

Dendrochronologic Evidence for the Frequency and Magnitude of Paleofloods

Thomas M. Yanosky
United States Geological Survey, Reston, Virginia USA

Robert D. Jarrett
United States Geological Survey, Lakewood, Colorado USA

Abstract: Tree-growth responses to flood damage can be used to document the frequency and magnitude of paleofloods, thereby extending the historical period of record and improving estimates of flood recurrence. Common responses include the formation of scars, sprouting from tilted stems, and eccentric ring growth; occasionally, ring-anatomical changes develop following damage to leaves and buds, or to prolonged root flooding that does not injure trees. The annual formation of rings permits flood dating to within a year, and sometimes to within several weeks in the case of anatomical responses. The average maximum height of scars provides a reliable indicator of paleoflood stages along both low- and high-gradient streams. Magnitude also can be estimated by recovering information of any kind from trees at successively higher flood-plain elevations. This paper discusses numerous paleoflood studies based on botanical evidence, and considers practical applications that include detection, sampling, and interpretation of botanical information.

INTRODUCTION

Background

In 1964, Robert S. Sigafos, United States Geological Survey (USGS), published his classic treatise showing that riparian trees could be used to document the occurrence of past floods and depositional events (Figure 1). At the time, few gaged streams in the United States had continuous records longer than 30 years. Sigafos argued that riparian trees sometimes live hundreds of years, form annual rings that can be dated precisely, and thus were an untapped resource for hydrologic inference. He studied tree-growth responses to flooding along reaches of the Potomac River near Washington, D.C., USA, verifying his findings against the systematic record of floods since 1930 (and since 1895 at Point of Rocks, Maryland, 67 km farther up-stream). Sigafos' primary intent was to develop a technique to improve estimates of flood-recurrence intervals, thereby more accurately defining flood-plain limits and facilitating the cost-appropriate construction or modification of bridges, dams, and levees.

Paleoflood hydrology originated in the United States during the early 19th century when geologists began to consider the role of floods in the evolution of landforms, and as a discipline began to expand exponentially after 1970 [Costa, 1987]. Studies are conducted to document flooding before the period of record, thereby extending flood histories, or to estimate the stages of known floods. In addition to providing information about floods, the broader field of paleohydrology also emphasizes hydrologic variability, most notably the frequency and magnitude of droughts, average monthly streamflow, and climate change. Paleohydrologic investigations often are interdisciplinary and may involve stratigraphy, chemical analysis of sediments, palynol-

ogy, radiometric techniques, archeology, and dendrochronology [Jarrett, 1991; Jarrett and Tomlinson, 2000]. Of these, only dendrochronology provides proxy data at the resolution of individual years for reconstructing long-term hydroclimatic variables. However, ring-width chronologies used traditionally for reconstructions cannot be used to determine the occurrence or magnitude of individual paleofloods. Rather, the botanical basis for paleoflood inference results from predictable tree-growth responses to damage of the bark- and wood-forming tissues, buds, and leaves, and to radial growth following partial uprooting of the trunk. The remainder of this paper summarizes the kinds of botanical evidence most useful in paleofloods studies, with several illustrations of each and some considerations for practical applications.

Tree Growth and Tree Rings

Trees grow in height only from the division and elongation of cells at stem tips. Thus, a scar on a trunk or branch will remain at its original height as the tree grows taller. Growth in diameter results from the division of a thin layer of living cells (the cambium) just inside the bark, each year producing a new layer of wood, or ring. Phipps [1985] describes the three-dimensional nature of rings as concentric circles in transverse section and as parabolas when viewed longitudinally (Figure 2). The age of the tree can be approximated by counting the number of rings in the lower trunk, but a precise year can be assigned to each ring only by crossdating; that is, by matching ring-width patterns of a tree with those of nearby trees [Fritts, 1976]. Rings are composed of specialized tissues that conduct sap, provide support, and store organic materials. The relative size, amount, and arrangement of these components confer the typical appearance and physical properties of the various woods [see Phipps, 1985]. The structure of wood sometimes is modified by environmental factors and events that occur during the growth season, thus preserving anatomical evidence of past growing conditions.

The widths of tree rings are controlled in large part by environmental processes, most notably climate, and for this reason have been used extensively to reconstruct climatic variables where records are incomplete or lacking [Fritts, 1976]. Severe flood damage sometimes results in the production of a narrow ring, or even reduced radial growth for several consecutive years [Yanosky, 1982a]. Narrow rings most typically are associated with droughts, however, and thus have little value for paleoflood documentations. Yanosky and Cleaveland [1998] and Yanosky [1999] provide further discussions of the uses and limitations of tree rings in hydrology, whereas others (see below) consider the relations between vegetation and hydrology from a dynamic, process-oriented perspective.

Vegetation and Hydrogeomorphology

Fluvial ecosystems are four dimensional, consisting of longitudinal (upstream-downstream), lateral (floodplain-upland), vertical (hyporheic-phreatic), and temporal components [Stanford and Ward, 1992]. The establishment and growth of riparian vegetation is controlled in large part by hydrogeomorphic processes, human disturbance, land use, and climate [Bedinger, 1971; Baker, 1977, 1994; Osterkamp and Hupp, 1984; Osterkamp and Costa, 1987; Hupp, 1987, 1988; Glavac et al., 1992; Stanford and Ward, 1992; Shroder and Bishop, 1995; Hupp and Osterkamp, 1996; Scott et al., 1996; Friedman et al., 1996a, 1996b]. Vegetation and hydrogeology are interrelated whether streams are ephemeral, intermittent, or perennial [Wolman and Miller, 1960; Baker, 1977, 1994; Wolman and Gerson, 1978; Hedman and Osterkamp,

1982; Nilsson, 1987; *Everitt*, 1995]. The age, abundance, and species distributions of riparian vegetation are controlled in part by flow-duration regimes, flood frequency, magnitude, and velocity (intensity), shear stress, stream power, and sediment-transport dynamics. In turn, vegetation may alter flood flows by increasing roughness and promoting deposition. For example, *Osterkamp and Hupp* [1984] and *Hupp and Osterkamp* [1985] showed that riparian landforms support predictable assemblages of vegetation related to flow characteristics of three streams in the Virginia piedmont.

Most studies investigating the dynamic associations between vegetation and hydrogeomorphology are based on direct-gradient analysis [*Auble et al.*, 1994] and relate vegetation to specific ranges of hydraulic variables. These associations may permit predictions concerning changes in riparian ecosystems from land use, regulation, and climate [*Williams and Wolman*, 1984; *Richter and Richter*, 1990; *Stanford and Ward*, 1992; *Hupp*, 1992; *Johnson*, 1994; *Scott et al.*, 1996], and thus also are important to researchers attempting to recover evidence of paleofloods. *Shroder and Bishop* [1995] suggest that remote sensing provides a way to monitor subtle changes in riparian ecosystems, and noted that dendrochronological methods were particularly effective in comparative studies of ecosystems in the United States and Pakistan. Improvements in predictive models will result in the refinement of dendrochronologic methods and permit applications to a wider variety of hydrologic and botanical problems.

DENDROCHRONOLOGICAL TECHNIQUES

Tree Age and Growth Habit

Catastrophic flooding sometimes destroys all existing vegetation and creates a new surface for colonization by trees. If the flood occurred within the typical life span of colonizing trees, a forest of mixed age will develop in which the oldest trees are the same age. The lack of an age-synchronous cohort suggests that the flood likely occurred longer ago than the lifespan of trees, and thus ages of the oldest trees afford only a minimum estimate of the flood date [*Sigafoos*, 1964; *Everitt*, 1968, 1995; *Helley and LaMarche*, 1968; *Costa*, 1978; *Hupp*, 1988; *Gottesfeld and Gottesfeld*, 1990]. Generally, hydrologic inference from age-synchronous trees is most reliable along high-gradient streams prone to unusually catastrophic flooding. For example, *Hack and Goodlett* [1960] studied the aftermath of a cloudburst flood in June 1949 along Little River, Virginia, USA, and concluded from the age of flood-plain trees that floods of comparable magnitude had not occurred in at least 150 years. They also located numerous revegetated debris chutes, none of which supported trees established before 1949. *Yanosky* [1982b] found that most trees along inside-channel bends of the Potomac River survived the catastrophic flood of June 1972, as well as even larger floods in 1936 and 1942. However, most trees were destroyed along outside-channel bends exposed to the full force of floodwaters, and none of the few survivors had been growing prior to 1942. This study showed that the age and form of riparian forests was related to flood-flow velocities rather than to magnitude alone.

Trees with the greatest life spans, such as those in western North America, provide the longest potential record of paleofloods, particularly in remote areas where anthropomorphic disturbances are minimal. For example, *Helley and LaMarche* [1968] found that a large flood in northern California, USA, in 1964 eroded a stream terrace covering the stumps of redwoods (*Sequoia sempervirens* (D. Don) Endl.) killed by an earlier flood of approximately the same magnitude. Radiocarbon analysis of terrace deposits revealed that the original surface had been buried

to a depth of ~6 m by a single flood that occurred ~A.D. 1560 \pm 100 years. Thus, the investigators were able to assign a 400-year return period to the 1964 flood. Similarly, *Hupp* [1984] used the ages of trees on newly-created depositional landforms to date a series of debris flows along five creeks near Mt. Shasta, California. He was able to document nine debris flows not reported previously, including one that occurred in ~1670. This and similar studies require estimates of the time for vegetation to establish on newly-created surfaces

Flood-plain trees along high-gradient streams commonly are small and shrubby, particularly when flooded frequently. Partial uprooting results in the formation of vertical sprouts along a leaning trunk, imparting a characteristic growth habit sometimes referred to as a "Sigafos tree" (Figure 3.). Trunk tilting or crown damage during dormancy results in the production of sprouts during the next growing season. Thus, the age of the sprout can be used to determine when the flood occurred [*Sigafos*, 1964]. Some trees in high-damage zones bear sprouts that document numerous floods, the oldest typically forming along lowest parts of the trunk. For example, *Sigafos* [1964] described one tree that formed sprouts documenting floods of the Potomac River that occurred in 1942, 1948, and 1955. If the crown and most of the bole are destroyed, two or more sprouts growing from the very base eventually impart a "split trunk" appearance similar to the multiple-stemmed trees growing from logged stumps.

Trunk tilting alters the widths of rings formed in subsequent years. Ring widths may be reasonably uniform along the circumference of vertical stems, whereas new growth becomes eccentric after a stem is tilted. That is, the width of a single ring may differ strikingly along the axis of lean. In hardwoods, rings are wider on the upper side than lower side of leaning trunks; rings in conifers are wider on the lower side. The number of eccentric rings can be used to determine how long the trunk has been tilted, and thus when the flood occurred.

Scars

Ice, logs, sediments, and other flood-borne debris sometimes abrade the bark and destroy part of the underlying cambium, resulting in the formation of scar tissue (callus) rather than new wood and bark. Callus is undifferentiated, often discolored tissue that forms a permanent record of localized cambial destruction. Eventually, new cambium grows over the scar and restores the production of wood and bark. Until this occurs, however, the scar is visible from the outside of the tree, sometimes for many years. Because trees grow in height only from shoot tips, the height of a scar above the low-water channel represents a minimum flood elevation (Figure 4), although the stage will be underestimated if the tree partly uproots after the scar forms. *Harrison and Reid* [1967] noted that the intensity of scarring does not necessarily reflect flood magnitude, but rather is a function of the amount of debris. Scarred trees most probably are found along stream reaches where bed gradients are high or flows are constricted, and are less frequent along streams with low gradients, wide flood plains, and small basin areas [*McCord*, 1996].

If abrasion destroys the bark and cambium but no underlying rings, an increment core [*Phipps*, 1985] can be taken directly into the scar face and through the entire trunk diameter. The flood year can be calculated by subtracting the number of rings along the scar-containing radius from that of the intact radius. However, the removal of a small wedge-shaped sample along the scar margin (Figure 4) is preferable when tissues beneath the cambium have been damaged or abraded away. Healed scars within the tree most likely are discovered when cross sections are examined (Figure 5), although this method is undesirable because it requires the sacrifice of the tree. Flood years are estimated by counting the number of rings between the healed

scar and the outside ring. Subtle changes in bark morphology sometimes suggest the presence of a healed scar close beneath the surface, but deeper scars are detected only by hit-or-miss increment corings taken along the trunk. A series of corings at selected intervals (~30 cm) along the upstream- or channel-facing trunk increases the likelihood of detecting healed scars [Waythomas and Jarrett, 1994; McCord, 1996].

The most extensive use of scars to extend flood records has been that by McCord [1990; 1996]. He used increment corings and wedge cuts from coniferous trees to extend flood histories at eight sites in Arizona, New Mexico, and Utah, USA. The longest reconstruction was for Kanab Creek in southern Utah (Figure 6), where evidence was recovered for floods that occurred in 1471, 1521, 1660, 1726, 1742, 1773, 1809, 1866, 1872, 1883, 1890, 1902, 1909, 1910, 1916, 1925, 1936, and 1949. Furthermore, McCord showed that floods were not random but rather clustered in the period 1866-1949. Climate change or land-use practices may account for the increased frequency of floods, which, in turn, probably initiated the formation of arroyos on Kanab Creek [Webb *et al.*, 1991].

Harrison and Reid [1967] compared a flood-frequency graph constructed from an analysis of ice-scarred trees to instrumented records for the Turtle River in eastern North Dakota, USA (Figure 7). Scars were recovered for 10 of the 12 floods during the 21-year period of record, despite that only three trees were studied. Evidence also was found for three floods that occurred before the period of record. More importantly, stage estimates from scar data generally were within 0.3-0.6 m of actual crest elevations recorded 32 km downstream. Thus, in addition to being the first to compare scar data to documented flows, Harrison and Reid [1967] showed that maximum scar heights corresponded to ice-laden flood crests along a low-gradient stream.

Scars on flood-plain trees were used by Gottesfeld and Gottesfeld [1990] to document 31 floods on the Morice River, British Columbia, Canada, during a 105-year interval. Log transport during peak stages was most likely to damage trees growing on stable banks, bedrock outcrops, and the upstream ends of bars. They also classified scars on the basis of their formation. "Impact" scars are small features caused by the collision of logs or ice with upstream-facing trunks; "rubbing" scars occur when logs are lodged against the trunk and slowly abrade the bark and cambium, sometimes remaining in contact with the tree for more than one flood. Rubbing scars may be vertically extensive along upstream- and downstream-facing trunks. Gottesfeld and Gottesfeld [1990] concluded that their 105-year proxy flood record for the Morice River was "nearly complete."

Gottesfeld [1996] conducted a comprehensive study of scar heights following a nival (snowmelt) flood (recurrence interval ~9 years) in 1990 on the Skeena River, British Columbia. Flood damage typically results from log transport rather than from ice. Along a 170-m reach, he selected 48 scarred trees (nine species) likely to preserve a long-term record of the 1990 flood; that is, he excluded small, flexible trees, those growing on unstable surfaces, and those in which the outer bark was abraded but the cambium was not damaged. The height of scars (Figure 8) ranged from +9 cm to -80 cm relative to the flood crest (mean -20 cm). Most scars (88%) formed along a zone approximately four trees in width beginning at the channel edge. He concluded that impact scarring occurs instantaneously, whereas abrasion scars form during a short interval corresponding to the duration of maximum flood stage. Thus, as along a low-gradient stream susceptible to ice-laden flooding [Harrison and Reid, 1967], the heights of scars along the Skeena River were good indicators of peak flood-crest stages.

A New Study of Scar Heights and Flood Stage

Previous studies relating the heights of scars to peak flood stages were conducted at single locations along low-gradient streams and for relatively frequent floods [Harrison and Reid, 1967; Gottesfeld, 1996]. Jarrett [this paper] studied the heights of scars formed by an extraordinary flood in 1996 along Buffalo Creek, a high-gradient stream in the Colorado Rocky Mountains southwest of Denver, Colorado USA. The study was conducted along an 8-km reach (rather than at a single location) with bed gradients ranging from 0.01 to 0.04 m/m, thus extending the range of hydraulic conditions for documented tree-scar data.

Buffalo Creek is a perennial stream augmented by reservoir outflow (typically 0.3 to 2 m³/s). The streambed contains pea gravel and boulders up to several meters in diameter, and average depth to bedrock is ~1 m; however, outcropping occurs locally along parts of the channel. Riparian trees include ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws.), lodgepole pine (*Pinus contorta* Dougl. Ex Loud.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), and cottonwood (*Populus fremontii* Wats.). Numerous ephemeral tributaries flowing into Buffalo Creek are fed primarily by melting snowpack and trans-basin flow diversions. Floods along Buffalo Creek and tributaries result from intense, localized thunderstorms, generalized rainstorms, and spring snowmelt [Jarrett, 1990]. Long-time residents reported no significant flooding in the study area during at least the previous 70 years.

On May 18, 1996, wildfire burned ~50 km² of forest within the Buffalo Creek watershed, destroying the organic litter of the shallow, moderately well-drained soils and increasing the susceptibility of the basin to flooding [Colorado Water Conservation Board, 1997]. A storm on July 12 generated 130 mm of rain within the burned area in slightly more than one hour [Henz, 1998]; according to Miller *et al.* [1973], the 100-year storm would be expected to produce ~70 mm of rain during a single hour. Peak discharges within parts of the burned basin were 20-40 times greater than those in nearby unburned areas. Some basins receiving maximum rainfall produced unit discharges (peak flow divided by drainage area) approximating 60 m³/s/km², compared to maximum estimates of 40 m³/s/km² for all known previous Colorado floods [Jarrett, 1990]. Along the reach of Buffalo Creek that tree scars were studied, the peak discharge ranged from ~85 m³/s near the west (upstream) end of the burned area to ~500 m³/s to the east (downstream), and in stage from ~1 to 5 m above bankfull. Compared to the 100-year flood estimate of 20 m³/s [Federal Emergency Management Agency, written communication, 1996], the flood was at least a 5,000-year event for pre-fire conditions [Jarrett and Browning, 1999]. Peak stages were reached within less than one hour and receded to within-bank flows one or two hours later. Well defined high-water marks on both streambanks consisted of deposition of black ash, charcoal, woody debris, and pines needles. Most trunk scarring is believed to have resulted from up-rooted trees, bedload, and even by saltation of boulder-sized rocks.

Scar data were collected from 102 riparian trees along an 8-km reach of Buffalo Creek. The elevation of each high-water mark along the streambank was extended to the top of the highest scar on each tree with a string line and bubble level. No older flood scars were observed, a finding consistent with the observations of local residents. The heights of all scars ranged from -60 to +150 cm relative to high-water marks (mean +21 cm); 64 scars (63%) were within 20 cm (Figure 8). Scar heights relative to high-water marks were slightly greater along lower than upper parts of the study reach, possibly owing to increased flow depths, velocities, turbulence, and durations. Increased debris transport along lower reaches may increase the likelihood of scarring

as large branches of uprooted trees protrude above the flood. A boulder ~75 cm in diameter was lodged 2 m above the streambank high-water mark in the branch forks of a cottonwood tree.

Scar data from the flood on Buffalo Creek also were analyzed according to the position of damaged trees within channel cross sections. Scar data were compared between streamside trees exposed to maximum flood-flow velocities ("main-channel" trees) and those more distant from the channel ("overbank" trees). The mean height of scars on 67 trees comprising the main-channel group was +23 cm relative to high-water marks, compared to +17 cm in 35 overbank trees. The lack of a significant difference between the two groups of scar heights probably reflects the extraordinary magnitude of the flood and the open-spaced nature of riparian forests in the semi-arid foothills of the Colorado Rocky Mountains. Additionally, some riparian areas along Buffalo Creek were burned severely, thus reducing even further the flow resistance typically provided by vegetation.

The mean height of scars relative to measured crest elevations along Buffalo Creek was ~40 cm greater than that determined along the lower-gradient Skeena River [Gottesfeld, 1996], and the range of scar heights also was greater (210 versus 90 cm). It is possible that extraordinary floods on low-gradient streams might possess sufficient energy to produce a tree-scar distribution similar to that of Buffalo Creek. Although additional tree-scar data are needed from a wider range of hydrologic and botanical conditions, the few studies conducted to date suggest that maximum scar heights provide acceptable estimates of paleoflood stages along low- and high-gradient streams, regardless of the kind of transported debris.

FLOOD-INDUCED ANATOMICAL RESPONSES

Although a scar technically is an anatomical response to flooding, callus growth is confined to small parts of trunks or branches. However, flooding sometimes alters the physiological processes that control radial growth, resulting in changes in the dimensions and proportions of tissues along much or the entire growth parabola of a ring; that is, along the circumference and height of the bole. Abnormal anatomical growth may be more difficult than a scar to interpret unambiguously, but nevertheless is easier to detect than small scars overgrown by new wood and bark.

Anomalous growth caused by flooding has been studied most intensely in ring-porous trees. Typically, ring-porous trees form one or several radial rows of large vessels (earlywood) during the expansion of leaves and elongation of twigs, and smaller vessels (latewood) thereafter for the remainder of the growth year. This striking difference in size between the two groups of vessels results in prominent ring boundaries. Yanosky [1983] found that ash trees (*Fraxinus pennsylvanica* Marsh.) growing along the Potomac River near Washington, D.C., sometimes formed rows of atypically large vessels ("flood rings") within the latewood (Figure 9a), and that anomalous vessels formed only during years when flooding occurred in late spring or summer. He observed that much or all of the leaf crop was stripped by flood currents, and that trees re-foliated soon after flooding subsided. As a new crop of leaves developed, another set of spring-like vessels developed. The position of anomalous vessels relative to the total width of the ring could be used to estimate when the flood occurred, usually to within about two weeks. Floods that occurred during the interval of earlywood formation also resulted in anomalous growth, most commonly as jumbled or additional ranks of earlywood vessels. Yanosky (1983) found evidence for 12 floods that preceded the 1930 period of record, including three prior to 1895 (the inception of record keeping at the Point of Rocks gaging station).

Yanosky [1983] also noted that earlywood vessels were abnormally small and sparse in many trees subjected to catastrophic ice jamming in 1948 and 1968. Because vessel enlargement is controlled in part by hormones produced by expanding leaves, *Yanosky* concluded that ice damage to shoots and buds during dormancy resulted in a later deficiency of hormones during budbreak, and thus to a reduction in vessel diameters. Flood-ring vessels also are smaller than typical earlywood vessels, most likely because post-flooding refoliation also produces smaller amounts of growth hormones.

Growth responses involving the formation and position of atypical vessels depend on mechanical damage typically caused by flooding along high-gradient stream reaches. However, periodic flooding only of roots (that is, without inundation of branches or crowns) also may result in anomalous ring growth. For example, *Yanosky* [1984] studied the fibers (non-conducting support tissue) of ash trees subjected to episodic root flooding (1-3 days) along the Potomac River, and found that fibers often had thinner walls and larger lumens than those typically observed in latewood (Figure 9b). Rather, the dimensions of fibers were comparable to those produced during spring. Compared to typical latewood fibers, anomalous fibers appeared as light-colored bands (“white rings”), sometimes marking two or more separate episodes of root flooding within a single ring. *Yanosky* [1984] concluded that summer root flooding accelerated the rate of fiber production, resulting in the formation of spring-like fibers within the latewood. Similarly, *Yamamoto et al.* [1995] observed the formation of atypical latewood fibers following flooding of *Alnus japonica*.

More recently, *Astrade and Begin* [1997] studied changes in the vessel morphology of English oak (*Quercus robur* L.) related to flooding along the Saone River, France. They found that trees flooded during the early part of the 1983 growth year produced a typical first rank of vessels followed by an extensive zone of unusually small earlywood vessels. Apparently, the anomalous earlywood zones did not form in response to bud and leaf damage, but rather to physiological alterations from prolonged root flooding, and may be somewhat analogous to the “extended earlywood” variant of flood rings described by *Yanosky* [1983].

The effects of flooding upon ring growth of bur oak (*Quercus macrocarpa* (Michx.)) were studied by *St. George and Nielson* [2000] in the basin of the Red River, Manitoba, Canada. They constructed a 536-year oak chronology from living trees, buried logs, and architectural beams. Prolonged root inundation during May 1826 and 1852, the largest 19th century floods, resulted in the formation of rings with single ranks of diffuse, uniformly small earlywood vessels. Latewood vessels are scattered evenly throughout the remainder of rings, rather than in typical flame-like patterns, and the walls of fibers are atypically thin (Figure 10). As along the Saone River in France, it seems unlikely that trees in the Red River basin were damaged mechanically by floodwaters. *St. George and Nielson* also discussed the possibility of estimating the peak elevation of the 1826 flood, the century’s largest, but most of their samples were from architectural structures for which tree-growing locations could not be determined.

Estimates of maximum flood stage from ring-anatomical features generally are less precise than those from scars. A tree displaying anomalous growth related only to root flooding provides evidence that flows at least reached the base of the trunk; hence, a series of trees at successively greater elevations might be used to estimate the maximum stage. However, trees that produced anomalous vessels (flood rings) in response to flood damage must have been flooded to a depth sufficient to damage the canopy. Flood rings within the outer rings of tall trees—that is, in those unlikely to be bent over by flood flows—indeed suggest that anomalous growth developed in response to a large flood. *Yanosky* [1983] found that flood-ring vessels that formed after

the great 1972 flood on the Potomac River had larger diameters than those that formed after smaller floods, presumably because the likelihood of crown damage is at least somewhat proportional to flood magnitude. If it is suspected that a flood temporarily tipped a small tree, thus resulting in an overestimation of stage, tree height in the year of the flood can be reconstructed by extracting cores at successive trunk heights. Even then, estimates of floodflow velocity near the tree also may be necessary to strengthen the contention that tipping did not occur.

ADDITIONAL CONSIDERATIONS AND CONCLUDING REMARKS

Botanical evidence used to recover hydrologic information is limited by the age and species of riparian trees. In the eastern United States, hardwoods (broad-leaved trees) commonly are plentiful along streams but do not attain the great ages typical of some western softwoods (coniferous trees). Unlike some softwoods, however, hardwoods commonly produce sprouts when tilted by floods, and ring-porous species such as the ashes and oaks sometimes produce anatomical responses to growing-season floods. Diffuse-porous hardwoods (the maples, gums, and willows, for example) typically form rings difficult to resolve, and have received little attention in paleofloods studies. Although scars and eccentric growth are the primary responses of conifers to flood damage, *Gottesfeld and Gottesfeld* [1990] noted the formation of traumatic resin canals in conifers flooded during late spring, but not in those flooded after the cessation of radial growth. Further studies are expected to demonstrate more fully the continuum of tree-growth responses to flooding, resulting in greater application and recovery of information.

The likelihood of locating botanical evidence of paleofloods increases if the researcher considers the seasonal distribution of floods and the probability of damage along various channel reaches. Floods that occur during predictable seasons are associated with predictable growth responses. For example, trunk scarring is predominant along streams that flood repeatedly during winter and early spring, whereas anatomical evidence commonly is preserved in trees likely flooded during the growing season. Nevertheless, scarring is easiest to detect and interpret unambiguously, and probably is the best evidence to seek initially. It is not uncommon to find individual trees scarred by numerous floods, sometimes manifesting other forms of evidence, as well, because some trees have an unusually high likelihood of sustaining damage on a frequent basis. For example, *Yanosky* [1983] found anatomical evidence of 18 floods in an ash tree growing in a frequently flooded, high-damage zone along the lower Potomac River.

Most paleoflood studies conducted to date analyzed from 20 to more than 200 trees, although the scar-based flood hydrograph by *Harrison and Reid* [1967] was constructed only from three trees, and *McCord's* [1996] excellent flood extension of Kanab Creek, Utah, was based on a chronology of only 13 trees. Yet, regardless of the number of trees preserving evidence of paleofloods, the investigator invariably must decide the amount of evidence needed to document each flood with acceptable confidence. *Gottesfeld and Gottesfeld* [1990] considered evidence "significant" only when it is preserved in at least two different trees, although their reconstruction included evidence found only in single trees; *Hupp* [1987] based his reconstruction of Passage Creek, Virginia, USA, on three trees per flood. Several flood reconstructions (i.e. *Harrison and Reid*, 1967; *McCord*, 1990; 1996), however, routinely incorporated evidence only from single trees. The confidence of the researcher in such situations depends on the likelihood that the evidence indeed was caused by flooding. Flood scars typically differ from those caused by other agents [*McCord*, 1990; 1996], but trunks tilted by windthrow develop eccentric radial growth

and vertical sprouts indistinguishable from flood-tilted trees, and defoliation by insects sometimes induces anatomical responses similar to flood rings. It seems reasonable that scarring along an upstream-facing trunk is reliable evidence of flood damage, particularly if additional scars or other flood-related features also are found in the same tree or in others nearby. That is, the prevalence of more recent evidence strengthens the contention that a single piece of older evidence also resulted from flooding. Similarly, anatomical abnormalities confined only to the rings of riparian trees likely resulted from defoliation by floods rather than by insects.

An additional consideration for the use of botanical evidence is that floods destroy evidence of earlier floods [Sigafos, 1964], thus constantly reducing the number of trees still likely to preserve evidence of those floods. High-magnitude floods, however, also are more likely than small floods to damage large numbers of trees, increasing the likelihood that botanical evidence initially will be preserved [Yanosky, 1982b; Hupp, 1988]. A tree growing near the crest altitude of a great flood preserves evidence of the flood until obliterated by another great flood, or until the tree dies. Thus, chance mortality and the maximum-likely life span of trees probably control the persistence of evidence along terraces and the uppermost boundaries of flood plains. Evidence of large floods also may be preserved for many years along channel reaches where damage to trees is unlikely during small floods [Yanosky, 1982b]. Consequently, sheltered reaches sometimes support older trees, and thus evidence of older floods, than do reaches exposed to the full force of flood currents.

Little is known concerning the length of time that paleoflood evidence is likely to persist. Sigafos [1964] found evidence of only two floods (1861 and 1889) on the Potomac River prior to the period of record at Point of Rocks; the earliest found by Yanosky [1983] was that for 1889 on the basis of flood-ring formation. The intent of both investigators, however, was to develop general methods to document paleofloods rather than to extend the flood history of the Potomac River. Hupp [1987] extended to 1720 the flood record of Passage Creek, but the earliest date derived from trunk scarring and/or sprout age was 1852. Thus, compared to the ~500-year scar record by McCord [1996] for a western stream, botanical evidence of paleofloods in the eastern United States is somewhat scanty, and the temporal limits of flood documentation await further study.

Geobotanical research during the previous three decades has built upon pioneering studies in the 1960s by Sigafos [1964] and Harrison and Reid [1967]. Investigations have defined further the relation between scars and paleoflood crest stages, noted that flooding sometimes alters ring-anatomical structure, and applied digital imagery to the analysis and monitoring of hydrologic systems. Thus, dendrochronology may provide valuable proxy data where stream-gaging stations are widely scattered and flow records are short or unavailable. In addition to flood preparedness, these studies also may be useful to evaluate longer-term processes such as anthropogenic climate change and the effects of streamflow regulation upon riverine ecosystems. Model validations under a wider range of hydrologic and botanical conditions will continue to improve the acceptance of dendrochronologic studies within the water-resources community [Jarrett and Tomlinson, 2000].

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Robert D. Jarrett, U.S. Geological Survey, MS 418, Lakewood,
CO 80225 USA (rjarrett@usgs.gov)
Thomas M. Yanosky, U.S. Geological Survey, MS 430, Reston,
VA 20192 USA (tyanosky@usgs.gov)

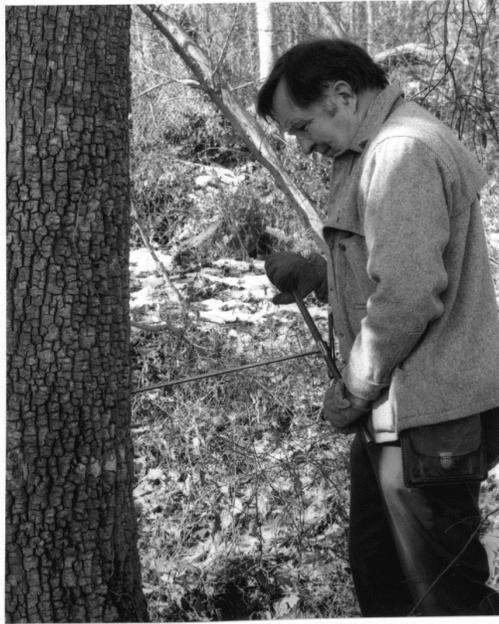


Figure 1. Robert Sigafos (1920-1995), USGS research botanist, using an increment borer to sample a flood-damaged ash tree (*Fraxinus pennsylvanica* Marsh.) growing along the Potomac River. Photo by D. Usher.

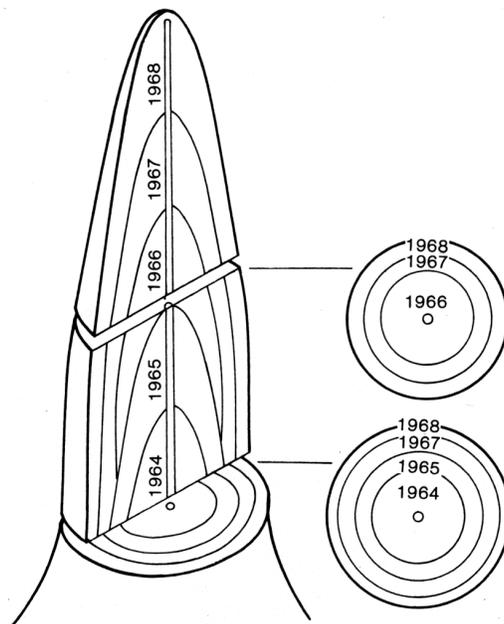


Figure 2. Stylized diagram of tree rings in transverse and longitudinal sections. From Phipps [1985].



Figure 3. Growth habit (“Sigafos tree”) of a white oak (*Quercus alba* L.) on a flood-plain terrace along the Potomac River near Washington, D.C. USA. The vertical sprout at right started to grow from the tilted trunk in 1937. The flood of record occurred in March 1936, followed by the 4th highest flood of the century in April 1937. Photo by T.M. Yanosky.



Figure 4. Impact scars on the trunk of a sycamore tree (*Platanus occidentalis* L.) growing along a stream in northwestern Virginia, USA. Scars document the occurrence of four floods and provide estimates of crest elevations. The uppermost scar is ~2.5 m above ground surface. The small wedge cut (arrow) along the margin of the bottom scar permits the counting of rings that formed since the cambium was damaged by flooding. Photo by C.R. Hupp.

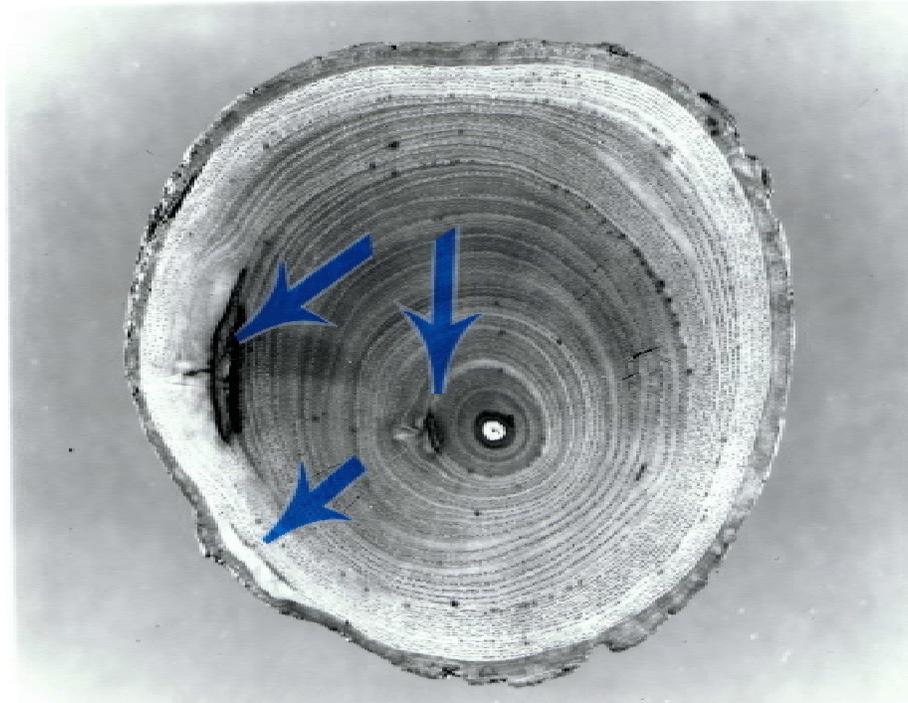


Figure 5. Impact scars healed by new growth. Three scars (arrows) formed along the upstream-facing radius. Life size. Photo by D. Usher.

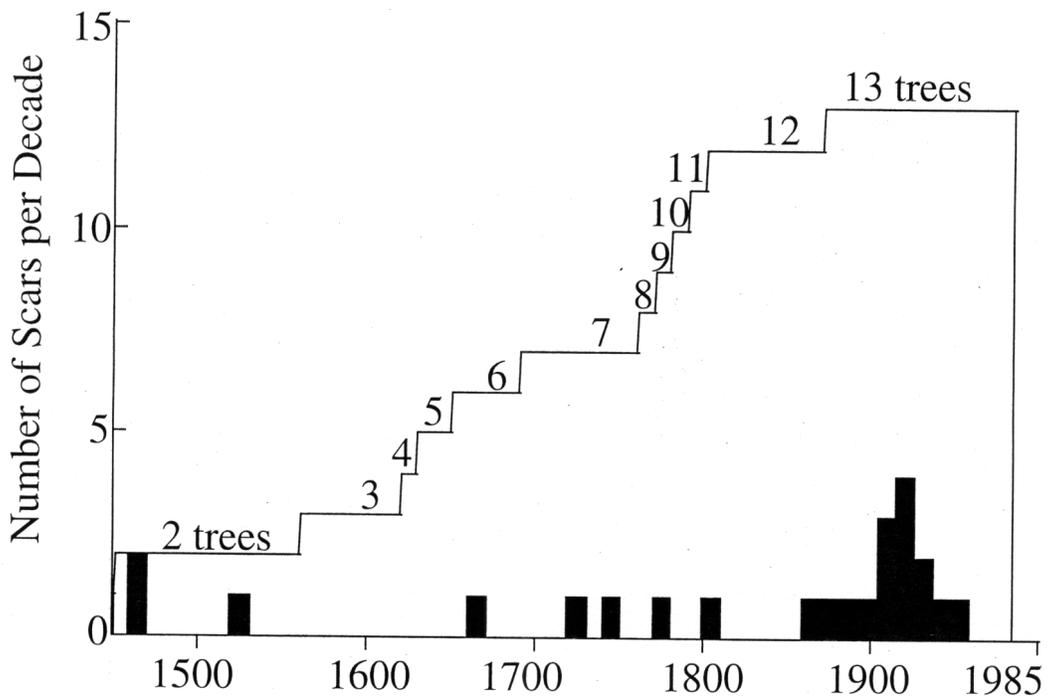


Figure 6. Flood-scar chronology by decade for Kanab Creek, Utah, USA. Note the clustering of floods during the 90-year interval beginning in the 1860s and the abrupt decrease in the number of study trees prior to the late 18th century. Modified from *McCord* [1996].

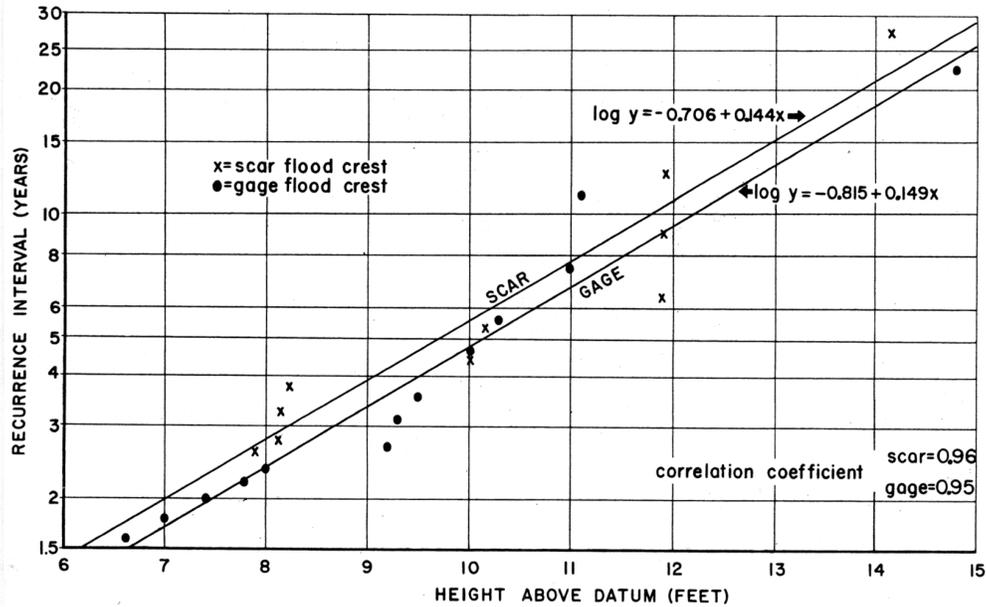


Figure 7. Flood-frequency graph for the Turtle River, North Dakota, constructed from instrumented records and from maximum scar heights. To convert stage heights to meters, divide by 3.281. From *Harrison and Reid* [1967].

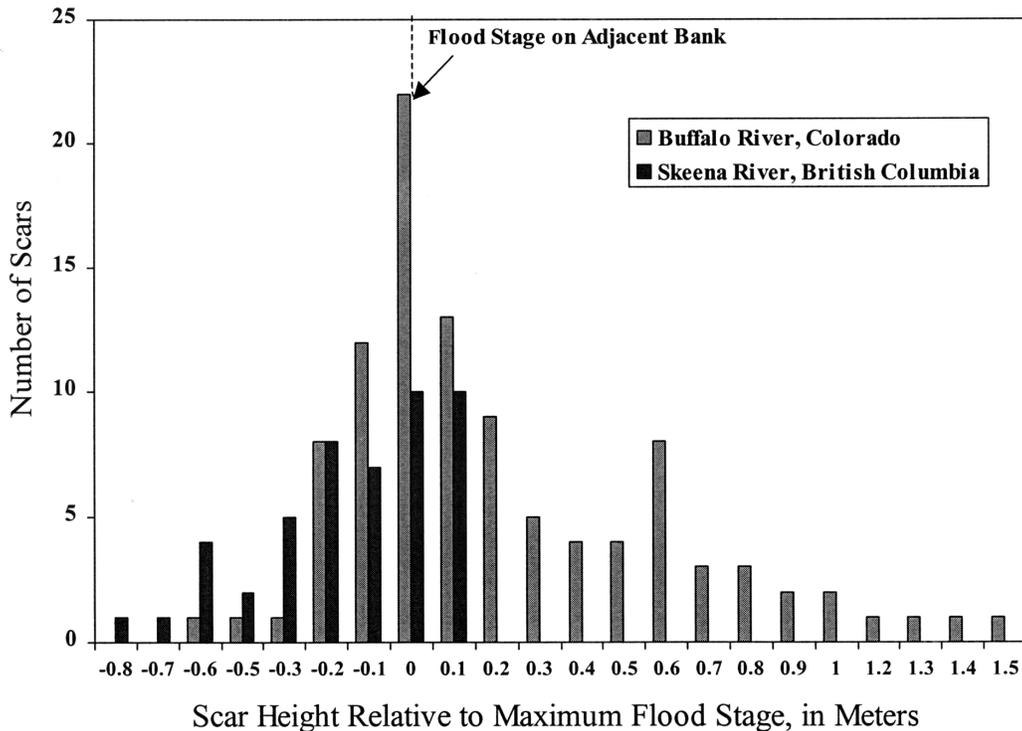


Figure 8. Maximum heights of scars on riparian trees relative to peak flood crests on the Skeena River, British Columbia (N=48 trees) [*Gottesfeld*, 1996] and on Buffalo Creek, Colorado (N=102 trees). Despite differences in gradient, flood magnitude, and the length of study reaches, the respective scar heights were reliable indicators of actual flood crests along both streams.

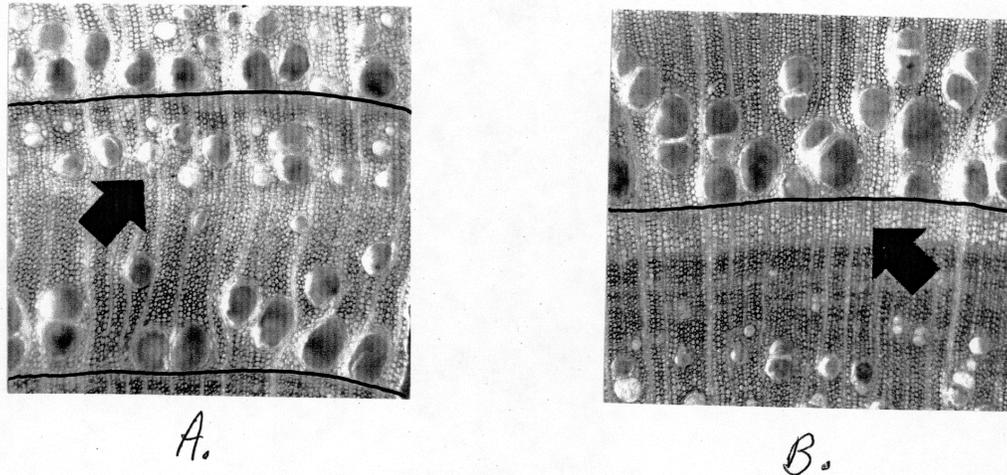


Figure 9. Ring anatomy of ash trees flooded during the growing season [Yanosky, 1983; 1984]. Direction of growth is from bottom to top, and ring boundaries are delineated by inked lines. Magnification X 60. (a) Large vessels (“flood ring”) (arrow) within the outer part of this ring formed when the tree produced a new leaf crop following the stripping of leaves by a flood in late-May, 1942. Typically, large vessels form only within the first part (earlywood) of a ring and not within the remainder (latewood). (b) A zone of atypically large and thin-walled fibers (“white ring”) (arrow) formed within the terminal latewood of this ring in response to late-summer root flooding (mid-August, 1942) that otherwise did not damage the leaf crop. Fibers produced before (below) the white ring are small and possess thick walls, thus imparting the dark hue typical of latewood. Photos by T.M. Yanosky.

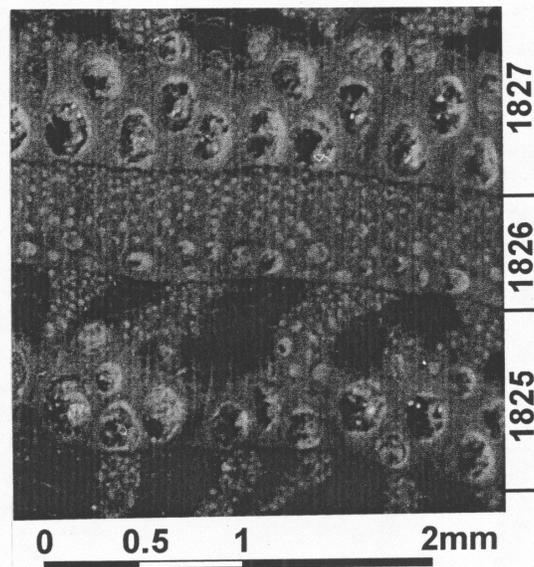


Figure 10. Ring anatomy of a bur oak (*Quercus macrocarpa* (Michx.)) inundated during the great flood of May 1826 flood on the Red River, Manitoba, Canada [St. George and Nielson, 2000]. Direction of growth is from bottom to top. Note the reduced width of the 1826 ring, the small, diffuse earlywood vessels, and the dearth of thick-walled fibers (the darkest tissues in adjoining rings). Photo by S. St. George.