helena.
5. DISCUSSION AND CONCLUSIONS

5.1. Discussion

My VR₁W measurement chronology demonstrates a novel method for efficiently quantifying interannual anatomical variability of a tree-ring sample collection. This measurement method can be performed concurrently with ring width measurement, allowing for expeditious assessment of collections for possible ecophysiological signals contained in anatomical variables. The strong signal related to flooding contained in the Scrubgrass Bayou VR₁W site chronology supports the use of floodplain trees as proxy records of river flooding, but also highlights the limitations of relying on records produced from complex physiological processes. Chief among these limitations is the temporal window of response defined by the growing season of the responding organism. In the case of the overcup oak individuals utilized for this study, that response window apparently excludes the winter months when important floods occur, a limitation exemplified by the near absence of evidence of the 1937 flood from both the VR₁W and RI chronologies. The VR₁W measurement method further narrows the temporal window of quantified response to the period affecting formation of the first rank of earlywood vessels, excluding anatomical variability present in the remainder of the annual growth increment. Nevertheless, the signal of spring flooding preserved in the vessel variability represents a significant source of information on past environmental variability. Although it is possible that such a model would improve with more selective or extensive sampling of trees, the influence of complex physiological processes controlling vessel formation will likely always be present in
any chronology of anatomical variability. Such proxy records of past environmental variability are often employed in concert with other natural archives in studies of historical ecology where any single line of evidence does not tell a sufficiently complete story [Swetnam et al., 1999]. Poor estimation of below-average MAM stage by the VR$_1$W linear-regression reconstruction indicates nonlinearity in the modeled relationship that can be explained by the upper limit placed on vessel size by tree physiology, which has adapted to avoid cavitation of the water column from hydraulic tension.

Visual identification of possible flood-ring anatomical anomalies remains a useful tool for exploration and analysis of tree-ring flood records. WRR RI values reflect relative magnitude of ranked historic crests better than the VR$_1$W chronology indices (Table 3), likely because the VR$_1$W measurement excludes dimensions of anatomical variability that may be deemed anomalous by qualitative visual analysis, including shape and arrangement of vessel pores, porous-zone proportion of total increment, instances of interruptive fiber bands or double-earlywood “false rings,” or presence of aerenchyma tissue. A more sophisticated approach to visually identified presence/absence records of anatomical anomalies could involve compiling a chronological record of separate occurrence of these multiple dimensions of anatomical variability, and seek to identify any links in patterns of anatomical response to specific environmental factors. Physiological processes driving patterns in tree-ring anatomy are not only affected by flooding [Fonti et al., 2006; Fonti and García-González, 2008]. It may be possible that some dimensions of anatomical variability do not relate to flooding, and yet have been grouped in with the others, possibly leading to spurious identification of flood rings.
Table 3. Rank correlation of lower White River historic crests with RI and VR₁W values

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Spearman's rank correlation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RI</td>
<td>VR₁W</td>
</tr>
<tr>
<td>St. Charles</td>
<td>0.60*</td>
<td>-0.45</td>
</tr>
<tr>
<td>Clarendon</td>
<td>0.45**</td>
<td>-0.38*</td>
</tr>
</tbody>
</table>

¹Spearman rank correlations computed for historic crests of the White River at St. Charles (n = 14 years) and Clarendon (n = 39 year) with RI and VR₁W chronology values for corresponding years. *p < 0.05; **p < 0.01.

Because the levels of the Mississippi River exert control over the flood regime of the lower White River, I expected to see Mississippi River flood years represented in the WRR RI and VR₁W chronology flood records developed here. Spearman rank correlations for both RI and VR₁W chronology values with RI values for Mississippi River floods as recorded by trees growing within Big Oak Tree State Park, Missouri (BOT) [Therrell and Bialecki, 2014] are insignificant (p > 0.05), indicating that Mississippi River floods recorded by BOT trees did not induce responses of corresponding magnitude in the WRR trees. Therrell and Bialecki [2014] list 15 “pre-instrumental” floods reflected in their flood-ring record and corroborated by historical comments in literature. Of these 15 flood years, eight are reflected by RI values indicating ten or greater percent of WRR trees exhibited flood rings. 74 percent of WRR trees exhibit flood rings for the year of the 1844 Mississippi River flood, and other pre-instrumental Mississippi River flood years corresponding to a strong (RI > 0.3) flood-ring response in WRR trees include 1858 (RI = 0.67), 1892 (RI = 0.64), 1865 (RI = 0.45), and 1851 (RI = 0.44). Flooding was documented on both the Mississippi and Arkansas Rivers in 1844, and the compound effect of those two rivers on the hydrology of the lower White River floodplain may explain the outstanding flood-ring response in that year. Of those flood years with a strong RI flood response at WRR, all but 1851 correspond to years with below-average VR₁W chronology values. The historical comment corroborating the 1851 flood indicated that the flood occurred in late May [Therrell and Bialecki,
2014], which may be too late in the growing season to affect formation of the first earlywood vessels. Nine of the fifteen pre-instrumental Mississippi River flood years correspond to below-average values in the VR1W index chronology, indicating some possible flood-related deviation in vessel size in those years; only the 1858 flood occurred in a year with a corresponding VR1W value over one standard deviation below the mean, suggesting that flood effected a greater impact on the White River than the others within the temporal window of first-vessel formation.

Daily stage data recorded at the Mississippi River gauge at Helena, AR exist for the years 1874 and 1892, and offer insight into the differential response of WRR trees in those Mississippi River flood years (Figure 15). Only six percent of WRR trees exhibited flood-ring responses for 1874, and 64 percent of WRR trees exhibited a response for 1892, but floodwaters in those two years crested at very similar heights and dates. The difference in flood ring response for those two years may be explained by the greater duration of flooding in 1892, when the Mississippi River remained above flood stage at Helena for 55 consecutive days, from 30 April to 23 June. The 1874 flood at Helena began on 6 May and remained above flood stage for only 13 days.
Table 4. Pre-instrumental Mississippi River flood-ring years and WRR response.\textsuperscript{1}

<table>
<thead>
<tr>
<th>Year</th>
<th>Percent injured, BOT</th>
<th>Percent injured, WRR</th>
<th>VR\textsubscript{1W} index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1785</td>
<td>67</td>
<td>0</td>
<td>0.972</td>
</tr>
<tr>
<td>1792</td>
<td>33</td>
<td>0</td>
<td>1.001</td>
</tr>
<tr>
<td>1811</td>
<td>33</td>
<td>0</td>
<td>1.021</td>
</tr>
<tr>
<td>1813</td>
<td>83</td>
<td>0</td>
<td>0.878</td>
</tr>
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<td>1815</td>
<td>83</td>
<td>11</td>
<td>0.948</td>
</tr>
<tr>
<td>1823</td>
<td>75</td>
<td>10</td>
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<td>54</td>
<td>74</td>
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<td>13</td>
<td>8</td>
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<td>1851</td>
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<td>1.165</td>
</tr>
<tr>
<td>1858</td>
<td>61</td>
<td>67</td>
<td>0.768</td>
</tr>
<tr>
<td>1859</td>
<td>39</td>
<td>22</td>
<td>1.111</td>
</tr>
<tr>
<td>1862</td>
<td>65</td>
<td>4</td>
<td>0.967</td>
</tr>
<tr>
<td>1865</td>
<td>85</td>
<td>45</td>
<td>0.909</td>
</tr>
<tr>
<td>1874</td>
<td>36</td>
<td>6</td>
<td>0.977</td>
</tr>
<tr>
<td>1892</td>
<td>91</td>
<td>64</td>
<td>0.913</td>
</tr>
</tbody>
</table>

\textsuperscript{1}Years of occurrence of Mississippi River floods noted in historical literature and corresponding response of trees at Big Oak Tree State Park (BOT) [Therrell and Bialecki, 2014], and at WRR.

Figure 15. Daily stage for water years 1874 and 1892. Solid (1874) and dashed (1892) black lines indicate daily stage heights recorded at the Mississippi River gauge at Helena, AR. Dotted horizontal gray line indicates 13.4-m flood stage at Helena.
Some instances of flood-ring response to St. Charles historic-crest floods demonstrate how long-duration, low-magnitude floods may correspond to a high rate of flood-ring response. 30 percent of trees showed anatomical anomalies in growth formed in 1991 and 1994, when comparable historic floods crested at St. Charles: 9 meters on 15 January 1991, and 8.5 meters on 28 April 1994. 58 percent of trees showed anatomical anomalies in growth formed in 1993, when waters reached 7.9 meters at St. Charles on 24 January. I could find no source of hydrologic information listing flood stage for the White River at St. Charles, but flood stage at the White River gauge at Clarendon is 7.9 meters, and that same stage height as measured at the St. Charles gauge is used as the criterion for closure of flood-prone areas of the WRR to deer hunting, according to the Arkansas Game and Fish Commission Hunting Guidebook 2014-2015 (http://www.agfc.com/). A graphical analysis of hydrographs for the 1993 and 1994 floods reveals that in both years, river levels remained above 7-meter stage for the full duration of months March and April, and most of May in their respective years of occurrence (Figure 16). This suggests that the RI response may reflect prolonged WRR site inundation during these lengthy periods of marginally high river levels. Although St. Charles gauge data are missing for calendar year 1991, the Clarendon gauge historic crest data list a 1 May 1991 crest of 9.3 meters, and the daily stage record at Clarendon indicated that waters remained above flood stage (7.9 m) for 42 days in the spring of 1991, from 14 April to 24 May. Historic floods in years 1927 and 1989 both crested in February, and although the 1937 flood reached much higher levels at St. Charles (12.2 m) than the 1989 flood (9.2 m), 21 percent of trees formed flood rings in 1989 and less than ten percent of trees formed flood rings in 1937. Daily hydrographs for 1937 and 1989 reveal that water levels were 1-2 meters higher throughout April of 1989 than they were in April of 1937, suggesting the 1989 tree-ring response may be attributed to prolonged low-magnitude
flooding (Figure 17). Future studies seeking to identify high-magnitude, pre-instrumental floods in the tree-ring record may attempt to identify any features that might distinguish anatomical anomalies resulting from long-duration, low-magnitude floods from anatomical anomalies resulting from high-magnitude floods. Careful site selection could also provide an elegant solution to this problem, e.g., *St. George and Nielsen* [2000, 2002, 2003] sampled trees growing on an elevated floodplain terrace subject to prolonged inundation from only high-magnitude floods.

![Figure 16](image)

Figure 16. Daily stage for water years 1993 and 1994. Solid (1993) and dashed (1994) black lines indicate daily stage heights recorded at the White River gauge at St. Charles, AR. Dotted horizontal gray line indicates 7.9-m stage at St. Charles.
Figure 17. Daily stage for water years 1937 and 1989. Solid (1937) and dashed (1989) black lines indicate daily stage heights recorded at the White River gauge at St. Charles, AR. Dotted horizontal gray line indicates 7.9-m stage at St. Charles.

The apparent lack of signal related to climate or streamflow variables in the RW chronology agrees with the common assumption that growth patterns resulting from competition for light and the effects of episodic disturbances mask climate response of trees growing in closed-canopy eastern forests. Climate signal represented at a site is expected to decline as forest structure approaches a closed-canopy form [Fritts, 1976]. Nevertheless, ring-width measurement series from Scrubgrass Bayou or similar bottomland hardwood sites may be of use for studies investigating ecological questions. Disturbance-related episodes of growth suppression and release evident in measurement series from individual trees could illuminate spatial or temporal patterns in forest processes. For example, the 1958-1964 growth suppression episode evident in many trees from the Scrubgrass collection presents one such possible point of dendroecological
inquiry. WRR bottomland hardwood forests are subject to disturbance from ice storms, tornadoes, hurricanes, fire, and insect infestation [United States Fish and Wildlife Service, 2012].

Image analysis offers a possible avenue for studying further dimensions of anatomical variability. However, such an undertaking would have to address a number of complicating issues. Image analysis programs rely on a critical gray-scale value that distinguishes objects of interest from the background, a problem that can be addressed by applying dark pigment to the sample surface, and filling pore spaces with chalk to improve optical contrast of vessel lumens within the exposed sample surface [Fonti et al., 2009]. Tyloses in earlywood vessels pose a problem, as they may pick up dark pigment and also block chalk from filling in pore space. Sample surfaces must be free of any scratches, because they will fill with chalk and register as pore space in the image analysis. The use of thin sections for image analysis can solve the lumen-cell wall contrast problem, but require additional equipment, time, and expertise. A single microscope slide may take hours to prepare and represent only one decade of growth increments. A persistent problem even with the use of thin sections is the need to choose a size threshold for the image analysis program to distinguish between earlywood and latewood vessels, a task that is complicated by diminished earlywood vessels in flood rings that may approximate latewood vessels in size. The presence of multiseriate rays inside the region of analysis can possibly skew any data for vessel density or area if the analyzed region is small, as on an increment-core surface where multiseriate rays can occupy as much as half the width of the sample surface. This problem could be addressed by the use of cross sections, where a wider region of analysis would decrease the effect of the rays. The great costs (time and money) of carrying out an image-analysis based study of anatomical variability over multiple tree-ring samples spanning centuries of annual growth increments necessitates careful selection of study site and samples. Qualitative
and quantitative visual analysis of anatomical variability, as well as the expeditious quantification of anatomical variability through the use of simple methods of measurement e.g., VR, W presented here offer cost-effective, time-saving approaches to assessing quality of samples and site.

The remains of trees buried and preserved in alluvial sediments, so called “subfossil wood,” can extend tree-ring records far beyond the limited temporal coverage represented by living and recently dead individuals. Stambaugh and Guyette [2009] have developed chronologies from subfossil white oak (Q. macrocarpa and Q. bicolor) retrieved from stream banks and stream bottoms in Missouri and Iowa, including an absolutely calendar-dated modern chronology extending over 1,000 years from AD 912-2004; as well as several “floating” chronologies associated with radiocarbon dates as old as 11,000 B.P. Q. macrocarpa individuals have been useful to the study of anatomical flood response [e.g., St. George and Nielson, 2003], and the related Q. bicolor may yield similar anatomical flood responses. Absolutely dated subfossil oak presents a potential wealth of material for establishing tree-ring records of flooding on North American rivers, where deforestation has limited the extent of flood-prone forest stands, and those trees that do remain are unlikely to be very old. The alluvial sediments of the Mississippi alluvial plain present a potential bounty of botanical paleoflood archives in the subfossil wood they preserve. Quercus species grow throughout the Mississippi River basin excepting the extreme western Great Plains [Burns and Honkala, 1990], and subfossil specimens may be preserved wherever stream morphology favored relatively rapid burial from aggradation of sediments in the past. The major challenges associated with subfossil dendrochronology are establishing the geographical and temporal provenance of the wood, because river-borne trees may travel as far downstream from their origin as waters may carry them, and can lay buried for
millennia. These challenges can be met with the development of extensive, high-spatial-resolution networks of robust local tree-ring chronologies from living and dead trees, and the continued investigation of climate-tree growth relationships and teleconnections that may permit the estimation or reconstruction of past eastern tree-growth patterns from the existing multi-millennial western chronologies.

5.2. Conclusions

VR₁W measurement and chronology development presents a valuable new method to extract information about tree-ring environmental sensitivity that may vary independent of standard tree-ring variables used to gauge sensitivity (e.g., ring width). This method requires negligible additional labor and no additional infrastructure as compared to standard ring-width measurement, and can be used for sites and species (e.g., bottomland hardwood forests, Quercus lyrata) with relatively poor representation in dendrochronological studies of hydrology and climate. Analysis of anatomical flood response by visual analysis remains important to paleofloods studies in dendrochronology, as shown by the failure of my novel VR₁W chronology to better reflect relative magnitude of past floods as compared to my visual response-index record. The record of flood response in WRR trees provides evidence of variable effect of important pre-instrumental Mississippi River floods on the lower White River Basin, suggesting possible differences in spatial persistence or behavior of those floods. Continued establishment of flood-ring sites and chronologies for the flood-prone bottomland forests throughout the Mississippi River basin will no doubt reveal more information about the magnitude, frequency, and spatial extent of past Mississippi River floods.
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