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# Vertical accretion sand proxies of gaged floods along the upper Little Tennessee River, Blue Ridge Mountains, USA

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Understanding environmental hazards presented by river flooding has been enhanced by paleoflood analysis, which uses sedimentary records to document floods beyond historical records. Bottomland overbank deposits (e.g., natural levees, floodbasins, meander scars, low terraces) have the potential as continuous paleoflood archives of flood frequency and magnitude, but they have been under-utilized because of uncertainty about their ability to derive flood magnitude estimates. The purpose of this paper is to provide a case study that illuminates tremendous potential of bottomland overbank sediments as reliable proxies of both flood frequency and magnitude. Methods involve correlation of particle-size measurements of the coarse tail of overbank deposits (>0.25 mm sand) from three separate sites with historical flood discharge records for the upper Little Tennessee River in the Blue Ridge Mountains of the southeastern United States. Results show that essentially all floods larger than a 20% probability event can be detected by the coarse tail of particle-size distributions, especially if the temporal resolution of sampling is annual or sub-annual. Coarser temporal resolution (1.0 to 2.5 year sample intervals) provides an adequate record of large floods, but is unable to discriminate individual floods separated by only one to three years. Measurements of >0.25 mm sand that are normalized against a smoothed trend line through the down-column data produce highly significant correlations ($R^2$ values of 0.50 to 0.60 with *p*-values of 0.004 to <0.001) between sand peak values and flood peak discharges, indicating that flood magnitude can be reliably estimated. In summary, bottomland overbank deposits can provide excellent continuous records of paleofloods when the following conditions are met: 1) Stable depositional sites should be chosen; 2) Analysis should concentrate on the coarse tails of particle-size distributions; 3) Sampling of sediment intervals should achieve annual or better resolution; 4) Time-series data of particle-size should be detrended to minimize variation from dynamic aspects of fluvial sedimentation that are not related to flood magnitude; and 5) Multiple sites should be chosen to allow for replication of findings.

## 1. Introduction

Floods are among the most dangerous and damaging natural hazards on earth, and flood magnitudes and frequencies can change significantly in response to only moderate changes in climate (Knox, 1993, 2000; Benito et al., 2008; Zielhofer et al., 2010; Benito et al., 2015a, 2015b). Thus, heightened awareness of past changes in climate has driven great research interest in better understanding of flood response to climate change. Modern flood gaging records typically lack sufficient temporal longevity to capture the full range of floods associated with centennial or longer-term climate change, but stratigraphic records of paleofloods (floods prior to the time of human observation or direct measurement by modern hydrologic procedures) provide excellent data for reconstructing long-term behavior of flood regimes (Kochel and Baker, 1982; Baker, 1987, 2008; Benito and O'Connor, 2013). Current and previous paleoflood research focuses much attention on high-stage slackwater sediments (Kochel and Baker, 1988; Benito and O'Connor, 2013; Bodoque et al., 2015), which are vertical accretion deposits preferentially found near where the peak stage of paleofloods is contained within bedrock gorges. These high-stage vertical accretion deposits usually are referred to simply as "slackwater" sediments, despite the fact that true slackwater sediments fell out of suspension over a very wide elevation range in the overbank environment. Unfortunately, high-stage slackwater sediments and requisite stable flood channel dimensions (e.g., bedrock gorges) do not exist in most places, which severely limits their geographic coverage, as well as their applicability to the rock-stratigraphic record. Furthermore, high-stage slackwater sedimentary records typically are fragmented and discontinuous, and they only reflect extreme floods, making it difficult to infer temporal changes in a broader spectrum of floods from a single stratigraphic section. In contrast, overbank vertical accretion sediments that fell out of suspension on bottomlands (slackwater deposits on floodplains, backswamps, oxbows, and low terraces) are ubiquitous in fluvial landscapes and offer great potential to provide continuous records of past flood frequency for floods exceeding bankfull discharge (e.g., Knox and Daniels, 2002; Knox, 2006; Werrity et al., 2006; Jones et al., 2010, 2012; Wang and Leigh,

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2012; Munoz et al., 2015; Toonen et al., 2015). However, overbank floodplain and low terrace sediments can introduce considerable uncertainty for determination of paleoflood stage or magnitude. Thus, largely because of uncertainty about paleoflood magnitude, these bottomland overbank sediments have received relatively little attention in the literature. Significant correlations have been observed between particle-size of suspended sediment and flood discharge (Lenzi and Marchi, 2000; Grangeon et al., 2012), but extrapolation to the stratigraphic record is not well understood. A few studies have described the sedimentology of overbank vertical accretion beds and laminae in relation to observed floods, indicating larger particle-sizes for larger floods (Kesel et al., 1974; Knox and Daniels, 2002; Knox, 2006; Wang and Leigh, 2012; Zhang et al., 2015; Heitmuller et al., 2017), but quantitative analysis of a continuous decadal to centennial time series is lacking. Thus, there is a need for better understanding of how the sedimentology of bottomland vertical accretion deposits relates to gaged histories of flooding. A unique, recent study by Toonen et al. (2015) along the Rhine River in Germany and the Netherlands finds that high-resolution particle-size measurements of the coarsest particles in vertical accretion deposits in oxbow lakes correlate very well ($R^2 = 0.80$) against observed peak flood magnitudes. However, more studies of this sort are needed from different river systems and different depositional environments, as well as studies using different methods, in order to develop a more thorough understanding of paleoflood reconstructions based on bottomland vertical accretion deposits. Most studies of this sort have focused on vertical accretion records from paleochannel fills (Werrity et al., 2006; Zielhofer et al., 2010; Munoz et al., 2015; Sitoe et al., 2015; Toonen et al., 2015), given that oxbow lakes are excellent sediment traps for overbank floods (Toonen et al., 2012). However, examination of other types of floodplain sedimentary environments is rare, and modern analogs of centennial-scale continuous records of floods from the stratigraphic record are particularly lacking. Research presented in this paper seeks to fill these voids with a centennial-scale example of the correlation between peak flood discharges and the proportions of medium and coarser sands (>0.25 mm) deposited on low terraces along the upper Little Tennessee River in western North Carolina, U.S.A.

The main objective in this study is to test the applicability of bottomland vertical accretion deposits on low terraces for reconstruction of past flood frequency and magnitude by correlating particle-size to gaged flood peaks. Impetus for this study was driven by the author's personal observation of thin beds of sandy sediments that were deposited on many parts of the upper Little Tennessee River bottomlands by the second largest flood on record at the Prentiss gage in 2004 ($317.2\ \mathrm{m^3\ s^{-1}}$ vs. average annual peak of $107.3\ \mathrm{m^3\ s^{-1}}$). The specific research tests the hypothesis that the relative proportion of >0.25 mm sand is a reliable proxy of large floods, which has been suggested by other studies. Focusing on the >0.25 mm sieved fraction keeps the analysis simple, efficient, and easy to process hundreds of samples, and it is a methodology readily available to all researchers worldwide. Indeed, Knox and Daniels (2002) found that measures of the 0.25–0.50 mm fraction in 1–2 cm down-column increments from bottomland overbank deposits served as good proxies for floods larger than the 10 year recurrence interval (termed 10 year RI) in the Driftless Area of the upper Mississippi River valley. They selected the 0.25–0.50 mm fraction because it was coarse enough to be sensitive to variations in flood energy, but fine enough to be transported in measurable quantities even during small floods. This agrees with Colby's (1963) observations on the source, transport, and deposition of fluvial sediments that indicate medium and coarser sands are only deposited from suspension during large floods.

Within the Blue Ridge Mountains, Simmons (1993, p. 53) observed that >0.25 mm sand comprised on average only 14% of suspended sediments transported during high flows, based on 12 samples from nine different gaging stations. More recently, Oblinger (2003, p. 20) reported the particle-size of four suspended sediment samples from small floods on the upper Little Tennessee River in the immediate vicinity of the Riverside stratigraphic section of this study (Fig. 1); and she found that >0.25 mm particles comprised <11% of suspended sediment. These local studies confirm that the >0.25 mm fraction is the coarse tail of suspended sediment in the study area and likely to be a good proxy for flood magnitude.

Wang and Leigh (2012) observed that the coarsest sand fractions in overbank deposits of the upper Little Tennessee River valley were indicative of changes in gaged flood magnitude and frequency averaged over decadal-scale time intervals, but they lacked finer temporal resolution. Toonen et al. (2015) emphasize that the coarsest end of particle-size distributions is the most useful for correlating vertical accretion deposits to flood magnitude and frequency from paleochannel fills in the lower Rhine River of Germany and the Netherlands, based on continuous particle-size distributions measured with a laser-diffraction particle-sizer.

The aforementioned studies indicate there is good evidence to suggest that the >0.25 mm fraction alone should be a good proxy for past floods in the study area, and research presented here seeks to test this flood proxy in a mountainous region whose streams carry abundant fine sediment. It is important to confirm that coarse ends of particle-size distributions relate strongly to bottomland overbank records of paleofloods, because the ease of measurement and cost effectiveness of this approach could facilitate its wider application toward a better understanding of flood hazards worldwide. While the >0.25 mm fraction appears appropriate for this study, it is also important to recognize that coarser or finer fractions may be more appropriate for other regions of the world, depending on the energy regime and sediment load of the river.

## 2. Study area and sample sites

The upper Little Tennessee River drains the Southern Blue Ridge Mountains flowing from northeastern Georgia northward through western North Carolina (Fig. 1). Three cutbank exposures of post-settlement (after CE 1870) bottomland vertical accretion deposits were sampled in 2004–2006 on the main stem of the river within a 20 km valley segment above the United States Geological Survey (USGS) gaging station near Prentiss (USGS 03500000), which has a 363 $\mathrm{km^2}$ drainage area. These three sites correspond to the State Line, Otto, and Riverside sites reported by Leigh (2016), except that the Riverside site reported here was sampled 110 m upstream of the one reported by Leigh (2016). Samples of post-settlement alluvium were obtained in contiguous intervals of 1 cm at State Line (167 samples), 3 cm at Otto (74 samples), and 2 cm at Riverside (77 samples), making a total of 318 samples. These sample intervals approximate annual resolution per sample at State Line, 1.6–2.1 year resolution at Otto, and 1.3–2.2 year resolution at Riverside, based on age models established for the sites (see explanation of age-depth models below). The meandering river channel has a sinuosity of 1.4 to 1.7 (channel length/valley length) encompassing the sites and is characterized by riffles and pools with coarse bedload of cobble, gravel, and coarse sand. The bankfull channel width increases from 15 m to 25 m downstream through the sites, and the channel typically is incised beneath a low historical terrace so that banks are 3 to 4 m high. In a few short reaches the river has migrated laterally to establish an incipient floodplain (Leigh, 2010) where the bank heights are 1.5 to 2.0 m high. All three sedimentary profiles are exposures of prograding natural levees on the low historical terrace. These overbank sediments generally are massive sandy loams, but they also contain many distinct thin planar beds and laminae of fine and medium sands that are flood beds (Fig. 2). There is no visible evidence of erosional truncation or agricultural cultivation in the stratigraphic sections. Post-settlement overbank alluvium at all three sites unconformably overlies an organically enriched paleosol developed in pre-settlement overbank alluvium (Fig. 2), which contains Cherokee and older Native American artifacts (observed by the author) and tends to be finer textured than the post-settlement alluvium (Leigh,

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