FLOW RECOMMENDATIONS FOR MAINTAINING RIPARIAN VEGETATION ALONG THE UPPER MISSOURI RIVER, MONTANA

Prepared for

Montana Power Company, Inc.

and

U.S. Bureau of Reclamation

by

Michael L. Scott, Gregor T. Auble, Jonathan M. Friedman,

Lee S. Ischinger, Erik D. Eggleston, Mark A. Wondzell,

Patrick B. Shafroth, Jennifer T. Back, and Mette S. Jordan

National Biological Survey
National Ecology Research Center
4512 McMurry Avenue
Fort Collins, Colorado 80525-3400

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EXECUTIVE SUMMARY

Montana Power Company, Inc. (MPC) submitted a final license application to the Federal Energy Regulatory Commission (FERC) on November 30, 1992. In this application, MPC proposed a plan for the protection of fish, wildlife, habitat, and water-quality resources. One concern was maintenance of woody riparian vegetation along the Missouri River, especially along the Wild and Scenic reach of the river, where the riparian forest occurs in relatively small discontinuous stands. The objectives of this project were 1) to recommend flows that would protect and enhance riparian forests along the Missouri River, and 2) to develop elements of an environmental monitoring program that could be used to assess the effectiveness of the recommended flows.

Plains cottonwood (*Populus deltoides* subsp. *monilifera*) is the key structural component of riparian forests along the Missouri River. Therefore, we focused our analysis on factors affecting populations of this species. Previous work had demonstrated that the age structure of cottonwood populations is strongly influenced by aspects of flow that promote successful establishment. In this study our approach was to determine the precise age of plains cottonwood trees growing along the Upper Missouri River and to relate years of establishment to the flow record.

Our work was carried out between Coal Banks Landing and the Fred G. Robinson Bridge within the Wild and Scenic portion of the Missouri River. This segment of the river occupies a narrow valley and exhibits little channel migration. Maps and notes from the journals of Lewis and Clark (1804-1806) suggest that the present distribution and abundance of cottonwoods within the study reach is generally similar to presettlement conditions. Flows in the study reach are influenced by a number of dams and diversions, most importantly, Canyon Ferry and Tiber Dams. Although flow regulation has decreased peak flows and increased low flows, the gross seasonal pattern of flow has not been greatly altered.

Most cottonwood establishment in our study reach occurred in years with a peak mean daily flow greater than 1,400 m^3/s (49,434 cfs), or in the two years following such a flow. These years include 35 out of the 111 years of record, and account for establishment of 47 of 60 trees examined, a highly significant relationship. Infrequent establishment of cottonwood trees is not the result of scarcity of seed or seedlings. In the study reach seedlings become established most years on bare, relatively low surfaces deposited by the river. However, the high elevation of establishment of all trees dating to before 1978 indicates that only individuals established on high flood deposits are able to survive subsequent floods and ice jams.

In order to maintain the present abundance of plains cottonwood in the study area we recommend flood flows in excess of 1,400 m^3/s (49,434 cfs) measured as mean daily discharge at Fort Benton (U.S. Geological Survey gage 06090800) with a recurrence interval of approximately 9 years. Because cottonwood seeds remain viable for only a few weeks, and because seedlings require a moist, bare surface, ***we further recommend maintenance of the historic timing of flooding with peak flood flows occurring between mid-May and late-June.***

Flow is not the only factor influencing cottonwood regeneration along this reach of the Missouri River. Land management, especially cattle grazing, is clearly having an impact, and changes in cottonwood populations could be expected if these practices were altered. However, the dependence of cottonwood establishment on high flow is clear in this reach in spite of the effects of other factors.

Given the value of the resource, we strongly suggest establishment of a monitoring program to determine the effectiveness of the recommended flows and to provide the data necessary for refining them. We recommend a monitoring program that would include:
1) ten permanent, widely spaced channel cross sections for annual measurement of channel geometry and cottonwood establishment, growth and survival; 2) five livestock exclosures to monitor the influence of grazing in the study area; and 3) low-elevation aerial photography of the reach every five years and after every flood to detect changes in channel geometry and forested area. Because cottonwood establishment is episodic, a long-term commitment to the monitoring effort is essential. In addition, cross sections and exclosures should be easy enough to access that measurements during flood years are possible.

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1. INTRODUCTION

1.1 Background

The Montana Power Company (MPC) operates seven dams along the Upper Missouri River in Montana: Hauser, Holter, Black Eagle, Rainbow, Cochrane, Ryan, and Morony. These seven dams, located below Canyon Ferry Reservoir, are operated largely as run-of-the-river hydropower facilities. Together with two dams on the Madison River, they are licensed as the Missouri-Madison Hydro-Project by the Federal Energy Regulatory Commission (FERC) (FERC Project No. 2188). MPC submitted a final license application to FERC in November 30, 1992. In this application, MPC proposed a plan for the protection of fish, wildlife, habitat, and water quality resources. A topic of specific concern was maintenance of woody riparian vegetation along the Missouri River; this vegetation provides essential habitat for many important vertebrate species in the western United States (Brinson et al. 1981).

Canyon Ferry Dam is situated on the main stem of the Missouri River (Figure 1) near Helena, Montana. This facility, owned and operated by the Bureau of Reclamation, has modified the historic hydrograph of the river, primarily by reducing spring peak flows and increasing winter low flows (Figure 2). The storage capacity of Canyon Ferry Reservoir ($\sim 2.5 * 10^9$ m^3 [$\sim 2.0 * 10^6$ acre-feet]) is allocated primarily to power generation and flood control; however, water is also released to meet irrigation needs on the Missouri River above Great Falls, Montana. Two additional Bureau of Reclamation Dams, Gibson Dam on the Sun River and Tiber Dam on the Marias River (Figure 1) regulate flows on these major tributaries and thus influence flow on the mainstem Missouri River. It is important to recognize that flow proposals for riparian vegetation will be highly dependent on the operation of these three Bureau of Reclamation Dams.

1.2. Study Objectives

The primary objective of this study is to identify flow characteristics that will protect and enhance riparian forests along the Missouri River. Secondarily, we present elements of an environmental monitoring program designed to assess the effectiveness of the recommended flows and to suggest refinements of our initial recommendations.

Land-use practices, particularly farming and grazing, have an important influence on riparian vegetation along the Missouri River. It is possible that excessive grazing reduces the effectiveness of recruitment flows. Specific land-use recommendations for maintenance and enhancement of riparian vegetation along the Missouri River are beyond the scope of this project. Ultimately, effective management of riparian vegetation along the Missouri River will require integrated management of flows and land use.

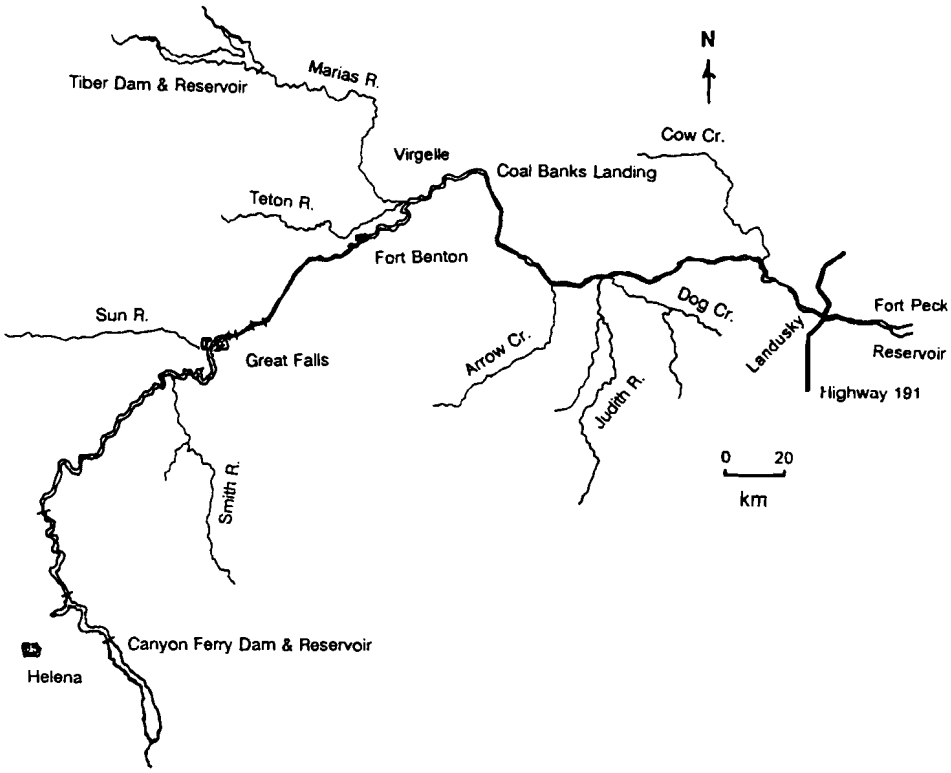

Figure 1. The Upper Missouri River, Montana, and its principal tributaries..

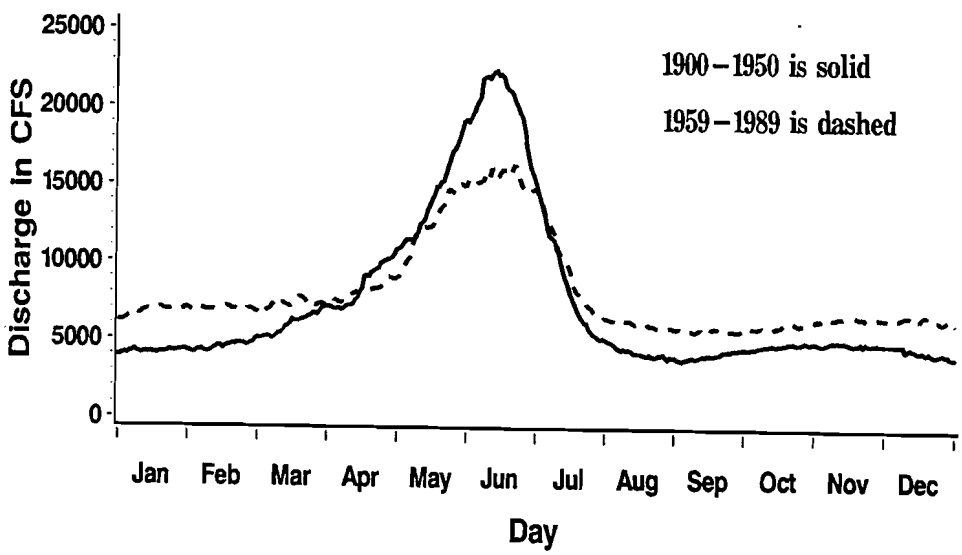

Figure 2. Mean daily flows of Missouri River at Fort Benton, Montana, before (1900-1950) and after (1959-1989) closing of Canyon Ferry Dam.

1.3 Approach

Plains cottonwood (*Populus deltoides* subsp. *monilifera*) is by far the largest and most abundant tree species along the Upper Missouri River; therefore, it is the primary habitat of riparian tree-nesting birds and mammals. As the principal canopy species, cottonwood has a strong influence on light and moisture availability for most other species in the riparian zone. For these reasons we focused our analysis on factors affecting populations of plains cottonwood. Previous studies had shown that the age structure of cottonwood populations is determined by events occurring in the establishment phase (Bradley and Smith 1986, Baker 1990, Stromberg et al. 1991). Furthermore, size structure of cottonwood populations along the Upper Missouri River suggested that establishment is relatively infrequent. We hypothesized that establishment is related to some aspect of the flow regime and that this relation strongly influences patterns of adult trees in spite of complicating effects of grazing and other land-use practices. Therefore, our approach was to determine the precise age of plains cottonwood trees growing along the Upper Missouri River and to relate years of establishment to the flow record.

2. SYSTEM DESCRIPTION

2.1 The Upper Missouri River System

The Missouri River is formed by the confluence of the Jefferson, Madison, and Gallatin Rivers in southwestern Montana. The river flows north from Three Forks to Great Falls, where it turns and flows northeast and east through central Montana. As defined by this study, the Upper Missouri River extends from Canyon Ferry Dam downstream to Fort Peck Reservoir (Figure 1). Along this 320-km (200-mile) reach, eight major tributaries join the Missouri. The Dearborn and Smith Rivers enter the Missouri 26 and 98 km (16 and 61 miles) below Holter Dam. The Sun River (regulated by Gibson Dam) joins at Great Falls, and Belt Creek enters 2.4 km (1.5 miles) below Morony Dam. The Marias and Judith Rivers, and Arrow and Cow Creeks join the Missouri 35, 124, 142, and 204 km (22, 77, 88, and 127 miles) downstream of Fort Benton.

2.2 Study Reach

The portion of the Missouri River selected for study extended from Coal Banks Landing to the crossing of Highway 191 at Fred Robinson Bridge (Figure 1). Selection of this reach was based on three primary considerations: 1) its designation as a Wild and Scenic River, 2) relatively simple access to study sites on land under State and Federal ownership, and 3) the concern that cottonwood regeneration was especially limited within this reach (Hansen 1989).

2.3 Glacial History

The study area is underlain by poorly lithified sandstones and shales of late Cretaceous to early Tertiary age. Pre-glacial drainage was primarily to the north and east, toward Hudson Bay. Pre-Wisconsinan continental glaciation diverted drainage southward into the Mississippi River (Wayne et al. 1991).

The modern course of the Missouri River between Coal Banks Landing and the confluence with the Milk River (Figure 3) corresponds roughly to the Late Illinoian ice margin (Wayne et al. 1991). This young section of the river is constrained by a narrow valley and exhibits low sinuosity. Comparison with a detailed map prepared in the 1890s (Missouri River Commission 1892-1895) indicates that little channel migration has occurred in this reach in the last 100 years. In contrast, relatively high sinuosities, wide valleys, and presumably more rapid channel migration are exhibited by the Missouri River upstream of Coal Banks Landing and downstream of the Milk River confluence.

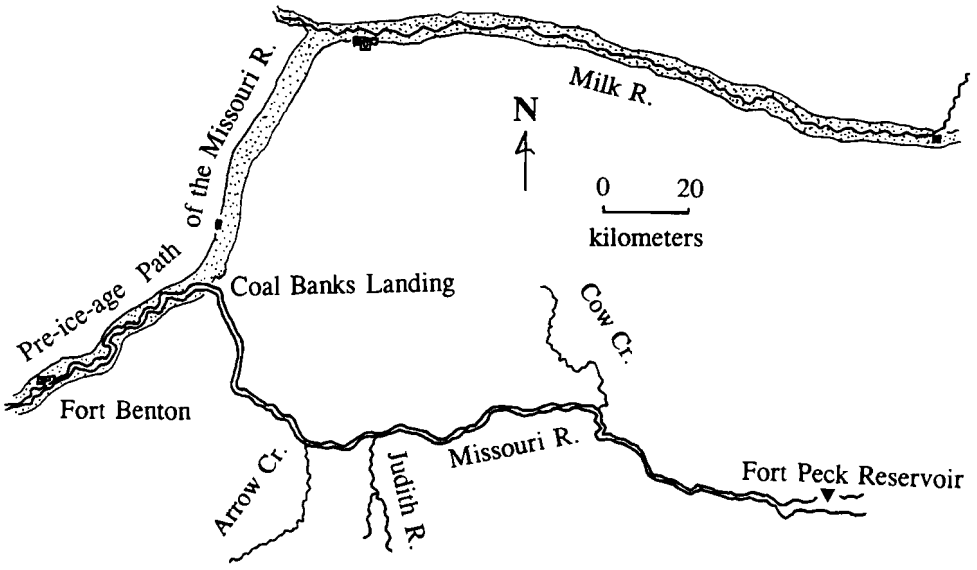

Figure 3. Pre- and post-glacial channels of the Missouri River, Montana, between Fort Benton and Fort Peck Reservoir.

2.4 Vegetation

The major tree species along the Upper Missouri River is plains cottonwood. Also present are box elder (*Acer negundo*), green ash (*Fraxinus pennsylvanica*), and peach-leaf willow (*Salix amygdaloides*). The shrub community includes yellow willow (*Salix lutea*), sandbar willow (*Salix exigua*), western snowberry (*Symphoricarpos occidentalis*), Wood's rose (*Rosa woodsii*), red-osier dogwood (*Cornus stolonifera*), and common chokecherry (*Prunus virginiana*). The adjacent upland areas are dominated by silver sagebrush (*Artemisia cana*) and black greasewood (*Sarcobatus vermiculatus*). Common herbaceous species include western wheatgrass (*Agropyron smithii*), quackgrass (*Agropyron repens*), smooth brome (*Bromus inermis*), spikesedges (*Eleocharis* spp.), leafy spurge (*Euphorbia esula*), fowl bluegrass, (*Poa palustris*), Kentucky bluegrass (*Poa pratensis*), prairie cordgrass (*Spartina pectinata*), horsetails (*Equisetum* spp.), alfalfa (*Medicago sativa*), sweet clover, (*Melilotus alba* and *Melilotus officinalis*), field mint (*Mentha arvensis*), common silverweed (*Potentilla anserina*), three-square bulrush (*Scirpus pungens*), and cocklebur (*Xanthium strumarium*) (Hansen et al. 1988).

As described above, the study area is a constrained portion of the river valley formed as a result of continental glaciation (Figure 3). In most locations, sandstone and shale formations limit lateral channel movement, and the cottonwood forest consists of discontinuous narrow, linear bands situated at the upper edge of a narrow flood plain. In more geomorphically active locations, such as tributary junctions and channel islands, cottonwood stands and alluvial surfaces are wider. Upstream of the study area, the meandering pre-glacial river channel is associated with a broad flood plain and more extensive cottonwood stands.

2.5 Hydrology

The Missouri is a snowmelt-dominated river with peak flows occurring in spring, usually during late May or early June, and low flows occurring in late fall and winter. At the Fort Benton gage (U.S. Geological Survey gage 06090800) the Missouri River drains an area of 64,100 km^2 (24,999 mi^2) and had a mean annual discharge of 219 m^3/s (7,733 ft^3/s) for the 99-year period from 1891 to 1989 (EarthInfo 1991). Canyon Ferry Dam was completed in 1953. Tiber Dam was completed in 1956; therefore, the approximate period 1950-1959 represents a time of transition from unregulated to regulated flow on the Upper Missouri River. Figure 2 indicates that gross seasonal timing of flows has not been greatly altered by flow regulation. However, peak flows have decreased and portions of the low-flow hydrograph have increased. Below Fred Robinson Bridge, backwaters from Fort Peck Reservoir begin to influence hydrology and fluvial geomorphology.

2.6 Historical Conditions

To place the status of cottonwood riparian ecosystems along the Upper Missouri River in proper context, it is important to consider the historical condition of this resource. Fortunately, detailed accounts from the Lewis and Clark expedition (1804-1806) provide some information on the extent of cottonwood stands before settlement (Coues 1893). These journals indicate that plains cottonwood was relatively scarce in the constrained post-glacial channel of the Upper Missouri River even before settlement (Table 1). For example, in the constrained reach above Cow Creek, Lewis and Clark noted that "there is, however, no timber on either side of the river, except a few pines on the hills." And at a location above Arrow Creek they stated "There is now no timber on the hills, and only a few scattering cottonwood, ash, boxelder, and willows along the water." In contrast, above Coal Banks Landing and below the confluence with the Marias River, where the Missouri meanders within the broad pre-glacial valley, they reported that the river's "timber increases in quantity, the low grounds become more level and extensive," and "we came-to for the night in a handsome, low cottonwood plain on the south".

Table 1. Excerpts from the Lewis and Clark journals (Coues 1893) from the post-glacial portion of the Missouri River between Coal Banks Landing and the confluence with the Milk River. All passages describing woody vegetation within this reach are included along with a brief reference to the location described.

[6 mi above Milk R.] "At a little distance from the river there is no timber on either side, the wood being confined to the margin of the river; so that unless the contrary is particularly mentioned, it is always to be understood that the upland is perfectly naked, and that we consider the low grounds well timbered if even a fifth be covered with wood."

[4.25 mi above Burnt Lodge Cr.] "The bed of the Missouri is much narrower than usual, being not more than between 200 and 300 yards in width, with an uncommonly large proportion of gravel; but the sand-bars, and low points covered with willows, have almost entirely disappeared. The timber on the river consists of scarcely anything more than a few scattered cottonwood trees."

[12.75 mi above Wiser's Cr.] "the willow has in a great measure disappeared, and even the cottonwood, almost the only timber remaining, is growing scarce."

[~20 mi above confluence with Musselshell R.] "During the whole day the bends of the river are short and sudden; the points are covered with some cottonwood, large or broad-leaved willow, and a small quantity of redwood"

[Near confluence with Armel Cr.] "The low grounds are narrow and without timber; the country is high and broken"

[4.74 mi above Cow Cr.] "there is, however, no timber on either side of the river, except a few pines on the hills."

[Above Chimney Bend] "the country is, if possible, more rugged and barren than that we passed yesterday; the only growth of the hills being a few pine, spruce, and dwarf cedar, interspersed with an occasional contrast, once in the course of some miles, of several acres of level ground, which supply a scanty subsistence for a few little cottonwoods."

[Chimney Bend] "Soon after setting out we passed a small untimbered island on the south; at about seven miles we reached a considerable bend which the river makes toward the southeast, and in the evening, after making 12.5 miles, camped on the south near two dead cottonwoods, the only timber for fuel which we could discover in the neighborhood."

Table 1. Continued.

[Between Birch Cr. and Judith R.] "Here the country assumed a totally different aspect; the hills retired on both sides from the river, which now spreads to more than three times its former size, and is filled with a number of small, handsome islands, covered with cottonwood. The low grounds on the river are again wide, fertile, and enriched with trees; those on the north are particularly wide; the hills being comparatively low, and opening into three large valleys, which extend for a considerable distance toward the north. These appearances of vegetation are delightful after the dreary hills over which we have passed,"

[Judith R.] "The water is clearer than any which we have yet seen; and the low grounds, as far as we could discern, are wider and more woody than those of the Missouri,"

[~6.5 mi above Judith R.] "Near this spot are a few trees of the ash, the first we have seen for a great distance, and from which we named the place Ash Rapids [now Deadman Rapids]. On these hills there is but little timber,"

[Arrow Cr.] "From the objects we had just passed, we called this river Slaughter River [now Arrow Cr.]. Its low grounds are narrow, and contain scarcely any timber."

[~8 mi above Arrow Cr.] "There is now no timber on the hills, and only a few scattering cottonwood, ash, box-elder, and willows along the water."

[downstream of Eagle Cr.] "The river to-day has been from about 150 to 250 yards wide, with but little timber."

2.7 Conditions Necessary for Establishment of Plains Cottonwood

The conditions associated with successful establishment of plains cottonwood are well understood (Scott et al. 1993). An abundant crop of wind- and water-dispersed seeds is released early each summer, synchronous with peak flow in unregulated streams dominated by snowmelt (Johnson in press, Friedman 1993). Along the Upper Missouri, we observed cottonwood seeds being released from early June to mid-July. Cottonwood seeds lose germinability under field conditions within a few weeks (Moss 1938, Ware and Penfound 1949, Kapustka 1972). Freshly deposited alluvium typically provides ideal substrate for germination and establishment. Because cottonwood is intolerant of shade, it rarely becomes established from seed under an existing stand of trees (Johnson et al. 1976) or herbs (Friedman 1993). This trait often leads to even-aged stands. Young seedlings require a continuously moist substrate during at least the first week of growth (Moss 1938, Read 1958). Root growth during the first month is slow (van Haverbeke 1990), but later in the first growing season seedlings are able to extend a taproot deep enough to survive declines in the water table of as much as 1 m (Mahoney and Rood 1991, Segelquist et al. 1993). Therefore, the vulnerability of cottonwood to low surface soil moisture conditions decreases rapidly with age. Cottonwood is tolerant of burial, and young individuals are able to sprout from stems or roots (van Haverbeke 1990). However, extensive mortality of young plants has been reported as a result of floods (Currier 1988) and ice scour (Johnson in press). Successful establishment tends to occur only in channel positions that are moist, bare, and protected from removal by subsequent disturbance (Everitt 1968, Noble 1979, Bradley and Smith 1986, Johnson in press).

3. METHODS

3.1 Field Methods

We selected nine sites for intensive sampling within the constrained reach (Figure 4). Sites were selected primarily to represent the range of geomorphic conditions that occur within the reach and were identified by river mile downstream of Fort Benton, Montana, as described in maps available from the Bureau of Land Management (Government Printing Office 1990). Because of our interest in factors influencing reproduction during the period of hydrologic record, we favored sites that included smaller trees. In some cases, it was impractical to sample the largest trees at a study site. At each site a transect was established perpendicular to the channel. Distinct topographic surfaces along the transect were noted and surveyed. Elevations were determined relative to the lowest extent of perennial emergent vegetation--the active channel shelf of Osterkamp and Hedman (1982).

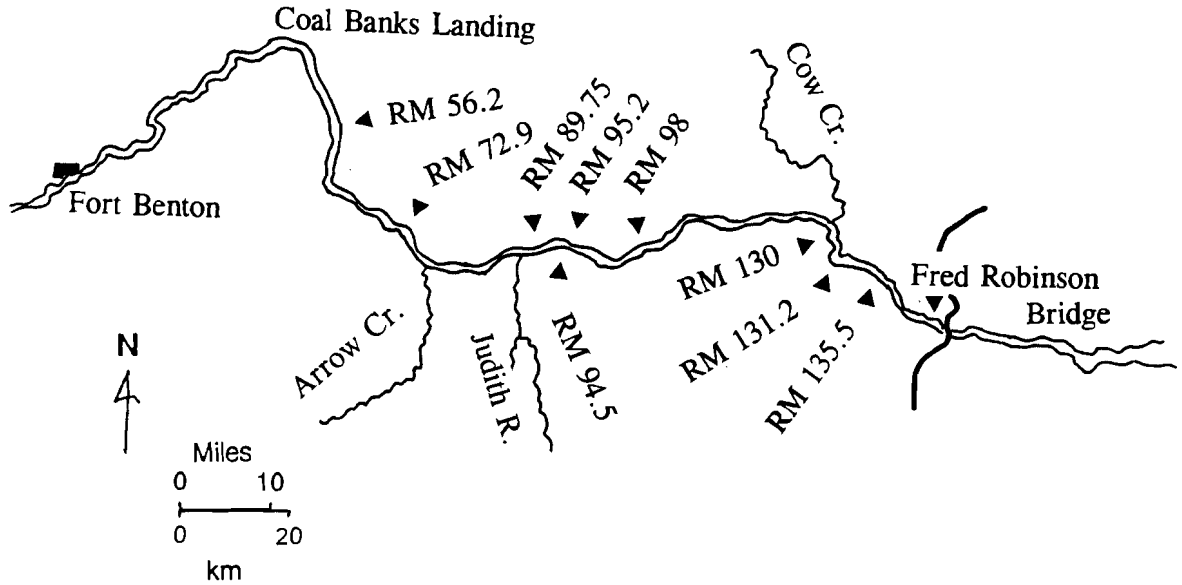

Figure 4. Location of sampled sites along the Upper Missouri River, Montana.

Four size classes of cottonwoods were defined: seedling (0-1 m tall); sapling (1 m tall to 10 cm in diameter); pole (10 cm to 30 cm in diameter); and tree (>30 cm in diameter). On each surface, downstream of the transect, four representative individuals in each size class were selected for age sampling. We estimated densities of cottonwoods on each surface by counting individuals by size class in rectangular quadrats downstream of the transect. The width of each quadrat was equal to the width of the respective surface along the transect and the downstream length was a distance that we estimated would be sufficient to record at least 10 individuals of each size class. We visited all sites between October 1992 and July 1993. Because of their small size, we did not attempt to count or collect any seedlings that germinated in 1993.

Relating the origin of cottonwood stands to specific flows requires precise dating of individual stems. This can be difficult with cottonwood for two reasons. First, the early years of growth are often well below the present surface because of sediment accretion (Everitt 1968). Second, cottonwood is a diffuse porous wood and can exhibit false or missing rings. We dealt with these potential problems through a combination of field and laboratory techniques.

In order to find the oldest wood on the tree we excavated each sampled stem well below the apparent establishment point and sectioned (or cored) the stem above, below and at the estimated point of establishment. Any sample taken above or below the first year's growth will underestimate the age of the tree. Thus, accurate determination of the establishment surface is important. Trees that grow on a stable surface have a flared base or root collar where secondary roots diverge from the primary root-stem axis. Subsequent alluvial deposition will typically not alter the form of the root collar (Figure 5A). In contrast, a tree that experiences early and repeated deposition following establishment will typically exhibit an inverted cone-shaped base with associated adventitious roots (Sigafoos 1964, Figure 5B).

We photographed and sketched each excavated stem, indicating the apparent establishment surface, its distance below the present ground surface, and the positions of the slabs (or cores) removed from the stem (Figure 6). In addition, we recorded the sediment stratigraphy associated with each excavated stem (Figure 6), noting the depth and texture of each distinctive stratum. Finally, we collected samples of flood or ice scars found on trees near our cross sections.

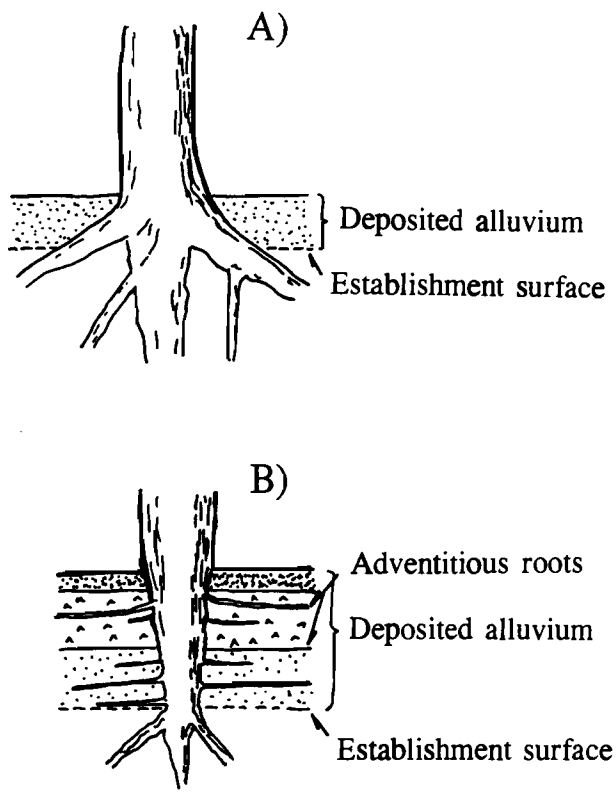

Figure 5. Tree root collars. A) Root collar of a tree growing on a stable surface that experienced a small amount of sediment deposition many years after establishment. B) Root collar of a tree that experienced repeated sediment deposition beginning at an early age.

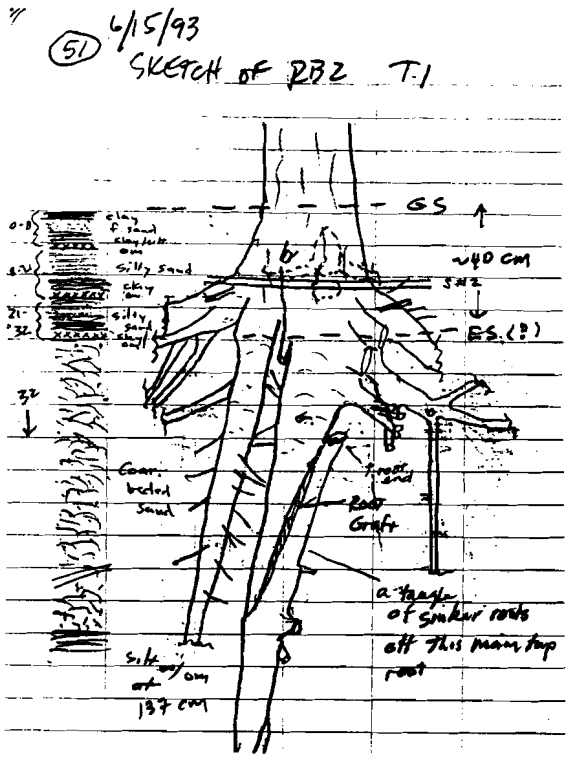

Figure 6. Field sketch of a tree root collar and associated sediment stratigraphy.

3.2 Laboratory Methods

All stem sections, cores, and scar samples were returned to the laboratory and air dried. Cores were mounted on wooden blocks (Phipps 1985) and all slabs and cores were sanded with progressively finer sandpapers up to 600 grit. At this point, the wood anatomy was clearly observable under magnification for most samples. Ring width and number were recorded using a University Model incremental measuring machine equipped with a digital display unit and computer interface (obtained from Curt Zahn, formerly Fred C. Henson Company), and the TRIMS, Version 1.2, software system from Madera Software to facilitate data capture. Measurements were accurate to within 0.01 mm per 10 mm. Each core or slab was interpreted by at least two readers.

We detected partial rings (i.e. rings that were not continuous around the circumference of the stem) and false rings, particularly in smaller stems that had been buried or repeatedly damaged by beaver. False rings were generally identifiable by an incomplete transition between early and late-wood vessels through some portion of the stem. Where possible, false and missing rings were confirmed by cross-dating (Stokes and Smiley 1968) both within and between trees. However, cross-dating was possible only after approximately the first 30 years of growth.

3.3 Hydrology

Flow records for three U.S. Geological Survey gaging stations on the main stem of the Missouri River were obtained from CD-ROM (EarthInfo 1991). Our flow recommendation and most analyses are based on the Fort Benton gage (06090800) at the upstream end of the study reach because of its long period of record. Recent flow records, including some provisional data, for this gage were obtained from the Water Resources Division of the U.S. Geological Survey in Helena, Montana. The currently accepted period of record starts in water year 1891. We also used records for water years 1881 to 1889 (United States Geological Survey 1922) which have since been judged unreliable by the U.S. Geological Survey (Earthinfo 1991). Although these earlier records exclude winter months and are less accurate, we judged that they would be acceptable for identification of flood years.

In order to identify ice-related events not reflected in the Fort Benton gage, we used records from the Virgelle gage (06109500) within the study reach and the Landusky gage (061152) near the downstream end of the study reach. Both records begin in the mid-1930s. We used SAS, Version 6.07, on a SUN SPARC2 workstation to manage and plot the hydrologic records.

3.4 Statistical analysis

We evaluated the significance of the association between high flows and establishment of saplings, poles, and trees by comparing our data to expectations from a null hypothesis that trees were independently and randomly established over time. In the null hypothesis, all individual saplings, poles, and trees have an equal chance of being established in any year, regardless of the flow in that year. Thus, under the null hypothesis, the probability of an individual being established in a suitable flow year is the total number of suitable flow years divided by the total number of years. Using the binomial distribution, we calculated the probability that the observed proportion of individuals established in suitable years could have occurred by chance alone (Snedecor and Cochran 1980). Probabilities from the binomial distribution were obtained using SAS, Version 6.07, on a SUN SPARC2 workstation.

4. RESULTS

4.1 Individual Study Sites

4.1.1 RM56.2 -- This site is on a Bureau of Land Management easement just downstream from the confluence with Eagle Creek. The left side of the river consists of four defined fluvial surfaces situated between cliffs of Eagle Sandstone (Figure 7). A map of the Missouri River from 1893 (Missouri River Commission 1892-1895) indicates a line of trees situated between a grassy terrace and a narrow sandbar at the channel edge. The present site is similar and includes a grassy terrace and a narrow surface inundated in years of high flow and occupied by cottonwoods ranging in size from 32 to 62 cm diameter at breast height

(dbh) arranged in single file. The understory of this surface includes *Rosa woodsii*, *Symphoricarpos occidentalis*, *Poa pratensis*, *Medicago sativa*, *Agropyron smithii*, and *Agropyron repens*.

Closer to the river are two lower surfaces dominated by herbaceous vegetation, including *Glycyrrhiza lepidota*, *Spartina pectinata*, and *Poa palustris* on the lowest surface (LB1) and *Glycyrrhiza lepidota*, *Poa pratensis*, *Medicago sativa*, *Medicago lupulina*, *Agropyron repens*, and *Euphorbia esula* on LB2. Excavation of mature cottonwoods on LB4 revealed establishment surfaces at depths of 42 to 70 cm. Stem morphology indicated that the trees had been damaged by one or more events and that heart-rot had set in at and below the site of the old injury. The four datable mature trees at this site were established in 1884, 1886, 1888, and 1897. Saplings on a lower surface (LB2, Figure 7) dated to 1978 and 1980. No cottonwoods were found on the lowest surface at this site. The single scar collected from this site dated to the winter of 1956-7.

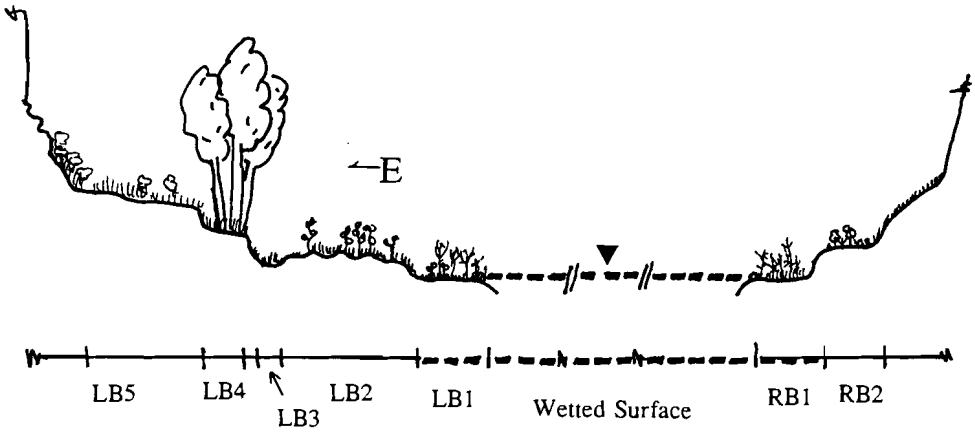

Figure 7. Sketch map of site RM56.2. Elevations and distances are not to scale. Perspective is looking downstream.

4.1.2 RM72.9 -- This site, adjacent to Pablo Rapids, includes a mature stand of cottonwood with an understory of *Artemisia cana*, *Agropyron smithii*, and a number of weedy species including *Bromus japonicus* and *Agropyron repens* that suggest heavy use by cattle. The mature trees are in two ranks at a density of 44/ha (109/acre) on an occasionally flooded surface between an upland terrace and two lower, vegetated surfaces (Figure 8). These two surfaces, subject to frequent ice scour, are dominated by *Plantago major*, *Scirpus americana*, *Potentilla anserina*, *Xanthium strumarium*, and *Veronica anagallis-aquatica*. The lowest surfaces on the left and right banks (RB1 and LB1) contain seedlings of cottonwood at densities of 106/ha (262/acre) and 1,071/ha (2651/acre), respectively, and sandbar willow.

This site on the 1893 map (Missouri River Commission 1892-1895) appears as a narrower terrace and a sand bar between the upland and the channel. Excavated stems had shallow root flares (35-45 cm deep) on top of a deposit of medium to fine sand. This suggests that establishment occurred at a relatively high topographic position in association with a large flow event. All sampled stems showed signs of injury, but all trees were solid to the center. On one tree, cores from the root flare were unreadable and the age was determined at the ground surface. Three mature trees dated to 1884-1885 and a fourth dated to 1874. Cottonwood seedlings on the lowest surface dated from 1987 to 1992.

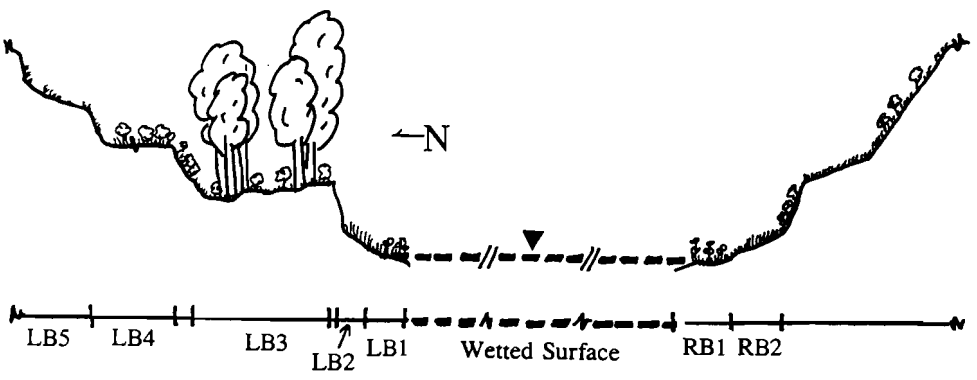

Figure 8. Sketch map of site RM72.9. Elevations and distances are not to scale. Perspective is looking downstream.

4.1.3 RM89.75 -- This site, on private land, is situated at a bend in the river below Council Island and the bridge crossing of Highway 236. The site includes a point bar on river left, with bands of trees on a series of progressively higher surfaces, and a tall, steep bank on river right (Figure 9). This portion of the river has changed since the 1890s: upstream, Council Island has formed, and downstream, two islands have attached to the mainland. On the 1893 map (Missouri River Commission 1892-1895), the study site appears as a grassy terrace adjacent to the channel. At present, a line of mature trees at a density of 92/ha (228/acre) occupies the highest alluvial surface subject to inundation (LB7). The understory of this surface includes *Artemesia cana*, *Rosa woodsii*, *Bromus inermus*, and a number of weedy agricultural species such as *Taraxacum officinalis* and *Medicago sativa*. Below this surface is a back channel (LB5) containing a linear band of larger cottonwoods (426 poles/ha [1,054 poles/acre] and 5,532 saplings/ha [13,693 saplings/acre]) and another surface (LB4) occupied by saplings of cottonwood (1,583/ha [3,918/acre]) and willow.

Lower surfaces (LB1-LB3), occupied by seedlings of cottonwood (1,000 to 29,412/ha [2,475 to 72,802/acre]) and sandbar willow, occur between LB5 and the channel edge (Figure 9). Seedlings, saplings, and poles were excavated from the five lower surfaces at this site. Many of these stems, particularly on the lower surfaces, showed evidence of flood-training and stem damage with subsequent resprouting. Seven of eight stems on surface LB5 and three of eight stems from surfaces LB3 and LB4 dated to the period 1978-1980. The remaining five stems dated to 1981 and 1982. Seedlings from surfaces RB1, LB1, and LB2 dated from 1990 to 1992.

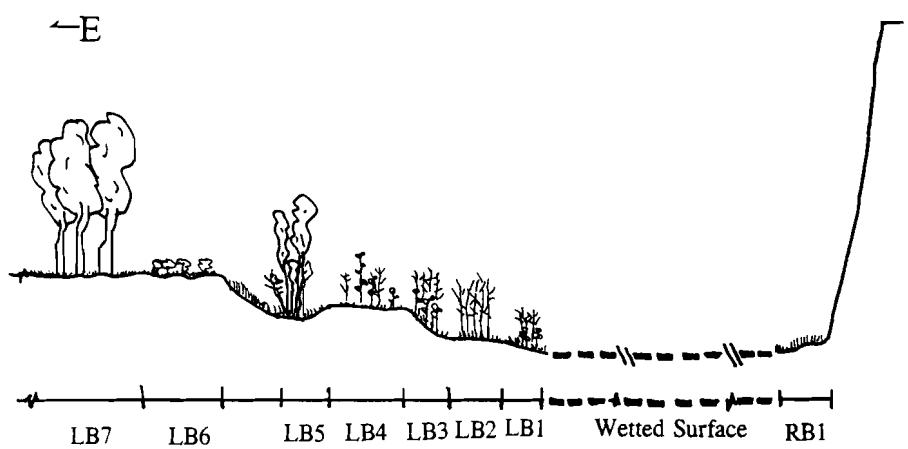

Figure 9. Sketch map of site RM89.75. Elevations and distances are not to scale. Perspective is looking downstream.

4.1.4 RM94.5 -- This site is located on the downstream end of the middle island in a group of three. At present, the two downstream-most islands appear to be in the process of attachment, through infilling of a small channel. The site consists of a high, narrow surface (IS3) that includes a band of poles (342/ha [846/acre]) and saplings (512/ha [1,267/acre]) showing evidence of ice or flood damage as well as beaver herbivory (Figure 10). To river left, this surface drops steeply to two low, narrow, vegetated surfaces (IS1 and IS2). To river right, the surface drops to a slightly lower, broader surface (IS4) across which are scattered poles (342/ha [846/acre]) and saplings (178/ha [441/acre]) that have been cut by beaver and have resprouted. This surface drops steeply to a low vegetated surface (IS5) next to the right channel. The lowest surfaces are dominated by moist-soil herbs such as *Plantago major*, *Scirpus americana*, *Potentilla anserina*, *Xanthium strumarium*, and *Polypogon monspeliensis* and include cottonwood seedlings at densities ranging from 5,143 to 64,348/ha (12,730 to 159,277/acre).

The position and size of the islands have changed since the 1890s. The Missouri River Commission map of 1893 (Missouri River Commission 1892-1895) shows a single island north of the present group, occupied by trees, and surrounded by a narrow sand bar. Two stems excavated from surface IS3 indicated rapid and extensive accretion. The establishment surface of these stems was more than 3 meters below the present surface. Precise dating of these stems was not possible, but establishment appears to have occurred in the 1950s. Stems excavated from surface IS4 were established on a sand and gravel deposit in 1964 and 1965. Seedlings from surface IS1 dated from 1990 to 1992, whereas seedlings from IS2 and IS5 dated from 1990 and 1991.

4.1.5 RM95.2 -- This site includes a stand of poles and trees at densities of 36 and 179/ha (89 and 443/acre) on a broad, flat surface (RB3) on river right (Figure 11). The trees occur in a broad arc between the toe of a steep slope and an area dominated by *Artemisia cana* and *Agropyron smithii*. The portion of the surface occupied by sage drops steeply to two lower, vegetated surfaces (RB1 and RB2) at the edge of the channel. These surfaces are dominated by the herbs *Plantago major*, *Scirpus americana*, *Eleocharis* sp., *Potentilla anserina*, *Xanthium strumarium*, and *Polypogon monspeliensis*, and include cottonwood seedlings at densities of 13,333 and 1,250/ha (33,002 and 3,094/acre).

The map of 1893 (Missouri River Commission 1892-1895) indicates that the sage-covered portion of RB3 was a small island occupied by a few cottonwoods and surrounded by a sand bar. The existing poles and trees were established in a former channel that filled in as the island attached to the mainland. Fifteen to twenty cottonwoods adjacent to the upland slope are dead or dying. This mortality appears to be related to sideslope deposition of clay from the upland. A stiff clay layer was noted in the upper 10 to 15 cm of the soil profile. The root flares of excavated trees occurred on a 20-cm layer of sand at a depth of approximately 45 cm. Three trees from this surface dated to 1928 and the fourth dated to 1929. Seedlings from surface RB1 and RB2 dated to 1992 and 1991, respectively. Scars collected from trees directly across the channel from this site indicated damage in 1978, 1979, and 1980.

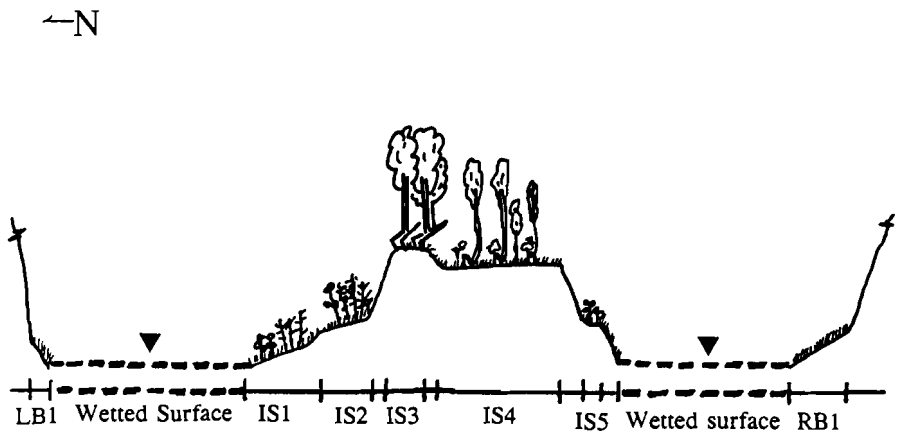

Figure 10. Sketch map of site RM94.5. Elevations and distances are not to scale. Perspective is looking downstream.

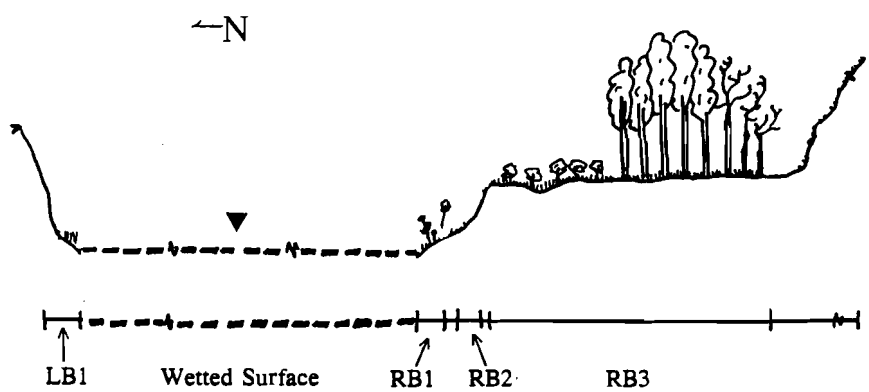

Figure 11. Sketch map of site RM95.2. Elevations and distances are not to scale. Perspective is looking downstream.

4.1.6 RM98.0 -- This site includes a single file of large trees at a density of 493/ha (1,220/acre) on the inside of a river bend, on river left, just downstream of Gallatin Rapids and upstream of Bear Rapids. The trees occupy the edge of a narrow, relatively high surface (LB4) with an understory of *Rosa woodsii* and *Symphoricarpos occidentalis* (Figure 12). The upland edge of the surface is occupied by scattered *Juniperus scopulorum* and *Artemisia tridentata*. Below this surface is another (LB3) that lacks cottonwood and is dominated by *Bromus inermis*, *Poa pratensis*, and *Euphorbia esula*. This surface drops to two lower ones (LB1 and LB2) that include seedlings of cottonwood at densities of 41,844 and 44,828/ha (103,574 and 110,960/acre) and willow.

This site has remained essentially unchanged since the 1890s. The 1893 map (Missouri River Commission 1892-1895) indicates a grassy upland separated from the channel edge by a single line of trees in essentially the same location as the present stand. In fact, the position of the channel throughout the bend appears to have remained stable during this 100-year period. The large trees along the edge of LB4 were excavated to the apparent root flare. Two trees were successfully cored; one dated to 1862 and the other to 1878. Both trees predated the hydrologic record for this reach of the Missouri. Seedlings located on the lowest surface (LB1) dated to 1992 and seedlings on LB2 dated to 1991.

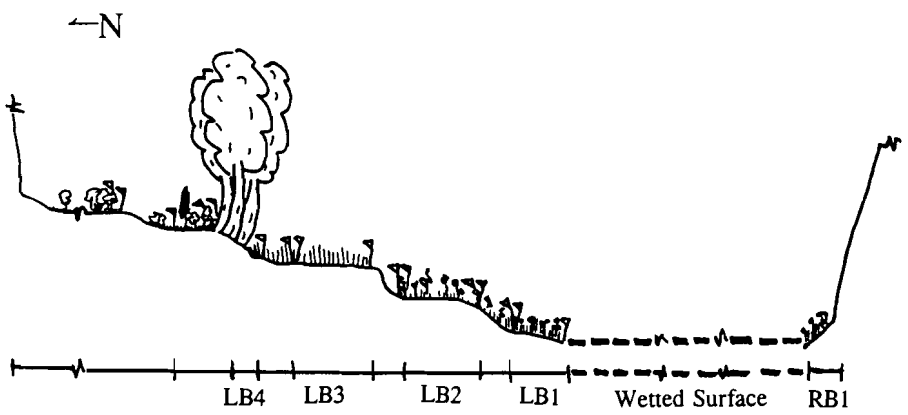

Figure 12. Sketch map of site RM98.0. Elevations and distances are not to scale. Perspective is looking downstream.

4.1.7 RM130.0 -- This site, originally a private homestead and now owned by the Bureau of Land Management, is located on river right on the inside of a bend downstream of Cow Island and just upstream of the confluence with Woodhawk Creek. The site includes a terrace that was cultivated until the 1950s adjacent to a slightly lower surface (RB4) with a rank of large trees (73 to 114 cm dbh) at a density of 173/ha (428/acre) (Figure 13). An apparent former back channel (RB3) separates these trees from RB2, a surface supporting a stand of poles and trees at densities of 244 and 264/ha (604 and 653/acre). The understory vegetation across surfaces RB2, RB3, and RB4 is dominated by *Bromus inermis*. *Artemisia cana* is scattered among the large trees on LB4 and a few peach-leaf willow are found on RB3. From surface RB2, a steep bank drops to a low vegetated surface (RB1) next to the channel edge. This surface is dominated by the moist-soil herbs *Scirpus pungens*, *Carex* sp., *Equisetum* spp., *Mentha arvensis*, *Xanthium strumarium*, and *Glycyrrhiza lepidota*, and includes seedlings of cottonwood at 398/ha (985/acre) and sand bar willow.

In the 1893 map (Missouri River Commission 1892-1895) this site appears as a grassy, treeless terrace that is separated from the channel by a narrow sand bar. The trees in the present stand appear to occupy the position of the sand bar in 1893. Only trees and poles on RB2 were excavated. These trees all had root flares between 30 and 40 cm below the present ground surface, and were situated on a thick deposit of medium to coarse sand that extended to a depth of approximately 1 meter. This deposit thinned toward RB3. Stem size appeared to increase with increasing depth of the sand deposit. Some of the stems showed evidence of fire scars; the site may have been intentionally burned on a number of occasions until the late 1950s (B. Damone pers. comm.). Four of the eight stems from RB2 dated to 1953 and 1954, one stem dated to 1950, and three dated to 1957 and 1958. Seedlings from RB1 were established from 1989 to 1992. Scars collected from the site dated to 1978, 1983, 1984, 1986, and 1989.

4.1.8 RM131.2 -- This site is located just downstream of the confluence with Woodhawk Creek on a gradual river bend. Four large cottonwoods (67 to 125 cm dbh) are scattered at a density of 23/ha (57/acre) along the edge of a surface on the outside of the bend (RB6) dominated by *Artemisia cana*, *Symphoricarpos occidentalis*, *Rosa woodsii*, and *Bromus inermis* (Figure 14). A small access road separates RB6 from a slightly lower surface (RB5). The cottonwoods in this stand occur in a relatively broad band at densities of 289 trees/ha (715 trees/acre) and 129 poles/ha (319 poles/acre). The understory of this stand is dominated by *Rosa woodsii*, *Agropyron repens*, and *Bromus inermis*. RB5 slopes down to another surface (RB4) on which another access road is located. This surface drops to a lower, sloping surface (RB3) occupied primarily by saplings of cottonwood and sandbar willow, along with some wetland herbs including *Mentha arvense*, *Verbena hastata*, and *Equisetum* spp. Below RB3 are two vegetated surfaces (RB1 and RB2) dominated by wetland herbs and seedlings of cottonwood and sand bar willow. Cottonwood seedlings occur on surfaces RB1 through RB4 at densities ranging from 833/ha (2,062/acre) on RB4 to 20,068/ha (49,673/acre) on RB2.

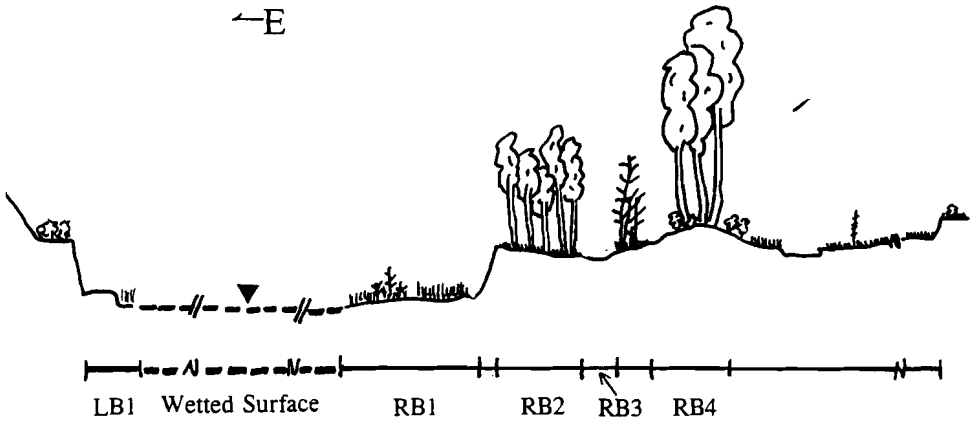

Figure 13. Sketch map of site RM130.0. Elevations and distances are not to scale. Perspective is looking downstream.

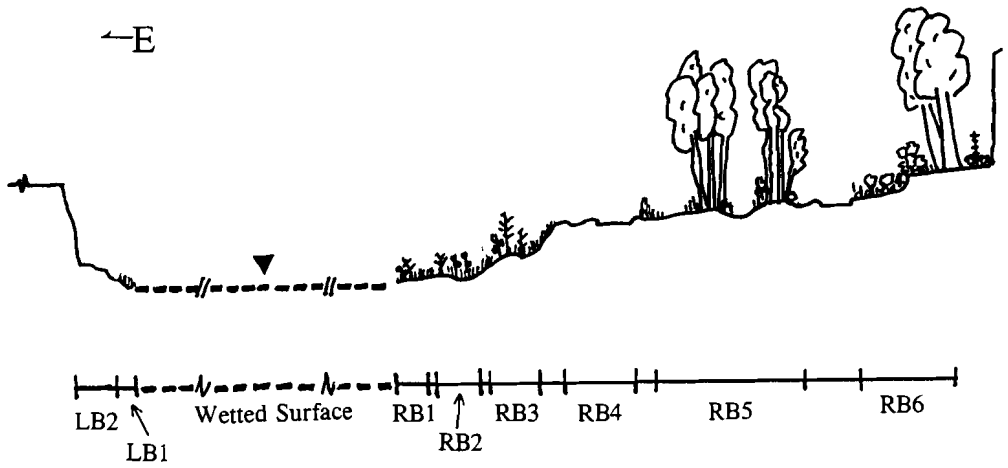

Figure 14. Sketch map of site RM131.2. Elevations and distances are not to scale. Perspective is looking downstream.

The river bend along this reach appears to have changed little in plan view since 1893 except for the portion of the bend occupied by the present stand. The map from 1893 (Missouri River Commission 1892-1895) shows an apparent cut bank separated from the upland by a narrow, grassy terrace. The present site occupies a position that was originally channel. Surfaces occupied by the stand may have been formed in part by sediment from Woodhawk Creek. Only those trees and poles on surface RB5 were excavated. Four trees from this surface were established in 1953 and 1954, two in 1950, one in 1955, and one in 1960. The stem that dated to 1960 may be a root sprout. Most of the seedlings from the lowest surfaces (LB1, LB 2, RB1, and RB2) dated from 1991 and 1992, but one individual dated to 1990. Similarly, seedlings on surfaces RB3 and RB4 dated to 1991 and 1992, except for one that dated to 1989. Scars collected from this site indicated stem injury occurring in 1952, 1978, 1986, 1988, and 1989.

4.1.9 RM135.5 -- This site is on private land on river right, downstream of an old power plant and approximately four miles upstream of Grand Island. The site consists of scattered cottonwoods (77/ha [191/acre]) in a line at the riverward edge of a terrace (RB4) that is now being cultivated and irrigated for crop production (Figure 15). *Bromus inermis*, *Agropyron repens*, *Symphoricarpos occidentalis*, and *Rosa woodsii* dominate the understory. This terrace drops abruptly to an apparent back channel (RB3) that is dominated by cottonwood saplings (1,556/ha [3,851/acre]) and poles (889/ha [2,200/acre]) with an understory of *Bromus inermis*. This surface rises toward the channel to an undulating surface (RB2) dominated by a relatively dense stand of sandbar willows up to 3 meters tall. Scattered throughout the willows are emergent cottonwood saplings and poles at densities of 4,783 and 580/ha (11,839 and 1,436/acre). Many of the cottonwoods on this surface appear to have been injured by ice and beaver. RB2 drops gradually to a narrow surface (RB1) adjacent to the channel with cottonwood seedlings at a density of 265/ha (656/acre).

According to the map of 1893 (Missouri River Commision 1892-1895), the site was formerly a narrow channel island covered by trees and surrounded by a sandbar. The present site includes the original island, which has become attached to the right bank. Cottonwood stems were excavated from surfaces RB1, RB2, and RB3. Every stem sampled on RB2 had been prostrated at least once by a flood or ice. Five individuals turned out to be sprouts from old damaged stems that were undatable because of rot. One stem from this surface dated to 1973 and two others dated to 1980. Stems from RB3 showed evidence of flood or ice damage and resprouting along with accretion of approximately 1 m of sediment. The seven trees sampled from this surface showed a considerable range in establishment dates. One tree dated to 1963, three to 1965 and 1966, one to 1969, one to 1971, and one to 1974. Seedlings from the lowest surfaces (LB1 and RB1) dated from 1990 to 1992.

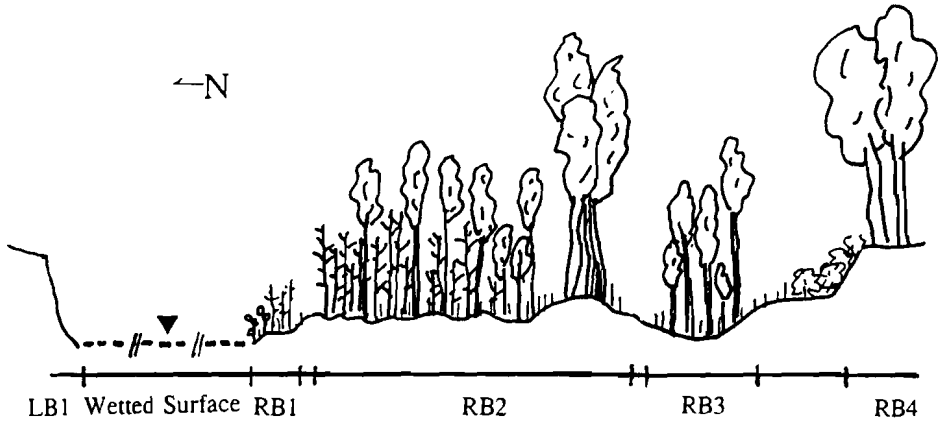

Figure 15. Sketch map of site RM135.5. Elevations and distances are not to scale. Perspective is looking downstream.

4.2 Summary Across Sites

Establishment of plains cottonwood along this reach of the Missouri River is strongly associated with floods. Thirty-four of 60 saplings, poles, and trees that were established during the period of record at Fort Benton date to years in which the highest mean daily discharge exceeded 1,400 m^3/s (49,434 cfs) or in the two years following these flood years (Figure 16). This large proportion of cottonwoods dating to the 32 flood and post-flood years in the 111-year record is inconsistent with the null hypothesis that all years had an equal likelihood of producing cottonwoods regardless of flow. The probability of getting this many or more cottonwoods associated with flood years by chance alone is $6.0 * 10^{-6}$.

An additional 14 trees were established from 1978 to 1980 following an ice jam that occurred within the study reach between the Fort Benton and Virgelle gages in March 1978 (Figures 16 and 17). This ice jam produced the highest stage of record (i.e., since 1934) at Landusky (Figure 17). When the jam broke, the Landusky gage recorded an instantaneous discharge of 3,060 m^3/s (108,049 cfs), the third highest discharge of record. When 1978 is considered a flood year, there are 35 flood or post-flood years out of a total of 111 and 47 trees establishing in flood or post-flood years out of a total of 60; the probability of getting this many or more cottonwoods associated with flood years by chance is $1.2 * 10^{-13}$. These results demonstrate a highly significant relationship between floods and cottonwood establishment.

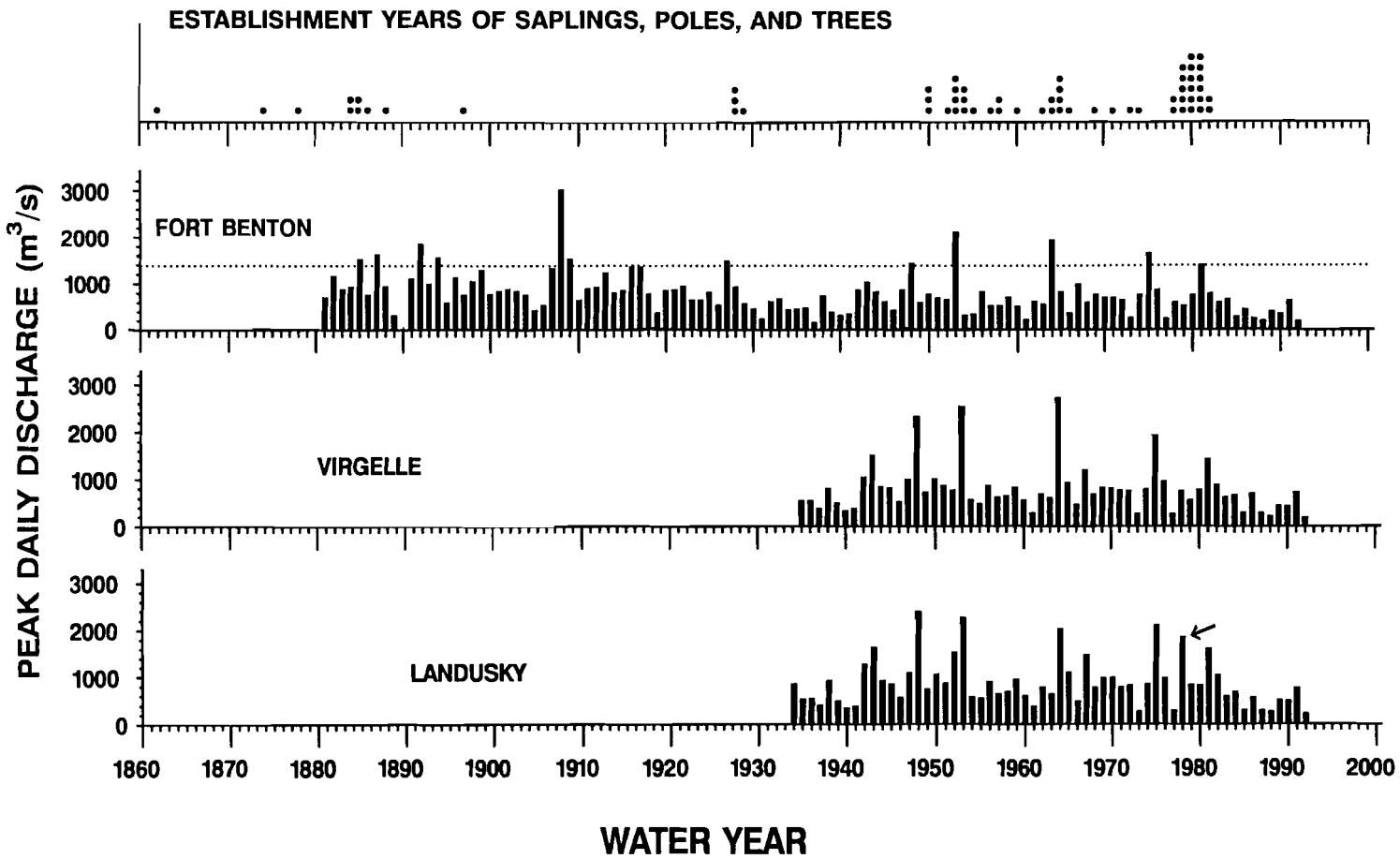

Figure 16. Establishment years of cottonwood trees, poles, and saplings along the Upper Missouri River, Montana, in relation to peak mean daily flows at Fort Benton, Virgelle, and Landusky gages. Dots represent cottonwood individuals. The dotted line indicates a value of 1,400 m^3/s (49,434 cfs) at Fort Benton. The ice-related flow at Landusky is marked by an arrow.

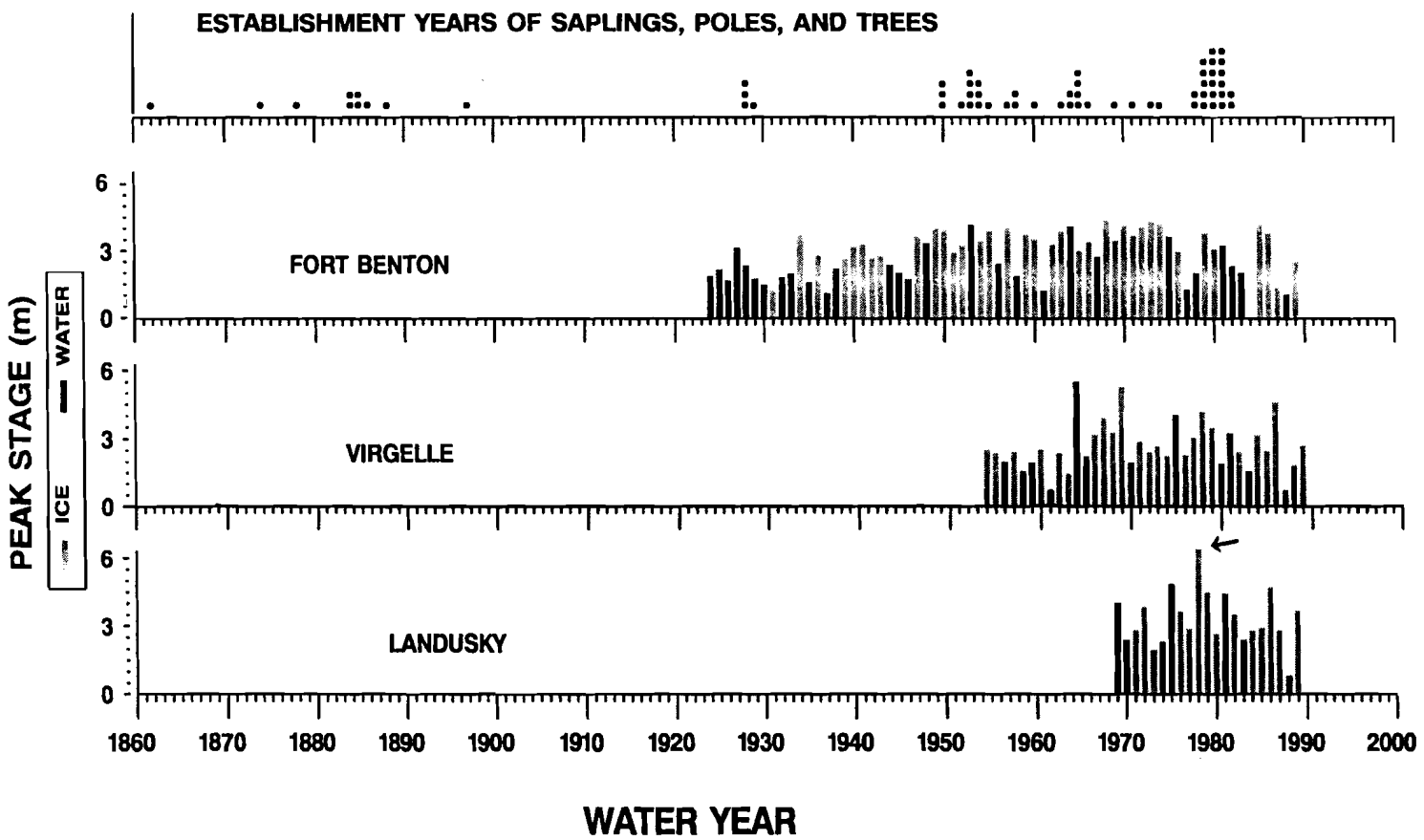

Figure 17. Establishment years of cottonwood trees, poles, and saplings along the Upper Missouri River, Montana, in relation to peak instantaneous stages at Fort Benton, Virgelle, and Landusky gages. Dots represent cottonwood individuals. Dark bars indicate high stages in the absence of ice. Light bars indicate high stages in the presence of ice. The ice-related stage at Landusky in 1978 is marked by an arrow.

Along the Upper Missouri River the highest flows almost always occur during the ice-free period (Figure 16), but the highest stages usually occur during ice jams (Figure 17). A similar pattern has been observed along the Turtle River in North Dakota (Harrison and Reid 1967). Most scars collected were produced by ice jams rather than ice-free floods. Two or more of the twenty-one collected scars date to each of four years: 1978, 1979, 1986, and 1989 (Figure 18). These are the four years of highest ice-related stage at Landusky since 1972. Only one scar dates to a year (1953) of discharge greater than 1,400 m^3/s (49,434 cfs) at Fort Benton (Figure 18). In almost all cases the wound generating the scar tissue occurred between growth rings, indicating that the tree was dormant at the time of the event. Although ice jams are more likely than ice-free floods to produce scars on pre-existing trees, ice-free floods are more likely to produce establishment of new trees. The only ice jam clearly associated with cottonwood establishment was that of 1978 (Figure 17). Unlike most ice jams, this event was associated with high discharge (Figures 16 and 17). Although icejams are unlikely to produce establishment, they may be an important source of mortality for established cottonwoods, particularly smaller individuals in relatively low channel positions. Ice has been shown to be an important source of cottonwood mortality elsewhere (Johnson in press).

Cottonwood age is strongly related to elevation of the establishment surface (Figure 19). The high elevation of establishment of most individuals dating to before 1978 supports the conclusion that these trees were established on flood deposits. The eighty-eight collected seedlings were established from 1987 to 1992 (Figure 20). Seedlings were established every year in this period, and there is no apparent relation between seedling establishment and high flows. Seedlings occurred at much lower elevations than did poles and trees (Figure 19). Most seedlings post-date the ice-jam of 1989, and none pre-date the even higher ice-related stage of 1986 (Figure 20).

All size classes of seedlings, saplings, poles, and trees were present at only two of the nine sites (RM89.75 and RM135.5). Seedlings were absent only at RM56.2, where high water on the day of sampling may have obscured seedlings in low positions. Trees were absent only from RM94.5, where rapid accretion may have kept some older individuals from attaining tree size. The pole size class was absent at 3 sites and the sapling class was absent at 5 of the 9 sites. Seedlings occurred on both banks (or both island edges) at all sites other than RM56.2 and RM130. Densities of seedlings where they occurred ranged from 106 to 64,348/ha (262 to 159,277/acre). Densities of saplings ranged from 61 to 5,532/ha (151 to 13,693/acre); poles from 36 to 580/ha (89 to 1,436/acre); and trees from 23 to 493/ha (57 to 1,220/acre).

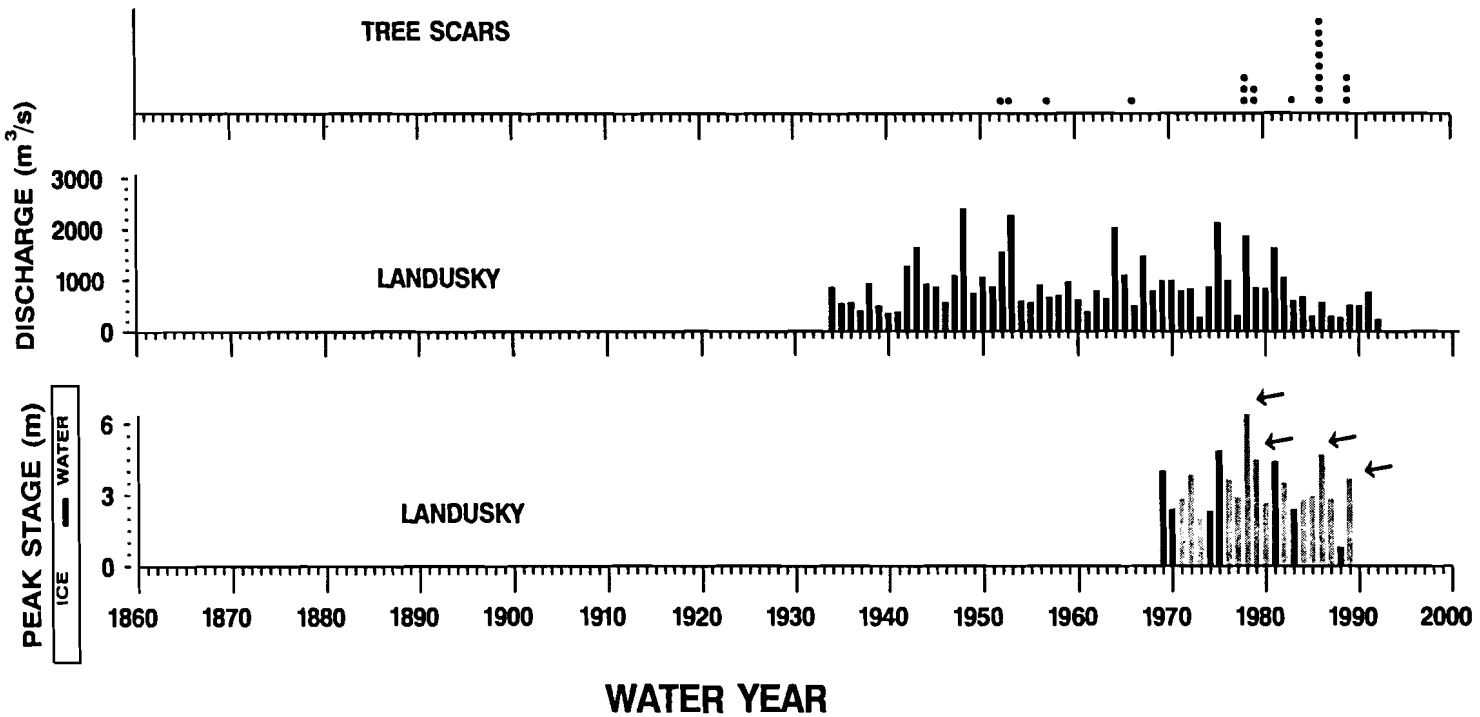

Figure 18. Dates of tree scars along the Upper Missouri River, Montana, in relation to peak mean daily flows and instantaneous stages at the Landusky gage. Dots represent individual scars. Dark bars indicate high stages in the absence of ice. Light bars indicate high stages in the presence of ice. Stages in years that produced two or more sampled scars are marked by arrows.

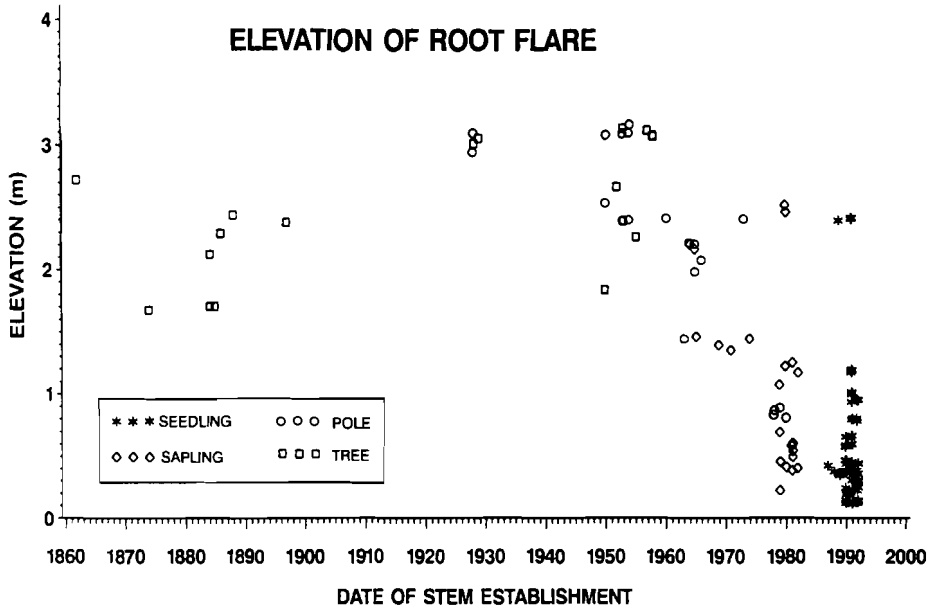

Figure 19. Elevation of establishment in relation to date of establishment for cottonwood trees, poles, saplings, and seedlings along the Upper Missouri River, Montana.

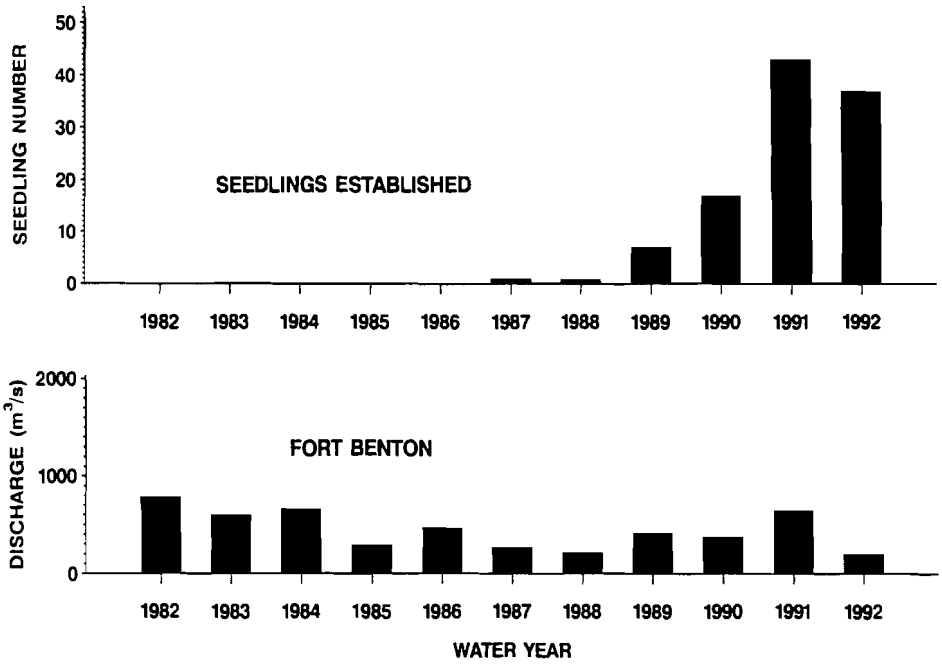

Figure 20. Establishment years of cottonwood seedlings along the Upper Missouri River, Montana, in relation to peak mean daily flows at the Fort Benton gage.

5. DISCUSSION

Most cottonwood establishment along the sampled sections of the Missouri River appears to occur in the year of a flood or the next two years (Figure 16). This evidence is consistent with the results of other studies suggesting that cottonwood reproduction is limited to bare, recently deposited substrates safe from future disturbance (Currier 1988, Friedman 1993, Scott et al. 1993). Although the peak stage in most years is associated with ice jams and most tree scars occur during ice jams, cottonwood establishment is more closely associated with floods than with ice jams (Figures 16 and 17). This may be because the high discharge of a flood transports more sediment than the relatively low discharge during an ice jam. As a result, floods deposit more of the bare surface necessary for cottonwood establishment than do ice jams.

Apparent establishment in the two years following a flood year could be an artifact resulting from the difficulty of finding the first year or two of growth. On the other hand, if establishment does in fact occur in subsequent years, then survival of seedlings along the Upper Missouri River is not entirely dependent upon the moisture left in a flood deposit by the flood. The best way to distinguish between these two possibilities would be to monitor seedling establishment following floods in permanent plots (Johnson in press).

Cottonwood seedlings occurred on both banks at almost all the sampled sites, as well as at almost all of the several dozen other locations in the study reach where we looked for them carefully. The ubiquitous occurrence of seedlings near the water's edge strongly suggests that the sparse pattern of older size classes cannot be explained by a shortage of seed. The presence of large numbers of cottonwood seedlings in the study reach should not be interpreted as a burst of successful recent reproduction. There is a strong inverse relation between year of establishment and elevation of the establishment surface at the root collar, with older individuals occupying higher surfaces (Figure 19). This reflects the fact that germination can occur most years on low, bare surfaces, but long-term survival is likely only when seedlings are established high enough to escape scouring by future high flows and ice jams (Friedman 1993, Johnson in press). For example, the ice jam of 1978 and flood of 1981 deposited surfaces suitable for cottonwood establishment (Figure 16); however, these events also removed any pre-existing cottonwoods on surfaces below approximately 1.3 m (Figure 19). The many seedlings established at lower elevations since 1981 (Figure 19) are unlikely to survive future high flows. Thus, only flows greater than roughly 1,400 m^3/s (49,434 cfs) are establishing seedlings in positions high enough to allow for long-term survival.

It could be argued that seedlings established at low elevations could survive over the long term if a series of moderate high flows caused accretion of the occupied surfaces without removing the seedlings. Such a process is typical of meandering and narrowing streams, where progressive channel movement helps to protect seedlings at low elevations (Everitt 1968, Nanson and Beach 1977, Johnson in press). However, if this process were common

along the study reach, there would be many trees that had established outside of flood years (Figure 16), and there would be many old trees with low elevations of establishment (Figure 19). Outside of the constrained post-glacial reach of the river (Figure 3) the valley is wider and the presence of point bars containing arcuate, even-sized bands of cottonwoods indicates that meandering is an important process (Everitt 1968, Noble 1979, Bradley and Smith 1986). In these areas we would expect that the relationship between floods and establishment would be relatively weak and that the elevation of establishment would be relatively low (Scott et al. in review).

Of the twelve floods with discharge greater than 1,400 m^3/s (49,434 cfs) at Fort Benton, only seven produced cottonwood establishment in the year of the flood and the two years following: 1885, 1887, 1927, 1948, 1953, 1964, and 1981 (Figure 16). We detected no establishment following the floods of 1892, 1894, 1908, 1909, and 1975. There are several possible factors contributing to the absence of apparent establishment following these five floods. The first is the small sample size. There may be unsampled sites in the study area that contain trees dating to these floods. The second factor is scouring by subsequent floods or ice jams. The highest recorded (i.e., since 1934) instantaneous stage and third highest instantaneous discharge at Landusky were associated with the ice jam of 1978. This ice jam may have removed young trees that had become established on surfaces deposited by the flood of 1975. Similarly the flood of 1908 was the highest discharge of record at Fort Benton (i.e., since 1881). This event may have removed young trees established following the floods of 1892 and 1894. The most interesting apparent failure of establishment following a flood occurred in the period 1908-1911 (Figure 16). It is possible that the flood of 1908 deposited surfaces too high and dry for establishment; however, if this were true establishment would have occurred on surfaces deposited in 1909. It is also possible that the high flows of 1907-1909 destabilized existing vegetation and initiated a period of widening. Such post-flood widening has been observed elsewhere (Osterkamp and Costa 1987). Other possible explanations include a period of hot dry weather (Baker 1990) or unusually intense grazing by livestock.

The study area has been grazed by livestock since the 1800s. We observed many seedlings that had been damaged by grazing. Recent reproduction of cottonwood seems to be more abundant at sites where cattle are excluded. It seems likely that grazing has had an important effect on cottonwood establishment and survival. However, this effect has not obscured the clear relationship between establishment and high flow. Construction and long-term monitoring of livestock exclosures would help to determine the importance of grazing in the study area.

In previous studies relating dates of establishment of bottomland trees to flow, investigators have used ages determined by cores taken above ground (Everitt 1968, Bradley and Smith 1986, Baker 1990, Stromberg et al. 1991). The error introduced by sampling above ground can either strengthen or weaken an apparent relation between high flow and establishment. Past microsite differences in environment or herbivory lead to different rates of growth in

now buried portions of a stem. As a result, two trees established following the same flood may have widely different ages at the present ground surface. On the other hand, two trees established in different years may have the same age at the present ground surface if they were cut back to ground level in the same year by flood or beaver.

Our decision to determine ages at the buried establishment point improved the precision of establishment ages, but also decreased the number of trees sampled. Excavation times of individual saplings, poles, and trees ranged from 1 to 12 hours, and preparation and reading of up to four slabs per tree increased several-fold the time necessary to determine the establishment year of a single tree. Determination of the establishment date is not critical in the many dendrochronological studies that focus on relating ring widths to environmental conditions. However, for the purposes of this study, it was essential to determine the establishment date as accurately as possible. Thus, we sacrificed a large sample size for confidence in the ages of the individuals we did sample.

6. FLOW RECOMMENDATION

In order to maintain the present abundance of plains cottonwood in the study area we recommend flood flows in excess of 1,400 m^3/s (49,434 cfs) measured as mean daily discharge at Fort Benton (U.S. Geological Survey gage 06090800) with a recurrence interval of approximately 9 years. We use the Fort Benton location primarily because this gage has the longest record and is therefore the best gage for relating historical flows to the establishment of existing trees. Tributaries and ice jams between Fort Benton and the study reach certainly influence establishment. However, we have been able to establish a strong relation between establishment in the study reach and the Fort Benton gage record alone. Those few downstream high flows that are not reflected in the Fort Benton gage can be viewed as exceptions that have occurred in the past and will likely occur in the future. Thus, the Fort Benton gage is a reasonable reference location for a flow recommendation concerning the reach from Fort Benton to the Fred Robinson Bridge in the absence of major new flow diversions or other flow alterations on the tributaries or mainstem Missouri River downstream of Fort Benton.

The hydrograph at Fort Benton is strongly influenced by snow-melt runoff. Thus, it is reasonable to assume that high flows are associated with large snow packs in the basin. Furthermore, it should be possible to use snow-pack information to predict flow volume in the following spring. An operational implementation of our recommendation could use such relations to ensure that flood flows for cottonwood establishment are released only in years of large snowpacks when there is an adequate amount of water available in the basin for other uses.

All twelve of the flood flows exceeding 1,400 m^3/s (49,434 cfs) at Fort Benton (Figure 16) occurred between mid May and late June. Our data cannot determine whether the timing of flow is important to establishment of plains cottonwood along the Upper Missouri River.

However, the results of several other studies have stressed the importance to cottonwood establishment of peak flows before the seed dispersal period (Fenner et al. 1985, Johnson in press). This timing is necessary because cottonwood seeds remain viable for only a few weeks, and because seedlings require a moist, bare surface. Therefore, ***we recommend maintenance of the historic pattern of flooding with peak flood flows occurring between mid-May and late-June.***

There are several other elements of a natural flow regime that are important to cottonwood that cannot be precisely quantified from our data. The rate of decline of the descending limb of the flood hydrograph should not be too steep (Scott et al. 1993). An extremely sharp decline will limit the geomorphic work done during the flood and may not maintain adequate moisture conditions in the rooting zone of young seedlings long enough for the seedlings to extend their roots to depths where moisture is adequate under non-flood conditions (Segelquist et al. 1993). Young cottonwood seedlings are also sensitive to inundation, especially by water that overtops the shoot; therefore, establishment is unlikely in areas subject to rapid oscillations of flow and stage such as occur with hydropeaking. Variability is important both with respect to the magnitude of the recommended flood flow and to the magnitude of peak flows in non-flood years. The channel widening and narrowing, meandering, and island dynamics associated with flow variation create the mix of eroding and accreting surfaces necessary to support cottonwood regeneration. Finally, both seedlings and older cottonwoods could be affected by significant decreases in mean flow of the river, especially during the growing season, to the extent that this affected ground water levels in the riparian zone.

We concentrated our sampling in a relatively constrained reach of the Missouri River where the new surfaces were primarily associated with large flood flows. In less constrained, more actively meandering reaches, relatively frequent high flows (e.g., 2-5 year recurrence interval) would probably play a more important role in cottonwood establishment (Bradley and Smith 1986). Nonetheless, even in less constrained reaches, a decrease in the magnitude or frequency of peak flows would probably decrease cottonwood establishment (Bradley and Smith 1986).

By developing a flow recommendation we do not mean to imply that flow is the only factor influencing cottonwood community dynamics and regeneration along this reach of the Missouri River. Land management and cattle grazing, in particular, are clearly having an impact, and changes in cottonwood populations could be expected if land management practices changed. However, the dependence of cottonwood establishment on high flow is clear in this reach in spite of the complicating effects of these other influences.

7. MONITORING PLAN

The above flow recommendation is our best judgement of the flows necessary to maintain the existing population of plains cottonwood along the Upper Missouri River, based on our analysis of the establishment of existing cottonwoods in relation to historical flows. However, the relation between flow and cottonwood establishment is complex. Only by tracking individual tree births and deaths over time can unequivocal relations between flow and sucessful, long-term establishment be developed. Furthermore, there are many other important riparian and riverine species that we have not addressed in this study. Given the value of the resource, we strongly suggest establishment of a monitoring program to determine the effectiveness of the recommended flows and to provide the data necessary for refining them. We recommend a monitoring program that would include the following activities.

1. Establishment of permanent widely spaced cross sections (approximately 10) along which annual measurements of the following would be carried out:
    a. Cross-sectional geometry.
    b. Establishment, growth, and mortality of cottonwood and other woody species.

2. Construction and maintenance of livestock exclosures (approximately 5) to monitor the influence of grazing in the study area. The density of cottonwood and other woody species inside and outside of the exclosures would need to be measured every 10 years, every flood year, and in the two years following every flood year.

3. Low-elevation aerial photography of the reach every five years and after every flood to detect changes in channel geometry and cottonwood forest.

Because cottonwood establishment is episodic, a long-term (> 20 years) commitment to the monitoring effort is essential. In addition, study areas should be accessible enough that measurements during flood years are possible.

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