Tree Rings as Paleoflood and Paleostage Indicators

Scott St. George

1 Introduction

Each year, floods cause enormous damage to property and kill thousands of people around the world. During the 1990s alone, freshwater flooding affected more than 1.4 billion people and caused about 100,000 deaths (Jonkman 2005). Worldwide, insured losses due to floods topped US$2 billion in 2008 (SwissRe 2009), making them the second-most expensive type of natural catastrophe (exceeded only by damages caused by tropical storms). In addition to the threats they pose to human communities, major floods are also important geological and biogeochemical agents that influence rates of erosion and sediment transport (Molnar 2001), redistribute organic matter and nutrients to downstream reaches (Velasco et al. 2006) and homogenize ecological processes and biological communities within floodplain systems (Thomaz et al. 2007).

In conventional flood science, the likelihood of floods occurring in the future is estimated from the frequency of similar floods in the past. Unfortunately, river and lake gauge records are often too short for hydrologists to make accurate predictions of the probability of large, infrequent floods (Klemeš 1989). Further-more, probabilistic flood-frequency analysis requires events to be identically distributed, independent and random through time, but real flood data usually violate these assumptions (Baker et al. 2002). Instrumental flood records are also relatively short compared to the time horizons used in the design of flood protection infrastructure and provide a limited perspective on the impact of climate or environmental change on flood risks.

S. St. George (✉)
Geological Survey of Canada, Ottawa ON, K1A 0E8, Canada
and
School of Environmental Studies, Queen's University,
Kingston ON, K7L 3N6, Canada
e-mail: sstgeorg@nrcan.gc.ca

M. Stoffel et al. (eds.), *Tree Rings and Natural Hazards: A State-of-the-Art*,
Advances in Global Change Research 41, DOI 10.1007/978-90-481-8736-2_22,

Paleoflood hydrology uses physical evidence left behind on the landscape to make inferences about past floods that were not directly observed or recorded by humans (Baker 2006). Paleoflood records based on geological and biological field evidence can span several hundreds or thousands of years and provide a prehistoric context for shorter modern flood records based on direct observations. Paleohydrological studies most commonly use geomorphic evidence of past flood stages (e.g. Baker 1987; Enzel et al. 1996; Knox 2000), but paleoflood studies can also draw upon contributions from geophysics (Pickup et al. 2002), limnology (Brown et al. 2000), archaeology (Brown et al. 2001), and dendrochronology (Yanosky and Jarrett 2002).

The argument that trees recorded evidence of past floods in their annual growth rings was first put forward by Robert Sigafoos of the United States Geological Survey in 1964. Working along the Potomac River near Washington, DC, USA, he showed that unusual growth forms in riparian trees, including vertical sprouts, partial uprooting and tilted trunks, developed in association with floods documented at nearby gauge records (Sigafoos 1964). By demonstrating that these trees represented a biological archive of past floods, this initial work created a new tool for paleoflood research that has been applied widely to hydrological problems in the subsequent four and a half decades. Dendrochronologists are now able to exploit a broad range of physical evidence preserved in tree rings to develop insights into the occurrence, extent and magnitude of floods prior to direct observations. The articles and case studies in this chapter illustrate how flood evidence from trees is being used around the world to address issues related to long-term hydrological change, the impacts of human modification of hydrological systems and future risks of extreme floods.

2 Flood Evidence in Tree Rings

Dendrochronologists use four main strategies to study past floods and high water using evidence from tree rings. Three of these approaches examine evidence created by the direct effects of flooding on inundated trees while the fourth depends on indirect connections between hydrology, climate and the growth environment of trees.

Scarring caused by abrasion or impact is the most common type of tree-ring evidence used in paleoflood research. Ice, logs, sediment or other debris rafted into riparian forests by high water can abrade or penetrate the bark and kill the underlying cambium. Trees will attempt to seal the wound by forming undifferentiated, often discoloured scar tissue (callus), which acts as a permanent record of local cambial death. Eventually, the scar will be overgrown by the cambium and disappear under newly formed wood and bark, but if the tree is subjected to repeated scarring at the same location, the cambium will not recover and the wound will remain exposed at the surface (Fig. 1). The timing of the flood can be determined by counting the number of rings between the scar and the outside ring, and the height of the

Fig. 1 Extensive scarring caused by ice jams on a plains cottonwood (*Populus deltoides*) along the bank of the Red River in Winnipeg, Canada

scar represents the minimum elevation of high water (Harrison and Reid 1967; McCord 1996; Zielonka et al. 2010, this volume). Along rivers, scarred trees are most frequent where steep gradients or channel constrictions increase stream velocity and its capacity to carry heavy debris. In nival environments, elevated lake levels can also lead to tree scarring when lake ice is pushed into onshore forests following spring break-up (Tardif and Bergeron 1997; Tardif et al. 2010, this volume).

Floods can also interfere with physiological processes that control tree growth and cause anatomical changes within a portion or the entirety of the annual growth increment. These features are often referred to as ‘flood rings’ and have been observed most often in ring-porous trees such as ash or oak. Flood rings can be produced in low-lying trees when floodwaters reach the crown and fully or partially defoliate the tree during late spring or early summer (Yanosky 1983). If the tree is able to refoliate after flooding subsides, its growth ring will often contain a double cohort of large conductive vessels separated by one or more rows of smaller vessels. Flood rings can also be formed in flood-plain trees when the roots and trunk are subjected to prolonged inundation during the early part of the growing season (Astrade and Bégin 1997; St. George and Nielsen 2000; St. George 2010, this volume). These signatures are usually distinguished by the presence of anomalously small vessels in the earlywood of the annual ring but they can also include other anatomical features such as fibers with unusually thin cell walls and disrupted flame parenchyma. Whether caused by defoliation or inundation, flood rings are generally believed to form in response to disruptions in the normal downward flow of auxin, which partly controls the size of earlywood vessels in hardwoods (Fig. 2).

In some circumstances, floods can damage trees by tilting or partial uprooting or can uproot them completely, causing their death. When catastrophic flooding kills all trees along a reach of a river, the age of the oldest trees that colonize the fresh surface provides a minimum estimate of the flood date (Sigafoos 1964; Gottesfeld and Gottesfeld 1990). This approach requires estimates of the ecesis interval, the delay between the exposure of the new surface and the establishment of new trees. Partial uprooting can cause smaller trees to form vertical sprouts along their main stem, with the age of the sprout indicating the date of the flood that caused the change in growth habit (Sigafoos 1964). In extreme cases, trees

Fig. 2 Riparian trees inundated by the 2009 Red River flood in Manitoba, Canada

that are repeatedly damaged by flooding adopt a growth form with multiple stems that can resemble the product of coppicing. Tilting can also cause trees to form tension or compression wood (depending on whether they are deciduous or conifers) and anomalously wide or narrow rings in subsequent years (Yanosky and Jarrett 2002).

Major long-lasting shifts in regional hydrology can also create indirect evidence of their occurrence by making microsite conditions more or less favorable to tree growth. This type of analysis usually requires the presence of a water body, usually an artificial reservoir, large enough to influence aspects of the local climate such as seasonal temperature changes, evaporation rates or near-surface wind regimes. Dendrochronologists often use a suite of tree-ring indicators to compare local trees against a control population growing too far away to be affected by the reservoir. Depending on the amount of time that has passed since its construction, investigators may also examine long-lived trees to compare tree growth before and after reservoir construction. Most studies using this approach have shown that trees growing in the immediate area display a complex set of anatomical and growth-form responses that depend strongly on their position relative to the newly-created reservoir. Observed responses include but are not limited to temporary growth reductions during reservoir filling, a reduction in wood density caused by an extended growing season, an increased frequency of traumatic resin canals forced by major foliar losses and the formation of reaction wood at exposed sites due to stronger winds (Tremblay and Bégin 2005; Bégin et al. 2010, this volume).

3 Strengths, Limitations and Future Directions

The principal advantage of paleoflood studies based on tree rings is their relatively high temporal resolution and dating accuracy compared to most other methods. Dendrochronological methods can routinely date past floods to the year of their occurrence and, in rare cases, can estimate the timing of floods that occur during the growing season to within 2 weeks. This high degree of chronological control, which is surpassed only by that provided by direct observation or instrumentation, can be used to determine whether floods in separate watersheds were synchronous or offset by several years and test hypotheses that suppose linkages between extreme floods and specific forcing mechanisms. The wide geographic distribution of tree species with dateable rings combined with the broad suite of methods available to examine interconnections between floods and tree growth allow dendrochronologists to apply their style of paleoflood hydrology in many settings that are not appropriate for techniques that depend on geological evidence.

To date, paleoflood analysis based on tree rings has been restricted to describing floods that occurred during the last 500 years. Flood signatures have been reported in more ancient trees (Bernard 2003) but as yet there has not been any attempt to compile tree-ring evidence of floods that occurred prior to roughly AD 1500. Naturally, the reason that most dendrochronologically-based paleoflood studies tend to be relatively short is because the life expectancy of trees growing in flood zones is comparatively brief. Because floods often kill trees and wash their remains downstream, it can be difficult to find evidence of floods that are older than the most recent catastrophic event and sample depth usually decreases back in time quite rapidly. It is possible to develop long paleoflood records from tree rings using samples collected from subfossil trees and historic buildings St. George and Nielsen (2000) but the success of this approach depends on the availability of ancient logs and archeological wood.

The use of tree rings to address questions related to flooding remains almost exclusively the domain of the scientific community, and there are very few examples where paleoflood evidence from trees has been formally incorporated into flood risk analysis. In part, the gap between scientific innovation and societal application is due to the fact that tree rings and other natural archives are well outside of the curriculum in civil engineering departments at most universities and, as a result, practitioners and decision-makers responsible for flood infrastructure can be unaware of the potential benefits offered by a broader geological perspective. At the same time, many lessons learned from tree rings can be difficult to apply to flood management because they do not relate to measures that are regarded as meaningful by decision-makers. Future paleoflood research involving tree rings will need to strike a balance between improving our understanding of the biological and fluvial processes that link tree growth to past floods and providing answers to questions about flood dynamics and flood hazards that are needed to safeguard people and property from future floods.

References

Astrade L, Bégin Y (1997) Tree-ring response of *Populus tremula* L. and *Quercus robur* L. to recent spring floods of the Saône River, France. Ecoscience 4:232–239

Baker VR (1987) Paleoflood hydrology and extraordinary flood events. J Hydrol 96:79–99

Baker VR, Webb RH, House PK (2002) The scientific and societal value of paleoflood hydrology, p 1–19. In: House PK, Levish DR, Webb RH, Baker VR (eds) Paleoflood hydrology. Am Geophys Union Monogr, Washington, p 385

Baker V (2006) Palaeoflood hydrology in a global context. Catena 66:161–168

Bégin Y, Sirois L, Meunier C (2010) The effects of hydroelectric flooding on a reservoir's peripheral forests and newly created forested islands. In: Stoffel M, Bollschweiler M, Butler DR, Luckman BH (eds) Tree rings and natural hazards: A state-of-the-art. Springer, Berlin, Heidelberg, New York, this volume

Bernard V (2003) North-western French Neolithic dendrochronology: prospects for a 2000 year oak chronology. Measure Sci Tech 14:1510–1515

Brown SL, Bierman PR, Lini A, Southon J (2000) 10,000 Year record of extreme hydrologic events. Geology 28:335–338

Brown AG, Cooper L, Salisbury CR, Smith DN (2001) Late Holocene channel changes of the Middle Trent: channel response to a thousand-year flood record. Geomorphology 39:69–82

Enzel Y, Ely LL, House PK, Baker V (1996) Magnitude and frequency of Holocene palaeofloods in the southwestern United States: A review and discussion of implications, pp 121–137. In: Branson J, Brown AG, Gregory KJ (eds) Global continental changes: the context of palaeohydrology, p 272. Geological Society Special Publication, Alden Press, Oxford

Gottesfeld AS, Gottesfeld LMJ (1990) Flood-plain dynamics of a wandering river, dendrochronology of the Morice River, British Columbia, Canada. Geomorphology 3:159–179

Harrison SS, Reid JR (1967) A flood-frequency graph based on tree-scar data. Proc North Dakota Acad Sci 21:23–33

Jonkman SN (2005) Global perspectives on loss of human life caused by floods. Nat Haz 34:151–175

Klemeš V (1989) The improbable probabilities of extreme floods and droughts, p 43–51. In: Starosolszky O, Melder OM (eds) Hydrology of disasters. James & James, London

Knox JC (2000) Sensitivity of modern and Holocene floods to climate change. Quat Sci Rev 19:439–458

McCord VA (1996) Fluvial process dendrogeomorphology: Reconstructions of flood events from the southwestern United States using flood-scarred trees. In: Dean JS, Meko DM, Swetnam TW (eds) Tree rings, environment and humanity. University of Arizona, Tucson, pp 689–699

Molnar P (2001) Climate change, flooding in arid environments, and erosion rates. Geology 29:1071–1074

Pickup G, Marks A, Bourke M (2002) Paleoflood reconstruction on flood-plains using geophysical survey data and hydraulic modeling. In: House PK, Levish DR, Webb RH, Baker VR (eds) Paleoflood hydrology. American Geophysical Union Monograph, Washington, DC, p 47–60

St. George S, Neilson E (2000) Signatures of high-magnitude 19th century floods in Quercus macrocarpa tree rings along the Red River, Manitoba, Canada. Geology 28:899–902

St. George S (2010) Dendrohydrology and extreme floods along the Red River, Canada. In: Stoffel M, Bollschweiler M, Butler DR, Luckman BH (eds) Tree rings and natural hazards: A state-of-the-art. Springer, Berlin, Heidelberg, New York, this volume

Sigafoos RS (1964) Botanical evidence of floods and flood-plain deposition. US Geol Surv Prof Paper 485A, p 35

SwissRe (2009) Natural catastrophes and man-made disasters in 2008. Swiss Reinsurance Company Ltd., Economic Research & Consulting, Zurich, Switzerland, p 43

Tardif JC, Bergeron Y (1997) Ice-flood history reconstructed with tree rings from the southern boreal forest limit, western Québec. Holocene 3:291–300

Tardif JC, Kames S, Bergeron Y (2010) Spring water levels reconstructed from ice-scarred trees and cross-sectional area of the earlywood vessels in tree-rings from eastern boreal Canada. In: Stoffel M, Bollschweiler M, Butler DR, Luckman BH (eds) Tree rings and natural hazards: A state-of-the-art. Springer, Berlin, Heidelberg, New York, this volume

Thomaz SM, Bini LM, Bozelli RL (2007) Floods increase similarity among aquatic habitats in river-floodplain systems. Hydrobiologia 579:1–13

Tremblay J, Bégin Y (2005) The effects of snow-packing on tree growth forms on an island in a recently created reservoir in northern Québec, Canada. Ecoscience 12:530–539

Velasco JM, Lioret J, Millan A, Marin A, Barahona J, Abellan P, Sanchez-Fernandez D (2006) Nutrient and particulate inputs into the Mar Menon Lagoon (SE Spain) from an intensive agricultural watershed. Wat Air Soil Pollut 176:37–56

Yanosky TM (1983) Evidence of floods on the Potomac River from anatomical abnormalities in the wood of flood-plain trees. US Geol Surv Prof Paper 1296, p 42

Yanosky TM, Jarrett RD (2002) Dendrochronologic evidence for the frequency and magnitude of paleofloods. In: House PK, Levish DR, Webb RH, Baker VR (eds) Paleoflood hydrology. American Geophysical Union Monograph, Washington, DC, p 77–89

Zielonka T, Holeksa J, Ciapała S (2010) A 100-year history of floods determined from tree rings in a small mountain stream in the Tatra Mountains, Poland. In: Stoffel M, Bollschweiler M, Butler DR, Luckman BH (eds) Tree rings and natural hazards: A state-of-the-art. Springer, Berlin, Heidelberg, New York, this volume