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Flood Ring Evidence and its Application to Paleoflood Hydrology of the Red River and Assiniboine River in Manitoba

Paléohydrologie des inondations dans les bassins des rivières Rouge et Assiniboine (Manitoba) à partir des cernes de croissance

Paleohidrología de las cuencas de los Red River y Assiniboine River (Manitoba) basada en las huellas de inundaciones dejadas en los anillos de crecimiento de los árboles

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Article abstract

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FLOOD RING EVIDENCE AND ITS APPLICATION TO PALEOFLOOD HYDROLOGY OF THE RED RIVER AND ASSINIBOINE RIVER IN MANITOBA*

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ABSTRACT Although paleoflood records developed from tree rings are much shorter than those developed from geological evidence, their brevity is offset by their exceptional utility for dating floods to a specific year. Inundation at the beginning of the growing season disturbs cambial processes in riparian *Quercus* spp., causing unusual anatomical features to develop within the annual ring, including small earlywood vessels, disrupted flame parenchyma and less wood fiber. These features are most strongly developed near the tree base, and may be caused by disruptions of auxin flow. Anatomical flood signatures can be used to determine the frequency, magnitude and hydrological causes of past floods, and to identify the influence of potential forcing mechanisms. In the lower Red River basin, Canada, flood-ring evidence has been used to identify several large floods during the mid 1700s, the early to mid 1800s and the latter half of the 20th century. Records for the Assiniboine River and the American portion of the Red River are developed from fewer trees, but suggest that severe floods in the Red and Assiniboine basins have coincided, albeit infrequently, during the past 500 years.

RÉSUMÉ *Paléohydrologie des inondations dans les bassins des rivières Rouge et Assiniboine (Manitoba) à partir des cernes de croissance.* Bien que les renseignements sur les paléoinondations tirés des cernes de croissance des arbres portent sur des intervalles beaucoup plus courts que ceux dérivés de la géologie, ils demeurent d'une exceptionnelle utilité pour dater l'année précise d'une inondation. Une inondation qui survient au début de la saison de croissance perturbe les processus cambiaux des chênes (*Quercus* spp.) riverains, ce qui provoque le développement de traits anatomiques inhabituels à l'intérieur du cerne de croissance annuel, dont de petits vaisseaux de bois initial, un parenchyme flammé perturbé et des fibres ligneuses moins nombreuses. Ces traits sont plus marqués près de la base de l'arbre et peuvent être causés par un arrêt de la circulation de l'auxine. Les empreintes anatomiques laissées par les inondations peuvent servir à déterminer la fréquence, l'ampleur et les causes hydrologiques des crues passées et à évaluer l'influence des mécanismes de forçage potentiels. Dans le bassin inférieur de la rivière Rouge, les indications sur les inondations tirées des cernes de croissance ont permis d'identifier plusieurs crues importantes survenues au milieu du XVIIIe siècle, du début au milieu du XIXe siècle et dans la deuxième moitié du XXe siècle. Pour la rivière Assiniboine et la partie américaine de la rivière Rouge, les données proviennent d'un moins grand nombre d'arbres, mais laissent croire que d'importantes inondations dans ces bassin ont parfois été synchrones au cours des 500 dernières années.

RESUMEN *Paleohidrología de las cuencas de los Red River y Assiniboine River (Manitoba) basada en las huellas de inundaciones dejadas en los anillos de crecimiento de los árboles*. Aun cuando el registro de paleo inundaciones presente en los anillos de crecimiento de árboles es más corto que el observado en una secuencia geológica, su brevedad nos permite situar de manera mas precisa la ocurrencia de inundaciones en un año en particular. La ocurrencia de una inundación al inicio del periodo de crecimiento genera cambios estructurales en el cámbium de los árboles. En caso del roble ribereño (*Quercus* spp.) los anillos de crecimiento que se forman cuando sucede una inundación presentan cambios anatómicos poco usuales. Dichos cambios incluyen la formación de madera con vasos jóvenes pequeños, un parénquima perturbado y la formación de fibras menos leñosas. Estas características se presentan principalmente a nivel de la base del árbol y podrían ser causadas por perturbaciones en el flujo de auxina. Estas huellas anatómicas de una inundación pueden ser usadas para determinar la frecuencia, la magnitud y las causas hidrológicas de inundaciones pasadas e identificar la influencia de mecanismos potenciales que las originan. En la parte baja de la cuenca del Red River (Canadá), las huellas presentes en los anillos de crecimiento han permitido identificar varios eventos de inundaciones durante mediados del siglo XVIII así como de inicios del siglo XIX y de mediados del siglo XX. Los registros observados en el Assiniboine River y en la parte estadounidense del Red River han sido desarrollados a partir de un número pequeño de árboles pero sugieren que durante los últimos 500 años ocurrieron, aunque con poca frecuencia, inundaciones importantes en las cuencas de los ríos Red y Assiniboine.

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INTRODUCTION

The likelihood of floods occurring in the future is estimated from the frequency of similar floods in the past. Unfortunately, because most instrumental records of river flow in Canada span less than 100 years (Ashmore and Church, 2001), gauge data for most watersheds are too short to determine the probability of large, infrequent floods accurately (Klemeš, 1989). Furthermore, probabilistic flood-frequency analysis techniques require annual flood series data to be identically distributed, independent and random through time, but real flood data often violate these assumptions (Baker *et al.*, 2002). Although historical accounts have been used to extend flood histories for some Canadian rivers by up to one hundred years (*e.g.*, Rannie, 1998), the entire period of record is still relatively short when compared with the time horizons used in the design of flood protection structures (typically between 100-1000 years). Relying exclusively on short flood records limits our understanding of floods and flood-generating processes. These records may be inadequate for documenting the occurrence and magnitude of extreme floods, and provide a limited perspective on the influence of environmental change on flood risks. This latter aspect is particularly important, because several studies have demonstrated that flooding is a dynamic process that is strongly linked to climate (*e.g.*, Knox, 1993, 2000; Changnon and Kunkel, 1995; Redmond *et al.*, 2002 and references therein).

Geological and biological field evidence can be exploited in order to develop extended flood records that span several hundreds, or thousands of years. The long records provided by such evidence establish a pre-historical context for recent instrumental observations, and allow us to estimate how the frequency and severity of extreme floods changes over time. Extended flood histories can also be used to identify specific mechanisms that have driven past increases or decreases in flood magnitude and occurrence (*e.g.*, Knox, 1993). Most paleohydrological studies in North America have used geomorphic evidence of past flood stages to develop flood records covering the mid to late Holocene (*e.g.*, Baker, 1987; Enzel *et al.*, 1996; Knox, 2000), but paleoflood studies are often broadly interdisciplinary, and may include contributions from such diverse fields as geophysics (Pickup *et al.*, 2002), limnology (Brown *et al.*, 2000), archaeology (Brown *et al.*, 2001), and dendrochronology (Yanosky and Jarrett, 2002).

Paleoflood records derived from tree rings usually cover much shorter intervals than those obtained from geological evidence (centuries rather than millennia), yet only dendrochronology can potentially offer records resolved to the individual year. The annual resolution of tree-ring records can provide credible evidence for synchronized flooding in separate drainage basins, and can tightly constrain linkages between extreme floods and potential forcing mechanisms. Most dendrochronological investigations related to paleoflood research have used impact and abrasion scars caused by ice and floating debris to estimate past flood stages (*e.g.*, Gottesfeld and Johnson Gottesfeld, 1990; McCord, 1996). In an alternative approach, anatomical ring anomalies induced by flooding can be used to identify past severe floods. In his analysis of white ash (*Fraxinus americanum* L.) and green ash (*F. pennsylvanica* Marsh.) growing along the Potomac River, Yanosky (1983) reported that rings formed during, and shortly after floods displayed a complex range of anatomical responses. Anatomical flood signatures (or “flood rings”) have excellent potential as high-quality proxies of past floods, but they have not been used widely in paleoflood investigations and only recently have been applied to selected rivers in France (Astrade and Bégin, 1997) and Canada (St. George and Nielsen, 2000, 2003).

In this paper, we describe the physical characteristics of flood rings produced by prolonged inundation, and discuss how the relative timing of flooding and cambial activity can affect the utility of this approach to paleoflood studies. Although flood rings may also be produced through the defoliation of riparian trees by high water, we refer the reader to Yanosky (1983) for a thorough description of that mechanism and its effects. In the second section of the paper, we illustrate the potential contribution of flood ring records to paleohydrology, drawing on examples from the Red and Assiniboine rivers in Manitoba, Canada. Previously published flood ring chronologies for the lower and upper Red River basin, as well as a new record for the Assiniboine River, are used to address questions related to the occurrence of extreme floods during the last 500 years and possible forcing mechanisms.

ANATOMICAL FLOOD SIGNATURES

Severe spring floods can directly affect the growth of some riparian tree species, leaving clear evidence of their occurrence that can be preserved for several centuries. Inundation of the roots and stem at the beginning of the growing season disturbs normal cambial processes and can lead to the development of unusual anatomical features within the annual ring. Such features have been reported in *Quercus robur* L. (Astrade and Bégin, 1997) and *Quercus macrocarpa* Michx. (St. George and Nielsen, 2000, 2003). Flood signature rings in oak usually contain anomalously small conductive vessels within their earlywood (Fig. 1a; Astrade and Bégin, 1997; St. George and Nielsen, 2000) and may also, in cases where the disturbance is more severe, feature amorphous latewood with disrupted flame parenchyma (cells that serve for storage and conduction of food materials) and little fiber in the latewood (Fig. 1b; St. George and Nielsen, 2003). Cross-sectional areas of earlywood vessels within flood rings are more than two standard deviations below the mean (St. George *et al.*, 2002; Fig. 2).

The strength of flood signatures varies with vertical distance along the trunk. A series of cores collected along the vertical axis of flood-affected *Q. macrocarpa* demonstrated that vessel anomalies for 20th century floods were developed strongly near the base of the tree, but gradually became less distinct upwards (St. George *et al.*, 2002). In some cases, flood rings that were clearly evident close to ground level were totally absent one metre higher (St. George *et al.*, 2002). However, an older (>279 years old) oak near the same river displayed a well-developed signature for a 19th century flood at a height of 5 m, with only minor vessel reductions at ground level (St. George and Nielsen, 2003). These inconsistent observations highlight our limited knowledge of the impact that prolonged inundation

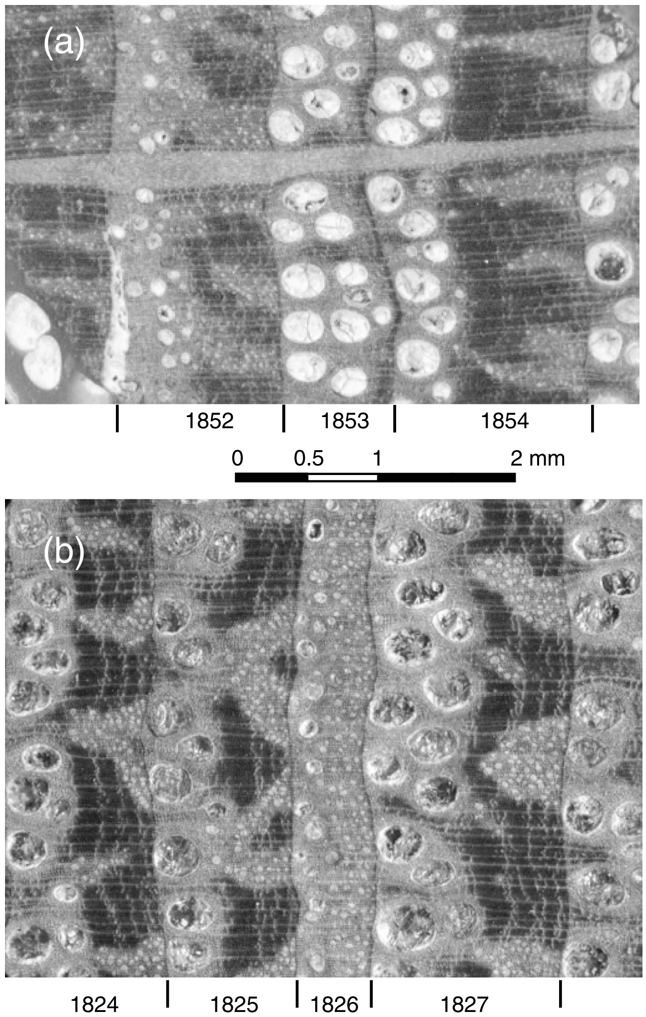

FIGURE 1. Anatomical signatures caused by flooding in bur oak. Normal (non-disrupted) rings, such as 1854 (a) and 1827 (b), contain one or two rows of circular earlywood vessels followed by dark-coloured latewood fiber and "flame" parenchyma. Typical flood rings, such as 1852 (a), display shrunken earlywood vessels but normal latewood. More severe and/or prolonged flooding can produce rings with additional anatomical anomalies. The ring formed during the record 1826 Red River flood (b) has unusually small vessels, but also has disorganised parenchyma and almost no latewood fiber. From St. George and Nielsen (2003).

Empreintes anatomiques des inondations chez le chêne à gros fruits. Les cernes normaux, comme en 1854 (a) et en 1827 (b), comprennent une ou deux rangées circulaires de vaisseaux de bois initial suivies de fibres de couleur foncée de bois final et d'un parenchyme flammé. Les cernes caractéristiques des années d'inondation, comme en 1852 (a), comprennent des vaisseaux de bois initial contractés et du bois final normal. Des inondations prolongées ou plus intenses peuvent engendrer des cernes comprenant davantage d'anomalies anatomiques. Le cerne formé pendant l'inondation exceptionnelle de la rivière Rouge en 1826 (b) comprend des vaisseaux particulièrement petits, un parenchyme désorganisé et à peu près pas de fibres de bois final. De St. George et Nielsen (2003).

has on mature oaks. Because the size of earlywood vessels in hardwoods is controlled partly by the flow of auxin from the leaves towards the roots (Aloni, 1987), flood signatures are probably caused by disruptions of the normal downward flow of auxin from the leaves to the stem. However, the specific mechanism of disturbance during floods is unknown. Auxin flow might be disrupted by direct contact with the water surface, or a disturbed pressure gradient caused by water surrounding the circulatory system of the tree. Reduced oxygen availability during and after prolonged inundation of the root system may also be an important contributing factor. Unfortunately, the only experimental work investigating the flood tolerance of bur oak (*Quercus macrocarpa*) (Tang and Kozlowski, 1982) used three-month old seedlings, which lack woody structure and display different anatomical responses to flooding than those observed in older trees. Without controlled experimentation conducted on mature trees, discussion of the mechanisms involved with flood-ring formation will remain conjectural.

The development of anatomical anomalies in an oak depends strongly on the relative timing between the interval of inundation and that of active cambial growth. Floods that occur during a tree's dormant period cannot influence anatomical development, and therefore flood-ring records do not document high stages in autumn or winter. Spring or summer floods may also go unrecorded, depending on their occurrence relative to the beginning of growth. Spring warmth that precedes flooding by several weeks may stimulate bud break and allow earlywood vessels to form completely before trees are flooded. Consequently, the potential for flood signature formation in that growth year is removed (St. George *et al.*, 2002). The differing responses of *Q. macrocarpa* along the Red River at Fort Dufferin, Manitoba, demonstrate the importance of flood timing (Fig. 3). Measurements collected at the nearby Emerson gauge station indicate that the Red River floods of 1950 and 1979 had roughly equivalent peak discharges (2 670 and 2 620 m^3/s, respectively). In 1950, the Red River began to flood the Fort Dufferin site on April 24, with the period of inundation persisting until June 2. Climate records at Emerson suggest that minimum temperatures at Fort Dufferin did not rise above 0 °C until May 2. These trees were therefore flooded during the entire first month that spring temperatures were warm enough to allow earlywood formation. Five of sixteen oaks sampled contained distinct flood signatures for 1950. The spring of 1979 was much warmer, with minimum temperatures at Emerson rising above 0 °C on April 2 (a month earlier than in 1950). Although the 1979 flood inundated the Fort Dufferin stand for 24 days, we suggest that the preceding three weeks of above-freezing temperatures allowed earlywood development to be completed before the onset of flooding. None of the sixteen oaks sampled at Fort Dufferin contained any unusual anatomical structures within their 1979 ring. To a certain degree, this narrow window of sensitivity limits the utility of flood-signature records, as floods that occur prior to or following earlywood formation will not cause the formation of anatomical markers. Because of this limitation, despite their excellent temporal resolution and good overall success in identifying past extreme floods, tree-ring paleoflood records should be viewed as minimum estimates of both flood frequency and magnitude (St. George and Nielsen, 2003).

FLOOD SIGNATURES AND PALEOFLOOD STUDIES IN THE RED RIVER BASIN

Spring flooding of the Red River is a major natural hazard in southern Manitoba. Because more than 70 % of Manitoba's

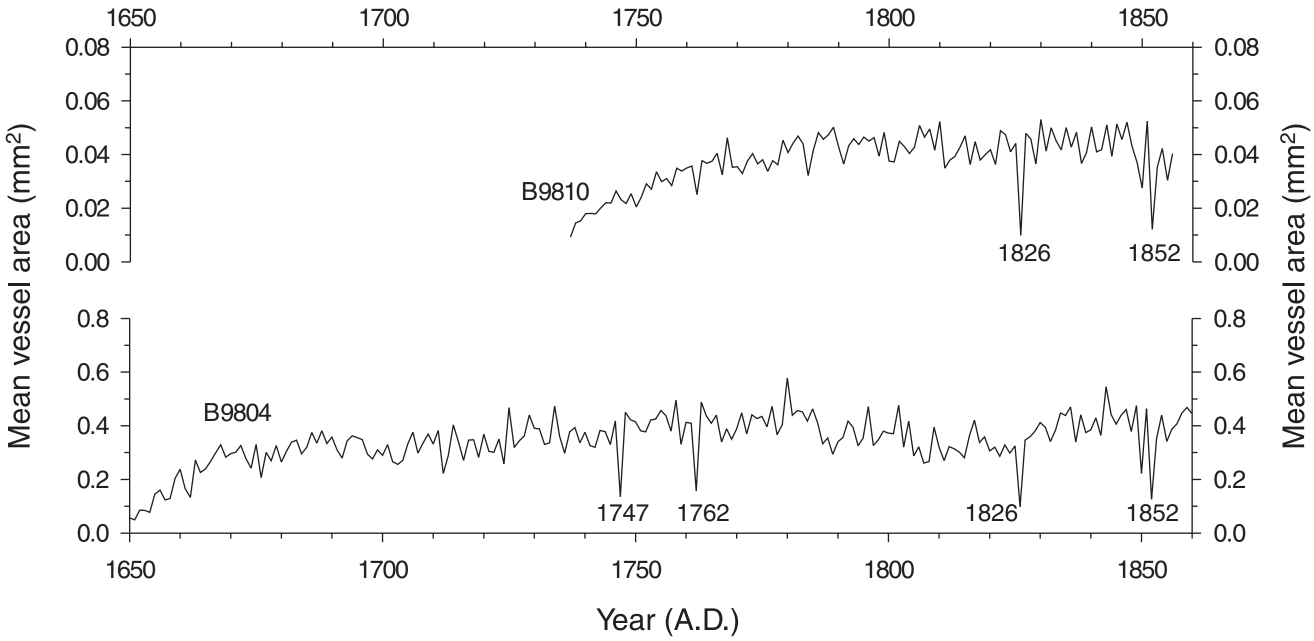

FIGURE 2. Measurements of earlywood vessel size in samples collected from Barber House in central Winnipeg. In sample B9810, flood signatures in 1826 and 1852 have marked decreases in vessel area. Small vessels are present in 1747, 1762, 1826 and 1852 in B9804. Methodology follows St. George *et al.* (2002).

Mesures des dimensions des vaisseaux de bois initial à partir des échantillons du Barber House, au centre de Winnipeg. Dans l'échantillon B9810, les empreintes des inondations de 1826 et de 1852 montrent nettement une diminution des vaisseaux. On note aussi de petits vaisseaux en 1747, 1762, 1826 et en 1852 dans l'échantillon B9804. Méthodologie selon St. George et al. *(2002).*

1.1 million citizens live along the Red River, severe floods have extracted a heavy social and economic toll from the province, including significant damage to property and agricultural livestock, forced evacuation of several thousand people and albeit rarely, the loss of life. During the most recent flood in 1997, costs for flood fighting and recovery were estimated at. $500 million (Cdn.) (Manitoba Water Commission, 1998). Flooding in the Canadian portion of the Red River basin has been controlled by a series of dikes, diversions and retention structures since the 1960s (Brooks and Nielsen, 2000), but several recent studies have suggested that the current capacity of these structures cannot defend communities adequately against the risks posed by future floods (International Joint Commission, 2000; KGS Group, 2001).

Recently, the Geological Survey of Canada and the Manitoba Geological Survey have completed a multi-disciplinary project investigating the geological history of the Red River and the possible influence of geological, geomorphic and climatic processes on flood hazards (Brooks *et al.*, 2003). This research has involved contributions from fluvial geomorphology (Brooks, 2003a, b), limnology (Medioli, 2003; Medioli and Brooks, 2003), paleoclimatology (St. George and Nielsen, 2002), historical hydrology (St. George and Rannie, 2003) and dendrohydrology (St. George and Nielsen, 2000, 2003). In the following sections, we describe how flood-ring evidence was used to develop extended flood records for the Red River and its main tributary, the Assiniboine River, and discuss the relevance of this long-term perspective to the flood hazard in the Red River basin today.

SETTING

The principal factor determining the extent and severity of Red River floods is the landscape of southern Manitoba. Throughout its northward course, the Red River flows across a virtually flat plain composed of glaciolacustrine sediments that aggraded within the main depositional basin of glacial Lake Agassiz. Although this broad plain is often described as the Red River valley, the true alluvial valley produced by the Red River is relatively narrow, between 1.5 to 2 km wide at most locations. Because of its shallowness and low downstream gradient (~0.0001), the alluvial valley has insufficient capacity to contain large floods (Brooks and Nielsen, 2000), causing flow to spill over onto the surrounding glaciolacustrine plain. During extremely high flows, the river can produce a broad, shallow flood zone up to 40 km across (Brooks and Nielsen, 2000).

The riparian forest surrounding the Red River in southern Manitoba is composed of several tree species, including plains cottonwoods (*Populus deltoides* Bartr. Ex Marsh. ssp. *monilifera* (Ait.) Eckenw.), willows (*Salix* spp.), basswood (*Tilia americana* L.), green ash (*Fraxinus pennsylvanica* var. *subintegerrima* (Vahl) Fern.), Manitoba maple (*Acer negundo* L.), American elm (*Ulmus americana* L.), and bur oak. The current age-structure of trees in these corridors, as well as historical accounts and photographs, indicate that the riparian forests of southern Manitoba were almost totally deforested during the 19th century. For example, bur oak can live for nearly 400 years in the northeastern Great Plains (Will, 1946) but most live oaks in the Red River basin are only 80 to 140 years old. The relative youth of modern trees in the Red River basin is due to intensive cutting

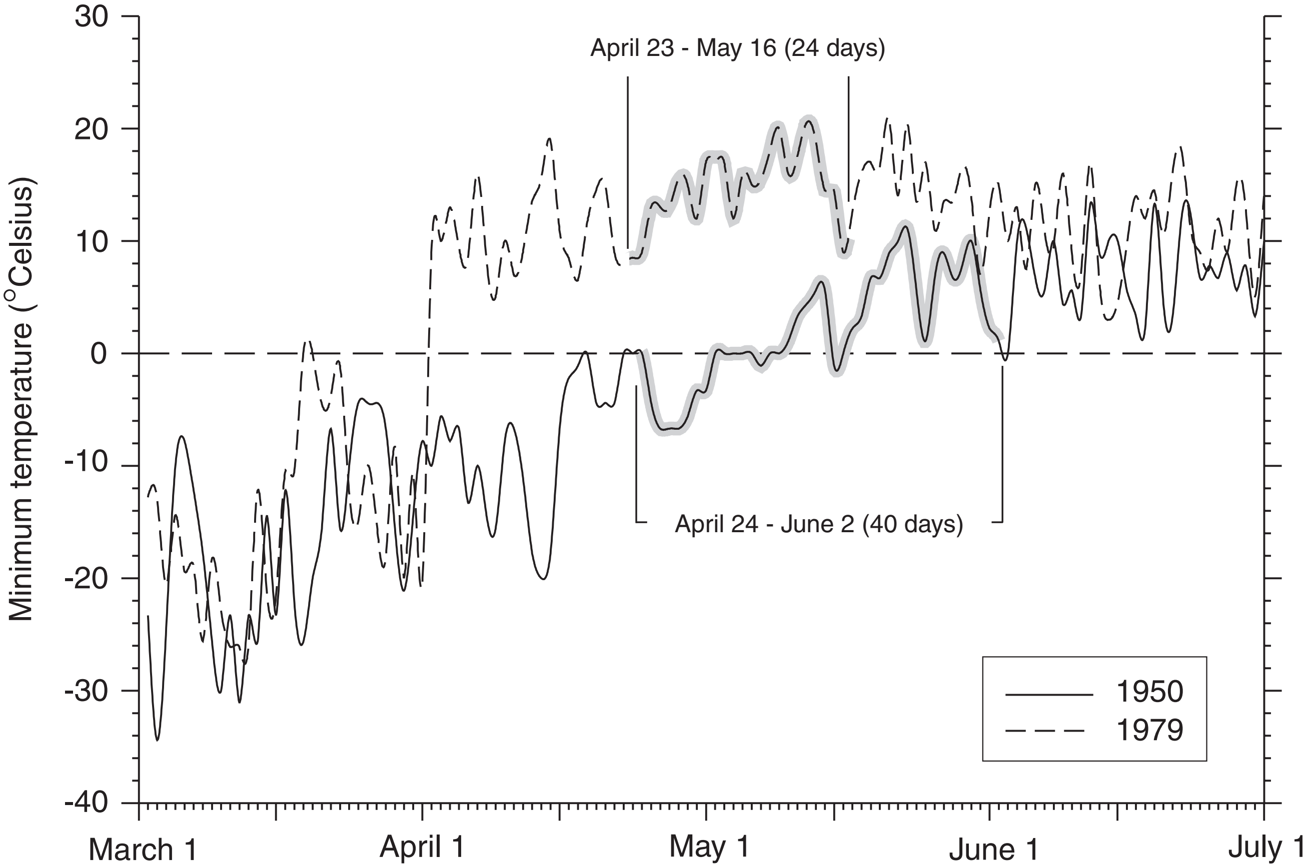

FIGURE 3. The progression of spring thaw during the 1950 and 1979 Red River floods. The shaded portions of the curves indicate the periods during which oaks were underwater in 1979 and 1950, as inferred from stage records at Emerson, Manitoba.

La progression de la fonte printanière pendant les inondations de la rivière Rouge, en 1950 et en 1979. La partie de la courbe comprenant un grisé identifie les périodes au cours desquelles les chênes ont été submergés, selon les registres d'Emerson, au Manitoba.

for construction timber and steamboat fuel, as observers reported that the forests near the Red River Settlement (modern Winnipeg) had been "entirely ruined, and rendered treeless" as early as the 1850s (Ross, 1856: 199).

DATA

A tree-ring dataset was developed for the Red River basin using samples from live trees, timbers from 19th century buildings and archaeological sites, and subfossil logs from river alluvium (Fig. 4). Our collection targeted bur oak due to its present abundance, widespread usage in 19th century construction, excellent preservation post-mortem, and its position relative to flood stage. Bur oak is ideally distributed in southern Manitoba for the purposes of paleoflood studies because its preferred growth location on the glaciolacustrine plain enhances its sensitivity to extreme flood stages. This relatively high surface protects the oaks from small to moderate flows, and thereby prevents the formation of any anatomical anomalies associated with minor flooding. However, high-magnitude floods spill overtop the river valley and may inundate these trees for several weeks, leaving behind extensive flood signatures. Their high elevation relative to the valley bottom filters out the "noise" of small floods, and causes the oaks to record only the occurrence of large floods (St. George and Nielsen, 2000). This filter is particularly helpful because high-magnitude floods obviously have the greatest impact on communities in southern Manitoba.

Samples from living trees were collected at thirteen sites along the Red River from Emerson, Manitoba to the northern limit of Winnipeg (Fig. 4). These trees grew between 100 and 200 m from the river's edge and were all within the natural flood zone of the Red River. However, some sites (particularly those inside Winnipeg) have been protected by dike or diversion systems since the mid-1960s. An additional site is located near the Canada-United States border on the Marais River, one of the Red River's minor tributaries. Only three living tree sites were developed along the Assiniboine River (Assiniboine Park, Bruce Park and Munson Park). These sites are less than 8 km from the Forks (the confluence of the Red and Assiniboine rivers), and are within the area affected by backwater flows during severe Red River floods. Although Case (2000) collected samples from bur oak at sites in the Assiniboine River basin near Brandon, her samples are not directly relevant to our paleoflood investigations because the work was carried out as part of a large-scale dendroclimatic study and did not target locations close to the river.

Oak timber samples were recovered from eleven buildings and archaeological sites inside Winnipeg, including several specimens obtained from the Upper Fort Garry of the

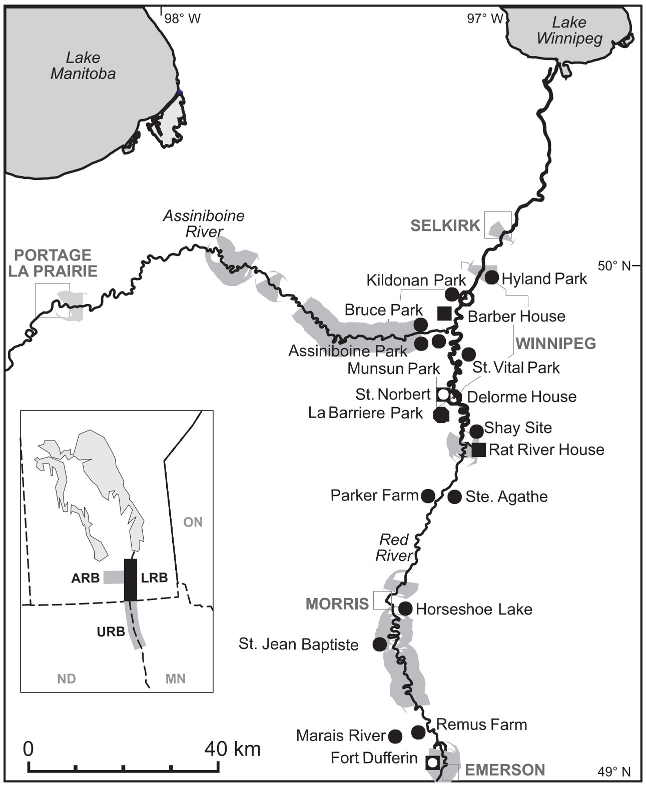

FIGURE 4. The bur oak sampling network in southern Manitoba. Circles represent living tree sites and squares indicate selected historical buildings. Shaded corridors represent reaches where subfossil logs were collected from river alluvium. Adapted from St. George and Nielsen (2003).

Le réseau d'échantillonnage du chêne à gros fruits, dans le sud du Manitoba. Les cercles identifient les sites comportant des arbres vivants et les carrés, des immeubles à caractère historique. Les zones en grisé correspondent aux endroits où l'on a recouvré des morceaux de bois subfossiles dans les alluvions. Adapté de St. George et Nielsen (2003).

Hudson's Bay Company. Nineteenth century settlers commonly used oak for construction, and several oak structures still survive in Manitoba as heritage buildings or private residences. However, the historical "window" useful for dendrochronology is relatively brief, because the arrival of the Canadian Pacific Railway to Winnipeg in 1881 brought an influx of lumber from non-local sources.

Eighty-one subfossil oaks were recovered from the Red and Assiniboine rivers, with most found in cut banks exposed by minor erosion and bank slumping during low-water stages in September and October. Subfossil logs in the Red River were concentrated between Emerson and Morris, with relatively few logs found along downstream reaches closer to Winnipeg. Most samples from the Assiniboine River were collected within 50 km of its confluence with the Red River, although a few logs were acquired further upstream, near Portage la Prairie.

RESULTS

RED RIVER BASIN TREE-RING CHRONOLOGIES

The combined oak record for southern Manitoba consists of 403 crossdated trees, and extends from AD 1999 to 1286[1]. This chronology is currently the longest tree-ring record from the Canadian Prairies and is only exceeded on the northern Great Plains by a ponderosa pine (*Pinus ponderosa* P. Laws.) chronology developed by Sieg *et al.* (1996) in the central Black Hills of South Dakota. Although live trees make up the bulk of the dataset after AD 1850, most samples covering the 18th and early 19th century were obtained from historical timbers. Prior to AD 1648, the record is composed entirely of subfossil logs. The earliest part of the record (between AD 1286 and 1448) was developed using only subfossil logs recovered from the Assiniboine River.

We divided the composite regional dataset into three subgroups based on the collection point, and inferred growth location, of each tree. The lower Red River basin (LRB) subgroup (Fig. 4; Fig. 5a) includes 322 samples from living trees and historical or archeological sources and pertains to the river reach between Emerson and Winnipeg. Although the growth locations of live trees within the LRB are self-evident, the origin of timbers recovered from historical buildings and archaeological sites is not. However, these trees were almost certainly harvested from the arboreal fringe surrounding the Red River and, in most cases, were probably cut within a few kilometres of building sites. The tree-ring record for the upper Red River basin (URB; Fig. 4) is derived exclusively from forty-four subfossil logs recovered from alluvial sections. Because subfossil logs must originate from upstream sources, oaks recovered between Emerson and Morris either grew at the southern end of the LRB corridor or at sites in North Dakota or Minnesota. We are unable to determine their original growth locations more specifically. The record for the Assiniboine River basin (ARB; Fig. 4) was also developed using only subfossil logs, and includes data from thirty-seven crossdated oaks spanning the period AD 1286-1968 (Fig. 5b). An additional floating chronology has been developed from four ARB oaks that covers an interval of 312 years, but radiocarbon dating suggests that the chronology terminates *circa* 1120 ± 60 yr BP (GSC-5212; Morlan *et al.*, 2000). It has not been possible to crossdate these specimens with the dated oak record, and therefore we omit these samples from the discussion below.

LOWER RED RIVER BASIN FLOOD SIGNATURES

Bur oak collected in the LRB contain anatomical evidence for high-magnitude floods during the period AD 1648 to 1999: 1997, 1979, 1950, 1852, 1826, 1762 and 1747 (Fig 5a; St. George and Nielsen, 2003). The five most recent floods were recorded by either instrumental or historical observations, but the 1747 and 1762 floods predate local written history. Despite comments by an early fur trapper who suggested flooding was unusually extensive in 1776 (Ross, 1856), there is no tree-ring evidence of flooding in this year. The relative rarity of floods in the tree-ring record (only seven in more than 350 years) illustrates the effectiveness of the filter provided by the growth position of the oaks. During the period covered by

1. Tree-ring data cited in this paper are available from the World Data Center for Paleoclimatology (http://www.ngdc.noaa.gov/paleo/data.html).

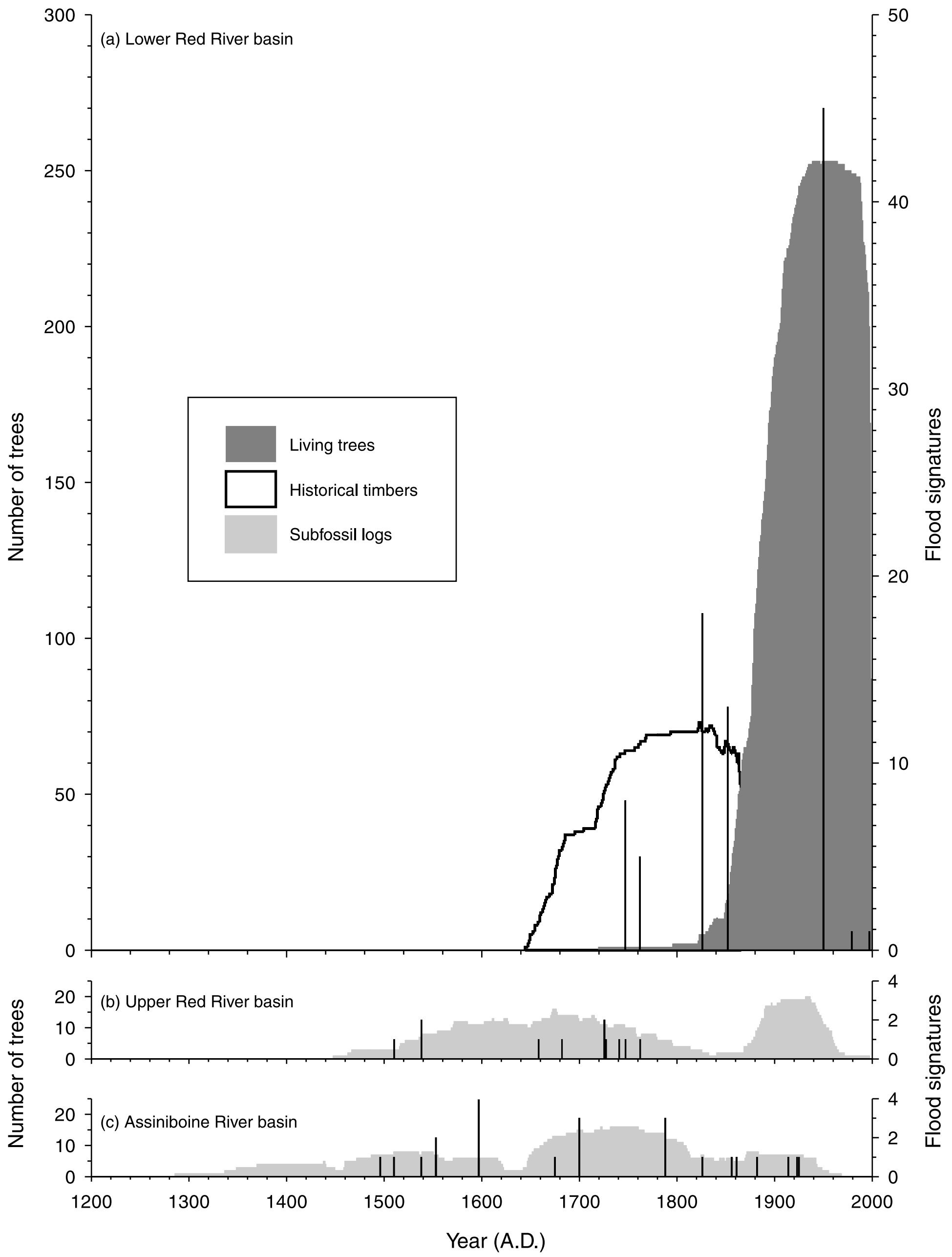

FIGURE 5. Flood signatures (black bars) and number of samples in the (a) lower Red River basin, (b) upper Red River basin and (c) Assiniboine River basin bur oak records.

Les empreintes d'inondation (traits verticaux) et le nombre d'échantillons de chênes à gros fruits provenant (a) du bassin inférieur de la rivière Rouge, (b) du bassin supérieur de la rivière Rouge et (c) du bassin de la rivière Assiniboine.

instrumental records, only those floods with peak discharges of 3 000 m^3/s or greater at Winnipeg created flood signatures, as the growth location of the trees has censored lesser floods from the LRB dendrohydrologic record. However, floods in 1861 and 1996 that produced discharges greater than this apparent threshold failed to induce flood-ring formation. The failure of these floods to create flood signatures is probably due to warmer spring temperatures and their relatively short period of flooding (St. George and Nielsen, 2003).

In order to produce an approximate estimate of flood magnitude, we assume that larger floods inundate more trees for a longer period than do smaller floods and thereby generate a greater number of anatomical tree-ring signatures (Yanosky, 1983; St. George and Nielsen, 2000). This assumption is appropriate for the Red River valley, given that the largest floods tend to rise and fall slowly over several weeks (Manitoba Conservation, unpublished data). Unfortunately, because the number of trees in the LRB varies through time, the total number of flood rings for each event cannot be used as a proxy for relative flood discharge. Our approach developed magnitude estimates by ranking flood signatures within trees and within sites (for a detailed description, see St. George and Nielsen, 2003). This method produced estimates that, in general, correspond well with instrumental and historical flood data. Our data indicate that the 1826 flood was the most severe in the LRB since at least AD 1648. Furthermore, our data suggest that the 1747 flood was equivalent in magnitude to the 1852 flood (~4 700 m^3/s), and that the 1762 and 1950 floods were approximately the same size (~3 000 m^3/s; St. George and Nielsen, 2003). Nevertheless, the ranking method underestimates the severity of the most recent floods in 1979 and 1997. We believe that these discrepancies are primarily due to the reduced number of trees available from the modern flood zone (St. George and Nielsen, 2003), and a non-optimal sampling procedure for the living trees (St. George *et al.*, 2002).

UPPER RED RIVER BASIN FLOOD SIGNATURES

The URB record spans the interval AD 1448 to 1997, and contains anatomical signatures for nine floods: 1762, 1747, 1741, 1727, 1726, 1682, 1658, 1538 and 1510 (Fig. 5b; St.George and Nielsen, 2003). Because of the limited number of samples in the URB record (only 44 trees), the preliminary flood history for the sub-basin must be interpreted with caution. No URB flood signatures are present during the 19th and 20th century, and therefore the frequency of flood ring formation cannot be linked to observed floods whose magnitudes were recorded by instrumental or historical sources. Consequently, we are unable to infer the relative magnitude of URB floods that occurred prior to the 19th century . However, the URB flood history preserved in subfossil logs does appear to differ from the LRB record. Of the floods occurring after AD 1648, only the 1747 and 1762 floods are common to both the URB and LRB. These results indicate that the history of flooding is not necessarily concordant throughout the Red River basin. For example, although it must be noted that the URB record is made up of less than five trees during the early 1800s, there is no evidence for either the 1852 or 1826 Red River floods in the upper basin. The apparent differences in flood history for these two reaches are intriguing, but more conclusive evidence can only be obtained through the future development of riparian tree-ring chronologies within the American portion of the Red River basin.

ASSINIBOINE RIVER BASIN FLOOD SIGNATURES

The ARB data set suffers from the same limitations as the alluvial Red River record: a limited number of samples during the 19th and 20th centuries, and the absence of data from a companion network of live trees. However, it does contain anatomical signatures in 1925, 1923, 1914, 1882, 1861, 1856, 1826, 1788, 1700, 1675, 1597, 1553, 1538, 1510 and 1496 (Fig. 5c). Several of these signatures coincide with known major Assiniboine River floods. The gauge record at Portage la Prairie reported a then-record crest on April 21, 1923, with high stages also reported at Headingly and Brandon (Morris, 1955). Based on observed stages at Brandon, the authors of the PFRA (1952) report suggested that the Assiniboine River also produced an exceptional flood in 1882, the largest flow prior to the current flood of record in 1976. Written documents from fur-trading posts in southwestern Manitoba and southeastern Saskatchewan suggest that significant Assiniboine River floods also occurred in 1861, 1856 and 1826 (Rannie, 2001). The ARB tree-ring record does not include flood signatures for major Assiniboine River floods in 1904, 1922 and 1955. In addition, the 1914 and 1925 signatures do not coincide with extensive flooding.

Given that only 20 % of all oaks sampled in the Red River and Assiniboine River basins contain flood signatures, these discrepancies are likely due to the limited number of ARB samples during the 20th century (less than six trees), and indicate that this flood signature chronology should be interpreted cautiously. Also, in rare cases, rings with shrunken vessels may be produced by conditions specific to the individual tree, such as poor local drainage, rather than extensive flooding (St. George and Nielsen, 2003). Because several ARB signatures are present in only one tree, it is important not to place too much emphasis on this record until additional samples containing the same signatures corroborate these events. Nevertheless, the ARB flood ring chronology may provide some insight into the flood history of southern Manitoba despite its preliminary nature. Because signatures for 1788, 1700, 1597 and 1533 are present in more than one tree, it is somewhat more certain that the Assiniboine River produced floods during these four years. Extended intervals with little or no indication of flooding also exist, especially during the 1600s and the interval between 1701 and 1787. Finally, signatures in the ARB coincide with LRB floods in 1861 and 1826 and with URB signatures in 1538 and 1510. This evidence suggests that, although it occurs infrequently, severe floods on the Red and Assiniboine rivers have coincided during the past 500 years. Attempts to model the record Red River flood of 1826 must account for this synchronieity accurately (St. George and Rannie, 2003). Previous studies have assumed only minor contributions from the Assiniboine River (Warkentin, 1999).

DISCUSSION

The good agreement between flood ring evidence and “conventional” flood records for the lower Red River basin suggests that the resulting paleoflood record may be a faithful reflection of long-term trends in flooding. Flood signature evidence for the upper Red River and the Assiniboine River has provided useful information related to the occurrence of past floods, but records for these sub-basins are not yet sufficiently developed to provide reliable estimates of changes in the frequency of large floods over time. During the last 350 years, the lower Red River basin appears to have experienced three periods containing multiple high-magnitude floods: the mid-1700s, the early to mid-1800s and the latter half of the 20th century. Conversely, tree-ring evidence suggests that the absence of severe flooding in the late 19th and early 20th century (a period that encompasses the incorporation of Winnipeg) was not without precedence. Other periods characterised by low-magnitude floods occurred between 1648-1746 and 1763-1810. These “high” and “low” flood modes imply that the probability of large floods occurring in the LRB has shifted several times since 1648, with such changes persisting for several decades. Prospective forcing mechanisms that might be responsible for these shifts include geological and geomorphic processes and climatic changes. Changes in land use may also be an important factor, as Euro-Canadian settlement in the Red River valley in 1812 was followed by extensive modifications to drainage patterns and the conversion of large wetlands to agriculture. However, Simonovic and Juliano (2001) have suggested that these changes have not influenced the peak discharges of Red River floods significantly. Moreover, there is little information about land use patterns in the Red River valley prior to 1870 (Hanuta, 2001). For these reasons, the potential effects of such changes on the occurrence of large floods in the LRB will not be discussed below.

The capacity of a river channel is strongly influenced by channel geometry and valley gradient. Changes in either or both of these parameters can modify channel capacity and thereby increase or decrease the likelihood of flooding. Recent research suggests that geological or geomorphic processes have not affected the characteristics of the Red River valley significantly during the last 350 years. Brooks *et al.* (submitted) have demonstrated that differential isostatic uplift has caused the Red River to lose approximately 60 % of its valley gradient since 8000 cal BP. Although hydraulic modelling of the modern Red River flood zone indicates that this loss of gradient has caused the extent and depth of flooding in the Red River valley to increase gradually over time, most of this change occurred during the first six thousand years following deglaciation. Between 8000 and 2000 cal BP, the flood zone increased by approximately 27 %, from 1 186 km^2 to 1 511 km^2. The increase in flood extent since 2000 cal BP is estimated to have been relatively minor (roughly 20 km^2 or 2 %). Brooks (2003b) has also shown that the rates of major geomorphological processes on the Red River, including lateral channel migration and incision, are very low to negligible, and have not measurably affected the discharge capacity of the river during the last thousand years. These processes can be considered to have changed flood characteristics only when viewed from a perspective of several millennia. For example, since 8000 cal BP, the increase in flood depth at several points along the river is equal to or greater than the required 0.6 m freeboard for flood protection structures in the Red River basin (Brooks, 2003b). Nevertheless, due to their slow rates of occurrence, no documented geological and geomorphic agent can be responsible for the apparent decadal-scale changes in the frequency of large floods present in the LRB record.

Long-term hydroclimatic change may be a better candidate to have influenced the occurrence of large floods over such timescales. Much of the earliest "low flood" interval in the LRB record coincided with the most prolonged dry interval in the lower Red River basin during the last 600 years. A dendroclimatic reconstruction derived from the Red River tree-ring data set (St. George and Nielsen, 2002) suggests that the lower basin received below normal precipitation every two years out of three between AD 1670 and 1775. These conditions appear to have affected the entire Red River watershed, as the AD 1700 dry episode is also recorded in lake sediment records from North Dakota and Minnesota (St. George and Nielsen, 2002). Although the Red River floods of 1747 and 1762 occurred during this period of overall aridity, both years were embedded within brief, two-to-three year periods of above-normal precipitation. At the other extreme, the 1826 and 1852 floods occurred during the two most prolonged wet intervals during the last 330 years (St. George and Nielsen, 2002). This correspondence hints that part of the variability in the occurrence of extreme floods may be driven by annual—to decadal-scale changes in precipitation. However, during the "low flood" intervals in 1763-1810 and 1862-1949, annual precipitation was not persistently below normal. Furthermore, during the "high-flood" 1950-2000 period, precipitation at Winnipeg was above normal in the 1950s, 60s and 70s and below normal in the 1980s and 90s. These latter examples suggest that there is not a simple relationship between large floods and long-term hydroclimatic change. From a meteorological standpoint, large Red River floods are produced through the interaction of a number of factors, including the delivery of precipitation through the year and spring temperature (Warkentin, 1999). While changes in the annual precipitation may contribute to shifts in the frequency of large Red River floods over time, the influence of important meteorological flood-generating factors over the long term is unknown, and remains a critical area for future study.

CONCLUSION

Compared with other paleohydrological techniques, the timespan of most tree-ring records is rather short. Although flood records developed from tree rings have not yet spanned even the last millennia, their brevity is offset by their exceptional utility for dating floods to a particular year. The utility of such finely resolved flood records is twofold. First, like other paleoflood records, flood-ring records can shed light on the past frequency of extreme floods, and provide a long-term context for contemporary observations. In some situations, flood-ring records enable one to infer the magnitude of paleofloods based on analogy with more recent floods for which detailed stage and discharge measurements are available. Second, annual dating offers the potential to deal more directly with questions related to timing of extreme floods and prospective hydroclimatic forcing mechanisms. Tree rings are ideally suited to identify the influence of climatic and geomorphic change on flooding at timescales of several decades or centuries, which cannot be determined by means of instrumental hydrological records. With complementary flood-ring records from tributary rivers and streams, it is also possible to obtain additional details concerning the relative contributions of individual sub-basins to past extreme floods. Ultimately, extended flood records derived from tree-ring data may be used to test assumptions of stationarity in annual flood series data, and to develop more accurate estimates of the probability of extreme flooding.

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