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A multi-century tree-ring record of spring flooding on the Mississippi River

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SUMMARY

Widespread destructive flooding is a common phenomenon along the Lower Mississippi River, and river managers have long sought to understand the temporal variability and relevant climatic factors of the system. One of the important drawbacks to better understanding the flood regime of this and similar large river systems is the relatively short instrumental record of flooding. In this study, we present a novel, annually-resolved tree-ring record of spring flooding based on anatomically anomalous "flood rings" preserved in trees growing about 60 km downstream of the Mississippi and Ohio River confluence. Our chronology records 39 flood-ring years between 1770 and 2009 including nearly all of the observed significant floods of the 20th century as well as severe floods documented in prior centuries. Comparison of the flood ring record with stream gage observations suggests that large-magnitude floods lasting for more than 10 days, during the spring flood season, are most likely to cause a flood ring in sampled trees. Instrumental and paleo-proxy records of atmospheric circulation features relevant to spring flooding on the Lower Mississippi were also examined. Results of this research suggest that similar flood-ring records could provide important insight into flood history elsewhere in the Mississippi River system and perhaps climate variability over North America.

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1. Introduction

Many regions of the U.S. are prone to destructive flooding (Downton et al., 2005). Communities along the Mississippi River and its major tributaries in particular have been affected by the great environmental and social impacts of flooding (e.g., Barry, 1997; Welky, 2011). Recent research has emphasized understanding the underlying mechanisms that force these types of events including the effects of climate variability (e.g., Changnon and Kunkel, 1995; Knox, 2000; Villarini et al., 2011), and human modification of the hydrology of the river (e.g., Pinter et al., 2008). Although estimating the natural variability of flooding on major rivers throughout the world is hindered by the relatively short (~120 years) instrumental record of streamflow (e.g., Klemes, 1989), paleoflood hydrology offers the potential to improve the spatial and temporal record of flooding and reduce uncertainty in hydrologic analyses of river flooding (e.g., Jarrett, 1991; Baker et al., 2002; Benito and Thorndycraft, 2005; Baker, 2008).

A variety of primarily geomorphological methods have been used to reconstruct the frequency and magnitude of past floods. Common approaches include studying: slackwater sediment deposits (e.g., Kochel and Baker, 1982, 1988; Jarrett, 1990; Wohl, 1992; Ely et al., 1993), deposits from more dynamic events (e.g., Costa, 1983; Wang and Leigh, 2012), fluvial geomorphology (e.g., Baker, 1977, 1987), speleothems (e.g., Springer, 2002; Gázquez et al., 2014), and archaeological materials (Patton and Dibble, 1982).

Dendrochronology has long been used to date a variety of geomorphological processes and hazards (Stoffel and Bollschweiler, 2008), and precisely dated tree rings can indicate past flooding through examination of mechanical or systemic damage to trees caused by flooding. Sigafoos (1964) was among the first to demonstrate the potential of precisely dated botanical evidence to indicate past flooding through an examination of mechanical damage to trees caused by flooding along the Potomac River. Other relevant studies focused on reconstructing flood history through examination of mechanical injury to riparian trees include those conducted by Harrison and Reid (1967) in North Dakota, Helley and LaMarche (1968), in California, Yanosky (1982, 1983) on the Potomac, McCord (1990, 1996) in the southwestern U.S., Gottesfeld and Johnson Gottesfeld (1990) in British Columbia, Fanok and Wohl

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(1997) on the Shenandoah in West Virginia, Tardif and Bergeron (1997) in Quebec, Yanosky and Jarrett (2002) in Colorado as well as Ballesteros et al. (2011) in Spain. Also see Hupp (1987, 1988). In 1983 Yanosky found that Ash (*Fraxinus* sp.) growing in the floodplain of the Potomac River formed "flood rings" as the result of massive defoliation of young trees inundated by floodwaters. Yanosky (1983) also discussed the development of anatomical anomalies resulting from inundation of only the roots of trees, rather than defoliation but did not find significant evidence of this type of response. However, Astrade and Bégin (1997) found that flood rings formed in *Quercus rober* as a result of root inundation along the Saone River in France. In North America, St. George (2010) and St. George and Nielsen (2000, 2003) and Wertz et al. (2013) have utilized similar flood ring evidence from *Quercus macrocarpa* trees to study paleoflood hydrology in the Red River basin in North Dakota and Manitoba, Canada.

In this study, we present the first long, annually resolved tree-ring record of destructive spring flooding on the Lower Mississippi River (LMR), which is based on anatomical tree-ring signatures of flooding from samples collected in the upper portion of the LMR. We also compare the tree-ring record of flooding to modern instrumental and historical records of flooding.

2. Materials and methods

2.1. Tree ring data

In 2009 as part of a dendroecological investigation, we collected tree-ring samples from 33 living and two dead oak (*Quercus lyrata* and *Q. macrocarpa*) trees, from Big Oak Tree State Park (BOT), which is located in Mississippi County in southeast Missouri (Fig. 1). This site represents one of the few remaining stands of virgin wet-mesic bottomland hardwood forests within the lower Mississippi alluvial valley (NPS, 1999). One or two increment core samples were extracted from each tree at breast height (~1.4 m) using 5-mm diameter Swedish increment borers. Cross-sections from dead trees were collected as close to the base of the tree as possible. All samples were absolutely crossdated using the skeleton-plot method of dendrochronology (Stokes and Smiley, 1996). Tree-ring widths were measured on a stage micrometer to a nominal resolution of 0.001 mm. We crosschecked the accuracy of our visual dating using the computer program COFECHA (e.g., Holmes, 1983).

Our tree-ring record extends from 1694 to 2009 and includes six trees over 200 years old. We determined flood-ring years by examining each tree-ring series for any evidence of flood injury consistent with the anomalous anatomical features caused by flooding as described by previous flood-ring studies (Astrade and Bégin, 1997; St. George and Nielsen, 2000, 2002; Wertz et al., 2013). Like several of the previous studies, we found that the most pronounced characteristic of flood rings in the oaks sampled is a reduction in the cross-sectional area of earlywood (EW) vessels during the year of inundation. Additional characteristics we used for identification included "jumbled" or "additional ranks" of EW vessels or zones of "extended earlywood" (Yanosky, 1983), and disorganized flame parenchyma (St. George and Nielsen, 2002) as well as "offset" EW ranks (Fig. 2). Although Yanosky's (1983) findings were primarily focused on the effects of defoliation of Ash trees (*Fraxinus* sp.) caused by flooding, we also observed similar anatomical anomalies in oaks sampled at the BOT site. For example, we also noted "jumbled" EW as well as "additional ranks" of EW vessels and zones of "extended earlywood" in our samples, which we know in many cases could not have been defoliated to any great extent by flooding given the height of the sampled trees.

Also, although "frost rings" are known to occur in other species of oaks (*Q. alba*, *Q. stellata*) in this general region (e.g., Stahle, 1990), the predominant anatomical features of frost rings are quite different from flood rings. For example, while we did observe some similar traumatic injury features such as EW cells that were offset from the terminal parenchyma of the previous year, we did not observe any instances of the most distinguishing feature of frost rings, which is the presence of crescent shaped or "lunate" EW vessels (Stahle, 1990). Furthermore, comparison of our flood ring record with frost ring records in the region (Stahle, 1990) indicates few years in common and we did not observe evidence of known widespread, severe frost ring events that we would expect to observe in our samples.

We listed the dates of potential flood rings for each tree and calculated an event response index similar to those developed for debris flows (e.g., Shroder, 1978), where "*I*" for each year (t) is the percentage of trees injured by flooding (R), divided by the total sample depth of trees (A) for each year t:

$$It = \left(\sum_{i=1}^{R} Rt\right) \Big/ \left(\sum_{i=1}^{R} At\right) * 100\%$$

Although the entire tree-ring chronology extends from 1694 to 2009, we only calculate the event response index from 1770 to 2009 when at least two trees are available for analysis and we do not include years in which less than 10% of trees sampled register injury (e.g., Reardon et al., 2008). This restriction resulted in the exclusion of 1907, 1993, and 1995 from the analysis. Although there was significant flooding in the region in these years these exclusions do not materially affect the analysis.

2.2. Streamflow data

We compared our flood-ring record with daily Mississippi River stage-height measurements obtained from gage MS115 located at New Madrid, Missouri for the period 1879–2010 (USACE, 2010). The New Madrid gage is located 22 km (13.6 miles) south of the BOT site near the outlet of the Birds Point-New Madrid Floodway, within which the study site is situated (Fig. 1). Other gages are geographically closer to the BOT site (e.g., Hickman, KY), but the New Madrid gage record is much longer. Although the BOT site is currently less than 2 km (1.24 miles) from the Mississippi River, its direct connectivity to the river has been obstructed to various degrees by levees since the early 20th century. However, the site has never been completely cut off from the river and routinely floods during periods of high water when backwater flooding occurs through a 460 m (1500 ft) gap in the levee near New Madrid (USACE, 2000).

The New Madrid stage hydrograph is typical of much of the Middle Mississippi River system, with a peak in March through May (MAM) and low stages occurring in autumn (Brooks et al., 2003). With notable exceptions (e.g., 1937, 1950), most of the high magnitude flooding that occurs along this portion of the river also takes place in the months of March–May.

The elevation of the study site ranges from 88.09 m (289 ft) to 89.92 m (295 ft) and local observers confirm that the site begins to flood when the New Madrid stage height reaches "flood" stage, which is 10.36 m (34 ft), and should be completely inundated at "moderate" (12.19 m; 40 ft) and "major" (>13.41 m; 44 ft) flood stage heights. In addition to the depth of flooding (represented by stage height), the season of occurrence and the duration of flooding strongly affect flood-ring formation (St. George and Nielsen, 2002). To determine duration of flooding, we calculated "days in flood" (DIF), or number of days that daily stage values exceeded flood stage (i.e., >10.36 m; 34 ft) and moderate flood

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