Effects of Flooding Upon Woody Vegetation along Parts of the Potomac River Flood Plain

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1206

EFFECTS OF FLOODING UPON WOODY VEGETATION ALONG PARTS OF THE POTOMAC RIVER FLOOD PLAIN

Potomac River at Great Falls Park, Va., June 22, 1972.

Effects of Flooding Upon Woody Vegetation along Parts of the Potomac River Flood Plain

By THOMAS M. YANOSKY

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GLOSSARY

Adventitious growth. Stems or roots that arise from parts of the plant where they would not arise under ordinary conditions. Adventitious growth often occurs following injury from flooding.

Alluvium. Sediment deposited by moving water.

Basal area. Cross-sectional area of a stem or trunk at breast height.

Botanical evidence. Evidence from vegetation for the past or present occurrence of geomorphic processes or land use.

Crest. The highest altitude of a flood.

Discharge. The rate of flow in a river or stream.

Flood. Any flow that rises above the banks and spreads across the flood plain.

Flood damage. In this report, the killing or injury of plants by flooding.

Flood plain. An area adjacent to a stream or river formed of deposition and erosion during floods.

Frequency. The average number of times per year that a given discharge is equaled or exceeded.

Monumented plot. In this report, study areas marked by concrete monuments that act as permanent reference points.

Peak discharge. The maximum discharge attained by a flood.

Recurrence interval. The average interval in years between flows that equal or exceed a given discharge.

Stage. The water-surface altitude of a stream.

Water year. The 12-month period, October 1-September 30.

Woody vegetation. In this report, trees and shrubs.

CONVERSION FACTORS

Units of measure used in this report are International System of Units (SI). The following factors can be used to convert SI units to U.S. customary units.

To convert from	*To*	*Multiply by*
centimeter (cm)	inch (in)	2.54
meter (m)	foot (ft)	3.281
	yard (yd)	1.094
kilometer (km)	mile (mi)	0.6214
meter^2 (m^2)	foot^2 (ft^2)	10.76
hectometer^2 (hm^2)	acre	2.471
meter^3 per second (m^3/s)	foot^3 per second (ft^3/s)	35.31

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ABSTRACT

A two-part study along the Potomac River flood plain near Washington, D.C., was undertaken to investigate the effects of flooding upon woody vegetation. Floods abrade bark, damage branches and canopies, and often uproot trees. The first study was of vegetation in five monumented flood-plain plots, which differed in the frequency and severity of flood flow over a 10-year period. Basal area and survival of trees appear to be related to velocity of flood flow, which in turn is related to flood magnitude and channel shape. However, the effects of flooding also depend on the nature of the flood-plain surface and size and growth habit of vegetation.

In the second study, a catastrophic flood following Hurricane Agnes in June 1972 was found to cause large-scale changes in the age, form, and species composition of flood-plain forests below Great Falls, Va. The impact of the flood depended primarily on the flow regime of the river; destruction was greatest in areas exposed to the maximum flood force, and minimal at sheltered locations. Age determinations from dead trunks and surviving trees suggest that most trees in severely damaged areas started to grow after the last great flood, which occurred in 1942. Trees along sheltered reaches survived several previous catastrophic floods. In addition, species varied in their ability to withstand damage from the Hurricane Agnes flood. The least likely to recover were species growing on infrequently flooded surfaces, which may explain, in part, their absence at lower flood-plain altitudes.

INTRODUCTION

Flood-plain forests are generally different from those on adjacent terraces and uplands. These differences in part are related to the local frequency, duration, and velocity of floodflow and are important in gaining an understanding of the hydrologic environment. In this study, woody vegetation along a part of the Potomac River between Washington, D.C., and Great Falls, Va., was investigated to determine the effects of flooding on plant growth and survival. In the first part of the investigation, vegetation was studied on two reaches of flood plain which differ in flood frequency and severity of flow velocities during high water. Another study area was in an upland forest which is never flooded. Woody stems were initially mapped and measured by personnel of the U.S. Geological Survey in a series of monumented plots in 1962 (flood plain) and 1965 (upland). Stems were remapped and remeasured after the 1972 growing season, and data from the two mappings were compared.

The second part of the study concerns specific effects of the catastrophic flood following Hurricane Agnes in June 1972. The age, form, and survival of flood-plain trees were studied where destruction was locally variable. Areas exposed to the maximum current velocities of the flood were compared to nearby reaches where vegetation was sheltered from severe floodflows.

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LITERATURE REVIEW

McGee (1891) defined a flood plain as land "within reach of the river and suffering overflows by freshets, or at least by great floods." More modern definitions emphasize dynamic associations between the stream and flood-plain formation (Kilpatrick and Barnes, 1964). During high flows, sediment may be deposited on flood plains, or previously deposited materials may be eroded away. The establishment of woody vegetation on flood plains is related to these processes in ways that are not completely understood. Seeds of some species germinate on thick alluvial deposits only after leaf litter and other organic debris have been removed by spring floods. Others are able to grow on thinly scattered alluvium overlying bedrock. Seedlings are often uprooted or buried by sediments due to flooding in late spring or early summer, suggesting that successful growth may coincide with periods of low flow (Sigafoos, 1964).

Once established, flood-plain forests may be inundated periodically for extended periods. Trees are often damaged by supernormal velocity and by debris transported at or near the water surface. Vegetation is most likely to be damaged or removed when velocity and quantity of debris are extreme, particularly when channels are choked with ice. Floods abrade bark, break branches and canopies, and often partially uproot trees. Although aerial parts may be lost, the roots are often not killed; stumps subsequently send out a profusion of adventitious sprouts and the tree survives.

Although literature on the ecology of flood-plain vegetation is abundant, most studies are primarily descriptions of bottomland communities and successional stages in their development. The most significant works are the vegetation studies along the Lower Illinois River (Turner, 1936), on flood plains of the Wabash and Tippecanoe Rivers, Ind. (Lindsey and others, 1961), and along the Raritan River, N.J. (Buell and Wistendahl, 1955; Wistendahl, 1958). Succession on an island in the Mississippi River was investigated by Schull (1944) and on levees along the Illinois River by Turner (1931). These and other studies confirm differences in climate, soils, and species composition between upland and flood-plain forests. Most workers believed that vegetational zones along flood plains represent normal successional stages that in time will be replaced by adjoining upland species.

Sigafoos (1961) offered the alternative hypothesis that flood-plain vegetation is related to the frequency and magnitude of looding. In a study along the White River, Ark., Bedinger (1971) found four distinct vegetation zones related to the frequency and duration of yearly flooding. Although he did not conclude that this was necessarily cause and effect, he found strong evidence for it. It seems unlikely, however, that flood frequency and duration alone control the distribution of vegetation along many eastern rivers and streams. Unlike the White River flood plain, eastern flood plains are often highly variable in width and topography, and the generally steeper stream gradients result in greater velocities. Trees in some areas are continually damaged or killed by floods. Factors such as flood magnitude and site characteristics explain the more variable nature of vegetation.

Other investigations have concentrated on the effects of partial or complete inundation on flood-plain vegetation. Hosner (1958) found that first-year seedlings of six flood-plain species died within 32 days after complete submergence and that different species died at different rates. In more extensive studies, Hosner (1960) found that seedlings survived for longer periods when only the roots were flooded because the crowns retained the capacity for gas exchange. Turner (1930) found that few trees along the Illinois River were killed when flooded for long durations during the fall and early winter of 1926 but suffered high mortality when inundated from April to mid-June in 1927. In a bottomland timber area permanently flooded by impoundment near the junction of the Illinois and Mississippi Rivers, Yeager (1949) found that standing water to a depth of 50 cm resulted in almost complete mortality of all trees within 8 years. Furthermore, mortality by species was highly variable, with white ash (*Fraxinus americana* L.) most resistant (8 years) and pin oak (*Quercus palustris* Muenchh.) most susceptible (3 years).

Broadfoot and Williston (1973) state that chemical properties of soil determine many of the effects of inundation upon roots. Toxic reactions may occur in soils with high sodium content, or in those which are highly acid. Harper (1938) attributed root mortality along the Canadian River, Okla., to oxygen deprivation after deposition of clay. Species vary in their abilities to develop adventitious roots and withstand leaf moisture deficits caused by the oxygen deficiency of saturated soils (Hosner and Boyce, 1962).

Other flood-plain studies have used botanical evidence to reconstruct the recent history of floods and flood-related phenomena. Sigafoos (1964) found that trees growing along the Potomac River near Washington, D.C., showed damage from numerous floods. By dating sprouts from inclined or broken trunks, flood dates could be determined. Sigafoos was also able to determine the year of burial of aerial shoots from changes in wood anatomy during subsequent growth. Similarly, Everitt (1968) used cottonwood (*Populus sargentii* Dode) as an indicator of channel movement and flood-plain development along the Little Missouri River, N. Dak.

Botanical evidence may be valuable where stream-flow records are lacking or short (Sigafoos, 1964). Harrison and Reid (1967) tested this hypothesis by constructing a flood-frequency graph based on scarred trees along the Turtle River, N. Dak. Their graph approximated frequencies recorded in 25 years of hydrologic data. Helley and LaMarche (1973) determined radiocarbon dates for trees buried in ancient flood deposits to extend the record of known catastrophic floods of northern California streams.

FLOODING ON THE POTOMAC RIVER NEAR WASHINGTON, D.C.

A stream floods when the volume of flow is so great that stream stages overtop the banks and spread across the flood plain. Flow discharge is measured at stream-gaging stations and is expressed in cubic meters per second (m^3/s). Once recorded, the annual peak discharges at a site can be used to define a flood-frequency curve, which relates discharge to recurrence interval (Patterson, 1964). For example, a flood with a recurrence interval of 2 years is equaled or exceeded on an average of once every 2 years or has a 50 percent probability of being equaled or exceeded in any 1 year. Discharges for the Potomac River near Washington, D.C., were continuously measured from 1930 to 1964 by a water-stage recorder 1.6 km upstream from Brookmont, Md., and from January 1965 to the present by a water-stage recorder with concrete control located at Brookmont. Datum, or zero of the gage, is 11.57 m, National Geodetic Vertical Datum of 1929.

Between 1930 and 1971, the flood of March 19, 1936 (13,707 m^3/s), was the maximum recorded on the Potomac River near Washington, D.C. Large floods also occurred in October 1942 (12,649 m^3/s) and April 1937 (9,827 m^3/s). Prior to 1930, a flood in May 1924 was probably about 8,500 m^3/s, and a flood on June 2, 1889, was approximately as great as that of 1936. These and all other streamflow data cited in this report were obtained from surface-water records of the U.S. Geological Survey.

The flood in the wake of Hurricane Agnes crested near Washington, D.C., at 10,167 m^3/s on June 24, 1972 (Bailey and others, 1975). This is the third highest discharge of the century, exceeded only in 1936 and 1942. The river rose to flood stage early on the morning of June 22 and remained above that level through June 25. Floods of this magnitude can be expected approximately once every 30 years (Darling, 1959).

The impact of floods in the Potomac River basin may be determined by factors other than magnitude of flow. Although floods at the same site are considered identical if they have the same peak discharge, no two floods have the same flow characteristics and hence the same potential for damaging vegetation. The duration of flood-flow and the amount and type of debris may differ greatly. Most physical damage to trees appears to result from floating debris, particularly large logs or blocks of ice. Small winter floods preceded by unusually cold weather may culminate in destructive ice jams, such as those which occurred near Chain Bridge in 1948 and 1968. Winter floods are generally of greater duration than summer freshets, exposing trees to longer periods of damaging flows.

Similarly, destruction along the river is often highly variable due to differences in gradient, channel sinuosity, width and depth, and obstructions in the bed. Maximum damage is most probable along steam sections where flood velocities are high, especially during debris-choked events of long duration. Damage is less likely along the higher altitudes of flood channels because roughness near shore reduces flow velocities. Even here, however, smaller plants may be buried under sediment or blocks of ice and larger trees may be damaged.

Most flooding along the Potomac River near Washington, D.C., takes place during winter or early spring, when vegetation is dormant. As was mentioned earlier, even prolonged inundation does not usually kill flood-plain vegetation at this time, although continued submergence during the growing season may cause mortality to some species. However, flood durations seldom exceed a few days; even the greatest flows on record remained above flood stage for less than 5 days, and thus inundation alone probably kills only a small number of trees and shrubs.

THE MONUMENTED PLOT STUDY

METHODS

A series of seven monumented study plots was established in 1962 by R. S. Sigafoos along the Potomac River flood plain near Chain Bridge and on the upland near Washington, D.C. Three are on the flood plain in Washington, D.C., two are on the flood plain of the S. P. Spalding "Potowmack farm" in northern Fairfax County, and two are in an oak-hickory upland on the Spalding farm (fig. 1).

Each monumented flood-plain plot is a 0.04 hm^2 circle with a radius of 11.3 m. A concrete post marks the center and acts as a reference point. All trees and shrubs 0.8 cm or greater in diameter were identified and measured by Sigafoos following the 1962 growing season. Diameter measurements were at breast height (dbh), except for saplings less than 2.5 cm in diameter, which were measured near the base. The location of each plant was mapped by use of a plane table. No herbaceous vegetation was recorded. After 10 growing seasons, plants were remeasured and remapped by Sigafoos and the author.

Many flood-damaged species bear multiple stems, often arising from a buried trunk. The normal growth habit of some flood-plain species, such as spicebush (*Lindera Benzoin* (L.) Blume) and red osier dogwood (*Cornus Amomum* Mill.), is almost invariably a shrub-like clump of stems. Each clump was considered an individual plant, although the number of aggregated stems was recorded. The stem size assigned to each clump, thus to an individual plant, was that of the largest stem.

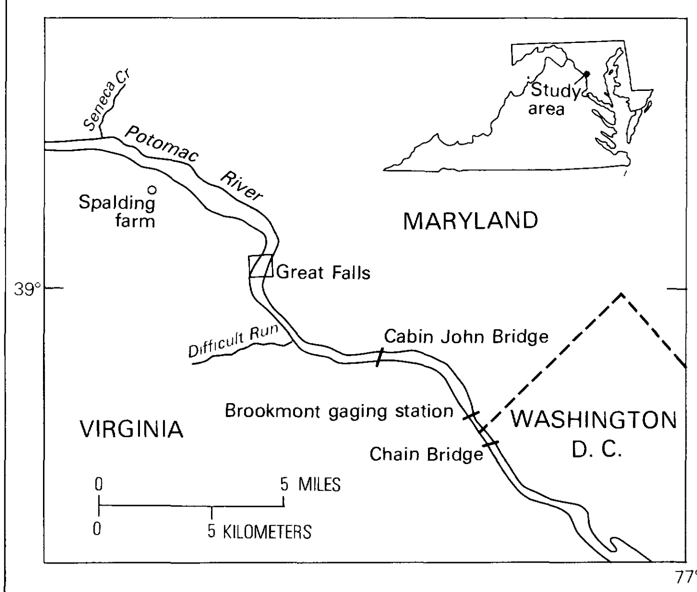

FIGURE 1.—Potomac River near Washington, D.C., showing study areas at Chain Bridge and Spalding farm. Base is from Washington and Baltimore quadrangle, 1:250,000.

From the 1962 and 1972 maps and data, the following computations were made for each plot: (1) total number of woody plants, (2) basal area (cross-sectional area at the point of measurement) of each species, (3) total basal area, which gives a measurement of standing crop per unit area, and (4) number of plants less than 2.5 cm in diameter and number greater than 2.5 cm. In addition, data were analyzed by species and size classes to determine which plants mapped in 1962 were still living in 1972. Surviving plants usually increased in basal area, although in some instances, as when large trunks were broken off and replaced by a mass of young sprouts, basal area was less.

The minimum discharge required to inundate each study plot was estimated from floodmarks and observations during high flows. Because the plots are nearly level, the discharge that inundates the fringes of the plot differs little from that which covers the entire area. The number of days that each plot was inundated is summarized in table 1.

The two upland study plots were originally mapped by Sigafoos and Phipps in 1965 (oral communication) and are contiguous 0.04-hm^2 rectangles.

THE STUDY AREAS

CHAIN BRIDGE

The Potomac River near Chain Bridge flows in a narrow channel bordered on the Virginia shore by steep palisades and on the Maryland-Washington, D.C. side by a broad, bedrock flood plain extending to the Chesapeake and Ohio (C & O) Canal. Channel width at this point increases dramatically from approximately 35 m at low flow to more than 335 m at flood stage (2,945 m^3/s). Bedrock increases gradually in altitude to the east and is covered at higher altitudes by alluvial deposits of variable thickness.

The straight channel, heavy flow volumes, and steep river bed descent of 11.6 m in 2.4 km between Brookmont, Md., and Chain Bridge result in high current velocities during floods. Leopold (1953) reports a maximum point velocity of 6.7 m/s at Chain Bridge during a minor flood on May 14, 1932. I estimated a surface velocity in the mainstream of at least 9 m/s during the flood of June 24, 1972, which had a peak discharge 10,167 m^3/s.[1]

Sigafoos (1961) lists 24 tree species common on the Chain Bridge flood plain. Predominant among these are sycamore (*Platanus occidentalis* L.), ash (*Fraxinus* L.), boxelder (*Acer negundo* L.), cottonwood (*Populus deltoides* Bartr.), river birch (*Betula nigra* L.), silver maple (*Acer saccharinum* L.), elm (*Ulmus* L.), and swamp white oak (*Quercus bicolor* Willd.). Most vegetation on the low bedrock flood plain is small and shrubby and shows damage from numerous floods and ice jams. Larger trees grow near the C & O canal, where floods are less frequent and flow velocities are lower. Alluvium overlies the bedrock. In spring, much of this area is a series of shallow swamps amid luxuriant masses of entangled vegetation.

The first permanent plot is about 60 m downstream from Chain Bridge and 35 m from the canal. This area is inundated by about 2,820 m^3/s, although it is not unusual for several years to elapse between floods of this magnitude. Leaf litter and other organic debris accumulate over the alluvium, and growth conditions for established trees are good. The largest trees in 1962 included an elm 43 cm and sycamores 69 and 104 cm dbh.

Most trees mapped in 1972 showed some flood damage. Few vertical trunks were observed, and many were deeply abraded on the upstream side. Most of this damage resulted from the June 1972 flood, which inundated the plot for about 4 days to a depth of 4 m at the crest. Despite this, the three largest trees survived.

Permanent plot 2 is about 600 m upstream from Chain Bridge and 150 m from the canal. Just upstream

[1]Estimations of surface velocities in this report were made by the surface-float method.

TABLE 1.—*Summary of flooding at seven monumented plots during 1963–72 water years*

Location	Plot	Discharge inundating plot[1] (cubic meters per second)	Number of floods during 1930–61 water years	Number of floods expected in period 1963–72[2]	Number of floods in period 1963–72	Total days of inundation
Chain Bridge ___	1	2,830	29	9	5	10
flood plain____	2	2,270	42	13	16	27
____	3	1,420	105	33	34	[3]83
Spalding farm __	4	2,550	37	12	10	17
flood plain____	5	2,830	29	9	5	10
Spalding farm __	6	Never flooded	—	—	—	—
upland ______	7	Never flooded	—	—	—	—

[1] Based on observation of stage at plot and simultaneous gage height for the Potomac River near Washington, D.C. Discharge at plot is believed to approximate discharge at gaging station.
[2] Calculated to compare flood frequencies during the study interval with the earlier period of 32 years.
[3] Includes 4 days representing peaks dependent on prior flows above 1,416 m^3/s (see Dalrymple, 1960, p. 12, para. 4.)

from the plot is a man-made tailrace running diagonally from the canal to the river. Parallel to the downstream edge of the tailrace is a ridge, about 3 m high, that acts as a levee for much of the area immediately below. Hence the plot is initially inundated at about 2,270 m^3/s by slow-moving backwaters that deposit alluvium over the bedrock. High velocities are reached only during floods exceeding about 2,900 m^3/s, when the tailrace levee is overtopped.

Alluvial deposits and lower frequencies of damaging floods in the plot have favored growth of larger trees than on bedrock areas of comparable elevation. Boxelder and ash exceeding 20 cm dbh were measured in 1962. The Hurricane Agnes flood (June 1972) damaged or destroyed all woody vegetation, completely removing most large trees and leaving others horizontal.

Permanent plot 3 is just upstream from the tailrace and at about the same altitutde as plot 2. Flooding at plot 3 occurs at about 1,420 m^3/s, and swift currents scour the bedrock. Alluvial deposits are confined to shallow depressions and other surface irregularities, and it is there that plants are growing. Most trees are shrubby and seldom exceed 8 cm dbh. This is probably due in part to the open environment and to the continual breakage of aerial parts and subsequent resprouting.

SPALDING FARM FLOOD PLAIN

Two flood-plain plots are located about 27 km upstream from Chain Bridge on the S. P. Spalding "Patowmack farm", in northern Fairfax County, Va. The channel here is about 730 m wide and the river flows slowly over a gradient averaging only about 1 m/km between Seneca, Md., and Aqueduct Dam (just above Great Falls). The river is shallow and dotted with islands and occasional riffles. Much of the flood plain in the Spalding farm study area is bordered along the channel by steep banks and hence not flooded until bankfull stage is exceeded. Alluvial soils are at least 4 m deep in some locations (Sigafoos, oral communication, 1975), and bedrock is exposed only along the edges of the main channel.

I estimated crest velocity of the June 1972 flood to be about 2–3 m/s in the main channel and at lower rates at increasing distance from the low-water channel. The main-channel velocity of smaller floods, such as those cresting March 22, 1963, and March 9, 1967, was estimated at approximately half that of the June 1972 flood.

Most woody species noted at Chain Bridge are also on the Spalding farm flood plain. Ash, boxelder, hackberry (*Celtis occidentalis* L.), sycamore, and elm are predominant, some exceeding 1 m in diamter. Less common are black walnut (*Juglans nigra* L.), basswood (*Tilia americana* L.), swamp white oak, swamp chestnut oak (*Quercus michauxii* Nutt.), and Shumard oak (*Quercus shumardii* Buckl.). Shrubs and small trees such as spicebush and pawpaw (*Asimina triloba* (1.) Dunal) abound in the understory. The flood-plain forest borders an oak-hickory upland or ends abruptly in cultivated fields.

Permanent plot 4 is on Patowmack Island, a small alluvial island near the Virginia shore about 2.3 km downstream from the mouth of Seneca Creek. The plot and most of the island are inundated by about 2,550 m^3/s. Six trees greater than 25 cm dbh were mapped in 1962, the largest a basswood 55 cm dbh. Spicebush was abundant in the understory.

Permanent plot 5 is on the Virginia shore, opposite plot 4 and about 100 m from the channel. It is inundated at about 2,830 m^3/s. Eleven trees exceeded 25 cm dbh in 1962, with a swamp white oak and a Shumard oak measuring 66 cm and 67 cm dbh, respectively. The understory was primarily spicebush and boxelder.

Vegetation on the Spalding farm flood plain shows damage from the Hurricane Agnes flood but not to the extent noted at Chain Bridge and at many other downstream areas. Some canopy and subcanopy sized trees were scarred or partly uprooted, although nothing comparable to the destruction of entire flood-plain forests was observed. Some small members of the understory were damaged or killed following burial by flood debris.

UPLANDS

Plots 6 and 7 are in an upland forest on the Spalding farm tract and have never been flooded. Most of this forest was selectively cut-over about the time of World War I (Sigafoos, oral communication, 1975) and is presently a privately owned wildlife refuge. Dominant canopy species include white oak (*Quercus alba* L.), scarlet oak (*Quercus coccinea* Muenchh.), red oak (*Quercus rubra* L.), black oak (*Quercus velutina* Lam.), mockernut hickory (*Carya tomentosa* Nutt.), pignut hickory (*Carya glabra* (Mill.) Sweet), and sour gum (*Nyssa sylvatica* Marsh.). Beech (*Fagus grandifolia* Ehrh.), tulip tree (*Liriodendron tulipifera* L.), cherry (*Prunus* L.), sassafras (*Sassafras albidum* (Nutt.) Nees), and flowering dogwood (*Cornus florida* L.) abound in the understory.

CHANGES IN WOODY VEGETATION

BASAL AREA

Numerous factors affect the growth and mortality of trees, and it is difficult to correlate changes in basal area solely with flooding. This study indicates that changes in basal area are most striking on frequently flooded surfaces at sites where flow velocities are high. Changes become less apparent on ground that is seldom flooded, and at sites where slower currents during high water are less likely to damage vegetation.

Basal area measurements at upland and flood-plain locations are shown in table 2. If flood plain plots are ordered by the minimum discharge inundating their surfaces, basal area cannot be related solely to flood frequency because of differences in the channels at the two locations. As was mentioned previously, flow velocities are higher at Chain Bridge than at the Spalding farm. However, basal areas at Chain Bridge increased as inundation discharge increased. For example, the 1962 basal area of plot 3 was 5.4 percent that of plot 2 and 2.8 percent that of plot 1. In 1972, the percentages were 38.6 and 3.3, respectively. This agrees with most field observations that trees at Chain Bridge are largest on infrequently flooded surfaces and progressively smaller nearer the river. Sigafoos (1961) related flood frequency to three general vegetation zones based on tree size and form near Chain Bridge.

Near the Spalding plots, woody vegetation is scarce along the steep banks that separate the low-water channel from the flood plain. Trees along the low-water channel are generally smaller than trees on the flood plain. However, unlike at Chain Bridge, the average size of trees of the same species seemingly does not increase on less frequently flooded portions of the flood plain. The basal area of plot 5 was nearly twice that of plot 4 after both mappings, even though both plots are inundated during great floods for approximately the same time interval (table 1). Plot 4, located more toward mainstream, may be exposed to greater flood velocities than is plot 5. Furthermore, near plot 5 are frequently flooded stretches with less sloping banks, commonly with large trees growing near the edge of the low-water channel. In some places, large trees grow on surfaces flooded by less than 550 m^3/s. These frequently flooded surfaces are exposed during floods to low velocities that deposit alluvium and rarely inflict serious damage to vegetation.

Differences between 1962 and 1972 basal area measurements were greatest at Chain Bridge, especially in the two most frequently flooded plots. Plot 2 decreased in basal area by 80 percent, while plots 1 and 3 increased by 23 percent and 44 percent, respectively. At the Spalding farm, where flood velocities are not as great, plot 4 decreased by 4 percent and plot 5 increased by 14 percent. The basal area of the two upland plots decreased by 7 percent and 1 percent in a somewhat shorter period.

Because large trees make up a greater percentage of total basal area in most of the plots, their fate has the greater influence on changes in basal area. In plot 1, for example, three large trees accounted for nearly 85 percent of the total 1962 basal area. Had one or more been killed between mappings, the 1972 figure would have been far less. However, each survived, and the additional 10 years of radial growth accounted for an increase in basal area despite high mortality among many smaller trees from the Hurricane Agnes flood. Basal area will continue to depend on these three trees, and since they survived a major flood equaled or exceeded on the average once in 30 years, they are unlikely to be killed or uprooted by more common floods. Mortality is more likely from other agents, such as windthrow, disease, insects, lightning, or senescence. Large fluctuations in basal area within this plot may thus be independent of flooding.

On frequently flooded surfaces, however, the range in size is generally less than on infrequently flooded surfaces, and basal area does not depend on a few large trees. Changes in stem number result in high percentage changes in total basal area. Basal area declines when flooding destroys many stems or increases when there is a profusion of new growth. For example, all stems measured in plot 3 in 1962 had diameters less than 8 cm; thus basal areas of largest and smallest stems differed only slightly. Frequent floods and extreme velocities during high water have prevented the growth of large trees. Germination of seedlings and continued production of sprouts from established roots cause large percent increases in plot basal area. On infrequently flooded surfaces, such growth has a negligible percent effect on total basal area. On the other hand, because stems in plot 3 are repeatedly broken off during high water, there are also large percent

TABLE 2.—*Basal area of woody vegetation at seven monumented plots*

Location	Plot	Inundation (cubic meters per second)	Basal area (square meters) 1962	1972	Basal area change (percent)
Chain Bridge	1	2,830	1.618	1.992	+23.1
flood plain	2	2,270	0.841	0.169	−79.9
	3	1,420	0.045	0.065	+44.4
Spalding farm	4	2,550	1.087	1.040	−4.3
flood plain	5	2,830	2.123	2.414	+13.7
Spalding farm	6	Never flooded	1.234	1.149	−6.9
upland[1]	7	Never flooded	0.942	0.931	−1.2

[1] Upland plots were mapped in 1965.

decreases. Basal area probably fluctuates significantly, being greatest after the growing season and smallest after winter or early spring floods.

It thus seems probable that fluctuations in basal area at Chain Bridge are greatest on frequently flooded surfaces and become less pronounced at higher altitutdes. Further supporting evidence is that all other study plots, including those on the Spalding farm flood plain and on the uplands, derived more than 99 percent of 1972 basal areas from continued growth of stems mapped in 1962; less than 1 percent resulted from stems which became measurable after that date. In plot 3, however, only 78.5 percent of the 1972 basal area resulted from originally mapped stems.

The 80 percent decline in basal area at plot 2 resulted primarily from the Hurricane Agnes flood. Perturbation on this scale had not occurred since 1948, when most vegetation was destroyed by an ice jam (Sigafoos, 1964). The presence of trees up to 20 cm dbh and a total basal area of 0.84 m^2 in 1962 suggest that even the August 1955 flood, 6,117 m^3/s, did not damage vegetation as severely as did the Hurricane Agnes flood. Minor floods during 1963–1971 water years, the largest being 4,163 m^3/s in March 1967, probably removed only a small number of trees; hence, just prior to the Hurricane Agnes flood, basal area was probably at least as great as at the 1962 mapping.

SURVIVAL

The survival and continued growth of originally mapped plants are primarily responsible for changes in basal area. It has already been noted that survival depends to a great extent on the channel characteristics at a particular location and not on flood frequency and duration alone. In addition to these factors, the size and growth habits of vegetation are important. In none of the flood-plain plots, for example, did survival of plants less than 2.5 cm exceed that of larger plants; on the uplands, however, survival for both size classes was about the same. At all sites, plants with multiple stems (clumps) survived at higher rates than did single-stemmed plants.

Numbers and survival percentages of plants at seven monumented plots are shown in table 3. On the uplands, 90 percent of the originally mapped plants survived in comparison with 40 percent on the five flood-plain plots. Differences in age and species composition only partly explain the lower survival at flood-plain sites. Survival of flood-plain plants ranged from 7 percent at plot 2 to 66 percent at plot 3; at plots 1, 4, and 5, which are inundated by flows exceeding 2,550 m^3/s, survival was approximately half that of the uplands.

Flood-plain plants with stem diameters exceeding 2.5 cm consistently survived at rates higher than did smaller plants. In plots 4 and 5, survival of plants greater than 2.5 cm compares favorably with that on the uplands; at plot 1, however, survival was about 25 percent lower, probably as a result of greater flow velocities at Chain Bridge. A similar trend was observed for plants less than 2.5 cm in diameter; survival on the Spalding farm flood plain exceeded that at plot 1 by about 50 percent, and on the uplands nearly 91 percent of the plants survived. Better established root systems may account for the increased survival of larger plants, while smaller plants may be more easily uprooted or buried by debris.

Plots 2 and 3 represent the extremes of flood-plain survival. Vegetation at plot 2, normally sheltered by the tailrace levee just upstream, was nearly all destroyed. At plot 3 there is no sheltering effect, and flooding is even more frequent; yet this plot had the highest survival percentage of any flood-plain tract. Part of the explanation may be that because frequent flooding has kept the vegetation small, trees were not battered by surface debris during the higher stages of the Hurricane Agnes flood. The larger trees in plot 2 were destroyed during higher flood stages when velocities and amounts of surface debris appeared greater. Debris

TABLE 3.—*Survival of plants at seven monumented plots*

Location	Plot	Inundation (cubic meters per second)	Total number of plants			Total plants <2.5 cm			Total plants ≥2.5 cm		
			1962	1972	Proportion surviving (percent)	1962	1972	Proportion surviving (percent)	1962	1972	Proportion surviving (percent)
Chain Bridge	1	2,830	142	66	46.5	66	18	27.3	76	48	63.8
flood plain	2	2,270	226	16	7.1	90	5	5.6	136	11	8.1
	3	1,420	47	31	66.0	23	13	56.5	24	18	75.0
Spalding farm	4	2,550	204	106	52.0	160	68	42.5	44	38	86.4
flood plain	5	2,830	765	336	43.9	690	275	39.9	75	61	81.3
Spalding farm	6	Never flooded	183	164	89.6	129	121	93.8	54	43	79.6
upland[1]	7	Never flooded	161	144	89.4	120	105	87.5	41	37	90.2

[1] Upland plots were mapped in 1965.

carried by flows of about 1-2 m above the surface of plot 3 possibly causes the greatest amount of stem breakage. However, velocities at such discharges were estimated at about 1.5 m/s and are unlikely to uproot plants.

There were small trees at plot 2, and nearly all were destroyed. A second factor may be the bedrock character of the flood plain above the tailrace. Because bedrock is resistant to erosion over short intervals of time, the surface probably remained essentially unchanged by flooding over the 10-year period. Due to frequent flooding, only those plants most firmly anchored in the bedrock have survived. Great floods may have no greater impact on this area than more frequent floods. In plot 2, however, alluvium was severely eroded by the Hurricane Agnes flood, in places stripping it to the bedrock and washing away much of the vegetation. It seems likely, therefore, that the flood-plain surfaces also influence survival of vegetation.

Many plants tallied in both 1962 and 1972 consisted of multiple stems. For example, of the 101 stems mapped in plot 3 in 1962, only 31 were single-stemmed plants; the remaining 70 stems comprised 16 plants. It is unknown how and to what extent this growth habit affected survival of 1962 plants. In all seven plots, however, plants with multiple stems survived at higher rates than those with single stems (table 4).

THE EFFECTS OF THE HURRICANE AGNES FLOOD ALONG THE POTOMAC RIVER DOWNSTREAM FROM GREAT FALLS

The effects of the Hurricane Agnes flood upon woody vegetation were observed in 1973 along a 4-km reach of the Potomac River downstream from Great Falls (fig. 2). Below the steep cataracts of the Falls, the river enters a deep and narrow gorge along a fault (U.S. Department of the Interior, 1970) where extremely high flow levels and velocities are reached during floods (figs. 3 and 4). Vegetation growing along the exposed rock walls of the gorge is flooded several times each year and is generally shrubby and of poor form. Sycamore, willow (*Salix* L.), elm, and ash are abundant. On higher, infrequently flooded terraces, red oak, chestnut oak (*Quercus prinus* L.), post oak (*Quercus stellata* Wangenh.), mockernut hickory, pignut hickory, and Virginia pine (*Pinus virginiana* Mill.) predominate.

In the lower part of the 4-km reach below Great Falls, the channel widens near Difficult Run and turns sharply to the northeast, followed closely by a sharp southeastern turn. Alluvium overlies the bedrock in numerous localities, supporting mixed flood-plain forests of sycamore, willow, boxelder, silver maple, river birch, and cottonwood. The four latter species are rare in the upper gorge.

Specific sites in the gorge and near Difficult Run were arbitrarily chosen where damage was greatest, and in other tracts where damage was minimal. At each site, the condition of flood-plain forests was related to the flow regime during floods. At some places, ages of survivors were determined. Also investigated was the ability of various flood-plain and upland-terrace species to recover from damage incurred during Hurricane Agnes. Tallies of species were taken in transects of arbitrary length and in several 10-m by 10-m plots. Species that are rare on the steep bedrock in the gorge were studied on broad alluvial flood plains near Difficult Run.

EFFECTS OF LOCAL SITE CHARACTERISTICS

This study indicates that maximum damage to vegetation occurred on flood plains adjoining outside bends of the main channel, where floodflow velocities appeared greatest. In these areas, large tracts of flood-plain forest were destroyed. Along the inside of channel bends, where trees were sheltered from high floodflow velocities, damage was minor (fig. 5). This "sheltering effect" was also observed on a local scale where destruction otherwise was greatest; some trees immediately downstream from rock outcrops suffered little damage even though other trees in the general vicinity were

TABLE 4.—*Survival of single-stemmed and clumped plants at seven monumented plots*

Location	Plot	Single-stemmed plants			Clumped plants		
		Number 1962	Number surviving, 1972	Proportion surviving (percent)	Number 1962	Number surviving, 1972	Proportion surviving (percent)
Chain Bridge	1	139	64	46.0	3	2	66.7
flood plain	2	223	15	6.7	3	1	33.3
	3	31	20	64.5	16	11	68.8
Spalding farm	4	153	69	45.1	51	36	70.6
flood plain	5	664	270	40.7	100	66	66.0
Spalding farm	6	175	156	89.1	8	8	100
upland[1]	7	153	136	88.9	8	8	100

[1] Upland plots were mapped in 1965.

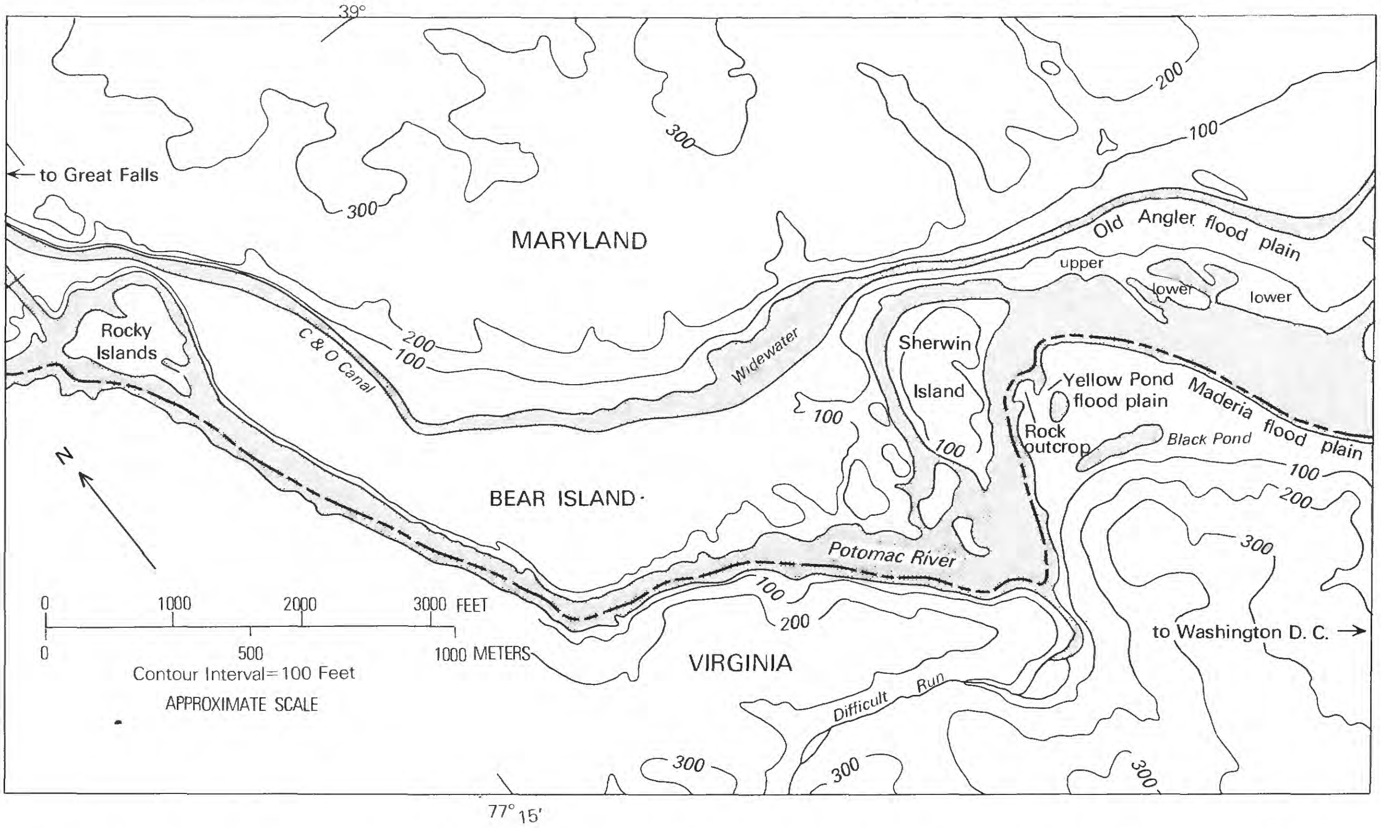

FIGURE 2.—Potomac River downstream from Great Falls showing study area. Map is enlarged from Falls Church, Va., quadrangle, 1:24,000.

FIGURE 3.—Downstream view of the Potomac River along the upper gorge below Great Falls in November 1968. Discharge is approximately 85 m^3/s. Floods such as those occurring in 1936, 1937, 1942, and 1972 covered the tops of the gorge.

FIGURE 4.—High water (about 4,250 m^3/s) in lower study area just upstream from Difficult Run. The water is about 6 m above summer levels.

destroyed. These findings suggest that characteristics of the main channel and flood plain, in addition to flood frequency and duration, determine many differences in composition, age, and form of flood-plain forests.

Many trees were killed on a 100-m by 30-m alluvial tract ("Yellow Pond flood plain") about 600 m east of Difficult Run. The location of this area and others is shown in figure 2. Prior to Hurricane Agnes, a silver maple-ash-cottonwood forest grew on this tract just downstream from a series of high rock walls. Even during the 4,163 m^3/s flood peak of March 9, 1967, inundated trees were sheltered from main-channel velocities, and

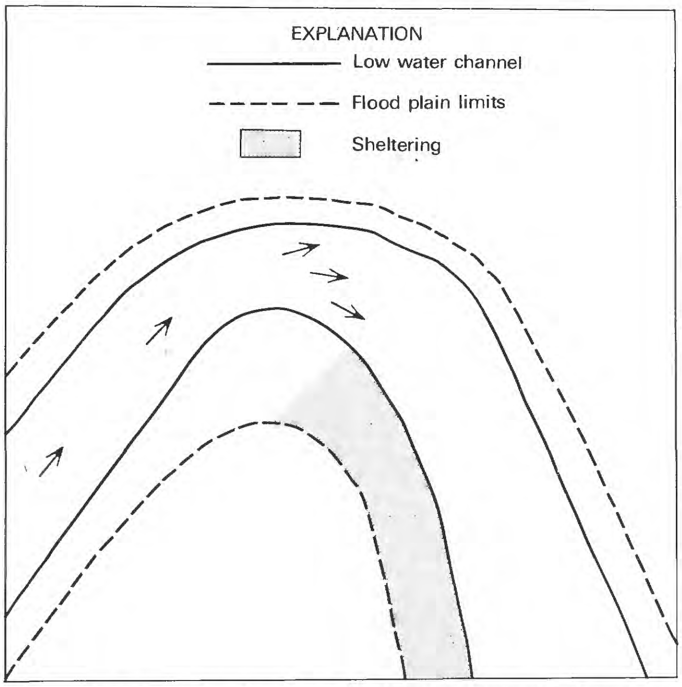

FIGURE 5.—Representation of sheltering during floods along inner and outer channel bends.

little damage was observed (fig. 6). The Hurricane Agnes flood, however, roared through a large gap in the rocks and swept across the downstream half of the tract, destroying all vegetation (fig. 7). In July 1973 a 20-m by 10-m plot on this lower part supported no trees, and in some areas the alluvium had been stripped to bedrock. A plot of identical size on the upstream half of the flood plain supported 20 trees. Tops of the rock walls sheltering this plot remained above the Hurricane Agnes flood, and 8 of 11 trees directly below were still living (fig. 8). Four showed little or no damage. Trees in the remainder of the upstream plot, however, grew just below a smaller wall inundated by about 5,000 m^3/s, and only 3 of 9 trees survived (table 5).

At the age of the main channel and adjacent to Yellow Pond flood plain is a large rock outcrop. The upstream face forms a vertical cliff about 10 m above the river at low flow, with the downstream wall sloping steeply to an alluvial flat at its base. In 1973, this flat measured 35 m by 20 m and was inundated by approximately 1,130 m^3/s. Prior to Hurricane Agnes, willow and silver

FIGURE 6.—The lower tract of the Yellow Pond flood plain along the Potomac River during the flood of March 9, 1967, peak flow 4,163 m^3/s. Trees are sheltered from flood currents by a rock wall just upstream. View is from the Virginia shore toward the main channel, which flows from left to right.

FIGURE 7.—The lower tract of the Yellow Pond flood plain in 1975. View is from the main channel looking toward the Virginia shore.

maple grew on the lower alluvium, with cottonwood, ash, and bitternut hickory (*Carya cordiformis* (Wangenh.) Koc) predominating on the higher alluvial surfaces. Red oak, chestunut oak, and black locust (*Robinia pseudoacacia* L.) grew along the downstream rock wall.

Vegetation is sheltered from high velocities, presumably until the entire outcrop is inundated at about 8,500 m^3/s. Even at about 5,700 m^3/s, when water is within about 4 m of the top of the rock, a large eddy extends immediately downstream; minor abrasion and breakage of stems may be caused by large pieces of debris floating in the backwash, but large trees are rarely destroyed. The Hurricane Agnes flood completely inundated the outcrop and eroded away part of the alluvium below (fig. 9), battering vegetation with currents estimated to exceed 9 m/s. Although the number of uprooted trees is unknown, all willows and most small trees were removed. Of those remaining, most were damaged, some so severely that they could be identified only by wood characteristics. Of 14 trees still standing in July 1973 on the downstream half of the tract, 10 were dead; 16 of 24 trees on the upstream half of the island were also dead (table 6).

Of four trees directly below the highest part of the rock wall, however, a red oak and two bitternut hickories showed no signs of damage. A third bitternut had a broken canopy. These four trees were cored with an increment borer to determine the years of germination. Unfortunately, all trees had rotten centers and exact ages could not be obtained. The partial core showed that the largest hickory started to grow before 1890. The crown-damaged hickory could be less precisely dated because a larger part of heartwood had rotted. The hickory was at least 38 years old at the time of the

FIGURE 8.—View of the upper tract of the Yellow Pond flood plain in 1975 and part of the rock walls just upstream. A small pond may be seen in the background at left. Note the striking difference between the upper and lower tracts of the flood plain. (See fig. 7.)

hurricane Agnes flood. Three cores from different sides of the red oak trunk averaged 24 years in 70 mm. Because this is only about one fourth of the total radius, the tree is probably considerably older.

At least three of these sheltered trees survived great floods in 1924, 1936, 1937, and 1942 that approximated or exceeded the discharge of the Hurricane Agnes flood. The oldest hickory (and perhaps the red oak) was alive during the flood of June 2, 1889, which was approximately the same magnitude as the March 1936 flood.

Downstream from the Yellow Pond flood plain, the river turns sharply to the southeast. Damage was minimal to trees on the Virginia shore ('Madeira flood plain') downstream from the inner bend. The gently sloping, alluvial flood plain supports a silver maple-ash-cottonwood forest; some trees reach 1 m dbh, and many grow on surfaces flooded by less than 700 m^3/s. Few trees were uprooted during the Hurricane Agnes flood, and most damage was confined to minor bark abrasions and shearing of low limbs.

On a 600-m reach of Maryland shore ('Old Angler flood plain') along and downstream from the outer bend most trees received the major force of the flood and were partly uprooted or destroyed (figs. 10, 11, and 12). This was most striking on a 100-m reach along the upstream part of the Old Angler flood plain. During floods of less than about 4,250 m^3/s, this area is sheltered by a rock outcrop just upstream, and a silver maple-sycamore-cottonwood forest developed. Downstream from this forest the sheltering effect is gradually lost, resulting in thin alluvial deposits or exposed bedrock at most locations. In contrast to the denser forest of larger

TABLE 5.—*Summary of condition of trees still standing in July 1973 on a 20-m by 10-m plot on the Yellow Pond flood plain just downstream from the protective wall*

Species	Diameter at breast height (centimeters)	Status[1]	Condition[2]
Behind rock shelter covered by the Hurricane Agnes flood			
Ash[3]	15/13	S/S	4/4
Ash	8	D	
Boxelder	8	D	
Boxelder	8	S	4
Birch, river	—	D	Diameter unknown.
Blue beech	10	D	
Elm[3]	51/56	D/D	Possibly dead prior to Hurricane Agnes.
Hickory, bitternut	8	D	
Maple, silver	31	S	1
Behind rock shelter not covered by the Hurricane Agnes flood			
Ash	31	S	2
Ash	20	S	1
Birch, river	10	D	
Black locust	10	S	1
Blue beech	13	S	2
Blue beech	8	D	
Blue beech	5	D	
Tulip tree[3]	51/10	S/S	1/1
Basswood	13	S	3
Hickory, bitternut	38	S	1
Oak, red	10	S	Cut by beavers in 1973.

[1] Status: D=Dead; S=survived.
[2] Condition: 1=no or little flood damage; 2=partially uprooted; 3=horizontal; and 4=broken or heavily damaged crown.
[3] Diameter, status, and condition for two-trunked tree.

trees along the upstream reach, most vegetation on bedrock was small and shrubby prior to Hurricane Agnes, consisting primarily of sycamore, elm, ash, and willow. Several sycamore and cottonwood reaching 60 cm dbh grew on localized stretches of thick alluvium, particularly near the low-water channel. The Hurricane Agnes flood heavily damaged most vegetation on bedrock and uprooted many of the larger trees; some parts overlain with thin alluvium were eroded to bedrock (fig. 13).

All flood-plain trees along the upstream tract were destroyed or heavily damaged. Survival was greatest just downstream from the protective wall, but even there, trees were partly uprooted or broken along the trunk. Age determinations indicated that none of the trees were growing prior to 1944 (table 7), which strongly suggests that the forest had grown up since the last major flood (1942). On the Madeira flood plain (figs. 14 and 15), however, trees were found that had germinated prior to floods, in 1924, 1936, 1937, and 1942. Large-scale destruction apparently did not occur. As a result of the sheltering effect below the inner bend, trees have a greater range in size and age. In addition, silver maple is dominant on the alluvium laid down by reduced current flow and rare on thinner alluvium and bedrock along lower parts of Old Angler flood plain.

In addition to the sheltering of large stretches of flood-plain forest, similar sheltering of smaller tracts was observed along the walls and rims of the gorge. Due to the velocity and flow levels attained by the Hurricane Agnes flood, destruction along this section was severe. In the midst of widespread damage, however, individual trees or small groups of trees immediately downstream from rock outcrops were often undamaged, particularly when the entire tree (or group) was sheltered (fig. 16). However, trees with canopies above the level of the shelter often were broken at some point along the trunk, commonly at altitudes approximating the top of the shelter (fig. 17).

While many examples of small-tract sheltering were observed, numerous other trees growing in apparently sheltered areas were destroyed. This suggests that sheltering decreases the probability of damage rather than entirely precludes it, although it is sometimes difficult to predict which areas will indeed provide shelter during high flows. Some flood plains just downstream from outcrops are inundated by severe backwash flows, resulting in destroyed or partly uprooted trees leaning heavily upstream. In some cases, deposition over roots kills trees that are undamaged by floating debris.

SPECIES SURVIVAL

A final consideration of the study below Great Falls concerns the survival of different species following the Hurricane Agnes flood. The poor form and sprout origin of many flood-plain trees are evidence of continued growth after numerous floods. However, observations in the summer of 1973 revealed that many damaged trees still standing after this flood died soon after the flood or within the following year. Furthermore, as the greater mortality of certain species indicates, differential survival is a factor in the distribution of flood-plain species.

Tallies of surviving trees do not completely describe the impact of the Hurricane Agnes flood, because the numbers and kinds of trees uprooted are unknown. Even frequently flooded trees, many of which previously had recovered from severe damage, were destroyed in great numbers as sandbars and gravel bars were completely eroded by the flood.

Willow and sycamore are the dominant trees on frequently flooded bedrock near Rocky Islands (fig. 2). Willow is most abundant along the lowest altitudes of the flood plain, often forming dense clumps, and is rare on surfaces flooded by more than about 570 m^3/s. Sycamore is also common, but also grows on less frequently flooded surfaces. Transects were established at elevations flooded by less than 850 m^3/s along bedrock channels at Rocky Islands and along the lower walls of the

FIGURE 9.—The large rock outcrop adjacent to Yellow Pond as seen from near the Maryland shore in 1975. Note living trees just downstream (to the left) from the rock wall. Several large cottonwood trees damaged by the Hurricane Agnes flood can be seen near the middle of the alluvial island; these trees were living in 1973, but most were dead at the time of the photograph. The alluvial island stretched at least 20 m farther downstream prior to the flood.

gorge just downstream. A tally of 148 willow and 236 sycamore was recorded. Of these, only 9 willow and 32 sycamore were dead, some of which may have died prior to Hurricane Agnes or succumbed to agents unrelated to flooding. Similarly, Schull (1944) found that black willow (*Salix nigra* Marsh) along the Mississippi River withstood great floods that often damaged aerial parts but seldom killed roots.

Other common species included in these transects were elm, ash, red osier dogwood, and black haw (*Viburnum prunifolium* L.). Most trees were small and shrubby, and nearly all showed damage from the Hurricane Agnes flood. In addition, mortality was greater among ash and elm than among willow and sycamore; 13 of 30 ash and 11 of 20 elm were dead.

Two 100-m transects at Rocky Islands along surfaces flooded by less than 2,800 m^3/s showed that despite severe damage most trees survived. An exception was one 10-m by 10-m tract where extreme deposition of unknown thickness had occurred. Seven trees still standing were dead. These included elm measuring 13, 18, and 18 cm and ash measuring 10, 20, 23, and 23 cm at dbh. Trees were partially uprooted and girdled at points along the trunk, but no sprouting was observed.

Because river birch and cottonwood are rare on bedrock, these species were investigated downstream near the Yellow Pond flood plain and on transects along nearby reaches where both species are common. It was found that trees growing in areas sheltered from high velocities during the Hurricane Agnes flood generally

TABLE 6.—*Summary of condition of trees still standing in July 1973 on the alluvial flat just downstream from the rock outcrop adjacent to Yellow Pond*

Species	Diameter at breast height (centimeters)	Status[1]	Condition[2]
Downstream half of flat			
Maple, silver	25	S	2,4
Maple, silver	51	D	
Maple, silver	25	D	
Maple, silver	10	D	
Maple, silver	25	D	
Maple, silver	8	D	
Maple, silver[3]	31/10	S/S	2,4/2,4
Cottonwood	41	D	
Cottonwood	61	S	Dead at start of 1974 growing season
Boxelder	10	D	
Boxelder[3]	5/8	D/D	
Persimmon	15	D	
Elm	15/15	S/D	2,4
Elm[3]		D	Diameter unknown
Upstream half of flat			
Maple, silver[3]	15/25	D/D	
Maple, silver	20	S	2
Maple, silver	51	S	2
Maple, silver	13	S	2
Maple, silver[3]	15/20	S/S	2/4
Cottonwood[3]	61/20	S/S	1/4
Cottonwood	61	S	2
Cottonwood	51	S	2
Boxelder	5	S	3
Elm	10	D	
Elm[3]	15/15	D/D	
Ash	18	D	
Ash	10	S	2
Ash	51	S	3
Ash	13	S	4
Ash	10	S	Cut by beavers in 1973
Ash	5	D	
Ash	5	D	
Ash	5	D	
Ash	5	D	
Birch, river	18	D	
Oak, red[4]	61	S	1
Hickory, bitternut[4]	18	S	4
Hickory, bitternut[4]	31	S	1
Hickory, bitternut[4]	33	S	1

[1] Status: D=dead; S=survived.
[2] Condition: 1=no or little flood damage; 2=partially uprooted; 3=horizontal; and 4=broken or heavily damaged crown.
[3] Diameter, status, and condition for two-trunked tree.
[4] Grows directly below the highest part of the rock wall.

survived. For example, transects along the Madeira flood plain and parts of the Virginia shore downstream tallied 58 cottonwoods and 69 river birch. Of these, only 6 cottonwood and 12 river birch were dead. However, along reaches where many other flood-plain species survived severe damage, 20 of 34 cottonwood and 18 of 23 river birch were killed. In addition, several large cottonwood trees surviving the flood died during the 1973 or 1974 growing season. Turner (1930) similarly observed high mortality of cottonwood along the Illinois River after the 1927 flood.

Trees were also tallied on surfaces that are inundated only by great floods. These high terraces were sampled on Rocky Islands at altitudes above the 6,117 m^3/s flood of August 1955 and have been flooded in this century in 1924, 1936, 1937, 1942, and 1972 (fig. 18).

Species greater than 2.5 cm dbh were counted on three main terraces. In addition, a 25-m transect and two plots measuring 10-m by 10-m were made at similar altitudes along parts of the Maryland shore just downstream from Rockey Islands. Dominant species are Virginia pine, post oak, and red oak; mockernut hickory, pignut hickory, black locust, and shadbush (*Amelanchier* Med.) are less common.

Virginia pine grows mainly on shallow alluvium flooded by more than 5,750 m^3/s and was the most abundant species tallied. Of 218 individuals, 129 were dead and many were partly uprooted (often nearly horizontal) or broken off along the trunk or canopy. Most survivors had minor damage, such as shearing of small stems or bark abrasions along upstream-facing trunks, and none showed adventitious sprouting. Most adjacent hardwoods, however, survived despite often severe damage to aerial parts and, in addition, rarely were partly uprooted. The greater proportion of uprooted pines may be due to their establishment in marginal sites where roots do not firmly anchor to underlying bedrock or to the generally shallow root systems. It thus appears that the survival of Virginia pine is precluded by damage often well tolerated by hardwood species.

Post oak is rare on surfaces flooded by less than about 4,250 m^3/s and, like Virginia pine, is confined to alluvium on terraces underlain by bedrock. It is rare on surfaces that are never flooded. Red oak grows at all elevations along the Potomac River but is most abundant on infrequently flooded surfaces. Both species near Rocky Islands were tallied less often than was Virginia pine, and most individuals were heavily damaged. Sprouting along basal parts was common, however, and 28 of 46 post oak and 24 of 29 red oak were still living. Other species in these infrequently flooded areas included mockernut and pignut hickory, although only 18 trees were tallied. Ten were living. Black locust, shadbush, chestnut oak, red cedar (*Juniperus virginiana* L.), and persimmon (*Diospyros virginiana* Mill.) were less common.

These results are preliminary and are not an attempt to rank species by differential mortality due to flood damage. The high survival rates of bedrock flood-plain species, particularly those at frequently flooded

FIGURE 10.—View of the flood plain forest on the upper part of Old Angler flood plain along the Potomac River during the flood of February 15, 1966, peak flow 2,512 m^3/s. Trees are sheltered from main-channel velocities by a rock wall just upstream.

elevations, suggest that even a great flood does not significantly alter species composition. Form of trees, however, may be highly altered by growth of new sprouts from broken trunks, resulting in aerial shoots much younger than roots. Vegetative reproduction appears to be the primary manner by which new aerial stems are produced. Seedlings are locally rare on frequently flooded bedrock, probably due to the lack of seeds or available sites for their establishment or to mortality from flooding.

On infrequently flooded surfaces, great floods may decrease numbers of individuals and alter species composition due to site factors or different genetic tolerances to inundation and damage. The time of year at which flooding occurs may also be important, with tolerance probably being lowest during the growing season. The absence at lower altitudes of Virginia pine, post oak, and mockernut and pignut hickory is likely due in part to these species' intolerance of continued flooding. The recovery of severely damaged trees in the subcanopy may also depend on the fate of larger trees within the stand, for not only are genetic considerations important in recovery but also the amount of light is often critical in sprouting of adventitious stems.

SUMMARY AND CONCLUSIONS

Flooding is the dominant environmental influence upon flood-plain forests of the Potomac River near Washington, D.C. Because catastrophic floods are particularly destructive to vegetation, such floods determine the age, form, and composition of many flood-plain forests. Trees are uprooted or severely damaged during smaller floods, but the simultaneous destruction of great numbers of trees is unlikely.

The variability in destruction by the Hurricane Agnes flood indicates that damage is mainly due to factors other than flood discharge. Characteristics of the flood channel determine where flood velocities are greatest. Destruction was most evident near Chain Bridge and the reach below Great Falls, where maximum velocities during the Hurricane Agnes flood were observed; conversely, the slower-flowing currents above

FIGURE 11—View from the middle of Old Angler flood plain looking toward main channel during low flow in 1975. Note sprouts from inclined boxelder (right) that survived the Hurricane Agnes flood. Much of the flood debris was cleared to make way for a canoe launching site.

Great Falls caused relatively little damage to trees on the Spalding farm flood plain. Even below Great Falls, however, destruction was highly variable. Many forests normally sheltered during smaller floods were totally destroyed when sheltering was lost during the Hurricane Agnes flood. Other areas are sheltered even during the greatest recorded floods, and widespread damage has apparently never occurred. As a result, trees in close proximity may differ strikingly in size and age depending on the shelter afforded. Similarly, the composition of flood-plain forests may be controlled by the different abilities of species to become established on highly altered surfaces and subsequently to withstand severe mechanical damage.

Flood-plain forests at many sites are destroyed by catastrophic floods, grow again, and are uprooted or killed during subsequent great floods. Understanding the rate of recurrence of these events is important in applying botanical evidence to determining past hydrologic events. Evidence may extend records of great floods or indicate recent occurrence on streams where data are unavailable. Evidence of catastrophic floods is most probably in areas where streamflow velocities are greatest and vegetation is not sheltered by obstructions or the channel geometry.

FIGURE 12.—A downstream view in 1975 from the protective wall at the head of Old Angler flood plain. Survival was greatest just below the wall (foreground), where numerous sprouts have grown from buried or severely damaged trunks.

TABLE 7.—*Summary of selected core data from Old Angler flood plain (upstream tract) and the Madeira flood plain along the Potomac River*

Species	Core height (centimeters)	Tree diameter (centimeters)	Age at onset of 1972 growing season (years)
Old Angler's flood plain (upstream tract)			
Cottonwood	25	38	18 (partial core)
Boxelder	20	36	18 (partial core)
Sycamore	15	23	25
Sycamore	10	23	25
Sycamore	stump		25
Sycamore	stump		25±1
Silver maple	stump		25±1
Silver maple	stump		24
Willow	25	31	28

FIGURE 13.—The lower part of Old Angler flood plain 3 years after the Hurricane Agnes flood. Note the contrasting state of the Madeira flood plain on the opposite shore.

TABLE 7.—*Summary of selected core data from Old Angler flood plain (upstream tract) and the Madeira flood plain along the Potomac River*—Continued

Species	Core height (centimeters)	Tree diameter (centimeters)	Age at onset of 1972 growing season (years)
Madeira flood plain			
Ash	31	56	29
Ash	46	41	92 (partial core)
Ash	20	23	33
Ash	91	43	78 (partial core)
Silver maple	71	61	48 (partial core)
Silver maple	38	89	40 (partial core)

FIGURE 14.—View of the Madeira (Virginia) flood plain opposite the lower portion of Old Angler flood plain. Photograph was taken in 1975 from midstream.

Flooding directly or indirectly influences the distribution of vegetation on flood plains. Just as upland and flood-plain forests are composed of different species, there appear to be vegetation zones on the flood plain based on some of the factors considered in this report. These zones do not represent successional stages in which flood-plain species are eventually replaced by upland species. Zonation is undoubtedly further complicated by vast differences in the topography and lateral size of flood-plain surfaces. Studies are needed that relate flooding to the distribution of flood-plain species, possibly leading to a botanical delineation of flood-plain boundaries.

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FIGURE 15.—Silver maple forest on Madeira flood plain in 1975. Many trees grow on surfaces flooded by less than 700 m^3/s.

FIGURE 16.—Sycamore growing in a shelter behind a rock wall downstream from Great Falls in 1975. This tree is larger and of different form than trees growing in more exposed locations. Direction of current is from left to right. Discharge is about 255 m^3/s.

FIGURE 17.—View of several sycamore broken along the trunk during the Hurricane Agnes flood at altitudes corresponding to shelter height. Photograph was taken in 1975 and looks directly upstream from a small cove in the lower study area.

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FIGURE 18.—View from Rocky Islands looking downstream along the Potomac River in 1968. Discharge is about 850 m^3/s. The main river is in the background. Upland species were tallied on high pinnacles that are rarely flooded.

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