Evidence of Floods on the Potomac River From Anatomical Abnormalities in the Wood of Flood-Plain Trees

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By THOMAS M. YANOSKY

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By Thomas M. Yanosky

ABSTRACT

Ash trees along the Potomac River flood plain near Washington, D.C., were studied to determine changes in wood anatomy related to flood damage. Samples were collected as cross sections, and anomalous growth was compared with flood records for April 15 to August 31, 1930 to 1979. Collectively, anatomical evidence was detected for 33 of the 34 growing-season floods during the study period. Evidence of 12 floods prior to 1930 was also noted, including catastrophic floods in 1889 and 1924.

Trees damaged after the transition from earlywood to latewood growth typically formed "flood rings" of enlarged vessels within the latewood zone. Trees damaged during the earlywood-growth interval developed flood rings within, or contiguous with, the earlywood zone. Both patterns are assumed to have developed after refoliation of flood-damaged crowns. Flood rings formed when trees produced a second crop of leaves. Trees damaged by high-magnitude floods developed well-formed flood rings along the entire height of the stem in which the growth ring was present and around the entire circumference of the stem. Smaller floods were generally associated with diffuse or discontinuous anomalies restricted to stem apices. Peak stages were positively related to the frequency of abnormal growth within samples, and the intraring position of abnormal growth relative to total ring width corresponded to the approximate time of the flood.

Some trees provided evidence of numerous floods. Those with the greatest number of flood rings grew on frequently flooded surfaces subject to flood-flow velocities of at least 1 meter per second, and more typically greater than 2 meters per second. Tree size, more than age, was related to flood-ring formation. Trees kept small by frequent flood damage had more flood rings than taller trees of comparable age. Flood rings formed only if tree crowns were inundated, presumably because leaves were stripped or damaged.

Anatomical evidence of floods, in addition to methods involving age determinations of flood scars and sprouts, can be used to document or extend streamflow records. Reconstructing tree heights in a year of flood-ring formation can provide estimates of peak stages along local stream reaches. Time of flood generation during the tree-growth season can be estimated from the radial position of anomalous growth relative to annual ring width. Further studies might define the minimum anatomical "signal" representing flood-affected growth in ash and other woody species, thus permitting more direct estimates of magnitude.

INTRODUCTION

Deciduous trees growing on the Potomac River flood plain near Washington, D.C., are occasionally flooded during the growing season. If crowns are damaged, the subsequent radial growth of stems produces wood that is often anatomically different from that of undamaged trees. A study was undertaken to relate anomalous wood to documented floods on the Potomac River and to determine if different patterns of anomalous growth were related to flood frequency and magnitude. These methods in turn may be used to document floods where hydrologic data are incomplete or lacking.

Typical spring growth in certain deciduous species is characterized by large-diameter cells (springwood or earlywood) and by smaller, thicker walled fibrous cells (summerwood or latewood) for the remainder of the growth year. Generally, earlywood growth in the Potomac basin commences in mid-April and continues into May. The transition to latewood growth is fairly abrupt, and subsequent radial growth may continue for several months. Under unusual circumstances, however, an extra, or false, ring of cells may develop within a growth increment. In deciduous species, false rings have been reported as a result of frost injury (frost rings) and from defoliation by insects (Fritts, 1976) but not from flooding.

Flood damage can produce a false ring, however. A large flood that crested on the Potomac River on June 24, 1972, killed great numbers of trees and severely damaged many others. Growth of many survivors was interrupted because of leaf and bud damage, but growth resumed after trees produced a second crop of leaves. The initial flush of radial growth after the flood typically resembled that of earlywood; that is, rings of large-diameter cells abrupty formed within the latewood. Abnormal growth may likewise develop within the earlywood zone if flood damage occurs in the early part of the growing season. Thus, "flood rings"[1] can be used to document the occurrence of floods, and the relative time of the flood can be estimated from the intraring position of the abnormal growth.

Previous uses of botanical evidence to document the occurrence of floods have primarily involved scars or sprouts growing from flood-tipped trunks. For example, Sigafoos (1964) found that trees along parts of the Potomac River flood plain were scarred by numerous floods and that the year of damage could be determined by counting the number of annual growth rings formed after the flood scar. Harrison and Reid (1967) similarly constructed a flood-frequency graph from scarred trees for the Turtle River, North Dakota, and C. R. Hupp of the U.S. Geological Survey (oral commun., 1982) used stem-deformation dates to extend the flood record of Passage Creek, Virginia. It was found that the ages of trees along parts of the Potomac River flood plain were related to the degree of sheltering during high flood-flow velocities (Yanosky, 1982a). Although most trees exposed to the full forces of a catastrophic flood in 1972 were destroyed, none had been growing prior to the last great flood in 1942. Numerous trees predating the 1942 flood, however, grew along nearby reaches that were sheltered from the maximum velocity of the 1972 flood. It was concluded that the ages of trees from reaches with a high probability of flood damage could be used to estimate the date of the last catastrophic flood. Another study comparing the widths of the 1972 and 1973 rings showed that many severely damaged trees formed atypically narrow 1973 rings (Yanosky, 1982b). Minimally damaged trees, however, often formed atypically wide 1973 rings if large numbers of surrounding trees had been destroyed. It was concluded that unusual departures from mean annual ring width can be used as indicators of catastrophic flooding and can also aid in determining variations in the local severity of flood flows.

Although these studies may be valuable, they are not without several practical limitations. Sprouts sometimes grow from trunks that have been pushed over by windthrow or slope failure rather than by flooding. The exact year of a flood cannot be determined from sprouts because growth can begin in the same year as the flood or in the following year. Old sprouts may have rotten center rings that preclude an exact determination of age, and floods often prune limbs and sprouts in which evidence of earlier floods was preserved. A tree may have scars that cannot be observed unless entire cross-sectional discs are collected at numerous stem heights.

Flood rings, however, can generally be observed in wood samples collected with an increment borer. Flood rings have been observed at all stem heights at which a growth ring is present and along most or all of the ring circumference. Hence, evidence is not subsequently lost unless the tree is destroyed. In addition, the time of a flood can be estimated to within 2 weeks based on the intraring position of abnormal growth. Most importantly, abnormal growth has not been found in annual increments formed when trees were not flooded or in upland trees; that is, it seems that abnormal growth observed in this study formed only in response to flood damage. If anomalous growth were due to a factor other than flooding, such as defoliation by insects, upland trees would also be expected to develop atypical radial growth.

METHODS

Botanical Methods

Ash trees (*Fraxinus americanum* L. and *F. pennsylvanica* Marsh.) were sampled along reaches of the Potomac River flood plain near Difficult Run, Virginia, and Chain Bridge, Washington, D.C. (fig. 1). Ash at both locations grows at most levels between the low-water channel and adjoining uplands. The flood plain near Chain Bridge is broad and gently sloping, with patchy tracts of alluvium and outcropping bedrock. Trees on low flood-plain levels are small due to frequent flooding (the return interval of flooding is about 0.33 year) and rarely exceed 40 years of age. Trees at higher levels are larger and generally older. At the site downstream from Difficult Run, the flood plain is narrow and more topographically varied than that near Chain Bridge. Trees close together may differ strikingly in age, size, and form. A more detailed account of the study reaches is given by Yanosky (1982a, b), and descriptions of individual trees and local site features are in appropriate parts of this text.

Forty-six trees were harvested with a bowsaw, and cross-sectional discs were taken near the base of the trunk and at succeeding stem heights

[1]The term "flood rings" to describe false rings due to flooding was originated by R. L. Phipps and was first used formally by Yanosky (1982b).

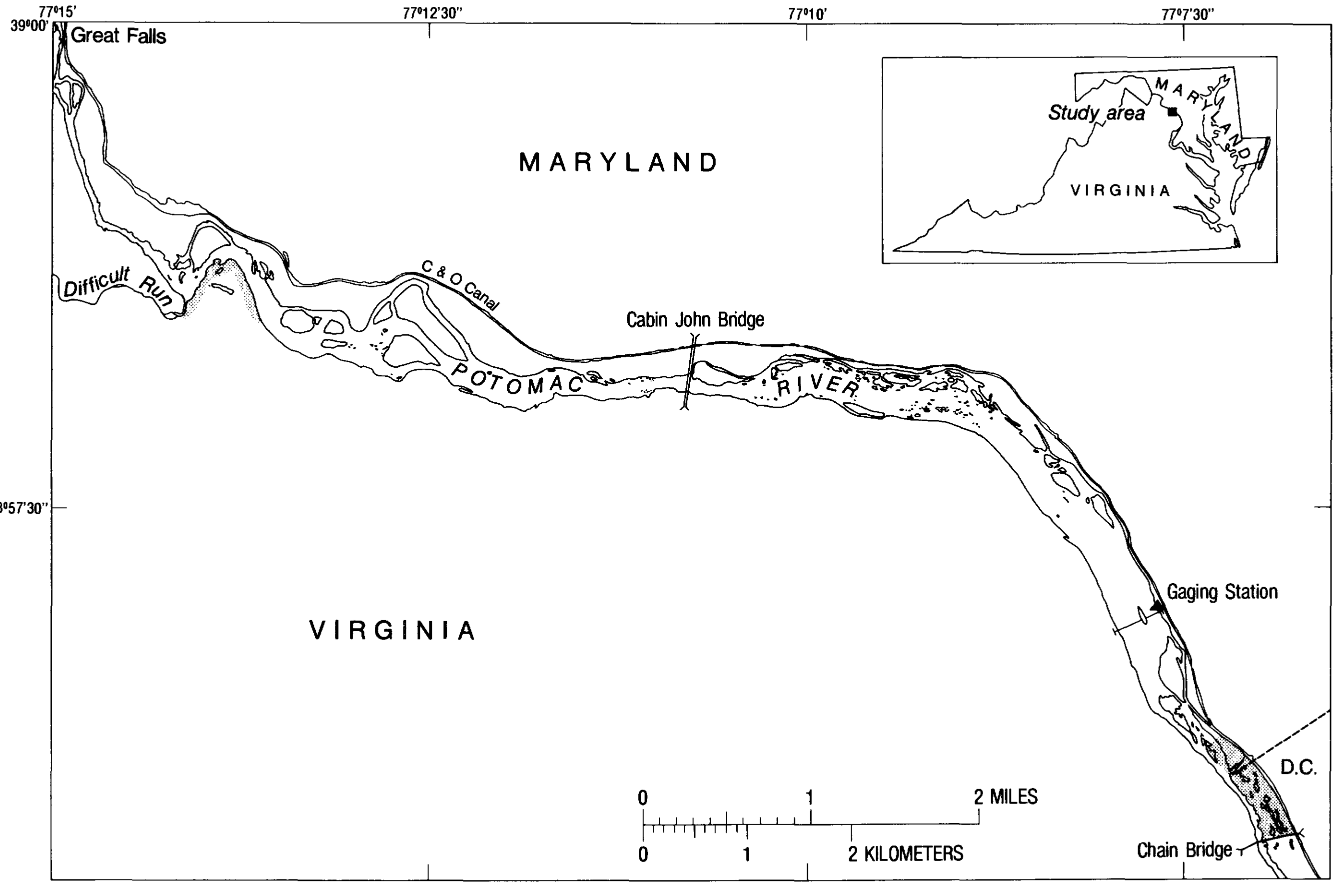


Figure 1. Potomac River near Washington, D.C., and study areas (shaded) near Difficult Run and Chain Bridge.

of about 1 to 2 m. Most trees were about 3 to 5 m in height, although a few were as tall as 12 m. Many had been uprooted or otherwise severely damaged by floods, and five were stumps from which only one section could be taken. Sections from four other trees cut in 1960 were also obtained. Additionally, the wood of 53 trees was sampled with an increment borer rather than as cut sections. The size range of these trees was comparable to that of harvested samples, but a larger percentage was tall. Two cores per tree were taken on opposite sides of the trunk and perpendicular to the channel. Although the term "sample" applies to cut sections or increment corings, it also refers to individual trees when the frequency of growth anomalies in specific years was tallied for the entire collection; for example, a tree with a 1972 flood ring was tallied only once even if abnormal 1972 growth was detected in more than one cut section or coring.

Samples were sanded on a drill press with a 100-grit garnet disc, followed successively by grits of 220, 320, and 400. Samples were then buffed with a lamb's wool pad. Sections were studied anatomically with a Bausch and Lomb dissecting microscope ("Microzoom"), generally at ×20 to ×80. A Pentax Spotmatic with Kodak Plus-X Pan film (ASA 125) was affixed to the trinocular eyepiece, and a Dyonics fiber-optic lamp was used for photographic illumination.[2]

Flood rings were classified according to intraring position. Those within the earlywood zone were designated "earlywood flood rings," and those within the latewood, as "latewood flood rings." Variations in the two types of flood rings were described, as was anomalous growth that appeared intermediate between the two. All anatomical descriptions, measurements, and photomicrographs are of tissues in transverse section.

Flood rings within the 1972 growth increment were present in the greatest number of sampled trees and were studied first. Flood rings formed in other years were tallied in each sample and compared with flood records for the Potomac River gaging station near Washington, D.C. (fig. 1). The study period (1930–79) included all floods occurring from April 15 to August 31 of each year.

[2]Any use of trade names in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

Anatomical variation of flood rings was noted among individual trees, different years within the same tree, and at various stem heights within the same tree. The presence of flood rings was compared to tree size and age, flood magnitude, and the degree of flood-flow exposure.

Hydrologic Methods

For each tree, the stage of the Potomac River was determined by the height of the water as it reached the trunk base. The discharge of this stage was determined by taking the simultaneous stage reading for the gage near Washington, D.C., and computing the corresponding discharge from a rating table for the station. The discharge that covers the trunk base is generally insufficient to damage the tree but can be used to determine the number of trees flooded by a given discharge. In this report, flooding refers only to the submergence of the trunk, whereas inundation implies the complete submergence of the tree. For each flood, the number of inundated trees was determined by comparing local crest stages with tree heights. Because most sampled trees had been kept small by frequent flood damage, the probability of crown inundation during specific events could be determined with reasonable certainty. The approximate height of taller trees in specific flood years, however, was estimated from typical age/height relations of trees growing along sampled reaches.

The average discharge of the Potomac River near Washington, D.C., from 1930 to 1980 was 325 m^3/s. The mean annual flood is about 3,800 m^3/s, and the partial duration flood series base is 1,270 m^3/s. Accordingly, the term "flood" in this report is used for peak discharges equal to or greater than the base discharge. Although the term "flood plain" typically refers to surfaces flooded on the average once every 2 years, the definition is broadened here to include lower levels. Surfaces near a low-water channel are reworked during flows smaller than the mean annual flood and may be regarded as part of the active channel (Osterkamp and Hedman, 1977). A flood was considered catastrophic if peak flow was more than twice that of the mean annual flood. Catastrophic floods occurred during the tree-growth season in June 1889, May 1924, April 1937, and June 1972 and during periods of dormancy in March 1936 and October 1942. All streamflow records cited in this report were compiled by the U.S. Geological Survey.

Most trees sampled for anatomical study grew along the active channel, including some on surfaces flooded by the average discharge. The degree of flood-flow exposure was determined near each tree from field observations during the base discharge (1,270 m^3/s) or, if trees grew on higher levels, at the discharge flooding the trunk to a depth of approximately 1 m. Trees were classified as "sheltered" if estimated velocities were less than 1 m/s, as "moderately sheltered" if velocities were betwen 1 and 2 m/s, and as "unsheltered" if velocities exceeded 2 m/s. As stage increases, velocities within these zones seem to increase in a fairly linear fashion, although velocities within some highly sheltered zones remain unchanged except during catastrophic floods. Trees sampled near Chain Bridge grew only in unsheltered flood zones, whereas those near Difficult Run were found in unsheltered, moderately sheltered, and sheltered zones.

Tree Growth and Wood Anatomy

Trees grow from the continued divisions of a thin sheath of cells composing the vascular cambium. The cambium, which lies just beneath the bark, tapers from the trunk to the apices of stems and roots and may be described geometrically as a double paraboloid joined at ground level (Phipps, 1967). Wood (xylem) is produced by cambial divisions oriented toward the center of the tree. This radial growth is in a series of annual increments, or tree rings, that can be counted to determine the age of the tree. The cambium remains between the outermost growth increment and the bark. Although radial growth occurs at all stem heights, longitudinal growth occurs only at stem tips. Initials carved on a tree trunk, for example, remain at their original height even though the tree grows taller. At increasing heights in the stem, however, diameter decreases because there are fewer growth rings; that is, age decreases at succeedingly higher parts of the stem, and all branch and root apices are 1 year of age.

Cells produced by the cambium enlarge and differentiate into specific xylary tissues. Cells elongate along their longitudinal axis, and a complex mixture of celluloses and lignins is deposited just inside the thin wall that surrounds each cell. This "secondary" wall confers rigidity to the wood after cells die.

Cells with the largest diameters in porous woods (including *Fraxinus*) are vessel elements, which typically are connected end-to-end. At maturity, the vessel elements die and the end walls partly or completely disappear, thus forming open tubes termed vessels. Fibers and tracheids are longer and thinner than vessel elements and are difficult to distinguish from each other in transverse section. Vessels and tracheids transport water, minerals, and certain organic molecules, whereas the thicker walled fibers provide mechanical support. A fourth type of xylem tissue remains alive at maturity and is oriented radially or longitudinally. Radial parenchymatous cells comprise "wood rays" that function for transport and storage of organic materials. Other parenchyma cells may be scattered or in tangential bands throughout the xylem of hardwoods but are lacking in softwoods.

The woods of tree species differ in the proportions and dimensions of these four xylary tissues. Wood is either nonporous or porous, depending on whether vessels (pores) are present. Conifers, or softwoods, have tracheids but not vessels, and, consequently, the wood is considered nonporous. The porous woods, or hardwoods, have vessels as well as tracheids and are subdivided according to the degree of contrast in vessel diameters across growth rings. In ring-porous species, vessels formed at the beginning of the growth season (earlywood vessels) are conspicuously larger than those formed during the remainder of the growth year (latewood vessels). Oak, ash, and hickory are ring porous. Woods in which vessel size is fairly constant within a growth ring are "diffuse porous." Ring boundaries are easier to distinguish in ring-porous than in diffuse-porous woods.

No anatomical differences pertinent to the objectives of this study were observed between woods of the two ash species. Earlywood vessels are large and thin walled and are surrounded by fibers, parenchyma, and some tracheids. Earlywood vessels are typically in two to three radial rows (ranks), followed abruptly by thick-walled fibers comprising the latewood zone. Vessels scattered within the latewood are smaller than earlywood vessels and are typically surrounded by longitudinal parenchyma distributed tangentially. The size difference between cells in the latewood of one year and the earlywood of the next permits an exact determination of ring boundaries. The transition from earlywood to latewood growth in a single ring can also be determined, although with less exactness. A typical sequence of growth rings from an ash tree sampled near Difficult Run is shown in figure 2.

The initiation and timing of ash growth in the lower Potomac basin is variable from year to year and from tree to tree. Bud break and the concurrent enlargement of earlywood vessels develop in mid-April, although individuals have been observed that lagged behind nearby trees by as much as 2 to 3 weeks. Generally, however, leaves are fully expanded by early May, and the earlywood zone is complete or nearly complete by mid- to late May. Latewood growth occurs thereafter and continues at least into August.

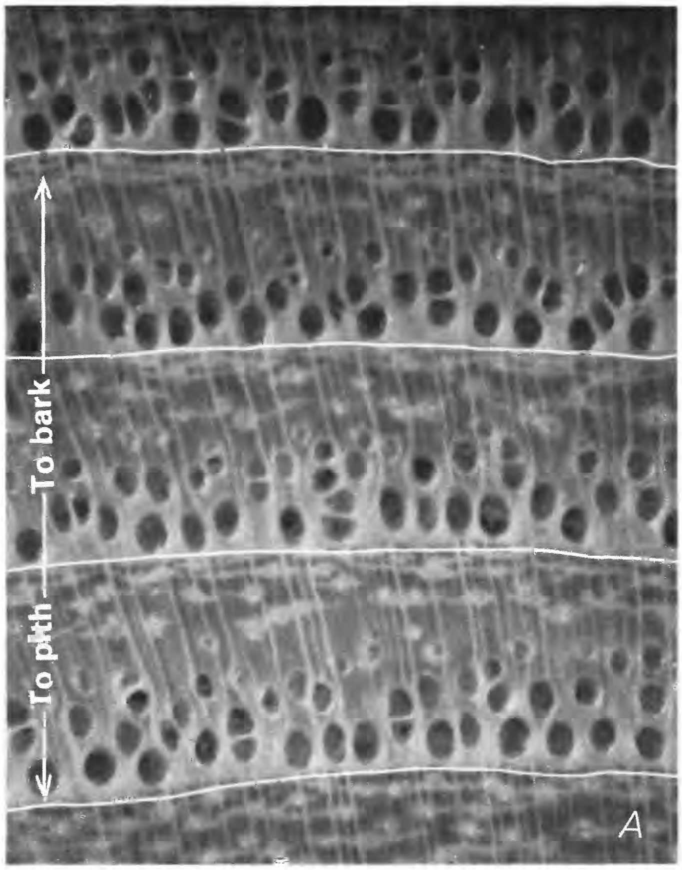
FLOOD RINGS WITHIN THE LATEWOOD ZONE

A flood ring consists of abnormally large vessels that develop from cells that otherwise would have remained much smaller. These vessels are highly conspicuous when they develop among the smaller cells composing the latewood zone. However, abnormal growth within or near the earlywood zone is difficult to distinguish from the typically large vessels in the earlywood. For this reason, latewood flood rings are discussed first. Flood rings within the latewood correlate with floods in June, July, and August; both latewood and earlywood flood rings are associated with May floods.

Flood Rings Formed in 1972

A flood of 10,200 m^3/s crested on the Potomac River near Washington, D.C., on June 24, 1972, and was exceeded in this century only in 1936 and 1942. The 1972 flood, however, was the largest that has occurred during a growing season. Accounts of the impact of this flood upon vegetation along specific reaches near Washington, D.C., are found in Yanosky (1982a, b).

Of 46 harvested trees from which cross sections were obtained, 38 were growing at the time of the June 1972 flood, and 32 of these developed a flood ring within the 1972 growth increment. All trees with flood rings were inundated during the June flood. Four trees without flood rings had crowns that remained above the crest of the flood. Only two trees with flood-covered crowns did not develop flood rings in 1972 and both had extremely narrow rings prior to and including 1972; rings consist mostly of earlywood zone and minimal latewood. Thus, radial growth of the two trees had greatly slowed or ceased prior to the flood, and postflooding radial growth apparently did not develop. In addition to the harvested trees, 53 trees were cored with an increment



borer to examine the 1972 annual rings. Of 27 trees inundated by the June flood, 25 formed flood rings; 26 additional trees were flooded but not inundated, and 1972 flood rings were not observed. The frequency of flood rings in the 1972 growth increments of cored and harvested trees is summarized in table 1.

Flood rings were first described anatomically from the basal sections of harvested trees at stem heights from about 0.2 to 1.0 m. Nearly all flood rings in these sections were continuous; that is, they extended along the entire circumference of the 1972 ring. However, the samples varied strikingly in the size of the largest flood vessels. Tangential diameters of vessels were generally less than one-half those of typical earlywood vessels. Considerable variation was also observed in the number of flood vessels per unit area; flood rings varied from jumbled groups of diffuse ves-

Figure 2. Typical growth rings of an undamaged ash tree. *A*, Four growth rings. Earlywood vessels are the rings of large cells that mark the beginning of each growth year. *B*, Ring formed during one growth year. Largest earlywood vessels are 125 to 225 μm in tangential diameter, whereas latewood vessels are typically 30 to 60 μm. Smallest cells are primarily fibers and parenchyma. *A*, X20; *B*, X70.

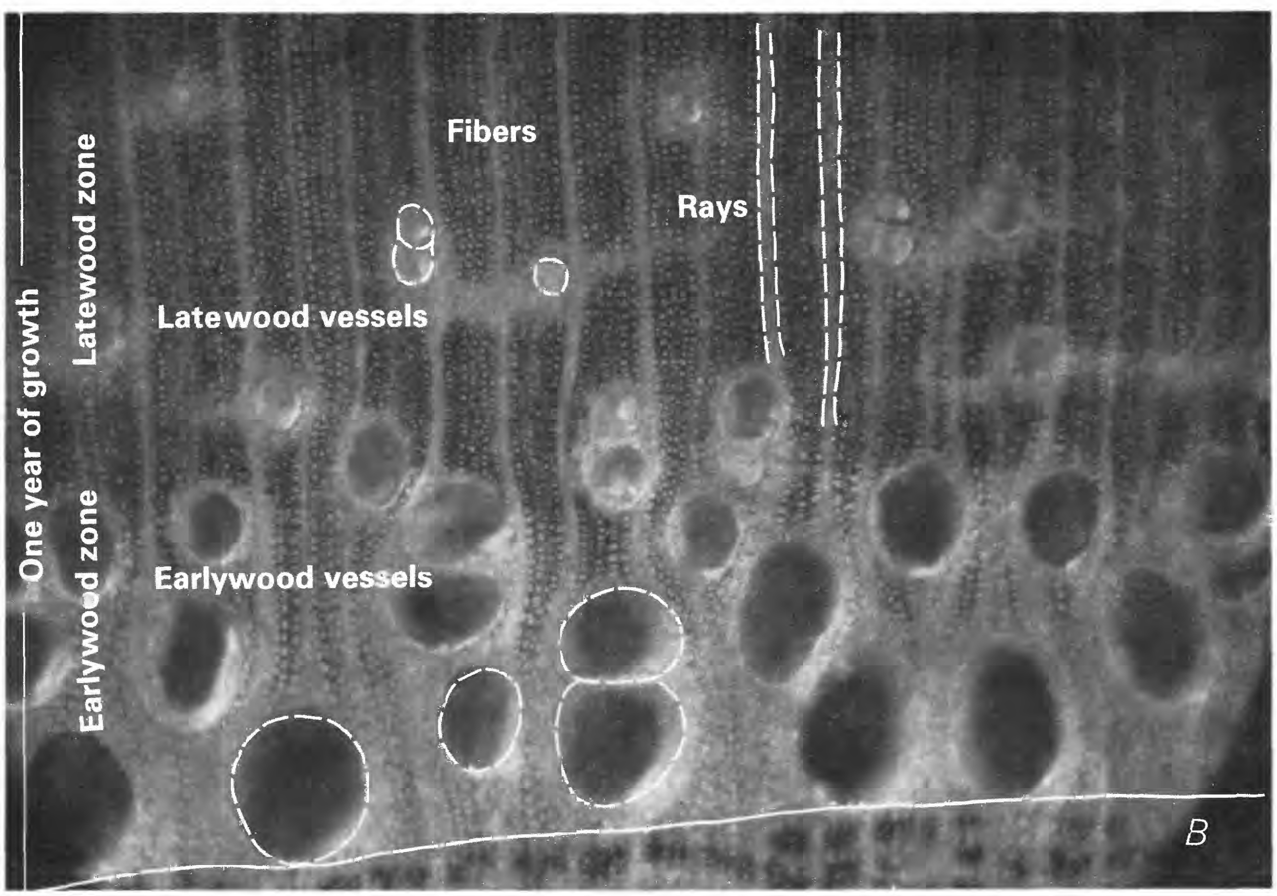


Table 1. Frequency of flood-ring formation in 91 trees flooded on June 24, 1972 (Peak discharge 10,200 m^3/s)

Method of sampling	Crowns flooded: Number of trees	Crowns flooded: Number of trees with flood ring	Crowns flooded: Percentage	Crowns unflooded: Number of trees	Crowns unflooded: Number of trees with flood ring	Crowns unflooded: Percentage
Harvest	34	32	94.1	4	0	0
Increment core	27	25	92.6	26	0	0
Total	61	57	—	30	0	—
Average			93.4			0

sels to closely grouped cells in a definite ring pattern that resembled vessel distribution in the earlywood (fig. 3). Flood vessels generally developed tyloses, which are living cells that protrude into the cavities of nonconducting vessels. Following the flood ring, a narrow zone of thin-walled cells typically formed the remainder of the 1972 latewood. The narrow width of this zone resulted, to some extent, because the flood occurred fairly late in the growing year. In addition, photosynthates produced by the second crop of leaves were probably minimally utilized for postflooding radial growth. Instead, it seems reasonable to assume that the bulk of new resources was used to set buds for the 1973 growing season and to store food reserves in the roots. Severely damaged trees, particularly those with broken crowns, had the least postflooding growth. In a few samples, however, postflooding growth accounted for nearly 50 percent of the width of the latewood, possibly because damage was not severe.

Anatomical descriptions of flood rings to this point have been from cross sections at stem height ranging from about 0.2 to 1.0 m. Sections higher

Figure 3. Flood rings formed after the flood of June 24, 1972 (10,200 m^3/s), in the lower trunks of three trees.

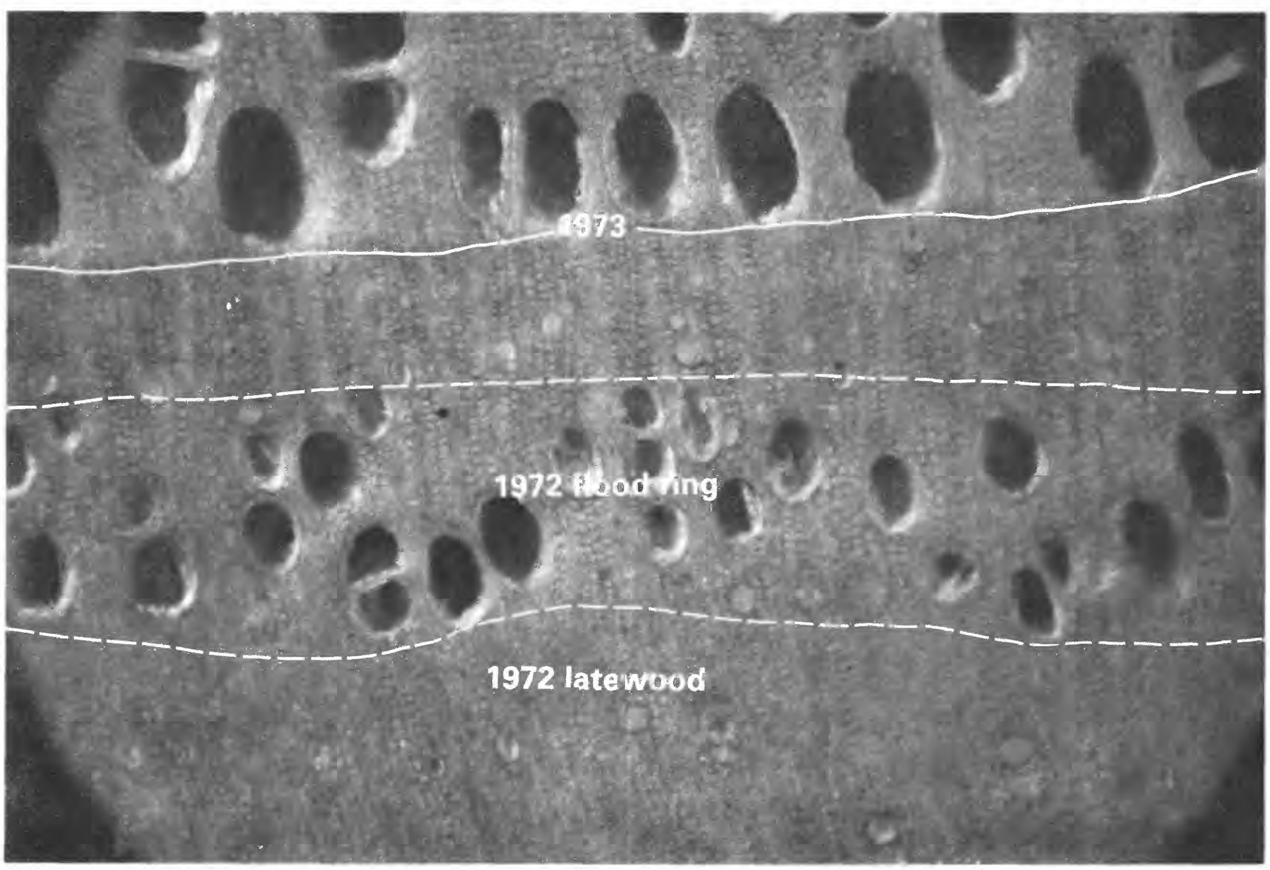


Figure 3A. Well-formed flood ring. Largest flood vessels are between 140 and 165 μm, although most are between 60 and 120 μm. Spacing of vessels is comparable to that of typical earlywood vessels. (X70.)

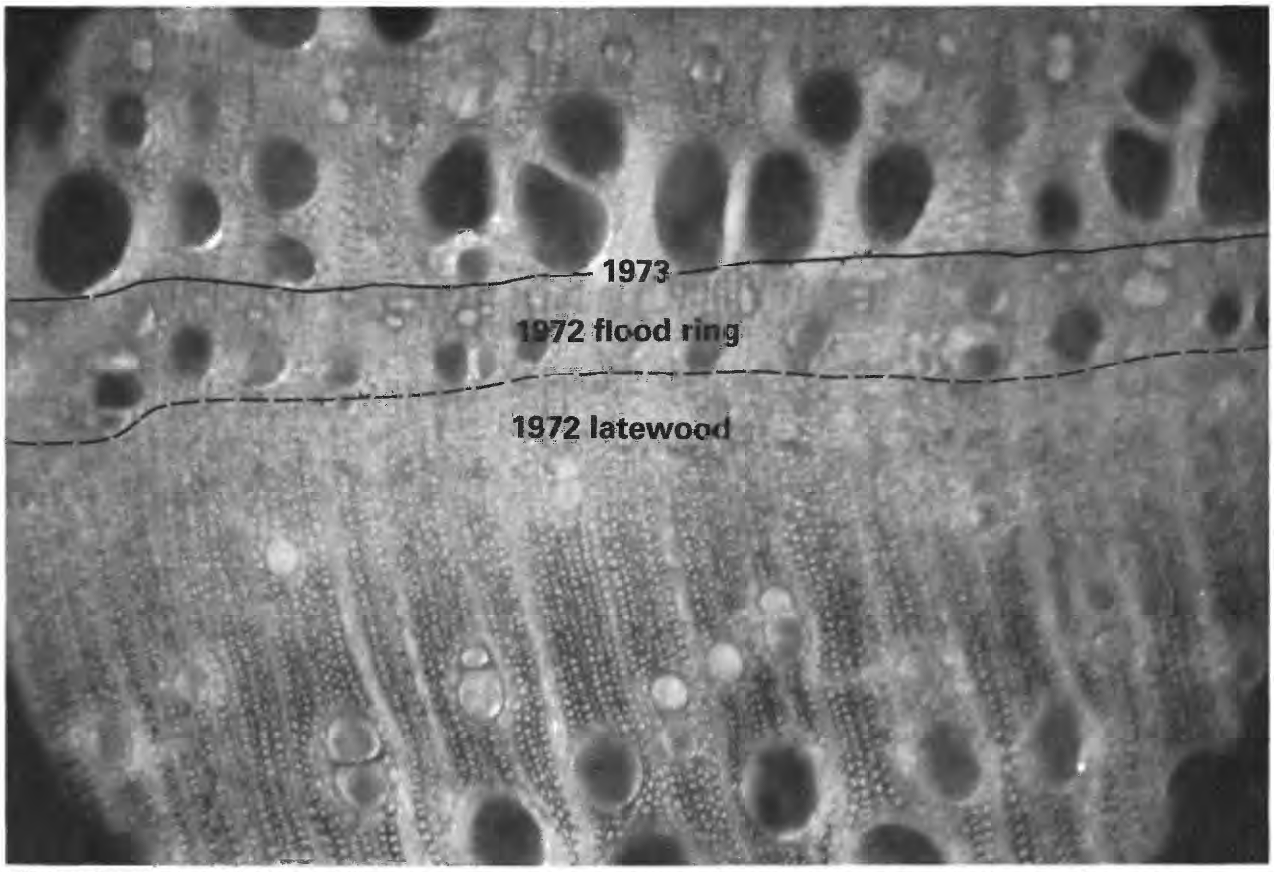


Figure 3B. Moderately formed flood ring. Most large flood vessels are between 90 and 110 μm and are more diffuse than earlywood vessels. (X70.)

in the stems also had flood rings in the 1972 growth increments. In none of the trees did a 1972 flood ring form at only one stem height. In other words, unlike a scar, the 1972 flood ring was a growth response within the entire 1972 growth paraboloid. In most trees, flood rings were more distinct in sections near the stem apex where flood vessels had larger diameters and were generally less diffuse than vessels in basal sections. Figure 4 shows the 1972 flood ring in one tree at four successive stem heights. Figure 5 shows wood near the apex of another tree in which the 1972 flood ring has the local appearance of a true ring.

Flood Rings Formed After June Floods, 1930 to 1979

In June, nine floods exceeded 1,270 m^3/s during the study period (1930–79). Table 2 lists the number of samples forming flood rings in these nine flood years. The largest flood peaks were on June 15, 1951 (3,120 m^3/s), June 20, 1949 (3,820 m^3/s), and June 24, 1972 (10,200 m^3/s). As mentioned previously, flood rings were observed within the 1972 annual rings of 32 harvested trees. Flood rings formed in 1951 were detected in 9 of 35 samples, and 1949 flood rings developed in 13 of 32 trees. Flood rings within the 1949 and 1951 growth increments (fig. 6), as well as those in 1972, are generally well developed throughout the height of the tree, although one sampled tree formed a flood ring (1949) only near the stem apex. The other six June floods ranged from 1,670 to 2,340 m^3/s. Flood rings formed in each of these flood years but less frequently than in the 3 years of larger floods. No sample had more than one flood ring in these 6 years, and flood rings in only 2 flood years (1946 and 1959) were tallied in more than one tree.

Variations in the anatomy of flood rings also seem related to flood magnitude, even though all samples with flood rings were inundated. Flood rings corresponding to the three largest June floods are generally well formed, but flood vessels formed in the six minor-flood years are typically small and diffuse (fig. 7). In addition to a scattered, poorly defined appearance, these flood rings generally are locally missing (discontinuous) along parts of the ring circumference.

Attempts were also made to correlate flood rings with June flows of less than 1,270 m^3/s.

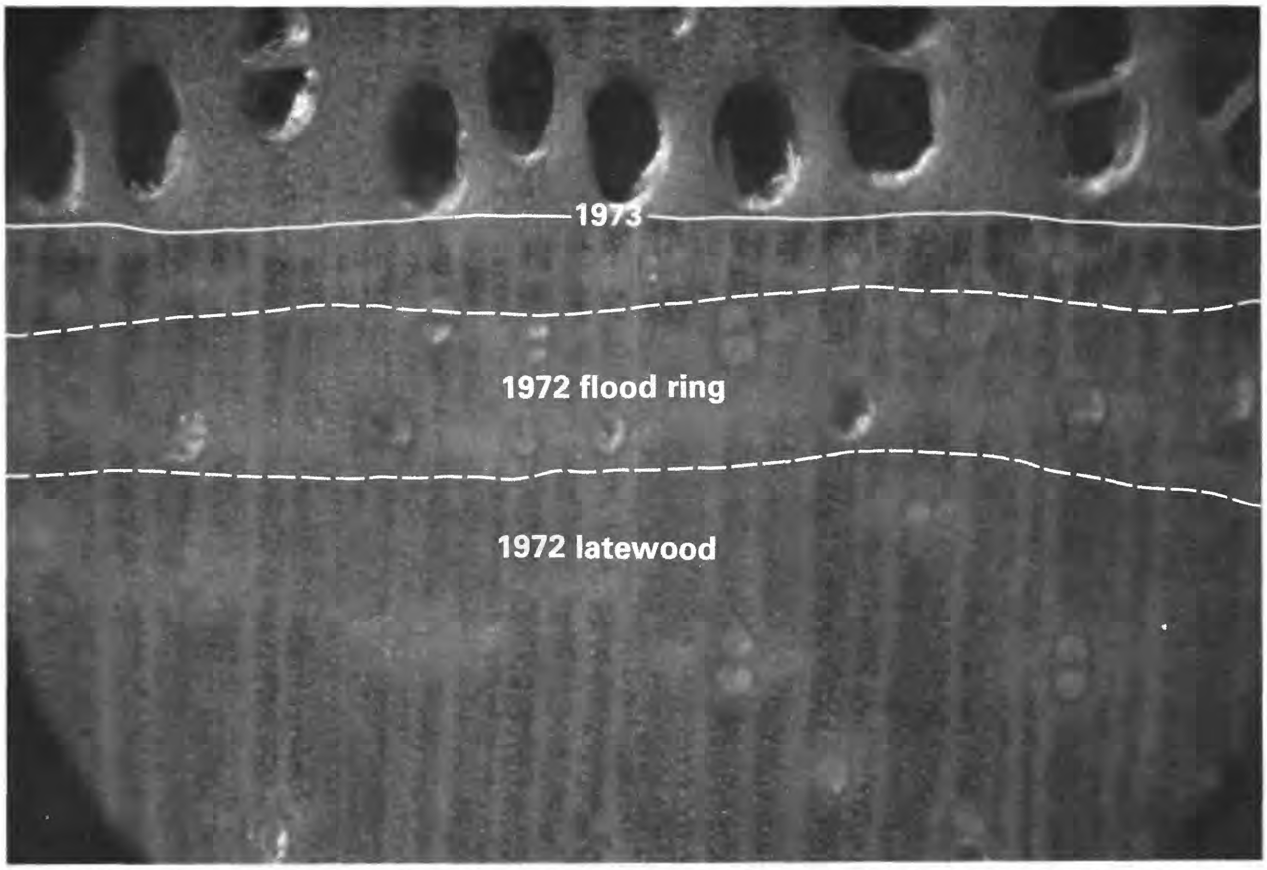


Figure 3C. Poorly formed flood ring. Largest vessels are as much as 100 μm, although most are less than 70 μm. Note paucity of flood vessels. (X70.)

This was done to describe the appearance of flood rings induced by small flows. Although trees growing on surfaces flooded by as little as 280 m^3/s were studied, no flood rings were detected. Instead, periods of root flooding produced fibers with atypically thin walls and large lumens. Unlike the formation of flood vessels, these responses are apparently associated with a growth spurt rather than with the damage that induces flood rings. These bands of anomalous fibers may permit the documentation of small summer flows.

Flood Rings Formed After July and August Floods, 1930 to 1979

Floods in July and August were less frequent than during the peak tree-growth months of May and June (table 3). July floods exceeding 1,270 m^3/s were recorded in 1949, 1956, 1970, and 1972, whereas August floods occurred in 1933, 1937, 1945, and 1955. The largest July–August flood peaked on August 20, 1955 (6,120 m^3/s). This discharge was exceeded in this century only in May 1924, March 1936, April 1937, October 1942, and June 1972. No other late-season floods exceeded 2,630 m^3/s.

The flood of July 21, 1956 (2,050 m^3/s), is one of only four late-season flow events for which corresponding flood rings have been detected. Two trees that developed a flood ring in the terminal part of the 1956 latewood zone are shown in figure 8. The ring of flood vessels in both trees is continuous along most of the outer circumference of the 1956 growth ring, although the vessels were much smaller and more diffuse than vessels typically formed after June floods. One of these trees grew near Chain Bridge on a surface flooded by approximately 850 m^3/s and had been damaged repeatedly to such an extent that in 1980 most of the upstream-facing bark and wood had been destroyed. Although the tree was in its first year of growth in 1956, the flood ring did not develop in a basal section; however, flood vessels formed in another section closer to the apex. The other tree, which was in its second year of growth at the time of the 1956 flood, grew about 600 m downstream from Difficult Run on a surface flooded by flows of 420 m^3/s.

Minor floods on August 1, 1945 (1,390 m^3/s), and July 11, 1970 (1,510 m^3/s), are associated with one and two trees, respectively, that developed flood rings. Each flood ring is composed of small,

Figure 4. Flood rings formed in 1972 at increasing stem heights of one tree. Tree height in 1980 was about 5 m. Photographs are along radii extending in the same compass direction. Flood vessels near the apex are larger and more closely grouped than those in the lower trunk.

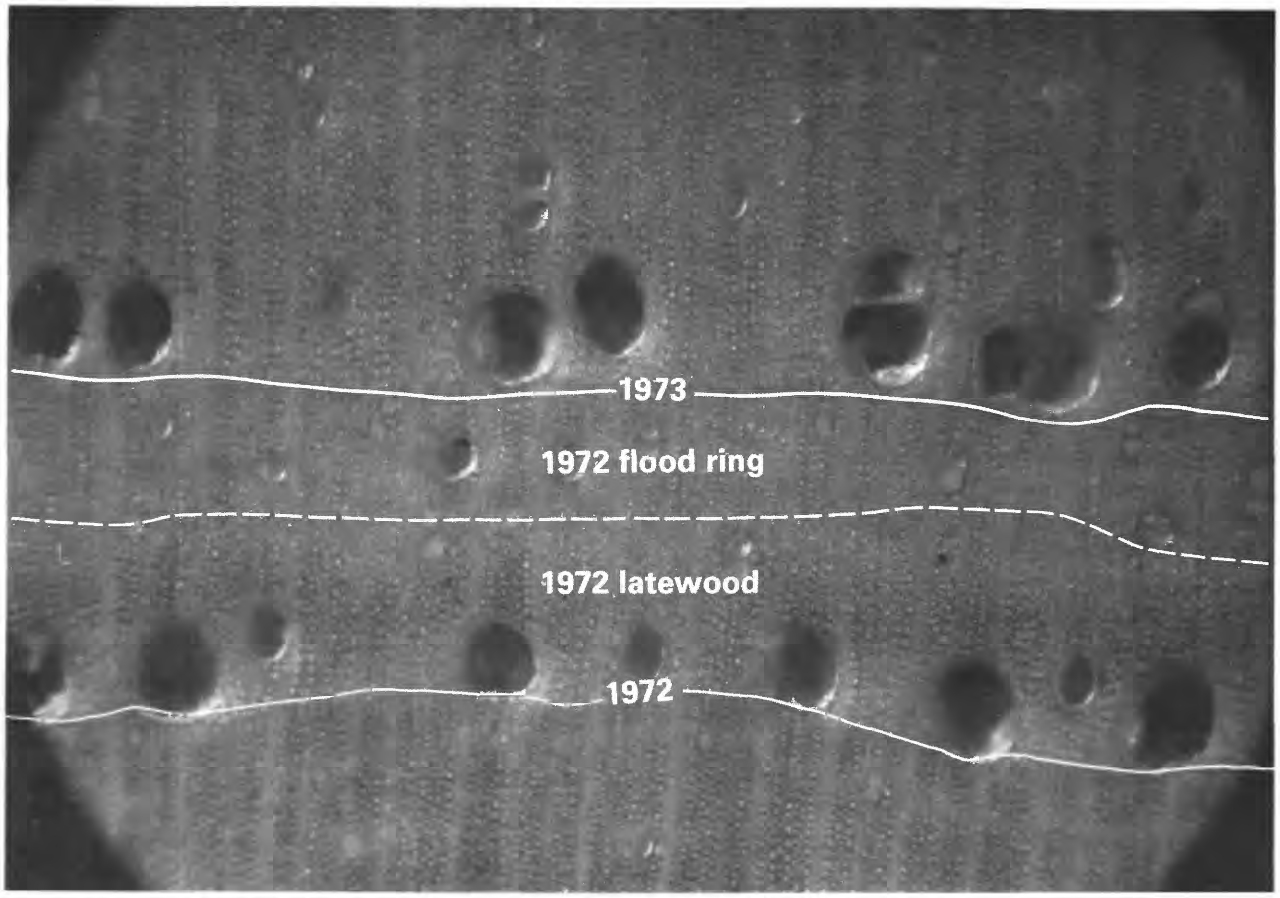


Figure 4A. At 0.2 m, most large vessels are 60 to 80 μm and are highly diffuse. (X70.)

diffuse flood vessels similar to those formed in 1956. The tree with the 1945 flood ring was 5 years of age at the time of the flood and grew near Chain Bridge on the upstream part of a rocky island. The roots of the tree were flooded by 310 m^3/s. The 1945 flood ring was observed in a section taken at a stem height of 1 m but was absent from a basal section. One tree with a 1970 flood ring also grew near Chain Bridge but on a surface flooded by approximately 850 m^3/s. The basal section started to grow in 1945. Sections 0.5, 1.0, and 1.5 m above the basal section, however, had center rings that formed in 1968, suggesting that much of the tree had been destroyed before the 1968 growing season and that a sprout had subsequently grown from the damaged trunk. An ice jam in January 1968, which severely damaged many trees on low flood-plain levels near Chain Bridge, may have damaged this stem (Yanosky, 1982b). The 1970 flood, which crested at approximately 1 to 1.5 m above the roots of the tree, most likely tipped, and thus inundated, the sprout. A 1970 flood ring developed in two sections near the apex but not in lower sections. The other tree with a 1970 flood ring grew on a low level near Chain Bridge and was inundated by the 1970 flood.

A flood ring was also observed in the outer latewood of the 1938 growth ring of a tree near Difficut Run. Growth of the tree began in 1937. Vessels comprising the 1938 flood ring are small but closely spaced and extend along approximately one-third of the ring circumference. Although flows exceeding 1,270 m^3/s did not occur during the 1938 growing season, records indicate an average flow of 850 m^3/s on May 25–26 and an average flow of 600 m^3/s on July 26. The flood ring in the outer latewood may have resulted from damage in July because flood vessels are separated from the earlywood by a broad band of latewood growth. The base of the tree is flooded by a discharge of 370 m^3/s, and a flow of 600 m^3/s (the minimum peak discharge) increases the

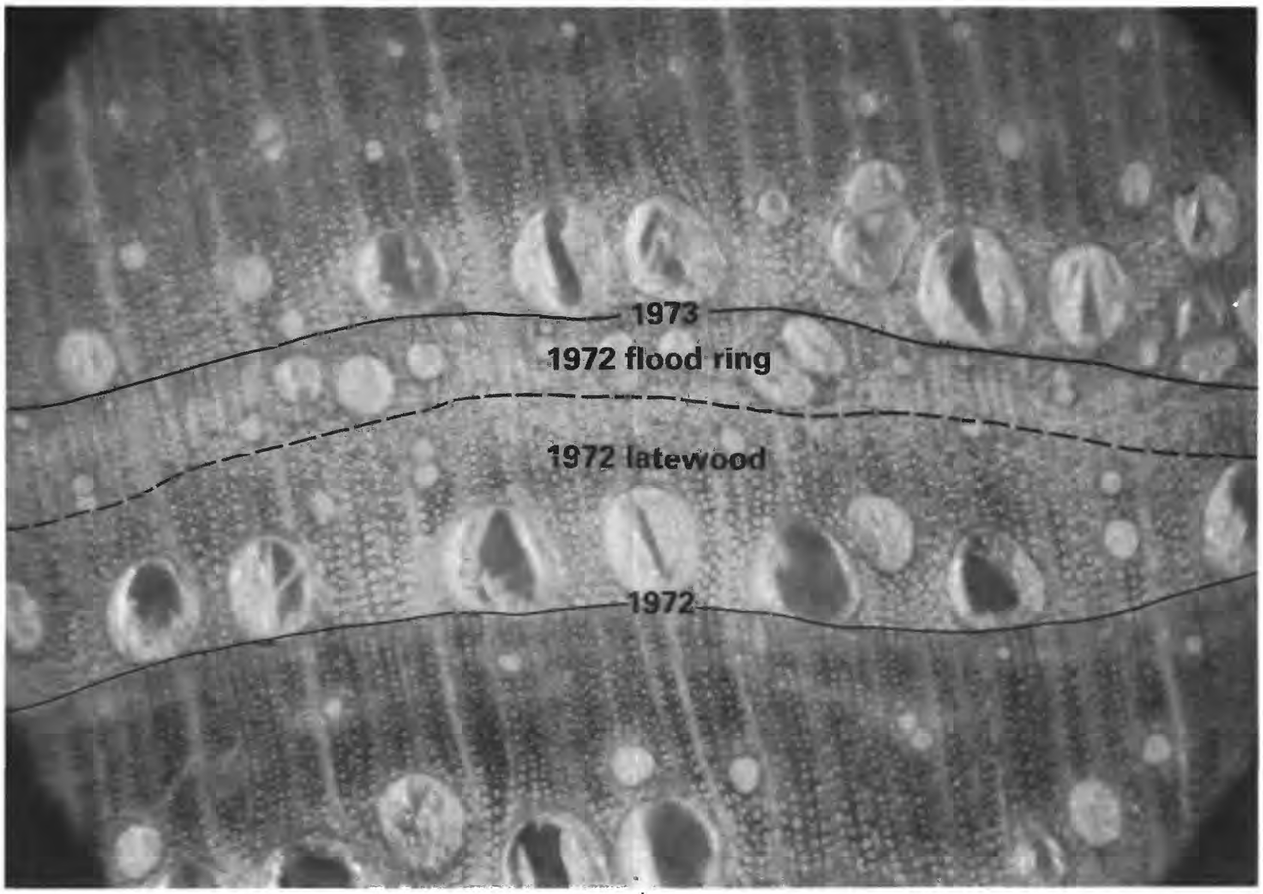


Figure 4B. At 1.0 m, most large vessels are 70 to 100 μm. (X70.)

depth of flooding to approximately 1 m. Velocities at this discharge would be expected to tip, and possibly damage, a small tree. The flow of late July 1983 is the smallest discharge for which a corresponding flood ring has been detected.

The flood of July 19, 1949 (2,590 m^3/s), was of sufficient magnitude that flood rings were highly likely to form. However, an earlier flood (3,820 m^3/s on June 20) is assumed to have induced the flood rings observed in the growth increments, primarily because flood vessels were generally larger and more numerous than those formed after the late-summer floods in 1945, 1956, and 1970. In other words, the pattern of anomalous growth in 1949 was similar to that formed in 1951 and 1972. Similarly, none of the 1972 flood rings probably formed as a result of the minor flood of July 1 (1,460 m^3/s).

Flood Rings Formed After May Floods, 1930 to 1979

Although flood rings were detected for all June-flood years, latewood flood rings were discerned in only 6 of 16 May-flood years during the study period. This lower frequency to some extent may be because six May floods were less than 1,410 m^3/s, whereas the smallest June flood was 1,670 m^3/s. However, four larger May floods, ranging from 2,330 to 4,760 m^3/s, were not associated with flood-ring formation in sampled trees. Consequently, a relation between latewood flood-ring frequency and flood magnitude is not immediately apparent for May floods. However, a relation results when flood-ring observations are tallied by subdividing May-flood years (table 4) into an "early May group" (May 1–May 15) and a "late May group" (May 16–May 31). In the early May group, 9 of 10 flood years are without corresponding latewood flood rings, whereas, in the late May group, 5 of 6 flood years are associated with flood rings in the wood samples. In 1 year (1960), a large flood occurred in early May and a smaller flood was generated in late May; flood rings in 1960 were placed in the early May group.

A probable explanation for differences in the frequency of flood rings in May-flood years is that radial growth during early May was different from that of late May. In the lower Potomac River

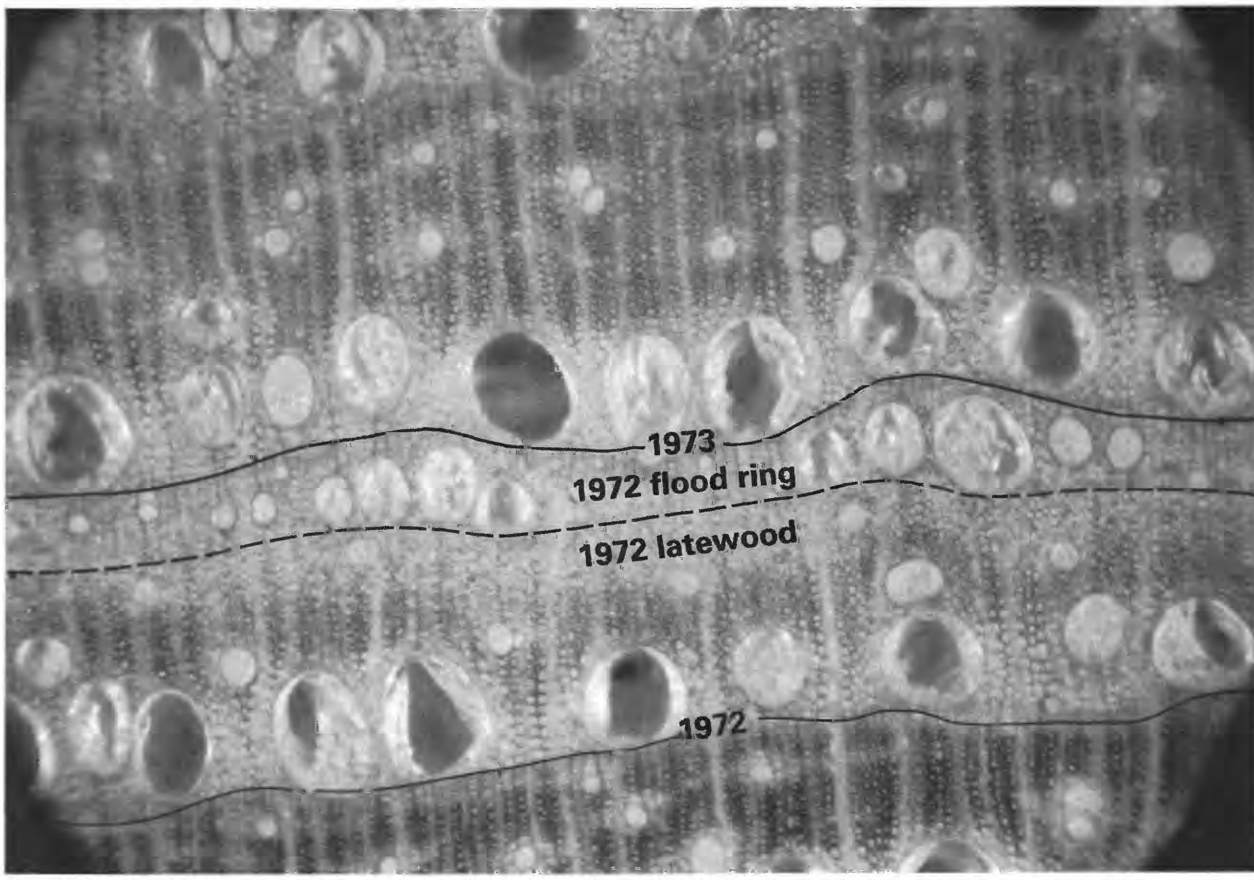


Figure 4C. At 2.5 m, most large vessels are 90 to 110 μm. (X70.)

basin, the date of transition from earlywood to latewood growth may be highly variable but is generally not beyond late May. Floods in the early part of the growth year, therefore, are during the earlywood-growth interval. Flood vessels, if formed, would be expected to be in the earlywood zone and might be difficult to distinguish from typical earlywood vessels. Abnormal growth of this type is discussed in the following section. Flood rings forming after the transition to latewood growth, however, are easily discerned because of the sharp contrast between large-diameter flood vessels and smaller latewood cells.

The largest late May flood (3,940 m^3/s) was on May 24, 1942, and 9 of 20 samples developed a well-formed flood ring along the entire circumference of the 1942 ring. Flood vessels generally were closer to the earlywood zone than were those formed after the late June floods of 1949, 1951, and 1972. In contrast, none of 30 samples developed flood rings after the flood of May 17, 1978 (3,310 m^3/s). Similarly, the flood of May 14, 1932 (4,760 m^3/s), was the largest May flood during the study interval, and yet no latewood flood rings were observed in the five samples growing at the time of this flood. Of the remaining 4 years in which late May floods occurred, 1 year (1968) is associated with flood rings in the wood of 2 of 26 samples. The peak discharge of the 1968 flood was 2,310 m^3/s. Anatomical evidence for another small flood during late May (1,910 m^3/s on May 22, 1943) was observed in only one sample and consisted of a poorly formed group of scattered vessels just outside the earlywood zone. The smallest late May flood peaked on May 20, 1950 (1,270 m^3/s), and was followed by the development of diffuse, discontinuous flood rings in 2 of 15 trees.

In addition to abnormal growth associated with peaks above the base floodflow, a flood ring formed in one sample after the flow of 850 m^3/s on May 25–26, 1938. A conspicuous, though discontinuous, band of small flood vessels formed just outside the earlywood. This tree also developed a discontinuous flood ring in the outer latewood after inundation in late July and was described more fully in the previous section. This is the only sample with two latewood flood rings within the same annual increment.

The greater frequency of flood rings formed in response to late May rather than early May floods

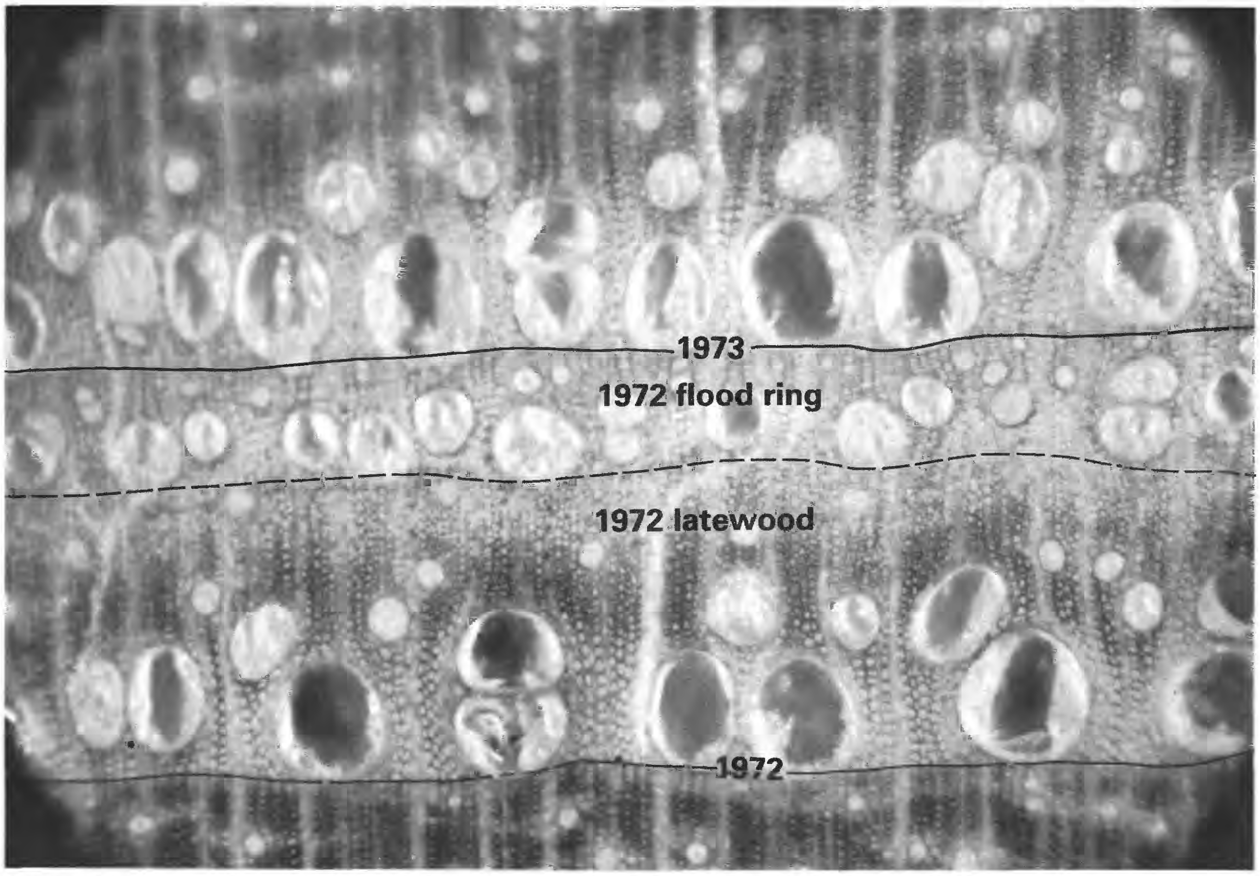
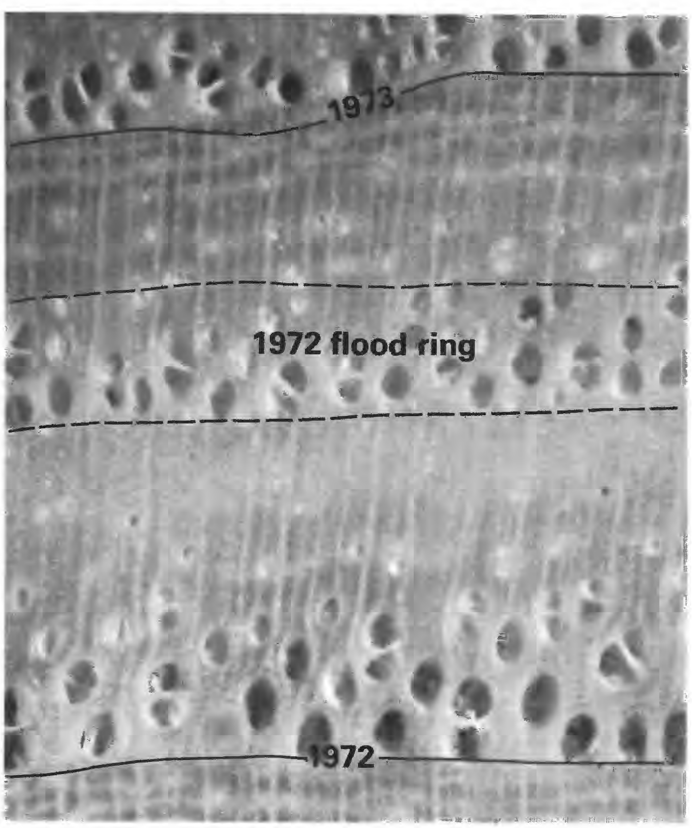


Figure 4D. At 4.0 m, most large vessels are 100 to 130 μm and are closely grouped. (X70.)



suggests that the timing of the growth transition between earlywood and latewood is closely related to the type of subsequent abnormal growth. Flood magnitude is less important than the timing of this growth activity. In other words, trees damaged by floods prior to the initiation of latewood growth develop abnormal earlywood growth (see next section) but not latewood flood rings. Despite the small size of floods in 1943, 1950, and 1968, flood-damaged trees developed abnormal latewood zones because latewood growth had commenced prior to these floods. The largest late May flood (1942) was associated with the greatest number of trees having flood rings.

In 1 of the 16 May flood years (1960), floods occurred on May 10 (3,510 m^3/s) and May 30 (1,450 m^3/s). Two trees had latewood flood rings. From the previous discussion, it would be expected

Figure 5. Flood ring formed in 1972 that has the local appearance of an extra ring. Section is near the apex of a tree that was about 4.0 m tall in 1972. Vessels are somewhat smaller and more diffuse along much of the remainder of the ring circumference at this height. Note that flood vessels are in more than one rank and generally lack tyloses. (X30.)

Table 2. Frequency of latewood flood rings formed in June-flood years, 1930 to 1979. Floods are ranked in order of increasing magnitude. Collectively, flood rings formed in 11.8 percent of trees inundated by the six smallest floods, compared to 53.5 percent of trees inundated by large floods in 1949, 1951, and 1972

Date of flood	Peak discharge (cubic meters per second)	Number of trees: With crown inundated[1]	Number of trees: With flood rings
June 4, 1974	1,670	19	1
June 10, 1955	1,710	15	1
June 4, 1959	1,740	17	2
June 4, 1946	1,950	20	7
June 2, 1940	2,250	16	1
June 1, 1971	2,340	23	1
June 15, 1951	3,120	35	9
June 20, 1949	3,820	32	13
June 24, 1972	10,200	34	32

[1]Determined by comparing local crest altitudes with estimated tree heights.

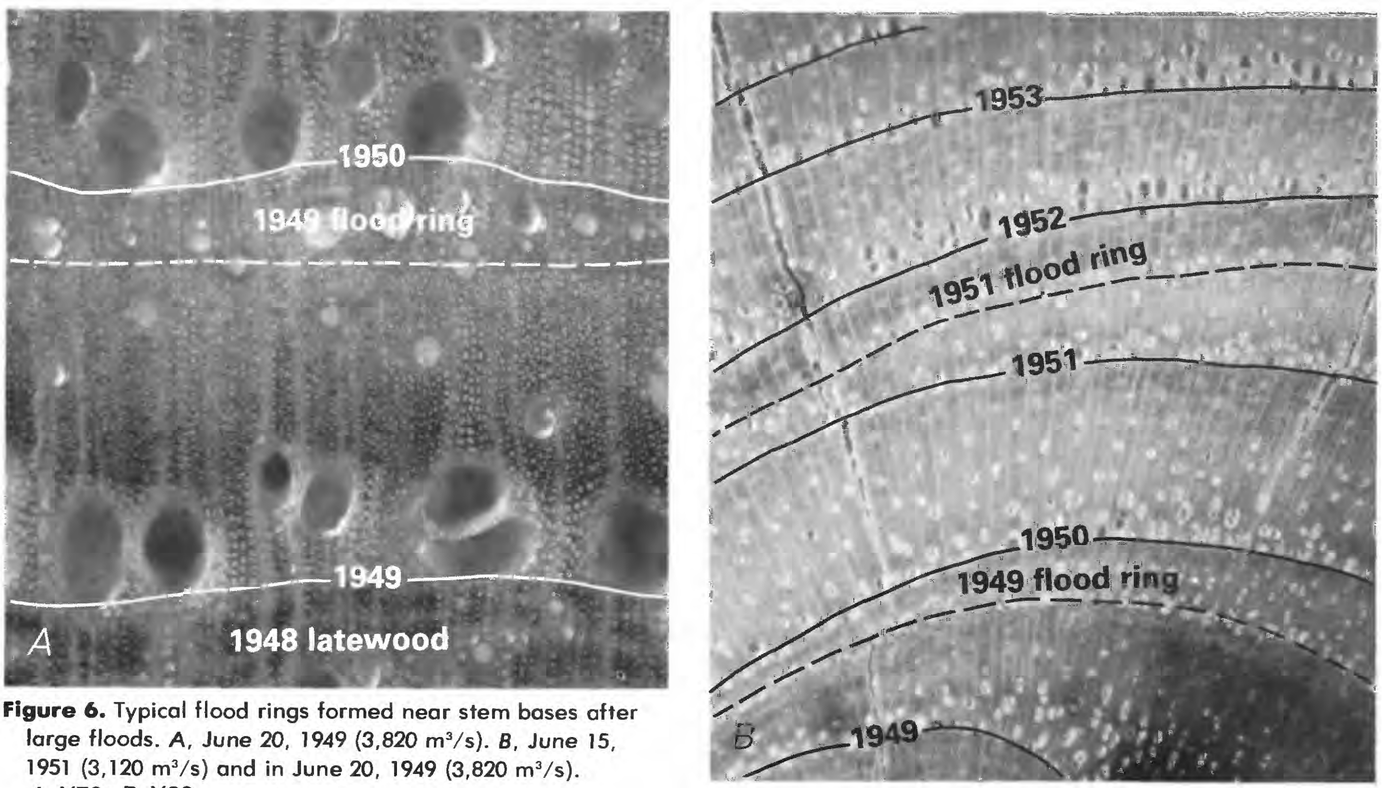


Figure 6. Typical flood rings formed near stem bases after large floods. *A*, June 20, 1949 (3,820 m^3/s). *B*, June 15, 1951 (3,120 m^3/s) and in June 20, 1949 (3,820 m^3/s). *A*, X70; *B*, X20.

that both flood rings developed after the flood of May 30, even though this flood was smaller than that of May 10. Additional evidence to support this view is that the 1960 growth increments of eight other trees had earlywood flood rings (see next section), all of which presumably formed after the larger flood of May 10. However, in one of the two trees with latewood flood rings, the appearance of the wood suggests that abnormal growth formed after the flood of May 10. Although its trunk base is covered by floods greater than 550 m^3/s, this tree grows along a reach where minor floods are unlikely to damage trees. Only a few trees sampled along this reach showed flood-related abnormal growth, and damage there was generally in response to floods exceeding 2,500 m^3/s. Thus, the flood of May 10, 1960, would have been more likely to damage this tree

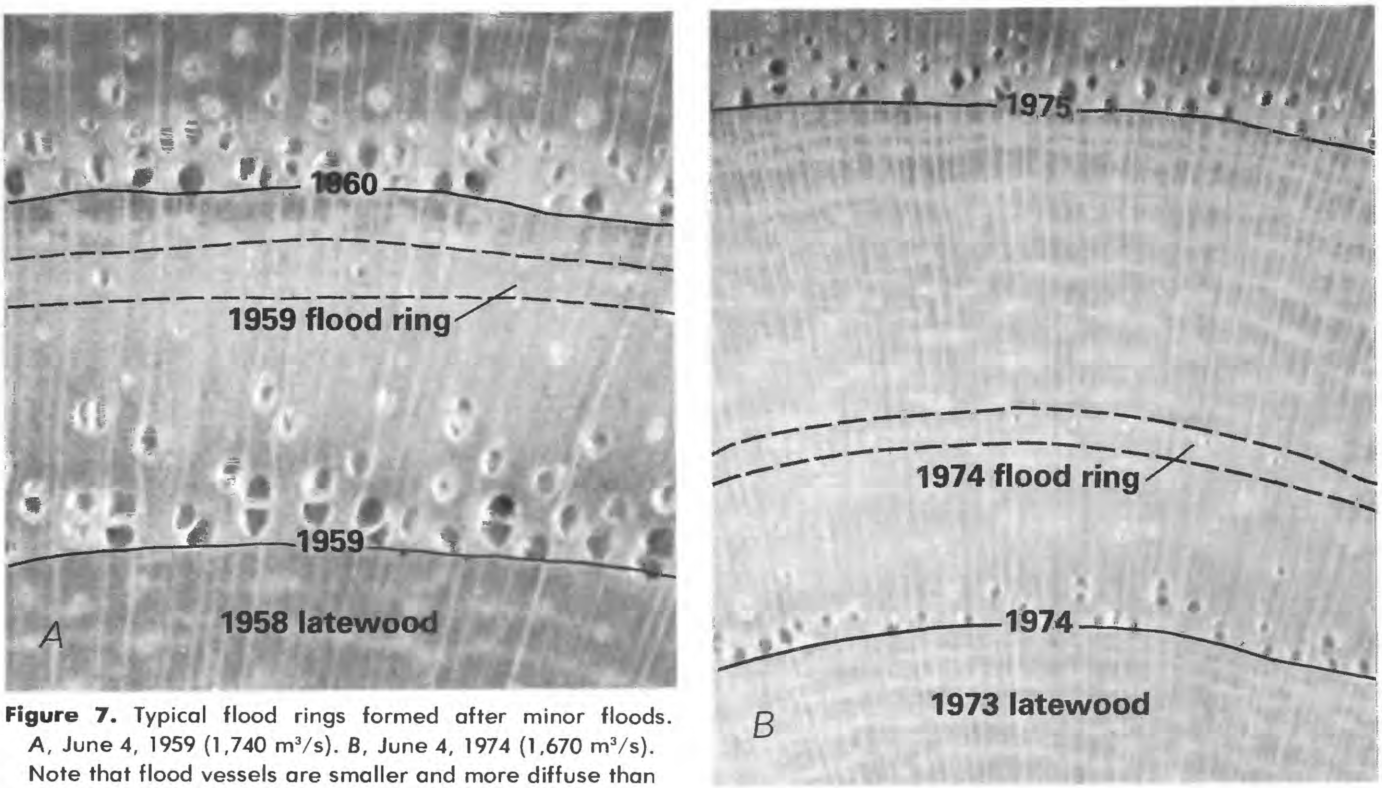


Figure 7. Typical flood rings formed after minor floods. *A*, June 4, 1959 (1,740 m^3/s). *B*, June 4, 1974 (1,670 m^3/s). Note that flood vessels are smaller and more diffuse than those formed after larger June floods (see fig. 6). *A*, X30; *B*, X20.

Table 3. Frequency of latewood flood rings formed in July- and August-flood years, 1930 to 1979. Floods are ranked in order of increasing magnitude

Date of flood	Peak discharge (cubic meters per second)	Number of trees	
		With crown inundated[1]	With flood rings
July floods:			
July 26, 1938	[2] 600	4	1
July 1, 1972	1,460	15	[3]NA
July 11, 1970	1,510	14	2
July 21, 1956	2,050	19	2
July 19, 1949	2,590	25	[3]NA
August floods:			
August 1, 1945	1,390	11	1
August 27, 1937	2,500	13	0
August 25, 1933	2,630	5	0
August 20, 1955	6,120	36	0

[1]Determined by comparing local crest altitudes with estimated tree heights.
[2]Mean daily discharge.
[3]Not applicable; larger flood occurred earlier in growth year.

than would the May 30 flood because velocities were higher at this larger discharge. In addition, this tree had a 1964 flood ring in which latewood flood vessels gradually merge into the earlywood zone along parts of the ring circumference. Thus, by May 1, when the 1964 flood crested (2,570 m^3/s), the tree had already made the transition to latewood growth along part of its circumfer-

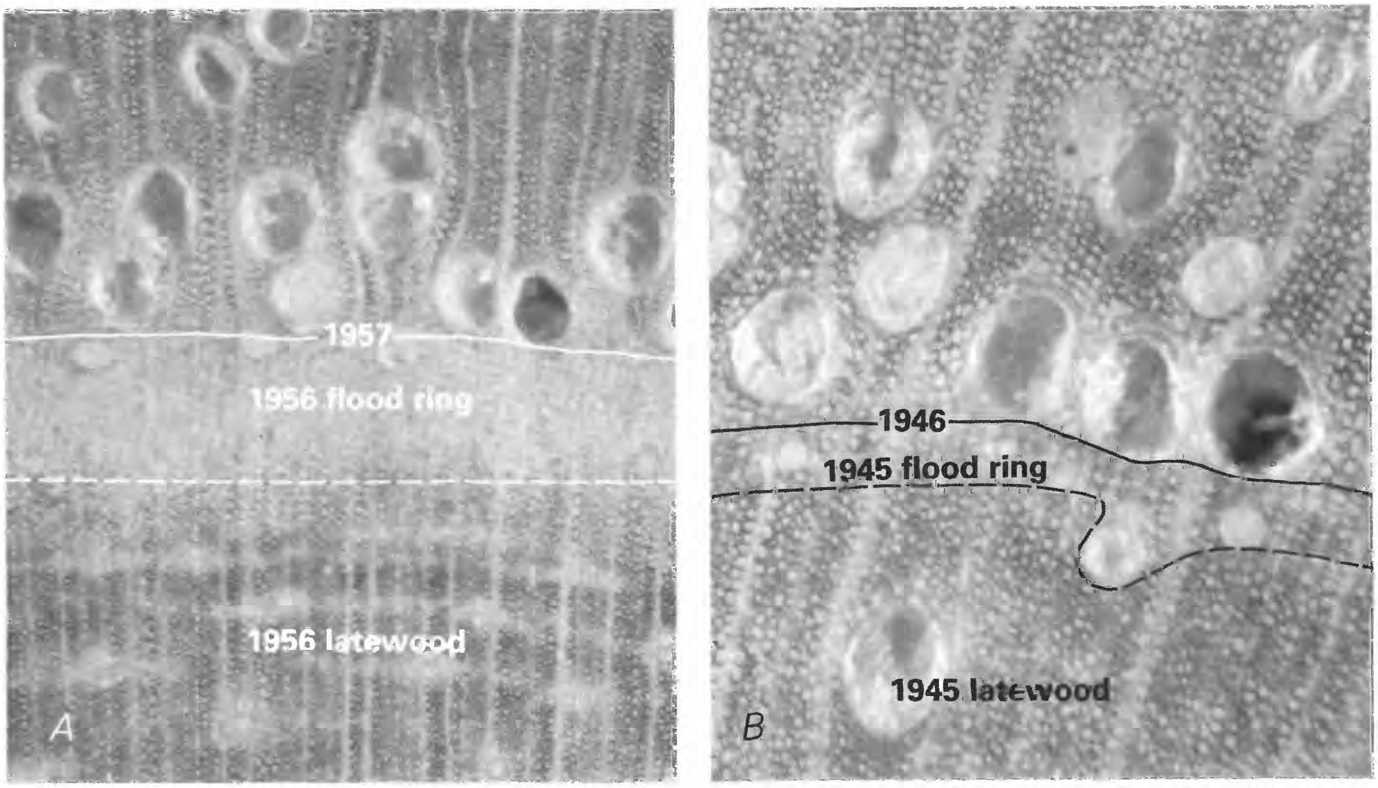


Figure 8. Flood rings formed after late-season floods. *A*, Flood ring formed after the flood of July 21, 1956 (2,050 m^3/s). A narrow band of thin-walled fibers precedes the flood vessels. Largest flood vessels are 50 to 60 μm, compared to typical vessels (25–35 μm) within the latewood. *B*, Flood ring formed after the flood of August 1, 1945 (1,390 m^3/s). Flood vessels are 45 to 70 μm. The large solitary vessel (110 μm) in the center of the ring is not part of the 1945 flood ring. *A*, X70; *B*, X70.

ence. In other words, because of genetic or unusually favorable site factors, the tree was in an advanced state of growth relative to most surrounding trees. The flood of May 10, 1960, was even later in the year than the 1964 flood and was preceded by the warmest April during the 50-year study period. Thus, latewood growth in the tree probably had already begun by early May 1960.

Flood Rings Within the Earlywood Zone

In addition to flood rings within the latewood zone, abnormal earlywood growth is commonly observed within the annual rings of flood-plain trees. As mentioned previously, earlywood growth in the lower Potomac basin typically begins in mid-April and continues into May. In this study, April 15 to May 31 is considered the interval of earlywood formation. It seems reasonable to expect that flood damage during earlywood growth would result in growth anomalies within the earlywood zone. Floods in mid- or late May, however, would be followed by latewood flood rings in some trees and earlywood flood rings in others, depending on the timing of the transition to latewood growth. Furthermore, abnormal growth might form within both the earlywood and latewood of a ring if flood damage occurred before the growth transition was complete along the entire ring circumference.

Anomalous earlywood growth is more variable than anomalous latewood growth and also more difficult to distinguish from typical growth. Diffuse, discontinuous latewood flood rings are generally easier to identify than is the minimum anatomical "signal" that represents anomalous earlywood growth. Accordingly, the designation of a particular ring as "anomalous" was made by comparing that ring not only to corresponding rings of other trees in the collection but also to several adjacent rings in the sample. This was particularly practical if patterns of earlywood growth varied little from year to year, even during most years of flooding. Unvaried patterns were common in trees growing along sheltered reaches or at high flood-plain altitudes. In contrast, frequently flooded trees along moderately sheltered and unsheltered reaches

Table 4. Frequency of latewood flood rings formed in early May (May 1–15) and late May (May 16–31) flood years, 1930 to 1979. Floods are ranked in order of ascending magnitude

Date of flood	Peak discharge (cubic meters per second)	Number of trees: With crown inundated[1]	Number of trees: With flood rings
Early May group:			
May 6, 1975	1,330	16	0
May 3, 1966	1,380	12	0
May 9, 1967	1,390	12	0
May 11, 1933	1,400	2	0
May 13, 1952	1,790	23	0
May 9, 1944	2,200	14	0
May 7, 1958	2,330	29	0
May 1, 1964	2,570	25	0
May 10, 1960	3,510	33 }	2
May 30, 1960	1,450	14 }	
May 14, 1932	4,760	5	0
Late May group:			
May 25–26, 1938	[2]850	5	1
May 20, 1950	1,270	15	2
May 22, 1943	1,910	13	1
May 30, 1968	2,310	26	2
May 17, 1978	3,310	30	0
May 18, 1942	1,720	13 }	9
May 24, 1942	3,940	20 }	

[1]Determined by comparing local crest altitudes with estimated tree heights.
[2]Mean daily discharge.

occasionally developed abnormal earlywood growth in numerous annual rings. In rings formed near the center during flood years, it was sometimes difficult to determine if a minor anatomical variation was caused by flooding because growth patterns in central rings commonly vary more than in outer rings. In all cases, therefore, the designation of anomalous earlywood growth was made conservatively.

Jumbled and Extended Earlywood

A common pattern of abnormal earlywood growth is the clustering of distorted vessels among, or replacing, typical vessels. These abnormal vessels generally have unusually small diameters, may be discolored or tylosic, and generally do not greatly increase the width of the earlywood zone. Local variations in the size and spacing of these vessels impart a "jumbled" appearance relative to typical earlywood growth. These jumbled patterns are similar to the clusters of irregular vessels composing latewood flood rings. On occasion, the entire width of the earlywood zone consists of jumbled vessels, but, generally, abnormal growth is confined to part of the width (fig. 9). The most striking examples of jumbled earlywood growth are generally related to floods that occurred prior to mid-May.

In another pattern of flood-related growth, an earlywood zone of typical width is formed, followed by a radially "extended" zone of abnormal vessels that is generally continuous around the circumference of the ring. Extreme variations were observed in the number, size, and spacing of these vessels and, hence, in the width and pattern of the extended zone. In the most striking cases, the extended zone consists of numerous vessel ranks that double or triple the typical width of the earlywood. Vessels are mostly uniform in size and arranged in diffuse, often tapered patterns. Zones of extended vessels are wider than latewood flood rings and are not separated from the earlywood by a conspicuous band of latewood. However, it may be difficult to distin-

Figure 9. Flood rings of jumbled vessels within the earlywood.

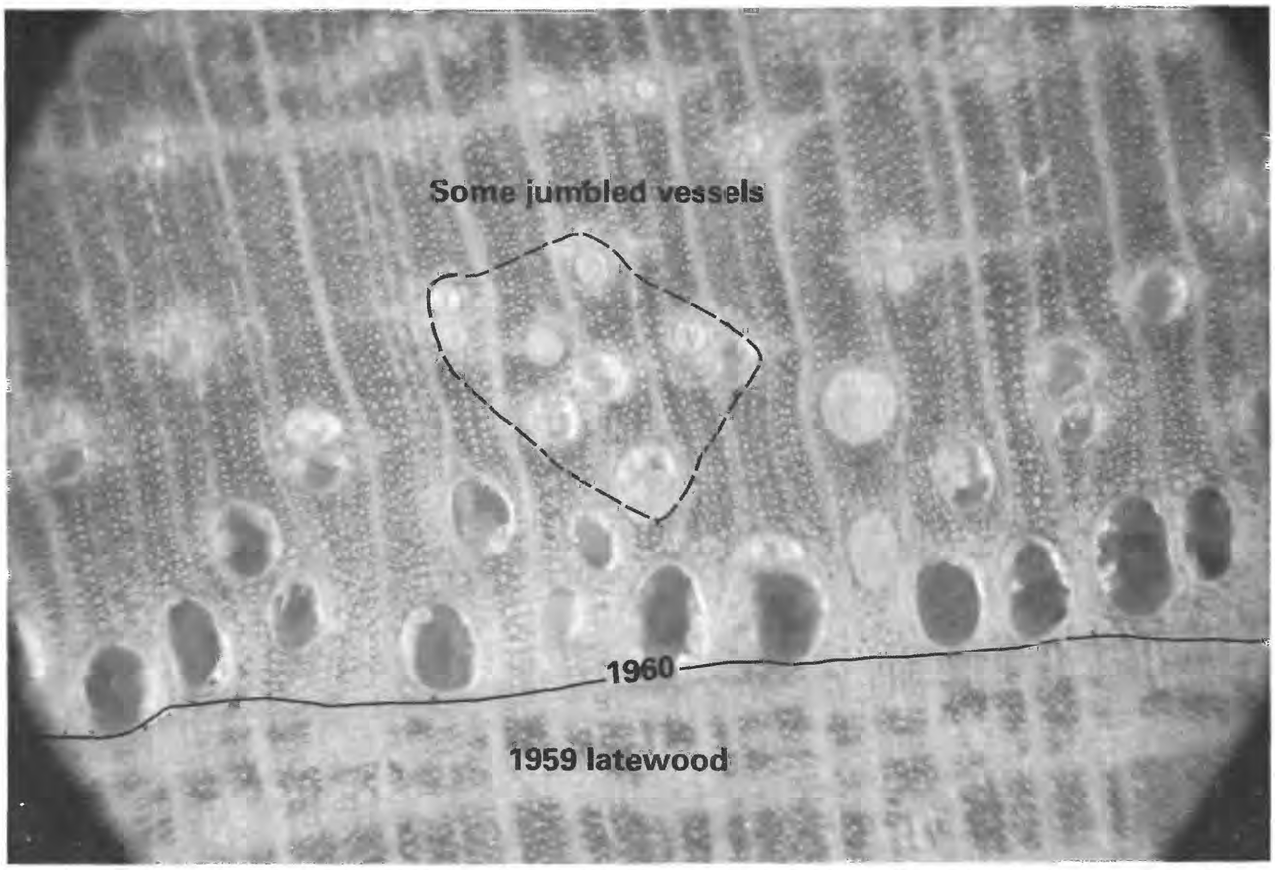


Figure 9A. Growth ring formed in 1960. The first rank of large vessels is followed by a jumbled group of smaller vessels, generally with tyloses. Floods occurred near the end of the earlywood-growth interval (May 10—3,510 m^3/s and May 30—1,450 m^3/s). (X70.)

guish the first rank of extended vessels from the terminal rank of typical earlywood. This type of growth is observed most frequently following mid- or late May floods. Examples of extended earlywood growth are shown in figure 10.

The designation of anatomical patterns as jumbled or extended was generally difficult. In many cases, both growth patterns were simultaneously observed in the same part of a ring. For example, part of the typical width of the earlywood zone and all of the extended zone may be composed of jumbled vessels; in other rings, the degree of jumbling or vessel extensions may be difficult to determine, or patterns may be highly variable and discontinuous around the ring circumference (fig. 11). In years in which a tree was flooded twice during earlywood growth, it is not always possible to determine which flood affected growth or if anomalous growth developed as a result of damage from both floods. Even a single flood sometimes produced a great range of growth responses, presumably due to differences in the stage of growth around the stem at the time of the flood or to differences in the amount of flood damage. As will be discussed later, it seems likely that anomalous growth patterns which develop from local injury to the cambium or expanding vessels differ from patterns that develop from damage to the crown. Because the kind of anomalous earlywood growth formed seems to be a result of many factors, all the anomalous patterns are in general referred to simply as earlywood flood rings.

Earlywood flood rings (jumbled and extended growth collectively) were observed within tree-growth rings formed in 26 of the years from 1930 to 1979. In 24 of these years, floods equaled or exceeded 1,270 m^3/s during the approximate time of earlywood formation. In the other 2 years (1938 and 1953), smaller peak discharges occurred, but each was large enough to inundate trees in which 1938 and 1953 earlywood abnormalities were observed. None of the earlywood flood rings developed during years in which floods were not generated during the earlywood growth interval. Minor floods in 1964, 1966, and 1970 are

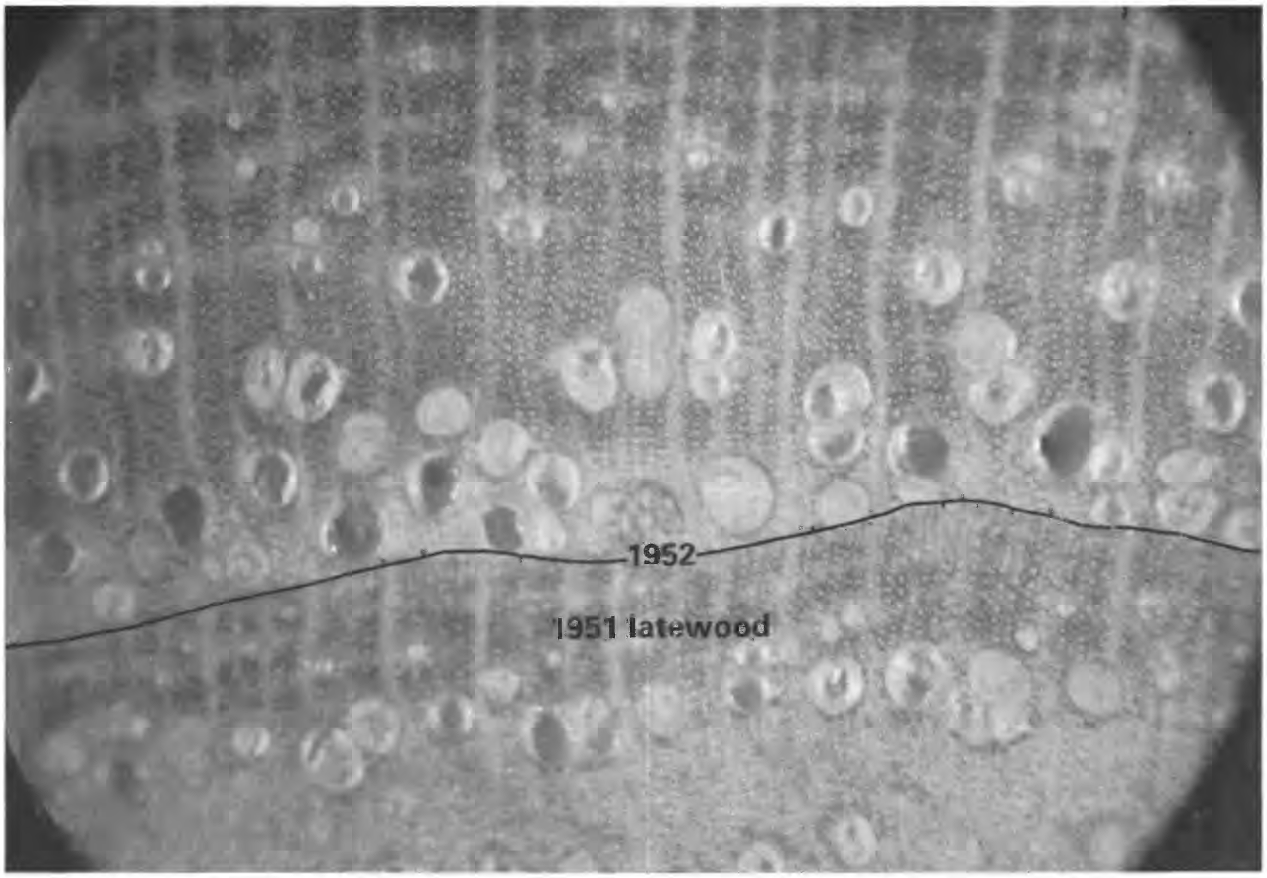


Figure 9B. Growth ring formed in 1952. Jumbled vessels compose much of the earlywood, although some vessels in the first rank appear typical. Flood damage in 1952 occurred at an earlier stage of earlywood growth than in 1960 (April 29—4,190 m^3/s and May 13—1,790 m^3/s). (X70.)

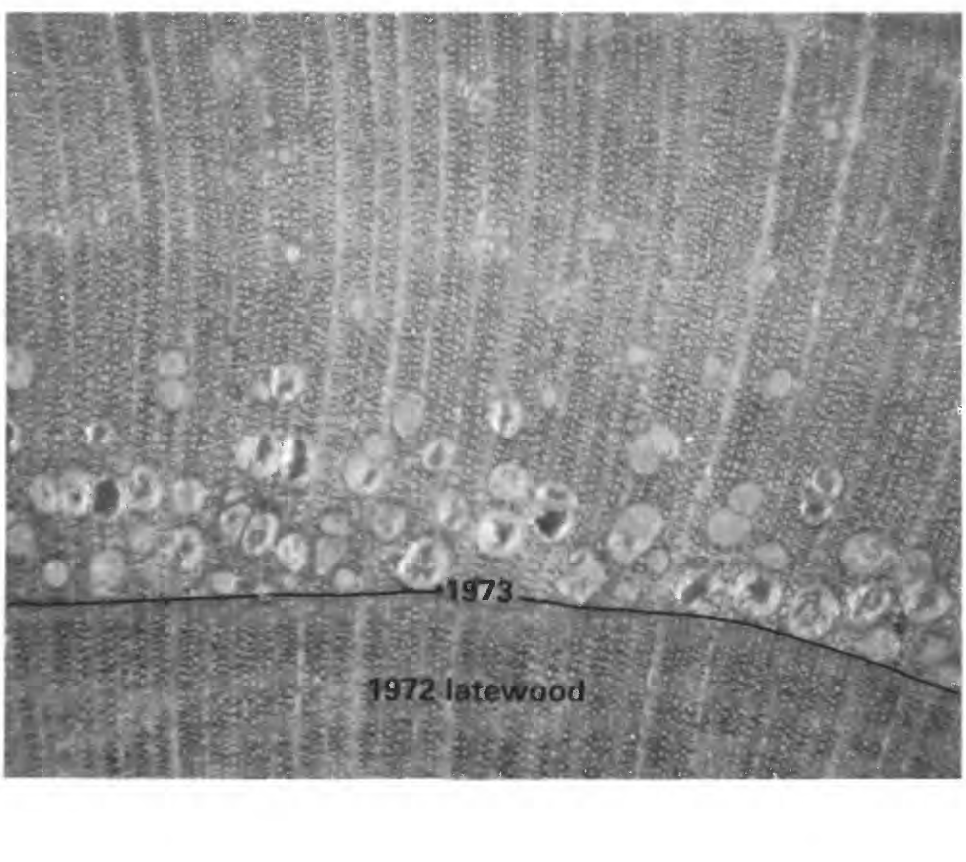


Figure 9C. Earlywood growth in 1973 (April 29—2,360 m^3/s), in which jumbled vessels compose almost the entire earlywood zone. Note the size range of vessels in the first rank. (X70.)

Figure 10. Flood rings in which the earlywood zone appears extended. Vessels may be jumbled and tylosic but generally to a lesser extent than those in figure 9.

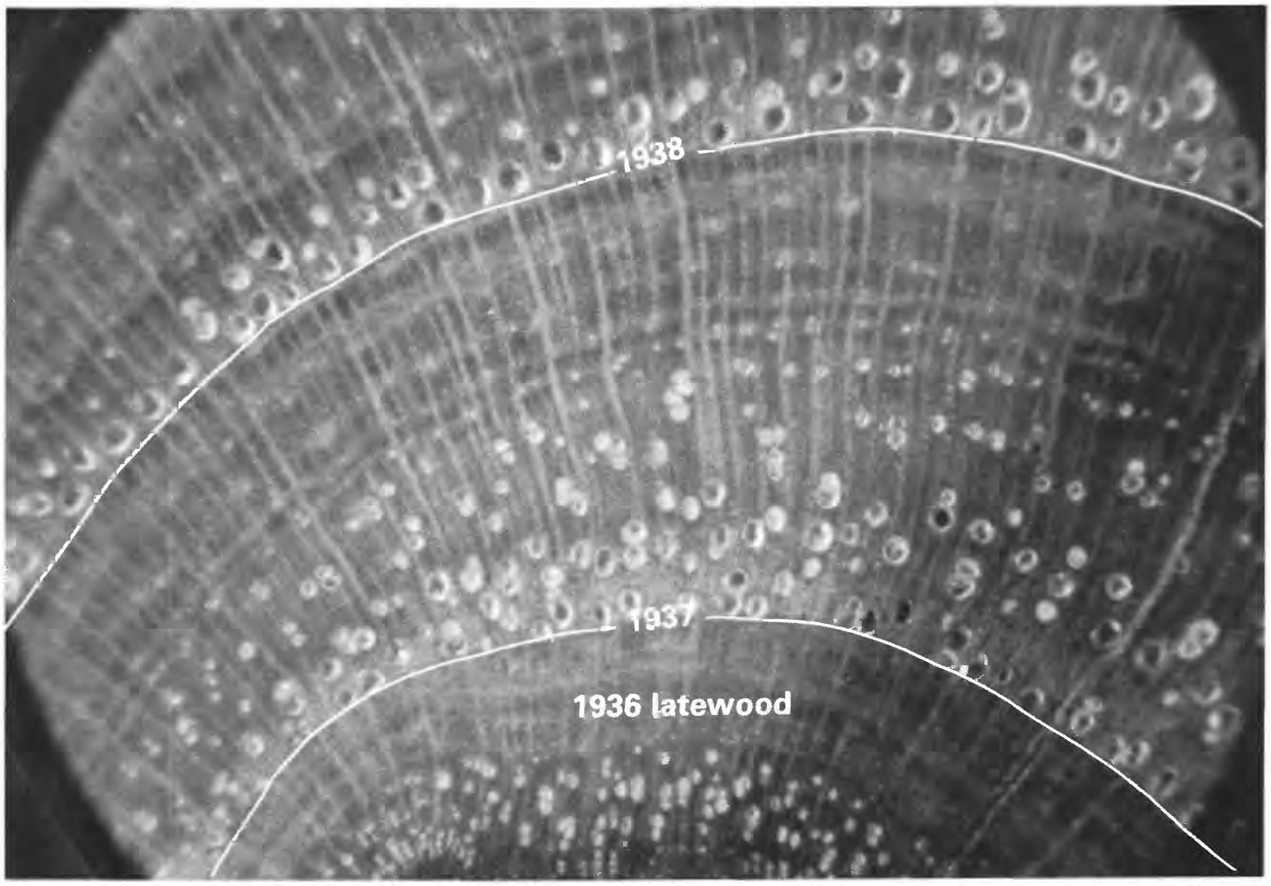


Figure 10A. Flood ring formed after the flood of April 28, 1937 (9,830 m^3/s). Extended vessels are similar to those in figure 10C, but the width of the flood ring is more variable. (X40.)

the only floods for which anomalous earlywood growth was not detected. Table 5 lists the 26 years of flooding and the corresponding earlywood flood rings that developed in 27 of the samples. In 9 flood years, two floods occurred during the earlywood growth interval. Collectively, 81 earlywood flood rings were observed compared to 58 latewood flood rings (excluding 1972) within the same period.

For single-flood years, the flood of April 29, 1973 (2,360 m^3/s), corresponds to anomalous ring development in the largest number (seven) of samples. Floods in 1937, 1939, 1940, 1944, 1950, 1951, 1953, and 1978 are each associated with anomalous growth in at least three trees. In 1932, 1938, 1961, and 1967, only one tree had atypical growth. Jumbled flood rings were more common than extended-vessel zones after floods in April and early May (particularly in 1932, 1948, 1949, 1951, 1967, and 1973). In years of floods in mid- to late May, however, the earlywood zone is generally not jumbled but is followed by a ring of extended vessels that may or may not appear jumbled.

In 9 of the 26 years in which earlywood flood rings were formed, two floods occurred during the earlywood growth interval. In 4 of these years (1943, 1952, 1958, and 1960), at least four trees developed abnormal growth. In 1952, for example, floods peaked on April 29 (4,190 m^3/s) and May 13 (1,790 m^3/s), and 11 samples developed anomalous growth. The earlywood zones of 9 of these 11 trees were mostly jumbled, and those of the other 2 trees were both jumbled and extended. It seems reasonable that the April-flood-damaged trees before the earlywood zone was complete, and, thus, much of the earlywood growth appears jumbled. The other two trees may have been damaged by the flood in mid-May, or earlywood growth may have been more nearly complete at the time of flood damage in April. The greater proportion of trees with jumbled earlywood is consistent with the hypothesis that the larger April flood damaged more trees than did the May flood.

In 1943, small floods occurred near the beginning and end of the earlywood growth interval (2,370 m^3/s on April 22 and 1,910 m^3/s on May 22).

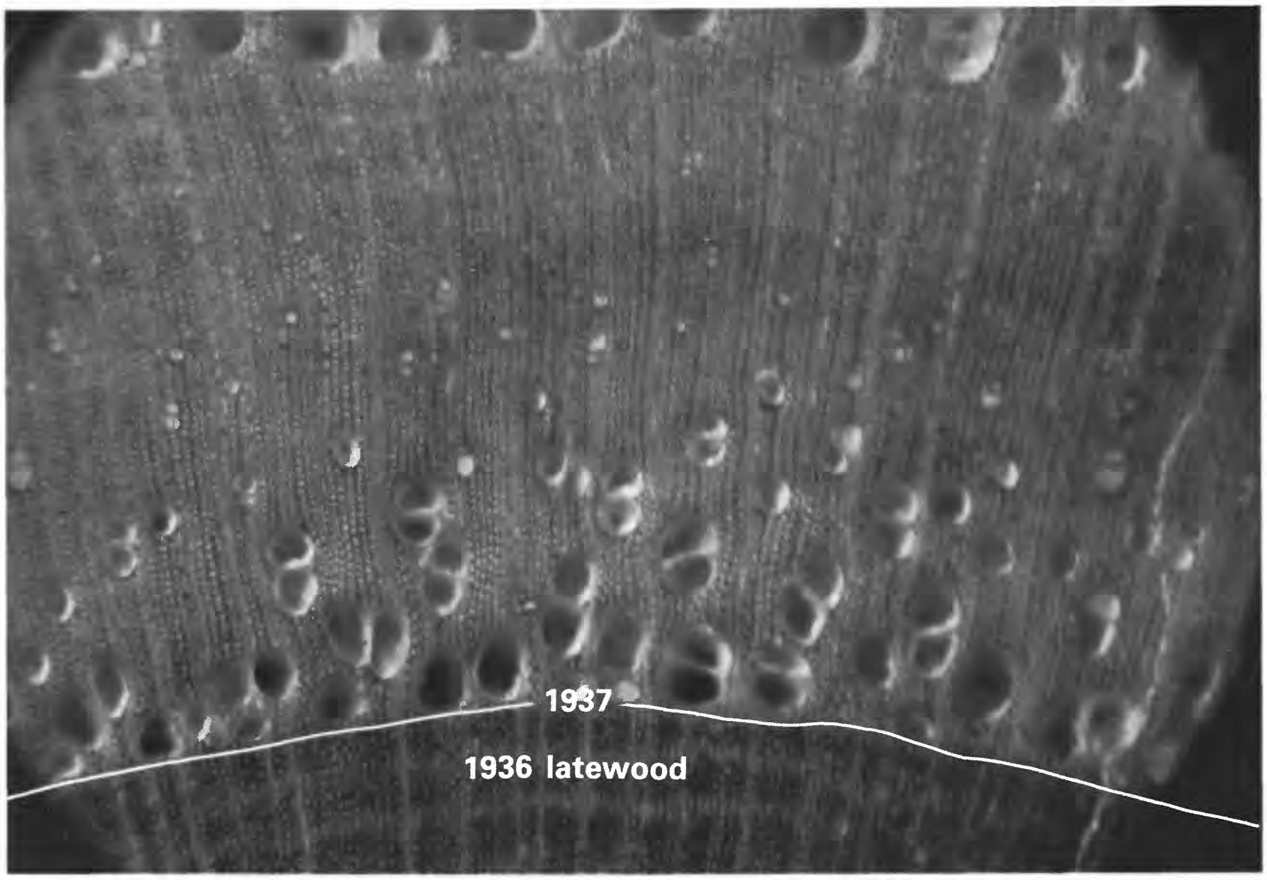


Figure 10B. Flood ring formed after the flood of April 1937 in which the width of the extended zone is only about three ranks of vessels. (X70.)

Unlike floods in 1952 and 1960, the floods in 1943 were of approximately the same magnitude. In the five trees that developed anomalous growth, several growth patterns were observed. In one tree, the earlywood zone was extended by a diffuse row of vessels documenting the May flood. In another tree, the first rank of vessels was jumbled, as was much of the remainder of the earlywood, and a widely extended zone of diffuse vessels also developed. Three other trees had jumbled growth within the first-formed part of the earlywood along small parts of the ring, whereas the remainder of the circumference was composed of predominately typical earlywood vessels followed by diffuse, extended zones. Generally, the annual rings were narrow near the jumbled vessels and wider where earlywood growth was more typical.

Combination Flood Rings

Eleven growth rings from nine harvested trees formed latewood flood rings along parts of the annual-ring circumference and earlywood flood rings along other parts (fig. 12). These 11 growth rings formed during 9 flood years between 1942 and 1974 (table 6). Generally, the position of latewood flood vessels gradually changes along the circumference until the flood vessels locally replace part of the typical earlywood and form an earlywood flood ring. One sample, however, developed an earlywood flood ring along all of the circumference except for a local flaring of vessels preceded by a band of typical latewood growth. The total ring width was greatest in the region of the latewood flood ring.

The single combination flood ring in 1964 was the only example of flood-related growth for that year in the entire collection. For the other 8 years in which combination flood rings formed, other trees in the collection had earlywood or latewood flood rings singly (see tables 2, 4, 5). For example, in 1942, 1943, 1946, 1960, 1968, and 1974, a total of 22 latewood flood rings were also observed, whereas a total of 34 earlywood flood rings formed in 1942, 1943, 1952, 1958, 1960, 1968, and 1974.[3]

[3]The 1974 flood ring formed after an early June flood and thus is not listed in table 5.

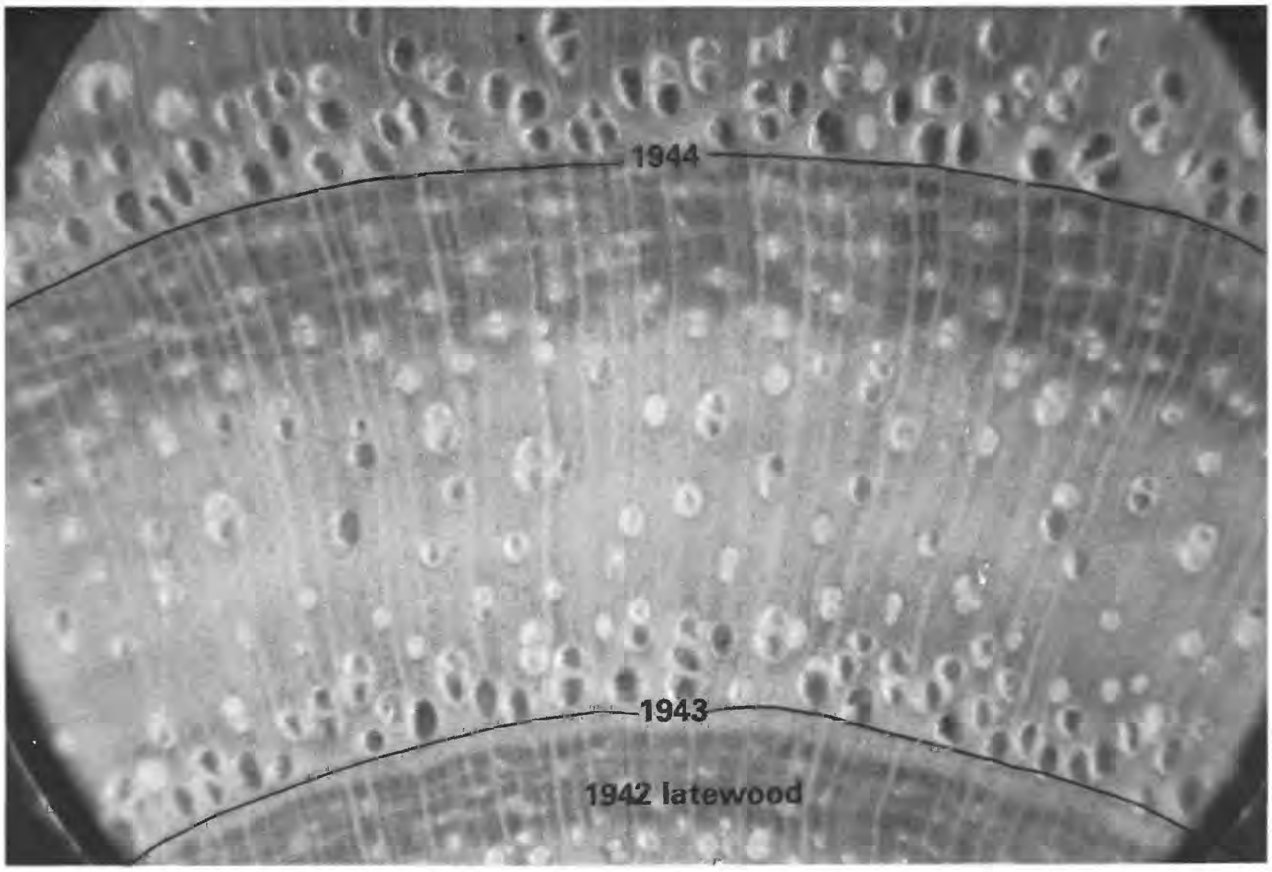


Figure 10C. Flood ring formed in 1943 (April 22—2,370 m^3/s and May 22—1,910 m^3/s) in which the extended zone composes approximately one-half the total ring width. Note the diffuse, symmetrical arrangement of vessels and that the extended zone is several times wider than the typical earlywood. Presumably, the extended zone is evidence of the May flood. (X35.)

Depauperate Earlywood

Another general category of abnormal growth is a narrow earlywood zone composed of vessels that were smaller and more diffuse than those typically formed. This abnormal pattern extends along part or all of the circumference and generally imparts a "depauperate" appearance to the earlywood zone (fig. 13). Generally, vessels are 30 to 50 percent of typical size and may be discolored or in jumbled clusters. Occasionally, vessels are so small and diffuse that earlywood appears discontinuous.

Depauperate earlywood was observed in 23 growth rings corresponding to seven of the years from 1930 to 1979 (table 7). The growth year most frequently associated with depauperate earlywood was 1961 (eight trees). It is followed by 1979 (four trees), 1958 and 1978 (each with three trees), and 1936 and 1948 (each with two trees), and 1968 (one tree). Each of these 7 years was marked by large floods and (or) heavy ice flows during times of tree-growth dormancy. For example, the flood of March 19, 1936 (13,700 m^3/s), is the largest known in the lower Potomac River basin. In 1979, another large flood (5,830 m^3/s) was generated on February 26, and smaller floods developed on January 26 (3,480 m^3/s) and March 7 (2,650 m^3/s). Ice jams or ice flows in the remaining 5 years associated with depauperate earlywood include a catastrophic jam in mid-February 1948, which destroyed many trees along the Chain Bridge reach (Sigafoos, 1964), and a smaller, less destructive jam in mid-January 1968, along with three small winter floods (Yanosky, 1982b). The flood of January 28, 1978 (4,110 m^3/s), carried large ice flows, and, although jamming did not occur, vegetation was severely damaged along much of the reach between Difficult Run and Chain Bridge. Other floods in 1978 occurred on March 16 (4,330 m^3/s) and March 28 (3,480 m^3/s). The frequency of flooding from January 1978 to February 1979 is striking in that 5 of the 29 largest floods during the study period were generated during this time.

Figure 11. Growth rings with enigmatic vessel patterns or with jumbled and extended vessels along the same radius.

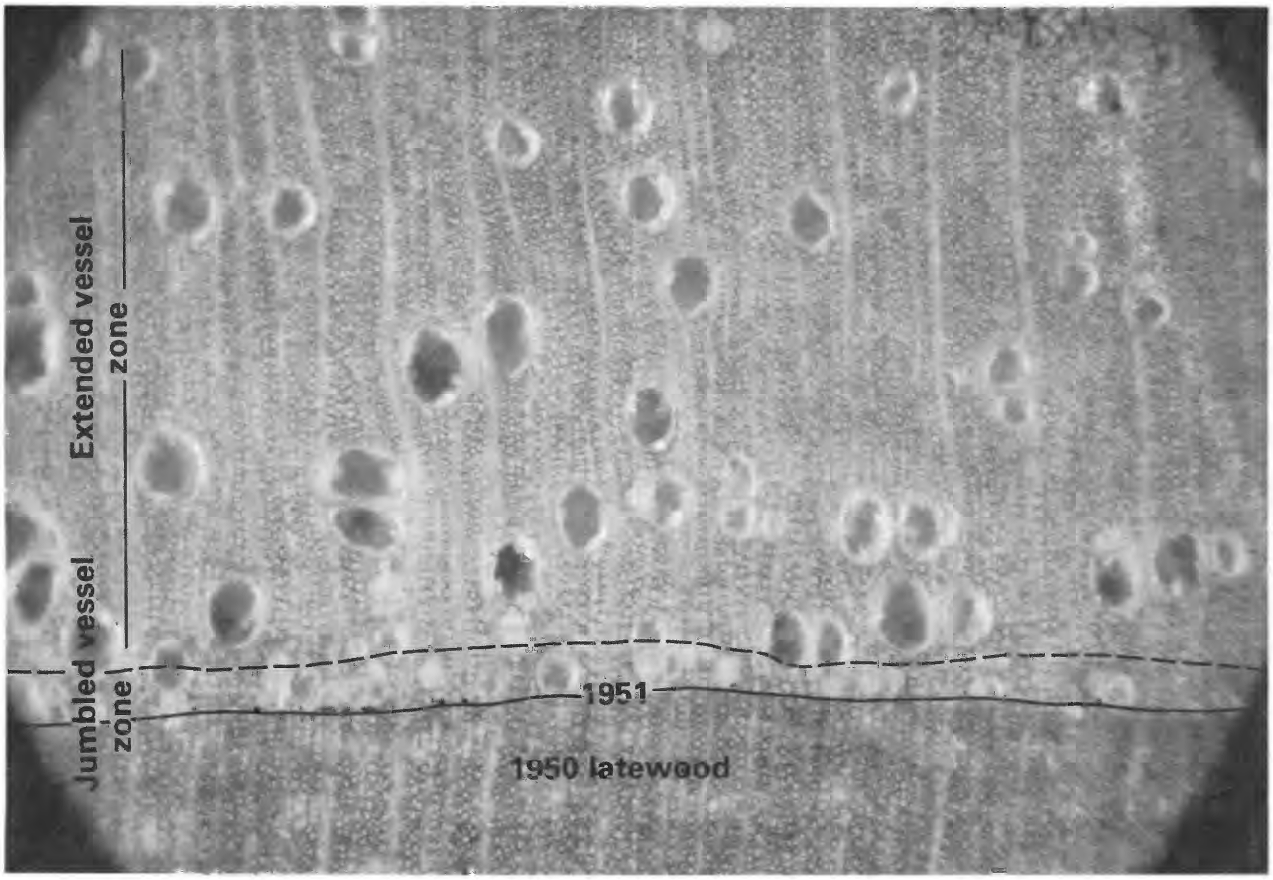


Figure 11A. Anomalous growth formed in 1951. The first rank is composed of jumbled groups of atypically small, tylosic vessels. Ranks of larger vessels are typical of earlywood cells but are extremely diffuse (compare to fig. 10). Floods occurred during the 1951 growing season on April 14 (1,710 m^3/s) and on June 15 (3,120 m^3/s). In addition, seven floods (1,420 m^3/s or greater) occurred between the end of the 1950 growth year and mid-April 1951. It is unknown which floods are associated with the growth zones. (X70.)

Depauperate and jumbled earlywood have been detected within separate annual rings formed in 1958. Jumbled earlywood (see table 5) probably developed after damage from the flood of May 7 (2,330 m^3/s). Depauperate earlywood in 1958, on the other hand, is believed to have resulted from ice damage before the onset of spring growth. According to records, stage-discharge relations of the gage near Washington, D.C., were affected by ice from January 6 to 14. On January 15, the daily average discharge increased from the previous 9-day average of approximately 130 m^3/s to at least 870 m^3/s, and, according to Sigafoos (1964), blocks of ice were deposited on parts of the flood plain near Chain Bridge. Another minor flood occurred on March 1 (1,390 m^3/s) but, according to discharge records, was preceded by 17 days of low flow, during which daily gage readings were affected by ice. Thus, the sudden rise in stage probably also resulted in ice-laden flows that damaged some trees. In addition, a small flood occurred on March 29 (1,900 m^3/s).

Floods were generated in 1961 on February 21 (3,290 m^3/s) and on February 27 (2,860 m^3/s). According to surface-water records, the first flood was preceded by 66 days during which stage-discharge relations were affected by ice. This flood carried large amounts of ice and severely damaged many trees (R. S. Sigafoos, U.S. Geological Survey, oral commun., 1965). In addition, average daily discharges exceeded 850 m^3/s for 16 days during March, and a minor flood (2,620 m^3/s) occurred on April 14 (just prior to the initiation of earlywood growth.

Discolored Earlywood

A final category of flood-related growth is the discoloration of tissues that otherwise are typically shades of amber yellow. Discolorations range

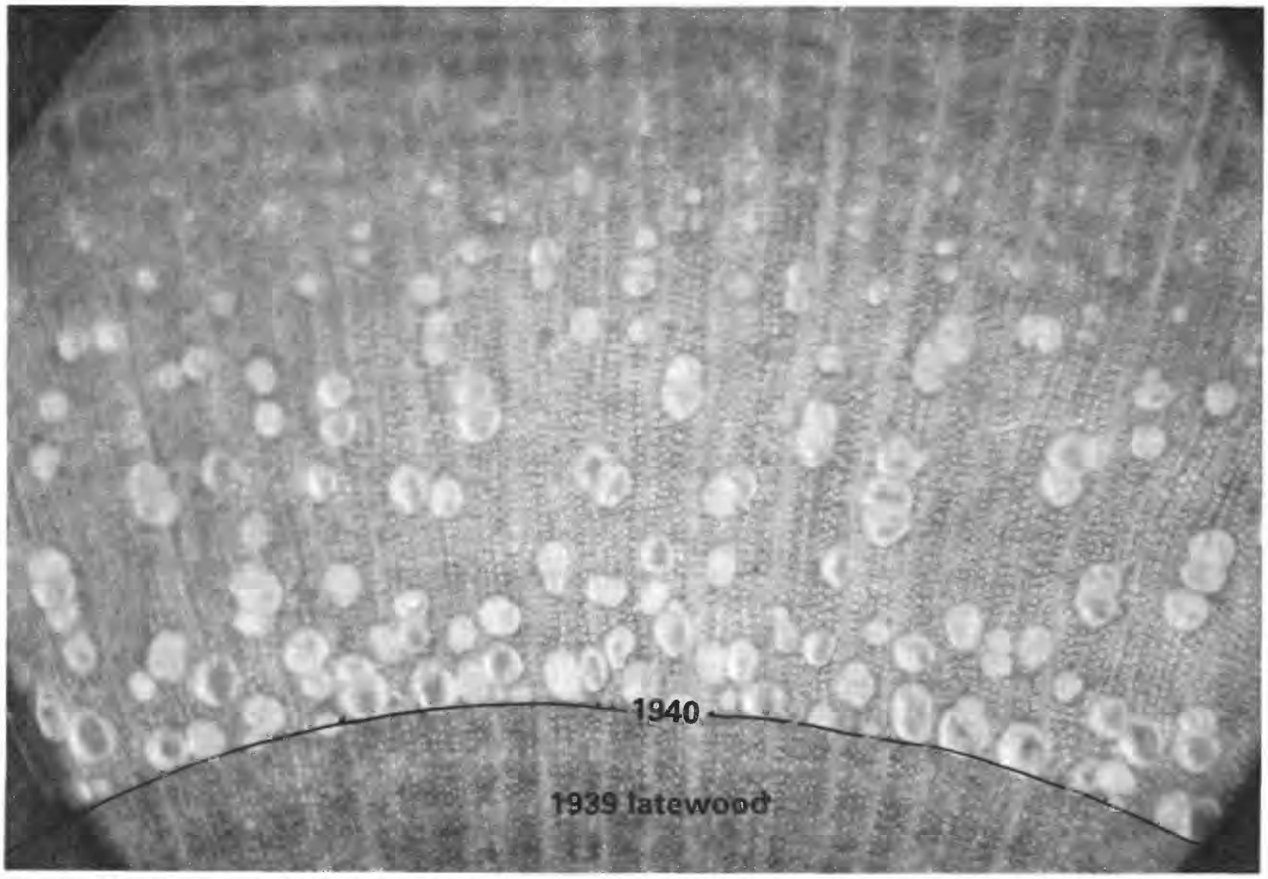


Figure 11B. Growth ring formed in 1940. Jumbled vessels in the first two ranks of the earlywood are followed abruptly by a zone of diffuse vessels. It appears that growth responded to two episodes of flooding (April 22—3,030 m^3/s and June 2—2,250 m^3/s). (X40.)

from shades of reddish brown to black. Discolored tissues are in discrete groups that may be irregular and diffuse or in nearly contiguous patterns that impart a "bruised" appearance even when viewed with the unaided eye. Groups of discolored cells were observed along the entire circumference of some growth rings. Despite differences in the spacing between groups, the area of each group is fairly uniform—0.5 to 1.0 mm^2. Ranks of discolored cells rarely extend radially for more than 1.0 mm but may traverse the entire width of extremely narrow rings. More commonly, however, the discolored tissues are primarily the thin-walled cells of the earlywood and first part of the latewood and part of the latewood of the previous year (fig. 14).

This pattern differs from the uniform darkening of the heartwood region that occurs with advancing tree age and from color changes associated with scar formation. In scars, wood cells are replaced by a mass of darkened, undifferentiated wound tissue ("callus"). The discolored tissues described in this report are composed of ordinary wood cells that are atypical only in color, even though they were frequently observed in growth increments in which flood rings formed.

Zones of heavily discolored wood along the entire ring circumferences were most frequent in 1972 annual rings. Latewood flood rings were present in all of these. Generally, discolorations were darkest in the 1972 earlywood, even in wide rings, and discolored vessels commonly developed tyloses. In some 1972 rings, discolorations also were observed within the latewood flood rings. Heavy discolorations along the entire circumference were also observed in growth rings formed in 1960 and 1967. Similar heavy discoloration along smaller parts of the ring circumference was observed in many rings corresponding to flood years from 1930 to 1979. Regardless of the time of flooding, heaviest discoloration was generally within earlywood growth regions.

For a particular growth ring, discolored tissues were observed at random stem heights. Flood rings, on the other hand, are most highly developed near the stem apex and, in many samples, were observed at all stem heights. This strongly suggests that discoloration develops not as a re-

Table 5. Frequency of earlywood flood rings, 1930 to 1979. Interval of earlywood growth is April 15 to May 31

Date of flood	Peak discharge (cubic meters per second)	Number of trees: With crown inundated[1]	Number of trees: With flood rings
May 14, 1932	4,760	5	1
April 22, 1933	3,600	5	1
May 11, 1933	1,400	2	
April 28, 1937	9,830	11	4
May 25–26, 1938	[2]850	5	1
April 19, 1939	2,200	15	3
April 22, 1940	3,030	18	3
May 18, 1942	1,720	13	3
May 24, 1942	3,940	20	
April 22, 1943	2,370	13	5
May 22, 1943	1,910	13	
May 9, 1944	2,200	14	5
April 16, 1948	2,760	17	2
April 16, 1949	1,340	12	2
May 20, 1950	1,270	15	3
April 15, 1951	[3]1,530	18	3
April 29, 1952	4,190	35	11
May 13, 1952	1,790	23	
May 18, 1953	[2]1,030	10	6
April 30, 1958	1,410	16	4
May 7, 1958	2,330	29	
May 10, 1960	3,510	33	8
May 30, 1960	1,450	14	
April 18, 1961	2,070	20	1
April 22, 1964	1,350	11	0
May 1, 1964	2,570	25	
May 3, 1966	1,380	12	0
May 9, 1967	1,390	12	1
May 30, 1968	2,310	26	2
April 16, 1970	1,770	15	0
April 26, 1970	1,710	15	
April 29, 1973	2,360	27	7
April 27, 1975	1,440	16	2
May 6, 1975	1,330	16	
May 17, 1978	3,310	30	3

[1]Determined by comparing local crest altitudes with estimated tree heights.
[2]Mean daily discharge.
[3]Mean daily discharge; preceded by flood peak on April 14 (1,710 m^3/s).

sult of flood-induced crown damage but rather from bark damage that permits the entry of micro-organismal fungi. It is possible that tissues are partly decomposed, and hence discolored, from the metabolic activities of these microorganisms and that the flaring of the discoloration to the preceding year's increment results from the radial spread of fungi through ray parenchyma. The discoloration may, however, result from the deposition of materials (for example, tannins) produced by flood-injured tissues. Regardless of the mechanisms of formation, it seems most probable that discolored tissues are a consequence of injury.

MECHANISMS AND TIMING OF FOOD-RELATED GROWTH

Earlywood and latewood flood rings did not develop in trees in which crowns were not inundated. Apparently, these types of abnormal growth formed only if leaves and buds were damaged,

Figure 12. Combination flood ring formed after the floods of May 18 (1,720 m^3/s) and May 24 (3,940 m^3/s), 1942.

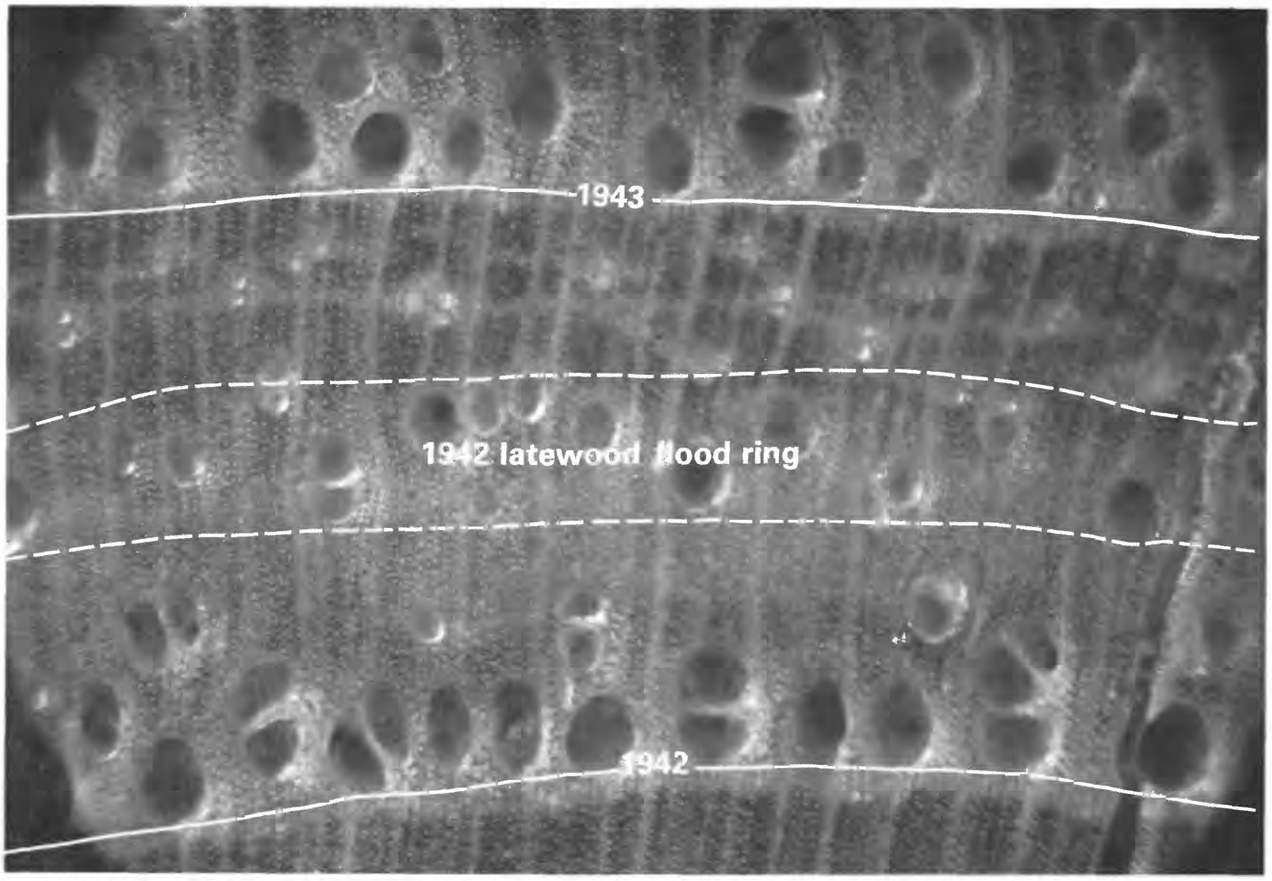


Figure 12A. Typical latewood part of the 1942 flood ring. The transition from earlywood to latewood growth had occurred along the part of the ring prior to the floods. Note that considerable radial growth developed after the formation of the flood ring. (X70.)

and a new leaf crop was subsequently produced. Entire branches may be stripped by flood waters, or, alternatively, leaves and buds may be locally removed. Many remaining leaves may be torn, covered with mud and debris, or shed after flood waters recede. Adventitious leaves and new sprouts typically form along the trunk or broken crown.

The formation of flood-induced growth may be explained by the mechanism believed to regulate the development of vessels. The enlargement of earlywood vessels (see fig. 2) is, to a large extent, induced by hormones produced in the buds and expanding leaves and transported basipetally to the newly formed cambial derivatives when dormancy is broken in early spring (Wareing and others, 1964). It is here suggested that refoliation is physiologically similar to this early spring growth. A flush of growth regulators, manufactured by the second crop of breaking buds and expanding leaves, initiates the development of large vessels within the latewood or earlywood. The size and number of flood vessels formed would be expected to be a function of the distance from the stem apex and the amount of hormones produced. It seems reasonable to assume that trees which completely refoliate produce a greater flush of hormones than partly refoliated trees and, therefore, are more likely to develop continuous rings of large-diameter flood vessels along the entire stem. Partly refoliated trees probably form distinct flood rings only near the apex because the supply of hormones is depleted before it reaches the base of the tree.

The hormonal control of flood-ring formation may also explain the positive relation between peak stages and the corresponding frequencies of flood rings in inundated trees. In addition to damaging more trees than small floods, large floods also presumably damage a greater proportion of leaves and buds of many trees. This may be due to increased velocities during large floods relative to smaller floods and to greater durations of crown submergence. A larger crop of new leaves,

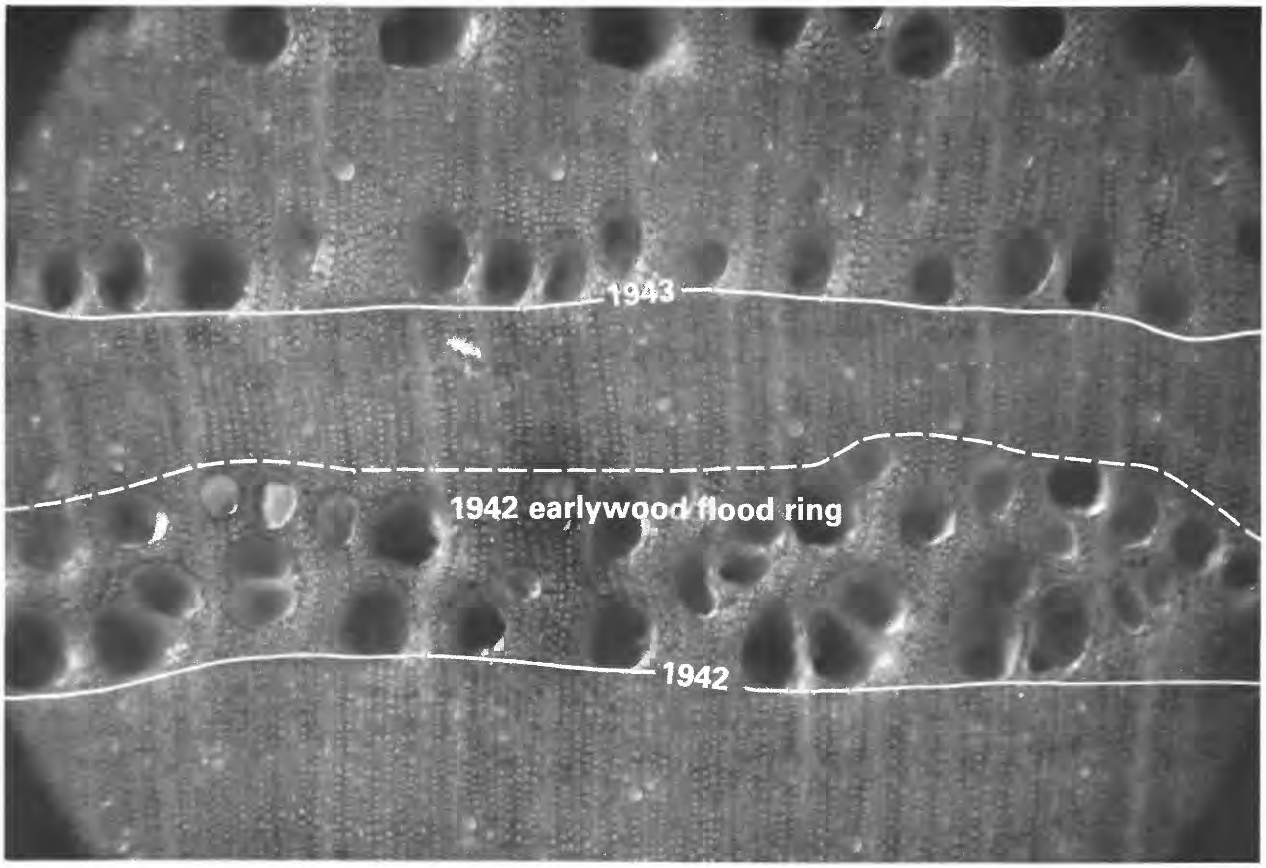


Figure 12B. Earlywood part of the 1942 flood ring along a different part of the growth increment. Flood vessels appear as part of the earlywood zone because growth was locally less advanced at the times of the floods. Note the difference in total ring width from that in figure 12A. (X70.)

Table 6. Frequency of combination flood rings, 1930 to 1979. Anomalous latewood and earlywood growth developed along different parts of an annual ring after a flood

Date of flood	Peak discharge (cubic meters per second)	Number of trees with combination flood rings
May 18, 1942	1,720	2
May 24, 1942	3,940	
April 22, 1943	2,370	1
May 22, 1943	1,910	
June 4, 1946	1,950	1
April 29, 1952	4,190	1
May 13, 1952	1,790	
April 30, 1958	1,410	1
May 7, 1958	2,330	
May 10, 1960	3,510	1
May 30, 1960	1,450	
April 22, 1964	1,350	1
May 1, 1964	2,570	
May 30, 1968	2,310	2
June 4, 1974	1,670	1

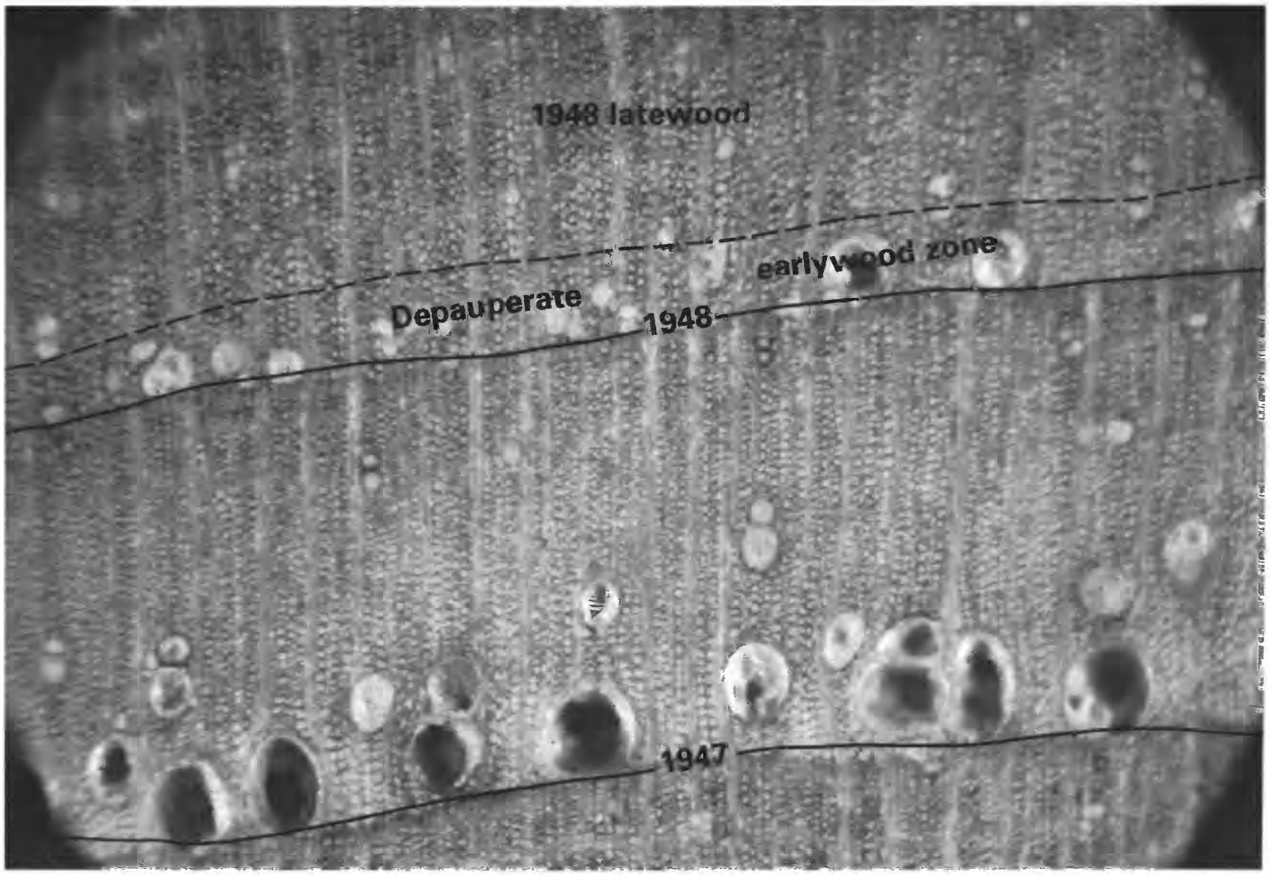


Figure 13. Depauperate earlywood formed after an ice jam in mid-February 1948. Earlywood vessels are smaller (25–85 μm) than those of the 1947 ring. Note tyloses in vessels of the depauperate zone. (X70.)

Table 7. Frequency of depauperate earlywood, 1930 to 1979, in 23 growth rings of 17 trees

Date of flood	Peak discharge (cubic meters per second)	Number of trees with depauperate earlywood
February 27, 1936	3,740	
March 13, 1936	3,000	2
March 19, 1936	13,700	
February 16, 1948	[1]2,120	
January 15, 1958	[2]870	3
February 21, 1961	[2]3,290	8
February 27, 1961	2,860	
January 15, 1968	[1]770	1
January 28, 1978	[2]4,110	
March 16, 1978	4,330	3
March 28, 1978	3,480	
January 26, 1979	3,480	
February 26, 1979	5,830	4
March 7, 1979	2,650	

[1]Bank-to-bank jamming of ice near Chain Bridge.
[2]Ice-block deposition on flood plain near Chain Bridge.

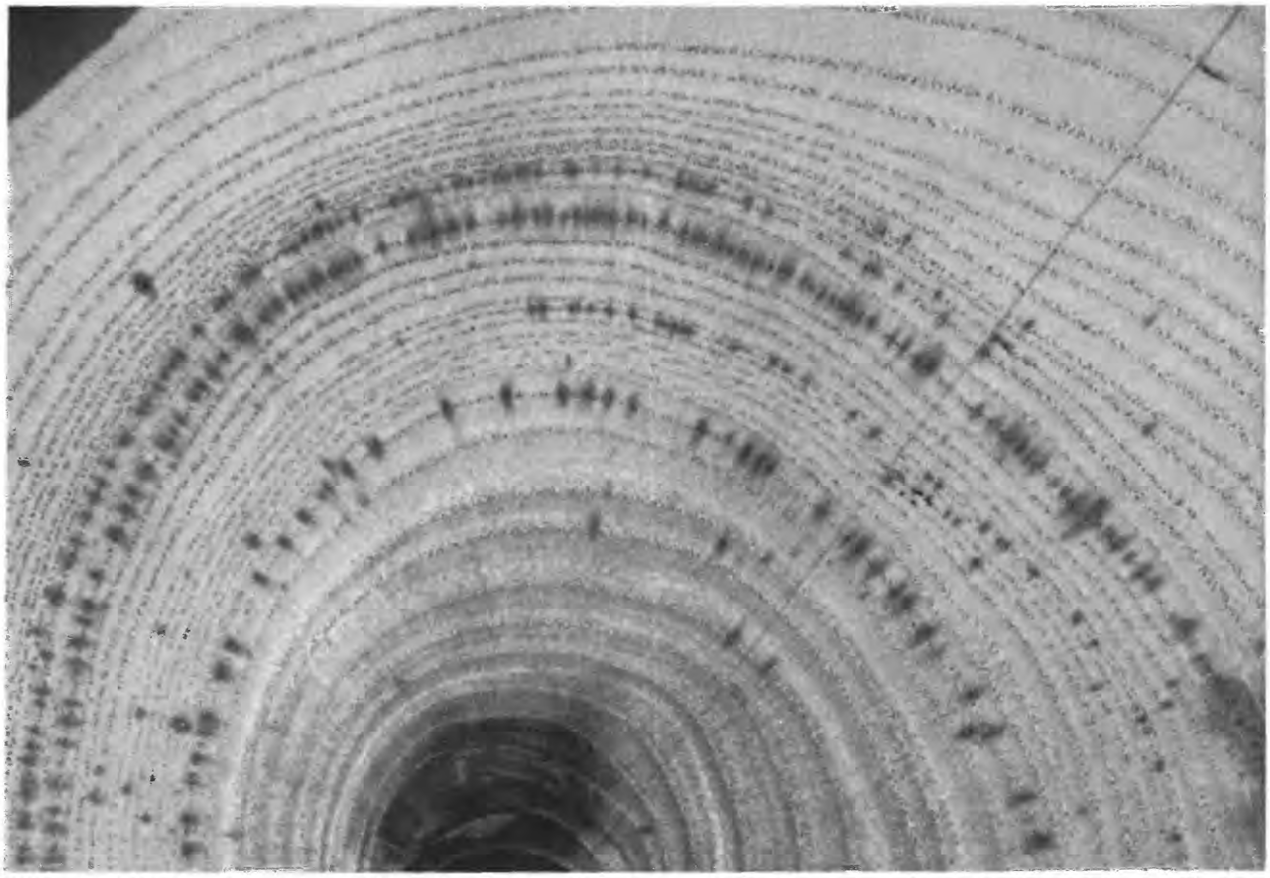


Figure 14. Discolored earlywood. Note that darkened tissues are in small clusters along ring circumference. The number of clusters varies considerably, occasionally forming dense, nearly continuous patterns. (X2.)

and consequently a greater flush of hormones, would be expected in severely damaged trees than in trees in which only a small part of the original crown was damaged. In severely damaged trees, flood rings are likely to form at considerable distances from the stem apex. When damage is minor, flood rings are unlikely to form at or near stem bases unless trees are extremely small.

Flood rings rarely form after late summer floods, probably because radial growth of trees in the lower Potomac basin is completed or greatly reduced from that in May or June. The timing of the reduction and the eventual cessation of annual growth probably depends to a large extent on environmental and genetic factors. However, the study of sample cross sections indicates that young trees often grow later into the summer than older trees on comparable sites. Radial files of fibers with strikingly thin secondary walls and large lumens have been observed within the latewood zones of young but not of older trees. These atypical fibers appear to form during growth spurts and are related to periods of intense precipitation and concomitant increases in Potomac River discharge. Thus, older trees, even if defoliated or damaged by a large flood such as that of August 20, 1955 (6,120 m^3/s), have already ceased radial growth or are growing so slowly that postflooding growth is negligible. Defoliation does not result in the production of a new leaf crop, and latewood flood rings do not form. Even young, vigorous trees may not produce new leaves in August.

Defoliation in July, however, is followed by refoliation and significant postflooding growth in some trees. Thus, flood rings are hypothetically more likely to form after July floods than after those of August, although less likely than after May or June floods. The trees forming flood rings after late-season floods were young, with relatively wide annual rings. If precipitation is generally abundant during most of the growing season preceding a late-year flood, it seems reasonable to assume that some small trees will still be growing vigorously enough to replace damaged leaves. If so, evidence of late-season floods would more likely be present in the inner than in the outer rings of old trees.

At the onset of the study, it seemed reasonable to assume that jumbled earlywood developed only as a result of direct damage to expanding vessel members. Direct damage probably occurred where vessels are jumbled only along a small part of the ring circumference. However, in growth increments with fairly continuous zones of jumbled earlywood, anomalous growth was generally less pronounced in basal than in apical sections. In several trees, jumbled zones were absent from wood samples near the tree base but well developed in sections near the apex. This strongly suggests that jumbled vessels, like flood vessels within the latewood zone, develop in response to a second flush of growth regulators following crown damage. If this were not the case, jumbled earlywood would have formed at random with respect to stem height. Furthermore, if jumbled growth resulted only from mechanical stresses, jumbling would be expected to be more frequent along upstream-facing sides of trunks than along downstream-facing sides. This has not been observed. A zone of jumbled earlywood, therefore, is a flood ring in which flood vessels develop primarily within, rather than outside, the terminal rank of typical earlywood growth.

Similarly, the extended earlywood of most trees is more fully developed near stem apices than bases. Vessel patterns of the narrowest extended zones are sometimes similar to those of latewood flood rings. In the widest zones, however, vessel arrangement differs from that of latewood flood rings; vessels are extremely diffuse and may form a radial zone several times the typical width of the earlywood (see fig. 10C), and, thus, the entire annual ring is unusually wide. If the rate of formation of earlywood were the same as that of a widely extended zone, there would be insufficient time for both an extended zone and latewood to develop. Therefore, it seems more likely that the growth rate of a widely extended zone exceeds that of the earlywood. Accordingly, the extended zone probably does not develop as a result of defoliation and refoliation because flood damage generally has a negative impact upon ring width. Nevertheless, the most striking examples of extended earlywood were detected in trees flood in April- and May-flood years. It may be, therefore, that extended growth in some trees is a response to flooding but not to flood damage; that is, prolonged root flooding may be favorable to growth if crowns are not damaged. Radial growth is accelerated, and large vessels continue to form, although size and spacing patterns differ from those of typical earlywood growth.

The extended-growth pattern may be somewhat analogous to radial growth in conifers, in which the transition from earlywood to latewood seems to be controlled in large part by water availability. Earlywood growth in conifers continues until water becomes limiting, and, thus, there may be great yearly differences in the proportions of the two zones. In ring-porous species, however, the transition from earlywood to latewood growth seems largely controlled by endogenous factors, and the width of the earlywood is often remarkably constant (R. L. Phipps, oral commun., 1982). This does not always appear to be the case in flooded ash trees, in which an environmental factor (extreme water availability) seems to prolong the period of earlywood formation. A widely extended zone, therefore, probably forms during a period of increased growth rate, producing a gradual rather than abrupt transition from earlywood to latewood growth. In 1953, for example, most growth rings are unusually wide relative to adjacent rings, and the extended zone of flooded trees is diffuse and flared. May 1953 was the wettest May during the study interval, although only a minor flood was generated.

Extended growth, like latewood and jumbled flood rings, is presumably regulated by hormones. As previously noted, it can be argued that refoliation produces large amounts of diffusable hormones that mediate the formation of abnormal growth. Thus, latewood and jumbled flood rings are generally more highly developed near stem apices than in lower trunk regions. This growth trend with respect to tree height is also observed in annual increments with extended earlywood zones, probably because it depends on a hormonal gradient from the crown down the trunk. If a hypothesis is correct that widely extended zones develop as a result of a growth-rate change, the controlling hormones must be produced from new leaves at stem tips, rather than from refoliation along entire branches. In other words, extended-earlywood growth is probably related to rapid shoot elongation. This seems reasonable because favorable conditions are generally associated with relative increases in both radial and apical growth. It should be emphasized, however, that some narrowly extended earlywood probably does form after refoliation, particularly when vessel patterns resemble those of latewood flood rings. It can be argued that narrowly extended zones are latewood flood rings that develop adjacent to the earlywood and, hence, are not true extensions of earlywood growth. In light of the great variety among abnormal growth patterns of all types, however, the simple classification of "latewood" and "earlywood" flood rings seems justified. Of greater importance than precise classification is the correlation of abnormal earlywood growth with early-season floods.

Depauperate earlywood is related to flooding before the growing season and to ice jams, but growth abnormalities do not appear to have resulted solely from damage to the cambium or developing vessels. Rather, it would seem that the small size of earlywood vessels resulted from a low concentration of diffusible hormones at the time of spring growth. Because of earlier damage to stems and leaf buds, bud break was unusually small, and expansion of vessels was retarded. This hypothesis is strengthened by studying cross sections from different stem heights. Although this could be done in only 5 of the 16 trees that developed depauperate earlywood, it was clear that the degree of abnormal growth was greatest in basal sections and became progressively less pronounced in apical sections. This suggests that abnormal growth was caused by a diminishing gradient of hormones from the apex to the lower trunk. Thus, it seems that trees with depauperate earlywood were severely damaged between the onset of growth and the cessation of growth in the previous year. Because the formation of depauperate earlywood and flood rings seems to be controlled by growth-regulating substances, it is reasonable to consider depauperate earlywood a special category of flood ring. However, unlike rows of flood vessels within the latewood zone and additional vessels jumbled among or just outside the earlywood, depauperate vessels develop only within the earlywood. This type of flood ring is evidence of floods in the fall, winter, or early spring, although at present there seems to be no practical means to estimate the time of occurrence of individual floods.

Field Experiments With Defoliated Trees

To test the hypothesis that flood rings develop after damage to leaves and buds, groups of small trees were manually defoliated (table 8) at monthly intervals from mid-May 1980 to mid-August 1980. Other trees were defoliated in mid-June 1981 and in spring 1982. Typically, study trees were 1 to 3 m in height and 2 to 5 cm in basal diameter. Ages ranged from 1 to 11 years. Trees defoliated in 1980 were harvested in October, and those defoliated in 1981 were cut down in mid-August. Samples from the trunk base, middle stem, and apex were collected, and, in some trees, a few sections from lateral branches were also taken.

Of 14 trees defoliated in June 1980 and 1981, 8 grew complete or moderately complete crops of new leaves. Refoliation typically began within 1 week, and first-formed leaves grew in small clusters at stem tips. No adventitious sprouts from trunks or roots were observed. Leaf sizes near the end of the growing season ranged from 50 to 100 percent of those of nearby trees. Abnormalities were not observed within the growth increments of June-defoliated trees that did not produce a second leaf crop. Refoliated trees, however, developed abnormal radial growth similar to latewood flood rings. In some trees, particularly when the second leaf crop approximated that of the original leaf cover, abnormalities were observed at all stem heights sampled. Partly refoliated trees developed abnormal growth only near stem apices. Anomalous growth in all refoliated trees formed the terminal ranks of the latewood so that no subsequent radial growth developed.

Of five trees defoliated in mid-July 1980, three refoliated, although only a small percentage of

Table 8. Summary of manual defoliation of ash trees, 1980 to 1982. Anomalous growth similar to flood rings developed in numerous defoliated trees but only when trees produced a second leaf crop

Date		Number of trees		Number of trees with abnormal radial growth	
Defoliated	**Harvested**	**Defoliated**	**Refoliated**	**Refoliated**	**Not refoliated**
June 17, 1980	October 22, 1980	4	3	3	0
June 23, 1981	August 17, 1981	10	5	5	0
July 21, 1980	October 17, 1980	5	[1]3	[2]3	0
August 22, 1980	October 17, 1980	6	0	0	0
May 15–16, 1980	October 17, 1980	8	8	4	0
May 1, 1982	May 29, 1982	9	9	2	0

[1]Refoliated only near apex.
[2]In one tree, abnormal growth at apex only.

the original leaf crop was replaced. The timing of bud break was comparable to that of trees defoliated in mid-June. One of the three trees fully refoliated only along the apical part of the stem. In this tree, rings of abnormal vessels developed in the outermost latewood zone from the apex to a point approximately half way to the trunk base. Latewood fibers surrounding these abnormal vessels appeared to have thinner walls and larger lumens than those formed earlier in the latewood and imparted a whitish appearance to the wood. Sections near the stem base did not develop abnormal rings. A second tree defoliated in July formed three fully expanded leaves along the terminal leader but otherwise did not refoliate. The pattern and distribution of abnormal vessels were the same as in the first tree. The third defoliated tree produced six leaves at the apex of a lateral branch, although leaves expanded only to about 10 percent of typical size. Abnormal vessels were observed in a twig section 2 cm from the branch apex but in no other stem sections.

None of the six trees defoliated in mid-August 1980 produced new leaves, even though buds on several trees had been left intact. Swelling of buds was not observed.

The growth responses of trees defoliated during the earlywood-growth interval were more variable than those of trees defoliated in June, July, and August. All nine of the trees defoliated on May 1, 1982, grew second sets of leaves and were harvested on May 29, 1982. Twigs were collected from most trees at the time of defoliation to determine the extent of earlywood growth. At harvest, control samples were taken from trees of comparable size which had not been defoliated.

Only one tree defoliated in early May developed a completely formed abnormal ring in the latewood. This tree was 1 m in height and grew along a tract of exposed bedrock near Difficult Run. The abnormal ring was well developed in a section 0.5 m from the apex but had not formed at the base. At the apex, abnormal vessels appeared to be forming but were not as large or numerous as those in the middle section. In the control tree, stem elongation by May 29 was nearly 0.6 m, and basal ring width was approximately twice that of the defoliated tree.

In another defoliated tree, clusters of abnormal vessels appeared to be developing at the time of harvest. Vessels were mostly contiguous with the first-formed ranks of the earlywood but seemed to be in jumbled patterns. No latewood growth was detected. In the control, a sprout from the parent trunk of the defoliated tree, the earlywood zone had completely formed, and considerable latewood growth had developed.

The other seven trees defoliated in early May appeared to be still forming earlywood upon harvest, and unambiguous patterns of earlywood vessels were not observed. Rather, defoliation was associated with a retardation of radial growth compared to the controls.

Of eight small trees defoliated in mid-May 1980, seven refoliated completely, and one formed only a few new leaves. At the time of defoliation, this last tree had a heavy fruit crop that was left intact. In 1980, unlike in May 1982, trees were not harvested until the completion of the growing season. Four trees did not develop abnormal growth and had extremely narrow 1980 rings. In one of the four trees that did develop growth similar to a flood ring, the 1980 ring was extremely narrow, and virtually no latewood was formed. The terminal rank of vessels appears jumbled relative to preceding vessels. Another tree, about 3 m in height, developed an abnormal ring at all stem heights. In the basal section, the abnormal growth was mostly within the latewood but appeared to merge with the earlywood along parts of the ring. In the narrowest parts of the ring, abnormal growth was not observed. Tyloses were locally abundant where the abnormal growth was most conspicuous. In sections closer to the apex, abnormal growth was continuous and formed in a greater proportion of the latewood. In a section near the apex, abnormal vessels were totally within the latewood. At all stem heights, there was little or no growth after the abnormal vessels, and ring width in 1980 was much narrower than that in 1979.

The two remaining trees defoliated in mid-May 1980 were approximately 1 m in height and appeared to grow from a single parent stump. Near the apex, each tree developed a multiranked zone of extremely jumbled vessels followed by a typical zone of latewood. Along most of the circumference of each ring, it was not possible to mark a clear transition between typical and atypical earlywood vessels. In basal sections, however, abnormal growth was less conspicuous than near apices. At the base of one of these trees, the width of the 1980 growth ring was highly asymmetrical. The earlywood appeared typical where the ring was narrowest and locally atypical along wider parts. Vessels were less jumbled and crowded than in the apical section. In the other tree, the 1980 ring was narrow near the trunk base, and jumbling was minimal and highly discontinuous.

The results of these field experiments explain to some extent why flood rings are most commonly associated with May and June floods. Many trees flooded in May and June typically replace most or all damaged leaves. Refoliation, however, apparently occurs only to a limited extent later in the growing season, when even severely damaged trees may not fully replace stripped or damaged leaves. Partial refoliation is associated with anomalous growth that forms only near stem apices. Variations in the type of growth responses after May defoliations are fairly consistent with observations in spring-flood years. The formation of latewood or jumbled flood rings appears to depend not only on the timing of tree-growth activities but probably also with rates of growth before and after crown damage. For example, growth conditions were probably unfavorable in 1980 and early 1982. Precipitation was low during both periods, and daily maximum temperatures during parts of summer 1980 were unusually high. Total growth (and presumably the rate of growth) of most trees, particularly defoliated trees, was thus probably somewhat reduced. Trees defoliated in May 1980 that produced new leaves, but without concomitant abnormal growth, had extremely narrow growth rings in 1980. In 1982, refoliated trees were harvested after only 4 weeks, but most had narrower rings than nearby trees, and most did not have abnormal vessels. It seems, therefore, that anomalies do not develop if growth rates are significantly limited. This may account for the low frequency of abnormal growth in manually defoliated trees. If water availability is the most important environmental factor correlated with the rate of tree growth, then trees damaged by floods are probably not as likely as manually defoliated trees to be growth limited by water stresses.

Botanical and Hydrologic Factors Associated With Flood-Related Growth

Selected trees were studied to determine the hydrologic and botanical factors most frequently associated with the formation of flood rings. These data support the hypothetical mechanism of flood-ring formation and may also facilitate the selection of samples for applied field studies. Because of considerable differences between trees, sites, and hydrologic histories, a factor is difficult to assess independently; nevertheless, several general conclusions are possible.

Only harvested trees were studied because discontinuous growth anomalies may not be detected in increment-core samples. To relate tree sizes (estimated from trunk diameters near breast height) and ages to years of flood-ring formation (figs. 15, 16), a subsample of 18 trees was chosen. These trees germinated between 1931 and 1956 and formed at least two flood rings during years of minor floods, as well as a flood ring after the catastrophic 1972 flood. All grew along unsheltered or moderately sheltered reaches and on surfaces flooded by less than 1,700 m^3/s, although these were not preconditions for sample selection.

The average age of the 18 trees when the first flood rings formed was 4.6±6.9 years, coefficient of variation (c.v.) equals 150 percent. Fourteen trees formed flood rings within the first 3 years, including three in the first growth year; one tree, however, was 31 years of age. The average stem diameter when the first flood ring formed was 1.3±1.1 cm (c.v.=84.6 percent). For last-formed flood rings associated with minor floods (that is, excluding 1972), tree ages ranged from 4 to 41 years ($\bar{x}$=20.0±11.3 years; c.v.=56.5 percent), and diameters averaged 4.9±2.1 cm (c.v.=42.8 percent). In six of these trees, the last minor-flood ring was formed after 1972. The diameter of these six trees ($\bar{x}$=4.7±1.7 cm) did not differ significantly at the 0.05 level from that of the 12 trees forming a final minor-flood ring before 1972 ($\bar{x}$=4.9±2.3 cm). However, flood rings in this latter group developed, on the average, 18.5±7.1 years before 1972. Furthermore, one of the six trees forming a final minor-flood ring after 1972 developed its initial flood ring in 1968, 31 years after germination. Trunk diameter in 1968, however, was only 3.2 cm, and tree height in 1980, was only 2 m.

These data indicate that formation of flood rings varies more with age than with size. The high frequency of minor-flood rings in young trees is because small trees are inundated even by minor floods. In addition, anomalous growth is generally easy to distinguish in the wide rings characteristic of young trees. When trees are older, and thus generally taller, crowns are inundated only by large, infrequent floods. Rings are also typically narrower than those near the center, and anomalous growth, therefore, may be more difficult to detect. If trees remain small because of frequent flood damage, however, they may develop flood rings despite increasing age.

In 1972, average age and diameter of the 18 samples were 31.0±6.3 years and 7.5±3.2 cm,

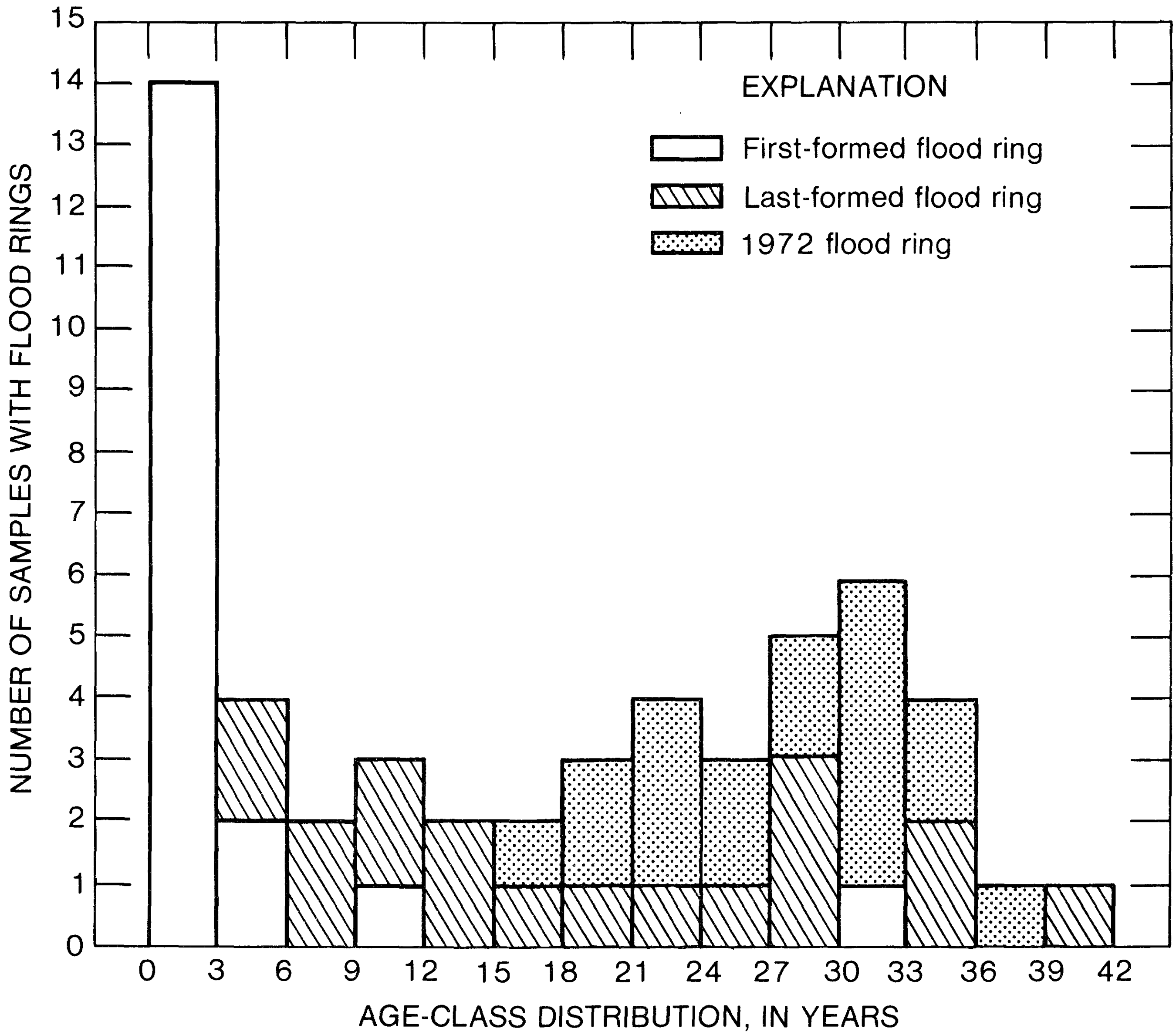


Figure 15. Ages of 18 trees at times of flood-ring formation. Each tree formed at least two flood rings in response to minor floods and also a flood ring in 1972. Average age when flood rings first formed was 4.6±6.9 years. Flood rings last formed after minor floods when trees were 20.0±11.3 years of age, and trees with flood rings in 1972 were 31.0±6.3 years of age.

respectively; two other trees not included with the 18 samples formed 1972 flood rings at ages 51 and 53 years, respectively. It is concluded that older trees are physiologically capable of recovering from flood damage and that the low frequency of minor-flood rings in older trees is because minor floods do not inundate the crowns of large trees.

Hydrologic factors associated with flood-ring formation were studied by comparing tree ages at the last minor-flood ring with flood frequency and exposure (fig. 17). The entire collection of harvested trees was considered, although trees were excluded if germination was after 1956 or if roots were above the stage of the 2-year flood.

Seven trees grew in moderately sheltered zones downstream from Difficult Run. Five were clustered in the lower part of the study area (see fig. 1), and minor-flood rings last formed when the trees were from 10 to 16 years of age; two other trees were in the upstream part of the study area and had lower age values (fig. 17). Of the five clustered trees, one was approximately 12 m in height in 1980, but all flood rings were formed within the first 16 years of growth. For another tree, stem height in 1980 was 6 m, and

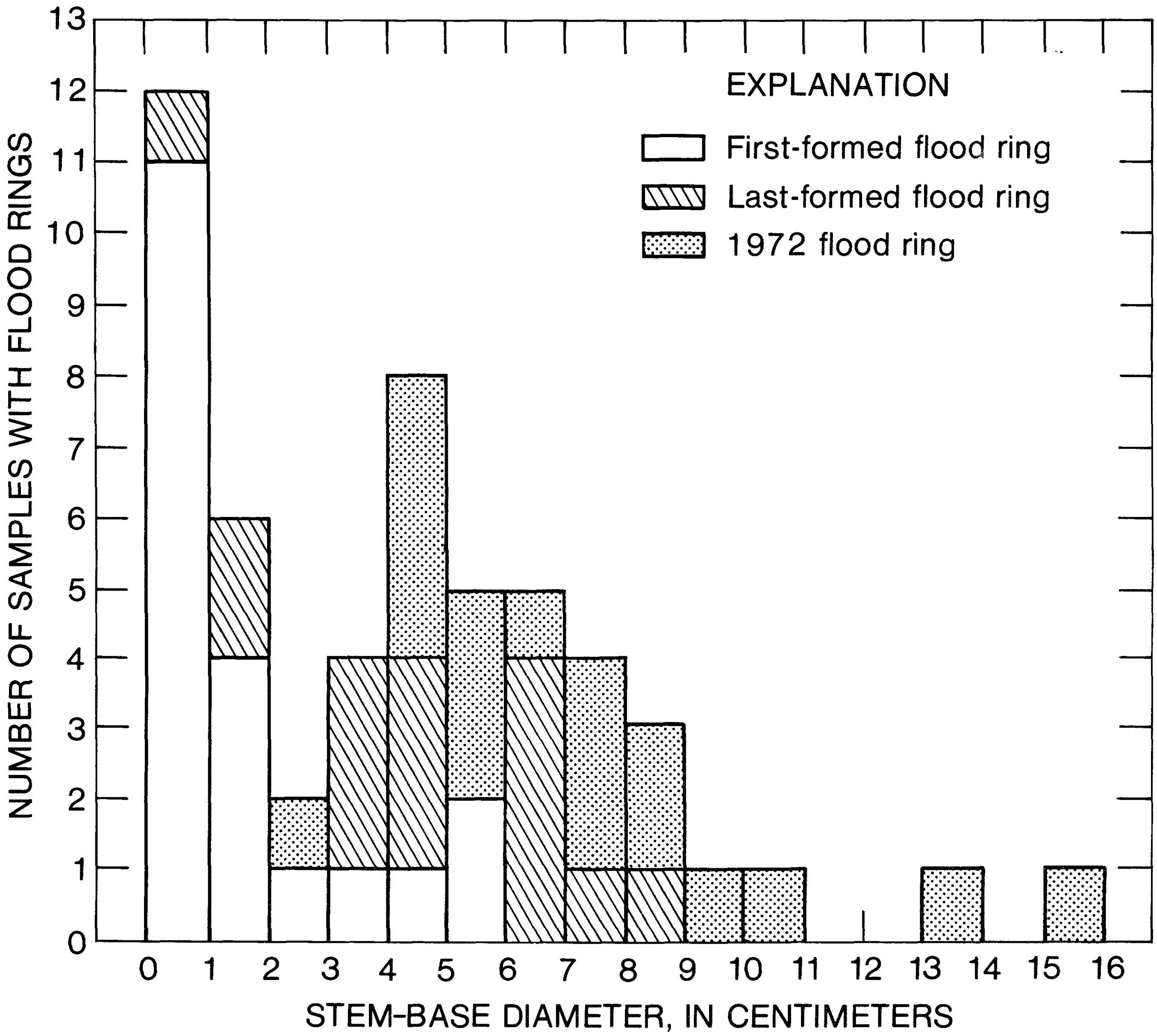


Figure 16. Trunk diameters of 18 trees at times of flood-ring formation. Samples are the same as those in figure 15. Average diameter when flood rings first formed was 1.3±1.1 cm. Flood rings last formed after minor floods when trees were 4.9±2.1 cm, and average diameter of trees with flood rings in 1972 was 7.5±3.2 cm.

the interval between germination and formation of the final minor-flood ring was 14 years. This interval for three other trees was 10, 10, and 16 years, although, in 1980, each tree was small because aerial parts above breast height had been destroyed (one during the flood of January 1978; another by an undetermined, earlier flood; and the third was felled by beavers after the 1979 growth year). Nearby, undamaged trees of comparable ages and trunk diameters were 6 to 12 m tall, and it seems reasonable to assume that the three damaged trees had previously attained similar heights. These data indicate that flood-flow velocities, even during minor floods, are sufficient to damage small trees in moderately sheltered areas. Damage, however, is apparently less severe than along unsheltered reaches because trees attain greater height.

Trees from unsheltered reaches formed flood rings until an older age than did trees from moderately sheltered or sheltered areas. Of 35 trees, 21 grew along unsheltered areas and, at harvest, ranged from 1 to 4 m in height. In some of these trees, vertical height was much less than stem length because the trees had been partly uprooted. Unsheltered trees on surfaces flooded by less

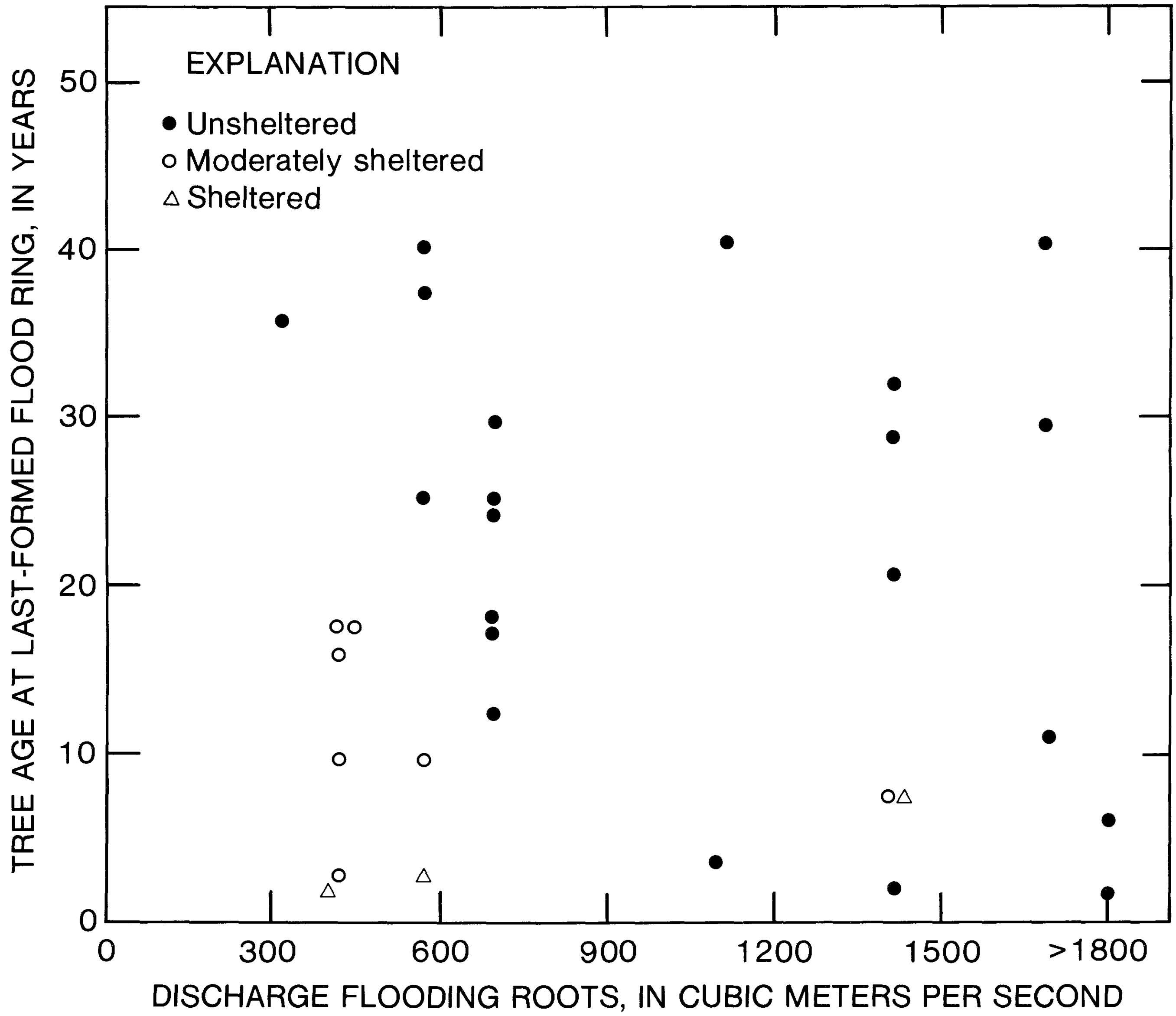


Figure 17. Ages at last minor-flood ring of 35 trees in zones of different flood frequency and exposure. All trees began growth before 1957. Because 4 of these 35 trees did not form flood rings, they are not graphed. These four trees, however, grew in sheltered zones. Two trees were flooded by 850 m^3/s and 1,100 m^3/s, respectively; the two others were flooded by about 2,800 m^3/s.

than 1,800 m^3/s were kept small by frequent damage, and the last flood rings of nine trees formed at ages greater than 28 years. Age values of the other 10 trees, however, ranged from 2 to 25 years. No relation was generally evident between age and decreasing flood frequency up to 1,800 m^3/s, although most age values of the unsheltered collection were greater than those of moderately sheltered and sheltered trees. Two small unsheltered trees on a surface flooded by about 2,500 m^3/s developed a final minor-flood ring in their second and sixth growth year, respectively. Both trees were about the same size and age as more frequently flooded trees that developed numerous minor-flood rings. It seems reasonable that minor-flood rings did not form late in the lives of both trees because flood damage is infrequent on high flood-plain levels.

Sheltered ash trees show few external signs of flood damage other than occasional corrasion scars, and ring-width patterns are less variable than those of trees from other flood-exposure zones (Yanosky, 1982b). Seven trees from sheltered locations were harvested along the Difficult Run study site, and numerous others were sampled with an increment borer. Four harvested trees did not develop minor-flood rings, and two others formed final minor-flood rings at 2 and 3 years of age, respectively. The seventh sheltered tree began growth in 1946 and formed a flood ring in 1952. Although the base of this tree was flooded by 1,400 m^3/s, it grew directly downstream from a large protective rock wall. This tree, and possibly much of the lowest part of the wall, were inundated by the April 1952 flood, the largest growing-season flood (4,190 m^3/s) between germination of the tree and 1972. In other words, some of the sheltering effect was lost, and the tree was damaged. Minor-flood rings were not observed in other sheltered trees cored with an increment borer, although, as mentioned previously, growth anomalies are sometimes not detected by this sampling method.

The data in figure 17 strengthen the hypothesis that, along uniform altitudes of the Potomac River flood plain, flood-channel geometry is the major factor controlling the growth and development of flood-plain forests. Trees in high-damage zones continue to suffer periodic damage and thus remain small, whereas trees in more sheltered zones commonly attain crowns above all but the greatest floods. Tree size (height) and form are, to a great extent, functions of flood-flow dynamics (Yanosky, 1982a, b).

The presence of numerous flood rings in certain trees indicates that these trees are "recorders" of many floods. Fifteen trees each developed at least 5 minor-flood rings, three trees had 10 or more, and one formed 18 flood rings. These three trees grew along an extremely unsheltered reach near the main channel at Chain Bridge. The sparse vegetation along much of this flood plain does not reduce flood velocities along downstream parts of the reach, as is often typical where vegetation density is great. Crowns are kept narrow by constant flood pruning, and sprouts from surviving branches are smaller than the older stems they replace. This crown form, in turn, may increase the probability of flood-ring formation because damage sustained by floating debris may be greater than if the crown were larger and more robust. A small crown is a small "target," but this would decrease the probability of damage only if paths of debris are random with regard to the flood wave. Observations from shore and from a canoe suggest that paths are not random, even within a particular zone of flood exposure. Rather, debris is routed along flow "corridors." Velocities may differ between nearby debris corridors or may change with flow volumes, presumably because of changes in flood-channel roughness. Flow differences within these corridors may be somewhat analogous to the simultaneous temperature differences in adjacent areas commonly recorded during microclimatic studies. Trees with numerous flood rings may be those in zones where debris flows are heaviest. It is also possible that the preponderance of flood rings in some trees is due in large part to genetic or edaphic factors. Nevertheless, it is striking to find anatomical evidence in one tree for 18 of 26 minor floods.

FLOOD RINGS FORMED PRIOR TO 1930

Although flow data for the Potomac River near Washington, D.C., were not recorded prior to 1930, a gaging station at Point of Rocks, Md. (about 50 km upstream), has been in operation since 1895. The drainage area at this location is 25,000 km^2, whereas it is 29,950 km^2 near Washington, D.C. Peak-flow data from the Point of Rocks station were used as minimum estimates of pre-1930 peak flows within the study area. Tree-ring abnormalities, therefore, can be related to known floods even though local peak-discharge data are unavailable.

Only two of the harvested trees were growing prior to 1930. Of these, the older tree had an indistinct series of narrow center rings but appears to have begun growth in approximately 1920. The younger tree started to grow in 1922. A closely spaced row of flood vessels just outside the 1924 earlywood zone of the younger tree indicates that the tree was flooded in the early part of the growing season. The Point of Rocks gaging station recorded a flood peak of 7,850 m^3/s on May 13, 1924. The flood peak near Washington, D.C., was probably slightly greater than at Point of Rocks, making it the fifth largest flood of the century. No other flood rings were formed in either tree during the 1920's.

Wood samples from several large trees were extracted with an increment borer rather than as cut sections. These trees grow along a reach of Virginia shore just downstream from a convex channel bend near Difficult Run, and trunks are flooded every 2 to 5 years. None formed flood rings in 1972 because tree crowns remained above the crest elevation of the flood. The innermost rings, however, which formed when trees were smaller, were expected to contain anatomical evidence of large floods.

A latewood flood ring in the 1924 growth ring was observed in a tree that in 1981 measured 18 cm in diameter and approximately 10 m in height. The trunk is flooded by approximately

3,500 m^3/s but grows along a highly sheltered reach where current velocities at this discharge are less than 0.1 m/s. At the start of the 1924 growing season, the diameter of the tree was approximately 2.5 cm at a stem height of 1.5 m. The height of the tree was probably about 3 m, which is a conservative estimate because the tree grows in a wooded tract where competition for light is presumed to limit growth. The crown would have been damaged in 1924 if debris accumulated in this backwash zone had tipped the tree or if the flood stage were high enough to increase current velocities within the zone. Neither occurrence is likely during small floods, but deposition of debris and damage to small trees in this vicinity have been observed after large floods in June 1972 and February 1979 (5,830 m^3/s). Thus, the anomalous growth observed in this tree is consistent with flood damage in 1924.

Another large tree near the previous sample grows in a less protected reach and is flooded about three times each year. The tree began growing in about 1890 and shows evidence of at least three, and possibly five, floods prior to 1930. An earlywood flood ring developed in the 1893 growth increment and would be expected to have formed after a flood in early to mid-May. A diffuse flood ring in the 1894 latewood suggests flood damage in late May or June. Both of these flood years were before gaging records were kept at Point of Rocks. Diffuse flood rings also appear to be present within the inner latewood zones of the 1907 and 1908 growth rings. Abnormal vessels in 1908 are larger and in a more ring-like pattern than those in 1907. Peak flows at Point of Rocks were 2,660 m^3/s (June 3) in 1907, and 2,750 m^3/s (May 8) and 3,480 m^3/s (May 23) in 1908.

At the time of the flood of May 1924, this tree was at least 10 cm in diameter near the base and probably no less than 5 m in height. As in the tree growing nearby at a higher altitude, a flood ring developed within the 1924 latewood zone. The diameters of some of the flood vessels are nearly as large as those of typical earlywood vessels. No flood rings were observed in growth increments forming after 1924.

The oldest tree sampled with an increment borer started to grow in approximately 1865 just downstream from a rock cliff that protects the tree from high current velocities during minor flooding. The base of the tree is flooded approximately twice every 3 years. The tree has a single, well-defined flood ring in the outer latewood in 1889, followed by a series of 30 narrow, indistinct rings (fig. 18). In 1889, the tree was approximately 9 cm in diameter and possibly as much as 5 m in height, and only a high-magnitude flood could have inundated the crown. The large diameter of vessels near the base of the tree and the narrow rings beginning in 1890 are evidence that the crown was severely damaged in the 1889 growing season. A peak discharge of 13,000 m^3/s on June 2, 1889, was estimated from flood marks at Point of Rocks and is approximately that of the maximum known flood near Washington, D.C. (13,700 m^3/s on March 19, 1936).

Growth rings from two trees collected in 1960 by R. S. Sigafoos were also studied for anatomical evidence of flooding prior to 1930. Because Sigafoos cut down trees rather than sampling them with an increment borer, a more precise anatomical study was possible. These trees started to grow in 1905 and 1920, respectively, along a rocky, frequently flooded reach near Chain Bridge where flood-flow velocities are great. The younger tree formed an earlywood flood ring in 1924 (7,850 m^3/s at Point of Rocks) and a latewood flood ring in 1921 (2,510 m^3/s on May 6). In the older tree, evidence was found for 10 floods from 1907 to 1924. Earlywood flood rings developed in 1908 (2,750 m^3/s on May 8 and 3,480 m^3/s on May 23), in 1919 (1,830 m^3/s on May 12), in 1921, and in 1924. Well-defined, generally continuous latewood flood rings formed in 1907 (2,660 m^3/s on June 3), in 1910 (4,390 m^3/s on June 18), in 1913 (1,880 m^3/s on May 29 and 1,440 m^3/s on June 1), and in 1915 (3,600 m^3/s on June 4). A diffuse flood ring corresponded to a minor flood on June 17–18, 1916 (1,390 m^3/s). The intraring position of abnormal growth in both trees corresponds to the approximate date of flooding, with flood rings forming within the earlywood after floods in early to mid-May and within the middle or outer latewood after late May or June floods.

APPLICATIONS

Sampling strategies consistent with the findings of this study are recommended in using anatomical data to reconstruct flood histories. Strategies will further depend on whether the researcher desires to document as many floods as possible or to estimate the relative magnitude of floods. These may be most useful along streams where hydrologic records are lacking. Short-term records can be extended by flood-ring evidence, catastrophic floods can be documented, and the mini-

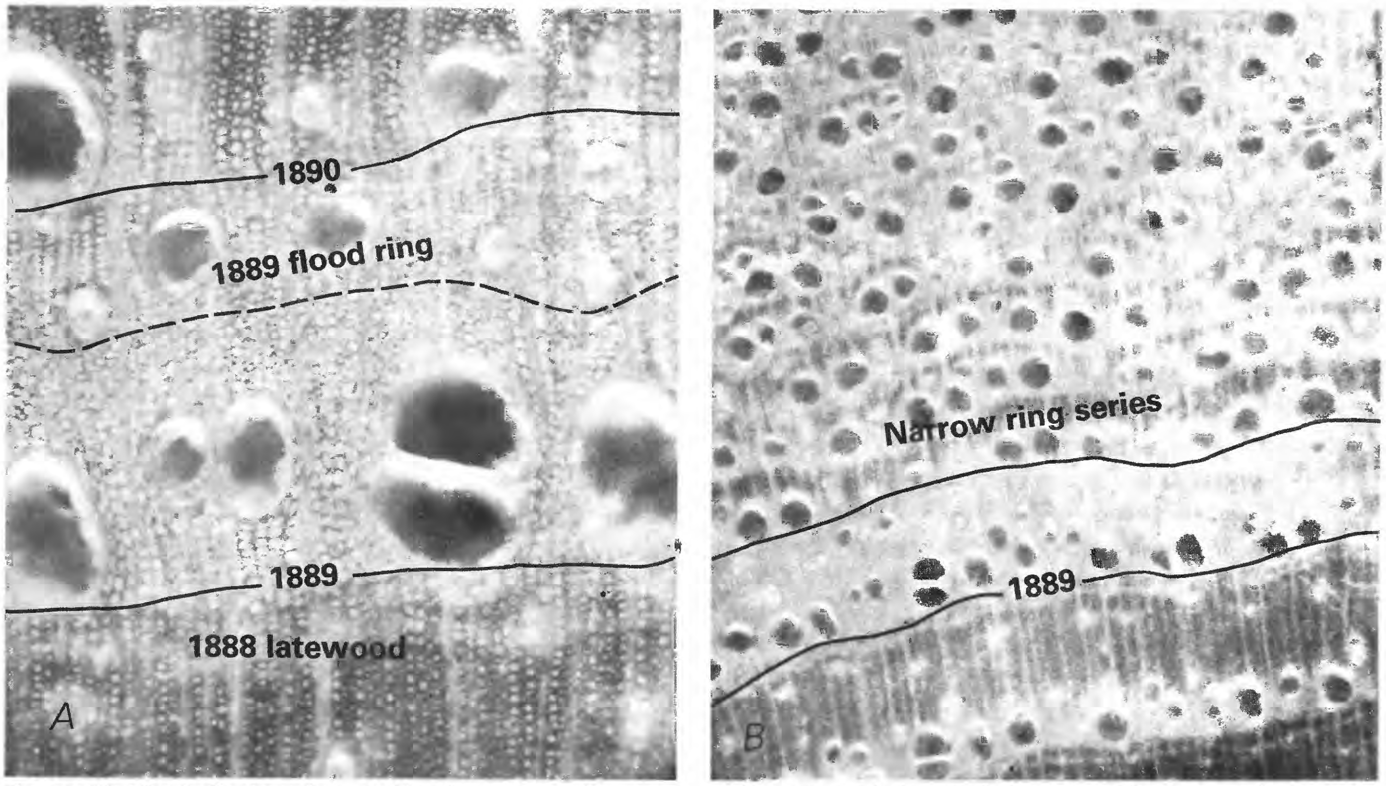


Figure 18. Wood of a tree damaged by the catastrophic flood of June 2, 1889 (estimated discharge 13,000 m^3/s near Point of Rocks, Md.). *A*, Flood ring formed in the lower trunk. Note that postflood growth in 1889 was minimal even though the flood occurred in the middle part of the growth year. *B*, Part of increment core showing ring-width patterns before and after 1889. The 20 growth rings prior to 1889 had an average width of about 2.0 mm. The 30 rings forming after 1889 averaged only about 0.4 mm, and ring widths comparable to those before 1889 did not develop again until the early 1920's. Narrow rings probably resulted from extremely severe damage in 1889. *A*, X70; *B*, X20.

mum crest stage can be estimated along local stream reaches.

Although only one genus (*Fraxinus*) was studied, flood rings have also been noted in swamp white oak (*Quercus bicolor* Willd.) collected near Chain Bridge and possibly in a post oak (*Quercus stellata* Wang.) specimen collected near Great Falls by J. F. Hill. Flood-related growth anomalies might be expected in elm (*Ulmus*) and hickory (*Carya*), both of which have easily distinguishable ring boundaries. Other flood-plain species, such as maple (*Acer*), willow (*Salix*), and sycamore (*Platanus*), are abundant on most flood plains in eastern North America, but their ring boundaries are difficult to determine. Willow, in particular, might be a useful indicator of recent floods because it commonly grows near the low-water channel. It is unknown whether flood-related growth develops in coniferous species.

Despite these possibilities, the author highly recommends ash. This genus grows under a wide range of edaphic and hydrologic conditions, has conspicuous growth rings, and occasionally attains advanced age. Although primarily a north temperate species, the genus is distributed southward into parts of Cuba and Mexico and is also found in northern Africa, southern Asia, and Java (U.S. Dept. of Agriculture, 1965). Ash may be damaged by floods smaller than those on a large river such as the Potomac. For example, flood rings have been observed in trees sampled along Difficult Run, Va., a small tributary of the Potomac River, and in sections harvested along Passage Creek, Va., by C. R. Hupp.

If the goal is to document as many floods as possible, trees along reaches of the low-water channel should be sampled. Trees with flood-trained crowns and numerous abrasion scars probably have the most flood rings. Trees can be cored first with an increment borer to determine whether anomalous growth is present. Most large floods are associated with well-defined, continuous flood rings that can be easily detected in increment cores. It may be advisable, however, to harvest several trees to become familiar with growth variations around the circumference and to detect diffuse flood rings that may otherwise not be observed. An upland tree might also be sampled for comparison. Stem and branch sections taken at intervals of 1 m or less are recommended. Skill in detecting latewood flood rings in ash is quickly gained even without an extensive anatomical background. Although anomalous earlywood growth may be difficult to recognize, the most striking examples can generally be identified. A 20X dissecting microscope is sufficient for studying samples that have been properly sanded and polished (see "Methods").

As the researcher becomes adept at recognizing patterns of abnormal growth, future samplings can be taken exclusively with an increment borer. Four core samples from each tree, preferably along the points of the compass, should be sufficient to detect most diffuse or discontinuous flood rings. It is also desirable to reach the center ring in at least two corings. Trees should then be marked in the event that additional samples are needed. If possible, it is also advisable to sample wood near the apex.

Trees of various sizes, ages, and growth forms should be sampled. Generally, flood rings are easiest to observe in the wide rings typically formed early in life, when trees were more likely to be damaged. Thus, the samples should include trees that began growth in successive decades, rather than just the oldest trees. This is desirable even if trees of different ages are about the same size. Trees sampled in this overlapping manner may provide a fairly complete flood-information series.

If the goal is to estimate relative flood magnitude (stage), several considerations are necessary. Flood rings common to a large percentage of samples may indicate a large flood. Smaller floods are associated with fewer flood rings and typically are restricted to trees on low flood-plain levels. The percentage of samples with flood rings during a flood year, therefore, is a rough measure of flood magnitude. In addition, large floods are typically associated with well-formed, continuous flood rings in basal stem sections, whereas anomalous growth restricted to apices is generally associated with minor-flood damage.

The crest stage of a flood can be estimated by sampling trees at progressively higher flood-plain levels until no further flood rings are found for that year. The height of the tallest tree damaged at the time of the flood can then be used as a minimum estimate of the flood crest. Height can be inferred by comparing the diameter in the flood year with that of trees presently of similar diameter. Alternatively, the tree can be cored at successive stem heights to determine the flood-year apex. An approximate crest stage can then be calculated by adding this height to the altitude of the trunk above the low-water channel.

Trees kept small by frequent flood damage are of little value for determining the crest stages of catastrophic floods. Evidence for catastrophic floods should instead be sought along reaches where damage is unlikely during smaller floods. Trees in low-damage zones commonly attain greater sizes and ages than those likely to be severely damaged or uprooted. Thus, trees downstream from convex channel bends may preserve anomalous growth that significantly extends the record of high-magnitude floods.

SUMMARY

The wood anatomy of ash commonly changes if flood-damaged crowns produce a second crop of leaves. Flood vessels may form in any part of the ring but are most conspicuous in the latewood zone. Latewood flood rings develop after floods from mid-May to early August. Anomalous earlywood growth develops after floods in the early part of the growing season and is generally more variable and difficult to interpret than anomalous latewood growth. Occasionally, a single flood is associated with both growth patterns along different parts of the circumference of an annual ring. Thus, anomalous growth not only documents a flood, but, in most cases, the time of the flood can be estimated from the position of the pattern.

The number of flood rings corresponding to flood years on the Potomac River during the growing season (approximately April 15 to August 31) is summarized in table 9. From 1930 to 1979, anatomical evidence was found for each flood year except 1966. Evidence was also found for catastrophic floods in 1889 and 1924 and for smaller floods from 1893 to 1921.

Within unsheltered and moderately sheltered flood zones, the frequency of flood rings seems in large part related to tree size and flood magnitude. For example, floods in 1942, 1949, 1951, 1952, and 1960 were among the largest (excluding 1972) during the study period, and numerous corresponding flood rings were detected. Fewer flood rings formed after smaller floods. Most tall trees developed flood rings only before they became large, whereas trees remaining small from frequent flood damage commonly formed flood rings throughout life; that is, increased age did not preclude the development of flood rings.

A catastrophic flood in 1972 was associated with anomalous growth in large trees only if crowns were inundated.

Anomalous growth patterns associated with large floods are generally more continuous around the ring circumference than are those from small floods. Minor-flood vessels are typically small, highly diffuse, and discontinuous and, consequently, may be difficult to observe unless entire cross sections are available. More importantly, minor-flood rings typically develop only near the stem apex. Flood rings associated with larger floods also develop near the base, although vessels are larger and more closely spaced near the apex. Apparently, this is because anomalous growth develops basipetally in response to a diminishing gradient of hormones produced during refoliation. It is assumed that the amount of diffusable hormones is proportional to the degree of refoliation, which, in turn, seems to depend on the amount of crown damage. Large floods are more likely than small floods to damage the crowns of most trees and, therefore, are more likely to initiate flood rings near the base of the trunk. Small trees near the channel, however, may be damaged even by minor floods and thus develop anomalous growth at all stem heights.

Trees with the most flood rings grew along unsheltered or moderately sheltered reaches. Within these zones, trees near the low-water channel formed more flood rings than did those at less frequently flooded altitudes. Trees that are presently tall developed abnormal growth only before crown height exceeded the crest altitude of most floods or if floods were extremely large. Trees in sheltered areas are seldom damaged during small floods and are taller and older than trees along exposed reaches; nevertheless, they may be damaged during catastrophic floods. Thus, evidence for maximum-record floods may be preserved in sheltered trees longer than in trees at more exposed sites.

Table 9. Summary of flood rings formed in 49 trees, 1889 to 1979. Three trees were sampled with an increment borer, and 46 were cut down. Depauperate and discolored tissues are not included

[—, no abnormal growth detected]

Year	Number of flood rings per year			Total
	Latewood	Earlywood	Combination	
1889	[1]1	—	—	1
1893	—	[1]1	—	1
1894	[1]1	—	—	1
1907	[2]2	—	—	2
1908	[1]1	1	—	2
1910	1	—	—	1
1913	1	—	—	1
1915	1	—	—	1
1916	1	—	—	1
1919	—	1	—	1
1921	1	1	—	2
1924	[1]2	2	—	4
1932	—	1	—	1
1933	—	1	—	1
1937	—	4	—	4
1938	2	1	—	3
1939	—	3	—	3
1940	1	3	—	4
1942	9	3	2	14
1943	1	5	1	7
1944	—	5	—	5
1945	1	—	—	1
1946	7	—	1	8
1948	—	2	—	2
1949	13	2	—	15
1950	2	3	—	5

Table 9. Summary of flood rings formed in 49 trees, 1889 to 1979. Three trees were sampled with an increment borer, and 46 were cut down. Depauperate and discolored tissues are not included—Continued

Year	Number of flood rings per year			Total
	Latewood	Earlywood	Combination	
1951	9	3	—	12
1952	—	11	1	12
1953	—	6	—	6
1955	1	—	—	1
1956	2	—	—	2
1958	—	4	1	5
1959	2	—	—	2
1960	2	8	1	11
1961	—	1	—	1
1964	—	—	1	1
1967	—	1	—	1
1968	2	2	2	6
1970	2	—	—	2
1971	1	[3]1	—	2
1972	33	—	—	33
1973	—	7	—	7
1974	1	[3]1	1	3
1975	—	2	—	2
1978	—	3	—	3
Total	103	89	11	203

[1]Sampled with increment borer.
[2]One tree sampled with increment borer.
[3]Formed after early June flood and thus not listed in table 5.

References Cited

Fritts, H. C., 1976, Tree rings and climate: London, Academic Press, 567 p.

Harrison, S. S., and Reid, J. R., 1967, A flood frequency graph based on treescar data: North Dakota Academy of Science, Proceedings, v. 21, p. 23–33.

Osterkamp, W. R., and Hedman, E. R., 1977, Variation of width and discharge for natural high-gradient stream channels: Water Resources Research, v. 13, p. 256–258.

Phipps, R. L., 1967, Annual growth of suppressed chestnut oak and red maple, a basis for hydrologic inference: U.S Geological Survey Professional Paper 485–C, 27 p.

Sigafoos, R. S., 1964, Botanical evidence of floods and flood-plain deposition: U.S. Geological Survey Professional Paper 485–A, 35 p.

U.S. Department of Agriculture, 1965, Silvics of forest trees of the United States: 762 p.

Wareing, P. F., Haney, C. E. A., and Digby, J., 1964, The role of endogenous hormones in cambial activity and xylem differentiation, *in* Zimmerman, M. H., ed., The formation of wood in forest trees: London, Academic Press, 562 p.

Yanosky, T. M., 1982a, Effects of flooding upon woody vegetation along parts of the Potomac River flood plain: U.S. Geological Survey Professional Paper 1206, 21 p.

_____ 1982b, Hydrologic inferences from ring widths of flood-damaged trees, Potomac River, Maryland: Environmental Geology, v. 4, p. 43–52.