Bulletin 139
November 1982

Altered Hydrology of the Missouri River and Its Effects on Floodplain Forest Ecosystems

W. Carter Johnson
Peggy W. Reily
L. Scott Andrews
James F. McLellan

Department of Biology
Virginia Polytechnic Institute and State University

John A. Brophy

Department of Geology
North Dakota State University
Fargo, North Dakota 58102

The work upon which this report is based was supported in part by funds provided by the United States Department of the Interior.

Project B-108-VA
VPI-VWRRC-BULL 139
3.5C

A publication of
Virginia Water Resources Research Center
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24060-3397

Additional copies of this publication,
while the supply lasts, may be obtained from
the Virginia Water Resources Research Center.
Single copies are provided free to persons
and organizations within Virginia. For those
out-of-state, the charge is $6 a copy
if payment accompanies the order, or $8
a copy if billing is to follow.

TABLE OF CONTENTS

List of Figures iv

List of Tables v

List of Microfiches vi

Acknowledgments vi

Abstract 1

Introduction 3

Study Area 5
- I. Physiography 5
- II. Geologic History 5
- III. Geologic Materials of the Trench 6
- IV. Soils 7
- V. Stream Hydrology 8
- VI. Natural Vegetation Dynamics 9

Tree Growth 12
- I. Methods 12
- II. Results and Discussion 14
  - A. Environmental Variables 14
  - B. Inter-Period Comparisons of Cumulative Growth 16
  - C. Patterns of Annual Radial Tree Growth 18
  - D. Multiple Regression Analysis 19

Land Use and River Hydrology 23
- I. Methods 23
  - A. River Meandering Rate 23
  - B. Land Use Change 24
- II. Results and Discussion 25

Tree Population Structure 30
- I. Methods 30
- II. Results and Discussion 31

Conclusions 36

Literature Cited 39

Figures 45

Tables 71

Microfiches . . . . insert

LIST OF FIGURES

1. Location and Number of Study Sites in North Dakota 47
2. Monthly Streamflow (1928-1977) from the Bismarck Gauging Station on the Missouri River 48
3. Streamflow for June and February 1928-1977, at the Bismarck Gauging Station on the Missouri River 50
4. Percent Change of Overbank Flooding at Different Terrace Elevations, Based on the Relationship Between Maximum Gauge Heights and Known Terrace Elevations 52
5. Groundwater and Streamflow Data (1971-1973) from the Missouri River near Bismarck 53
6. American Elm Chronologies (1928-1977) from Stands 12, 13, 19, and 16 54
7. Bur Oak Chronologies (1928-1977) from Stand 16 and the Scarp Woodland Reference Site 56
8. Cottonwood Chronology (1928-1977) from the Little Missouri Reference Site 58
9. Cottonwood Chronologies (1928-1977) from Stands 5 and 14 . . . 60
10. Smoothed Plots of Spring AE Versus Year and Spring (May, June, July) Streamflow Versus Year 62

11. Results of Stepwise Multiple Regression Analysis of Cottonwood from Stands 5 and 14 for Pre-Dam (1928-1952) and Post-Dam (1953-1977) Periods. 64

12. Age Structure of American Elm and Boxelder Populations in Four Treatment Stands on the Missouri River Floodplain in North Dakota 66

13. Age Structure of American Elm and Boxelder Populations in Reference Stands on the Missouri River Floodplain in North Dakota 68

LIST OF TABLES

1. Precipitation and AE Statistics for Pre-Dam (1935-1954) and Post-Dam (1955-1974) Periods. 73

2. Mean Total Radial Wood Growth by Species and Site for 20-Year Pre-Dam (1935-1954) and Post-Dam (1955-1974) (Unadjusted and Adjusted for Age) Periods. 74

3. Median Percent Change in Growth for Pre-Dam (1935-1954) and Post-Dam (1955-1974) (Adjusted for Age) Periods. 76

4. Frequency Table (Number of Stands) of Change in Growth Relative to Terrace Elevation .76

5. Characteristics of Stands Sampled for Tree-Ring Chronologies . . .77

6. Results of Stepwise Multiple Regression Analysis Using Tree-Ring Index as the Dependent Variable and 15 Independent Variables (Climate, Streamflow, Previous Year's Growth) 78

7. Results from the Modified Regression Model 82

8. Missouri River Erosion and Deposition Rates at Various Time Intervals 82

9. Missouri River Land Use Changes Since Early Settlement 83

LIST OF MICROFICHES

1. Missouri River Channel Changes . . . . insert

2. Missouri River Floodplain Land Use . . . . insert

ACKNOWLEDGMENTS

A number of colleagues assisted us during the course of the project: N. Fetcher (Duke University), T. Sharik (Virginia Tech), R. Burgess (SUNY-Syracuse), and J. Cairns, Jr. (Virginia Tech). We especially thank R. Phipps of the USGS Tree-Ring Lab for the use of the Reston, Virginia, facilities. G. Holtzman and the Virginia Tech Statistical Consulting Lab advised us in statistical matters. The North Dakota Historical Society and the North Dakota Water Commission provided maps and other historical information. Robert Levis (Cross Ranch) and the Nature Conservancy were helpful during the field work.

Special acknowledgment is made to the following, who generously gave their time to a critical review of the manuscript: Benjamin L. Everitt, Division of Water Resources, State of Utah, Salt Lake City; Marjorie M. Holland, Department of Biology, College of New Rochelle, New Rochelle, New York; and Philip A. Robertson, Department of Botany, Southern Illinois University at Carbondale. Acknowledgment is made also to Nancy L. Chapman for editorial processing and typesetting and to Gretchen S. Bingman for layout composition.

ABSTRACT

It is generally expected that construction and operation of a floodplain protection project will alter a river system's hydrologic regimen. But this altered regimen also has been suspected of having major, long-term effects on the natural dynamics of riparian ecosystems that remain in gaps between large reservoirs. This study confirms that hypothesis by documenting some of those impacts in an area between Garrison Dam and Oahe Reservoir on the Missouri River in south-central North Dakota. Specifically, it examines post-dam changes in river meandering rate, floodplain forest composition, tree population structure, and tree growth rate.

Post-dam hydrologic regimen differs markedly from the pre-dam regimen. Although precipitation and actual evapotranspiration have changed little since Garrison Dam's construction, streamflow patterns have changed considerably. Large amounts of water are now released for electricity generation in the nongrowing-season months, and streamflow for June (mid-growing season) is now lower than June flows recorded in the drought years of the 1930's. Post-dam flow patterns, therefore, are out of phase with the vernal growth pattern typical of floodplain trees. Since the dam's construction, flooding has been eliminated on terraces more than 2 m above mean river level, thus reducing moisture and nutrient influx to higher terraces. River meandering has all but ceased; accretion rates have fallen to 1 percent and erosion rates to 25 percent of pre-dam levels.

Data were collected at 13 forest stands within the 130-river-km study area and at two reference sites (one on a stream unaltered by flood control structures and the other a scarp woodland located above the floodplain). Floodplain tree species studied were cottonwood (*Populus deltoides*), peach-leaved willow (*Salix amygdaloides*), boxelder (*Acer negundo*), green ash (*Fraxinus pennsylvanica* var. *lanceolata*), American elm (*Ulmus americana*), and bur oak (*Quercus macrocarpa*). Evaluation of the data revealed that Garrison Dam and Oahe Reservoir have had significant impact on the area's riparian ecosystem, including altering streamflow patterns; eliminating much of the flooding and silt deposition that had occurred along the pre-dam river; decreasing river meandering rates but widening the river channel; causing a decline in radial tree growth in species whose natural sources of moisture have been altered by the dam; changing the composition of floodplain forests by preventing regeneration of *Populus-Salix* forests and lowering seedling survivorship of *Ulmus americana* and *Acer negundo;* and encouraging the clearing of floodplain forests for agriculture with improved irrigation opportunities.

Results of this study should have application to forests on other floodplains where the natural hydrologic regimen has been altered by man. This research should stimulate further study of riparian ecosystems so that a more general assessment can be made of the ecological effects of floodplain protection.

Key Words: Floodplains, Floodplain Protection, Floods, Forests, Dams, Riparian Ecosystems, Riparian, Vegetation, Rivers, River Meandering, Growth, Survivorship, Land Use, North Dakota, Missouri River

INTRODUCTION

The ecological impacts of constructing impoundments on river systems are many and varied. On-site impacts have been the focus of most research [Baxter, 1977]. A few studies document the rapid loss of native riparian habitats within the impoundment basin (for example, Yeager [1949]), but most evaluate changes in aquatic organisms and water quality during and after the filling of reservoirs [Kujawa, 1974; Ridley and Steele, 1975]. Off-site impacts of reservoir construction have received little study, except for the river environment itself (water quality monitoring, fish population dynamics). Potential downstream effects associated with adjacent floodplain ecosystems have been neglected, perhaps because (1) the effects are not immediately noticeable and hence less dramatic compared to the changes associated with the filling of reservoirs, or (2) native riparian ecosystems had, on many floodplains, largely been removed for agriculture before dam construction. Recently, Kosler [1979] noted serious gaps in research concerning wetland/flood interrelationships and the reaction of wetlands and floodplains to stress.

Trees on floodplains in semi-arid regions exhibit vernal growth patterns [Brown, Lowe, and Hausler, 1977; Everitt, 1980]. That is, growth occurs early in the growing season when water is readily available and ceases in mid-summer as moisture is depleted. Production and dissemination of seeds also occur in the spring. Although moisture is of major importance to the distribution and growth of floodplain trees, the relative importance of the various sources of water available is poorly known.

Potential sources of moisture for floodplain trees include overbank flooding, groundwater, and precipitation (capillary water). Overbank flooding is responsible for much physical damage to floodplain trees [McKenzie 1936; Sigafoos, 1964] and in humid climates may be responsible for the distribution of floodplain species according to their tolerance to flooding [Bedinger, 1971; Bell and del Moral, 1977; Robertson, Weaver, and Cavanaugh, 1978]. In dry climates, however, flooding may benefit trees by saturating the rooting zone and raising the water table just before the onset of growth.

The dynamics of riparian woodlands are closely tied to the dynamics of two physical processes, flooding and river meandering. Significant changes in the rates of these natural perturbations would be expected to alter the properties of riparian ecosystems and the floodplain landscape. Our studies indicate that the cessation of flooding and related changes in hydrologic regimen, associated with the presence and operation of reservoirs, are having major and long-term effects on the natural dynamics of remnant riparian ecosystems. This conclusion is based on investigations of a protected floodplain, bounded north and south by two large reservoirs, along the upper Missouri River in North Dakota.

Johnson, Burgess, and Keammerer [1976] first noted that major ecological changes in riparian ecosystems along this stretch of the Missouri River had been initiated by reservoir construction. The purpose of this research was specifically to test three hypotheses [Johnson, Burgess, and Keammerer, 1976] through new field research in 1979 and 1980. The three hypotheses were that the altered hydrologic regimen caused by the presence and operation of reservoirs had initiated (1) a decline in diameter growth rate of trees, (2) a reduction in river meandering rate and landscape composition and diversity, and (3) changes in the population structure of several important tree species. Tests of the three hypotheses are considered separately in this report: effects on tree growth are considered first; meandering rate and forest composition, second; and population structure, third. Historic and recent patterns of land use change also are analyzed in the second section.

STUDY AREA

The study area included floodplain forests along a 130-river km portion of the Missouri River Valley located in south-central North Dakota *(Figure 1).* Garrison Dam (Lake Sakakawea), completed in 1953, forms the northern border, while the Oahe Reservoir, some 10 km south of Bismarck, forms the southern border. Most forests studied were on the floodplain within the study area; however, reference sites for tree growth analysis were selected in scarp woodlands west of Price, North Dakota, and along the Little Missouri River in western North Dakota *(Figure 1).* The climate of the study area is characterized by low humidity and low annual precipitation. Mean annual precipitation is 39 cm, 70 percent of it occurring during the growing season (approximately May 10 to September 27) [Randich and Hatchett, 1966].

I. Physiography

This segment of the Missouri Valley lies in the Missouri Slope district of the Glaciated Missouri Plateau section of the Great Plains physiographic province [Fenneman, 1931; Lemke and Colton, 1958; Clayton, 1962]. The valley is trench-like, varying in width from about 1 km to more than 11 km and is cut as much as 170 m below an upland underlain by glacial drift and Tertiary and Cretaceous bedrock. The trench is floored by a broad floodplain bounded locally by terraces. The floodplain descends from an elevation of 515 m at Garrison Dam to 494 m at the junction with Oahe Reservoir, a total drop of 21 m in about 130 river km, giving an overall gradient of about 0.15 m per km.

II. Geologic History

This segment of the Missouri Valley did not exist before Quaternary glaciation. The preglacial Missouri flowed northeastward from Montana across the northwest corner of North Dakota into Saskatchewan [Lemke et al., 1965] and was diverted into its present course by southwestward advancing continental ice sheets. The timing and sequence of events involved in this diversion are not completely known.

The most recent studies of this problem are by Bluemle [1971] and Carlson [1973], both of whom suggest a complex history of diversions by various ice advances, which forced the Missouri into a course involving segments of eastward-trending preglacial valleys and new segments cut by water diverted across former divides. Bluemle shows that the wide segments of the present trench are those that were parts of preglacial valleys and the narrow segments are those that were cut by water diverted across divides. He also suggests that final diverting and assumption of the present course of the Missouri did not occur until late Wisconsinan time, less than 15,000 years ago.

The terraces along the trench were developed as the river incised itself below former floodplain levels, leaving remnants of those floodplains. Some of them are eroded bedrock surfaces mantled with glacial drift and represent floodplains formed in reoccupied preglacial valley segments formed during pre-Wisconsinan glacial diversion [Carlson, 1973]. Other terraces are underlain by sand and gravel and resulted from glacial valley trains [Brockman et al., 1979].

The definitive study of Missouri River terraces has not yet been made, and various authors who have studied different segments of the trench disagree on the number of terraces and their historical interpretation. Kume and Hanson [1965] recognized four terrace levels in Burleigh County, two high outwash terraces and two low alluvial terraces. Carlson [1973], working in Mercer and Oliver counties, recognized only two terraces, an upper one that corresponded to the high outwash terraces of Kume and Hanson and a lower one that included their two lower alluvial terraces. Carlson believed that the two lower terraces represent the predam floodplain.

Post-glacial changes in the trench have not been great. The floodplain was established and modified by lateral cutting of the meandering river. The valley walls have been gullied by new drainage lines eroding headward into adjacent uplands and by slopewash. Wind has piled sand into dunes locally, and soils have formed on the various trench sediments.

III. Geologic Materials of the Trench

The trench walls expose the various materials cut through by the eroding river. At the top are glacial sediments (generally thin and locally lacking), including till and lesser amounts of glacio-fluvial sands and gravels, loess, eolian sand, and glacial lake sediments. Most of the depth of the trench is cut in bedrock of early Tertiary and (in the Bismarck-Mandan area) late Cretaceous age [Kume and Hanson,1965; Bluemle, 1971; Carlson, 1973]. The Tertiary units include interbedded sands, silts, clays, shales, and lignite beds belonging to the Paleocene Cannonball, Slope, Bullion Creek, and Sentinel Butte formations. The late Cretaceous beds are mudstones, sandy shales, sandstones, and lignites of the Hell Creek formation.

Most of the high terraces are underlain by sand and gravel and are loess-covered in some areas, but some are underlain by drift-mantled bedrock [Kume and Hanson, 1965; Carlson, 1973]. The low terraces, essentially the modern, pre-dam floodplain, are underlain by recent alluvium, including flood overbank deposits, channel deposits, and natural levee deposits. Overbank silts and clays compose about 90 percent of these sediments, with sand and gravel of channel and levee deposits composing about 10 percent [Bluemle, 1971]. The thickness of this Holocene component may be as much as 35 m or more, but it is often difficult to distinguish from similar glacial sediments upon which it rests.

IV. Soils

Soils of the Missouri trench have been described in county soil surveys of McLean County [Brockman et al., 1979], Oliver County [Weiser, 1975], Mercer County [Wilhelm, 1978], and Burleigh County [Stout et al., 1974]. The floodplain soils that support the forests of the study area are Entisols of the Typic Ustifluvent or Typic Fluvaquept subgroups. The Havrelon series dominates, generally comprising 50 to 75 percent of the floodplain soils. It is formed from loamy alluvium on the slightly higher elevations and is calcareous and well drained. It has moderate permeability, high available water capacity, medium natural fertility, and low organic matter.

Areas of sandy alluvium such as natural levees and inter-channel islands are occupied mainly by the Banks series, which has moderately rapid permeability, low available water capacity, low natural fertility, and low organic matter. Clayey alluvium of floodplain depressions (mainly oxbows) is occupied mainly by the Lallie series, which has slow permeability, high available water capacity, low natural fertility, and low organic matter.

Floodplain soil profiles tend to have thin, greyish A horizons, no B horizons, and C horizons that vary somewhat in texture because of alluvial stratification. All horizons tend to be mildly to moderately alkaline.

V. Stream Hydrology

The filling of Lake Sakakawea began in November 1953. At that time, the natural hydrologic regimen was replaced by a controlled-release regimen, and the river began a series of adjustments to this alteration.

Two major alterations in downstream regimen could be expected to result from damming: (1) reduction of peak annual flow (mean annual flood) because of impoundment of excess runoff, and (2) reduction of sediment load because of sediment deposition in the reservoir from upstream.

Continuous daily discharge records from 1928 to present, recorded at the U.S. Geological Survey Gauging Station No. 06342500 at Bismarck (120 km downstream from the dam), permit a comparison of the pre-dam and post-dam discharge. These data show no significant change in overall discharge. The mean of daily discharge readings for 25 pre-dam years (water years 1928-29 to 1952-53) is 1,999 cms compared to 2,204 cms for 25 post-dam years (water years 1954-55 through 1978-79). This decrease in discharge because of the initial filling of the reservoir (1953-1963) was offset by the low discharges resulting from the dry climate of the 1930's.

Seasonality of discharge has changed considerably. The pre-dam (1928-1952) pattern of monthly streamflow shows peak flow occurring from April to July and minimum flow occurring from December to March *(Figure 2).* The sharp peaks in streamflow in the spring and early summer in the pre-dam period are largely absent after 1953. Overall, peak flow now occurs in February and March instead of April, May, and June, and minimum flow occurs mainly in May and September instead of January and February.

Seasonal flow rates are especially different for the months of June and February *(Figure 3).* June streamflow in the drought years of the 1930's was much higher than June streamflow since completion of the dam. Extrapolating from gauge height, the spring water table on the average would be considerably lower since 1953 and the late-summer water table would perhaps be higher. Therefore, the period of peak flow is now out of phase with the vernal growth pattern typical of floodplain trees.

Mean annual low flow (mean of the lowest mean daily discharge readings over a number of years) has been increased by about 155 percent. Mean annual low flow for the 25 pre-dam years was 405 cms compared to 1,032 cms for the 25 post-dam years. The minimum annual low flow for the 25 pre-dam years was 167 cms (January 1940) compared to 372 cms (March 1955) in the 25 post-dam years, an increase of about 122 percent.

In addition to these changes in flow, changes in the sediment load could also be expected. Both suspended load and bed load from upstream are trapped in the reservoir. Thus, the water released into the trench below the dam is essentially sediment-free and able to acquire a new load from materials available in the trench. Unfortunately, data are not available to compare pre-dam and post-dam sediment loads.

Overbank flooding is the element most obviously missing from the post-dam floodplain environment. Flooding now occurs on only the lowest terraces, in part as a result of local ice jams in the spring. Flooding above the 2-m terrace elevation has been eliminated *(Figure 4).* In the past, the 3-m elevation was flooded on the average of once in 3.5 years, and the 4-m elevation approximately once in 6 years. Terrace elevations of the stands sampled ranged from 3 to 5 m above mean river level. The highest stand was flooded on the average of once in 25 years. Because of ice jams in the pre-dam period, the above frequencies are probably low for some locales. Landowners report higher flood frequencies (25 percent or greater).

The mean annual flood (mean of the highest mean daily discharge readings over a number of years) has been reduced by about 68 percent. Mean annual flood for the 25 pre-dam years was 11,064 cms compared to 3,554 cms for the 25 post-dam years. The maximum annual flood (highest mean daily discharge reading) for the 25-year pre-dam period was 33,736 cms (April 1952) compared to 6,394 (July 1975) in the 25 post-dam years, a reduction of 81 percent.

VI. Natural Vegetation Dynamics

The predominant vegetation of the region is mixed grass prairie [Kuchler, 1964]. Small pockets of scarp woodland occur in protected upland ravines, but the most extensive forests occur on the floodplain. Clearing for agriculture has reduced these forests to about 50 percent of their original extent. Floodplain tree species include cottonwood *(Populus* *deltoides),* peach-leaved willow *(Salix amygdaloides),* boxelder *(Acer negundo),* green ash *(Fraxinus pennsylvanica* var. *lanceolata),* American elm *(Ulmus americana),* and bur oak *(Quercus macrocarpa).*

Most of the world's floodplains have been formed by the effects of deposition and overbank flow [Wolman and Leopold, 1957]. Deposition, as well as erosion, is dependent upon lateral migration of the river across the floodplain. As the river deposits alluvium on the inside of a meander, it erodes material from the opposite bankline. Overbank flow usually results from heavy spring rains combined with rapid snow melt. Downcutting by the river and upbuilding of the terrace from alluvial deposition during floods eventually leaves some terraces well above the active floodplain. Leopold, Wolman, and Miller [1964] referred to such river terraces as the ''abandoned floodplain.''

Vegetation patterns correspond to the dynamics of deposition and erosion. Lateral movement of the river initiates a dynamic series of vegetation events. As the river meanders, it erodes away established banks often covered with forest vegetation in different stages of development. However, fully exposed alluvium deposited in the inside of river curves is prime habitat for the establishment of tree seedlings of pioneer species (for example, cottonwood, peach-leaved willow). Of the six tree species occurring on the floodplain, only cottonwood and willow germinate and persist under these conditions. Cottonwood and willow are classic pioneer species; the seeds of neither species germinate under a forest canopy or in light gaps. This illustrates the importance of point bar deposition by the meandering river in maintaining cottonwood-willow communities as an important and integral component of the floodplain ecosystem.

If cottonwood-willow communities remain uneroded, forests of these tree species will develop. Should they be missed by the meandering river for centuries, however, the overstory will be replaced by admixtures of green ash, boxelder, American elm, and bur oak through natural succession. Thus, there is a strong positive correlation between terrace elevation and forest successional stage. Higher terraces that have escaped erosion and were exposed to fewer floods of less intensity are more likely to contain vegetation of advanced successional stages.

The cessation of flooding and a decline in the meandering rate would have at least two major consequences: (1) reduce the amount of substrate (freshly deposited alluvium) for the regeneration of new cottonwood-willow forests, and (2) allow a greater proportion of existing forests to age and change type through natural succession. The net effect would be to reduce the land area of cottonwood-willow forest, now the most extensive forest type, in favor of forests of ash, boxelder, elm, and oak. Old cottonwood-willow forests exhibit the greatest tree species diversity [Johnson, Burgess, and Keammerer, 1976] and have the greatest richness and density of breeding birds [Hibbard, 1972]. The major forest communities also exhibit divergent understory species, mineral cycling patterns, and fauna [Kroodsma, 1970; Hibbard, 1972; Keammerer, 1972; Keammerer, Johnson, and Burgess, 1975].

TREE GROWTH

Research to test the hypothesis that alteration of the hydrologic regimen was responsible for decreased tree growth had three components. First, we examined the degree to which environmental variables important to tree growth had changed from pre-dam to post-dam periods. Second, cumulative growth of trees was compared during two 20-year periods to determine pre-dam and post-dam growth patterns. Third, tree-ring chronologies were constructed and the growth patterns related statistically to a series of environmental variables using multiple regression procedures.

I. Methods

Thirteen forest stands *(Figure 1)* were selected for tree core sampling. The stands included a range of vegetation and physiographic conditions and showed little or no sign of current or past disturbance. One reference site was located along the Little Missouri River in western North Dakota within the Theodore Roosevelt National Park *(Figure 1)*. The Little Missouri is a free-flowing stream whose flow patterns have not been altered by flood control structures. Cottonwood and willow predominate, although green ash, boxelder, and American elm occur as well. The Little Missouri is a much smaller river than the Missouri; average flows are 17.33 for the Little Missouri and 640.9 cms for the Missouri [U.S. Geological Survey, 1928-1977].

A second reference site was a scarp woodland [Wells, 1965] located above the floodplain *(Figure 1)*. Vegetation was similar in composition to that of the mesic terraces of the Missouri River with bur oak, green ash, American elm, and boxelder the dominant tree species. Scarp woodland trees rely exclusively on precipitation, which is concentrated in local ravines. Growth of these trees should more closely reflect patterns of precipitation than floodplain trees.

The reference sites were selected because they were similar to the Missouri River floodplain sites in vegetation and general climatic conditions but had not undergone any major environmental modifications between pre- and post-dam periods. The term "reference" was used rather than "control" because a number of small differences existed between reference and treatment sites (for example, 39 cm mean annual precipitation for the Missouri, 37 cm for the Little Missouri).

Trees were selected for sampling if they were at least 70 years old and displayed no signs of disease or decay. Also, trees were excluded if a nearby competitor had died. Tree cores were collected using an increment borer and were dried, mounted, and surfaced. A number of cores were initially measured with a dendrochronometer to establish a system of cross-dating to facilitate accurate measurement of the remaining samples [Stokes and Smiley, 1968].

Three 20-year increments of growth (two pre-dam periods 1915-1934, 1935-1954; one post-dam period 1955-1974) were measured for all cores. Because diameter growth of trees usually decreases with age, it was necessary to adjust the measurements of the post-dam growth to compare them to growth during the immediate pre-dam period when trees were younger. Standard dendrochronological procedures to correct for aging [Fritts, 1976] were not suitable here as none discriminates between decrease in growth due to age and decrease due to long-term environmental changes (for example, altered river hydrology); low-frequency trends are removed.

To correct for age, we adjusted (increased) post-dam growth by multiplying it by the proportional change in growth that occurred between the two pre-dam periods. The proportional change, or multiplier, was the quotient calculated by dividing growth during the first pre-dam period (1915-1934) by growth during the second (1935-1954). Cores that showed a growth decline between the pre-dam periods were adjusted in the above manner for all species except bur oak (henceforth referred to as "adjusted for age"). For example, a core with 50 mm and 40 mm growth, respectively, during the first and second pre-dam periods would result in a multiplier of 1.25. Therefore, the growth during the post-dam period, say 20 mm, would be adjusted to 25 mm. Our method thus assumes a uniform rate of decline in growth with age. Bur oak was not adjusted because most cores were from old trees that showed small increases, not decreases, in growth between the two pre-dam periods.

Finally, 90 of the cores used above in the inter-period comparisons were selected for multiple regression analysis to examine year-to-year variation in growth in relation to environment. Cores were selected from stands for which there were at least 8 cores per species from trees at least 80 years old, except for elm in stand 16 where only 3 cores were available. The number of cores per species for the Missouri River floodplain was 24 for cottonwood, 30 for elm, and 12 for oak, with 8 for cottonwood on the Little Missouri and 16 for oak in the scarp woodland.

Individual ring widths were measured for a 50-year period (1928-1977) for each core. Measurements were standardized (converted to indices) by fitting a polynomial curve to the data and then dividing each ring width by the corresponding curve value (henceforth referred to as "standardized"). In this way, long-term trends in growth were removed (for example, due to senescence) and year-to-year variation was emphasized [Fritts, 1976]. The computer program used in the standardization procedure was developed at the Laboratory of Tree-Ring Research in Tuscon, Arizona [Fritts, Mosimann, and Botroff, 1969] and adapted for use by the U.S. Geological Survey Tree-Ring Laboratory in Reston, Virginia. Ring-width indices for all cores from a stand were averaged by species to construct chronologies: three of cottonwood (including one from the Little Missouri), two of oak (including one from the scarp woodland), and three of elm.

Precipitation data were from the U.S. Weather Bureau station at Bismarck. To integrate temperature (energy) and moisture, actual evapotranspiration (AE) was also calculated [Thornthwaite and Mather, 1957] and used as an independent variable in growth correlations. AE was calculated assuming 2.5 cm of available water per 15 cm of soil, a surface rooting zone of 1.2 m, and equal water availability between field capacity and permanent wilting point (-15 bars) [Johnson, Burgess, and Keammerer, 1976].

II. Results and Discussion

A. Environmental Variables

Primary environmental variables potentially important to tree growth during the two periods included precipitation, groundwater, overbank flooding, and soils. To determine whether low precipitation might have been responsible for the decrease in tree growth during the post-dam period, Johnson, Burgess, and Keammerer [1976] compared average annual precipitation and AE for two 15-year periods, 1940-1954 and 1955-1969. They found a slight decrease in both parameters in the post-dam period. We also found a slight decrease in average annual precipitation and AE for two 20-year periods and for the primary growing season months (April, May, June, and July), although the means were not significantly different ($p < 0.75$) and the minimum values were much smaller in the pre-dam period *(Table 1).* It is unlikely that the small average decrease in AE and precipitation could have caused a large decline in growth in the post-dam period. As will be shown later, tree growth of one reference site actually increased significantly during the post-dam period.

Depth to the water table ranges from near zero to 9 m in the study area [Greenman, 1953]. Water table depth changes seasonally in response to periods of aquifer recharge and discharge *(Figure 5).* Recharge occurs mainly in early spring from lateral movement of water from the Missouri River at high stages (bank storage), subsurface flow from adjacent bedrock above the floodplain, and percolation of soil gravitational water from precipitation and runoff. Discharge from the aquifer occurs mainly in the summer as a result of transpiration, flow to the Missouri River at low stages, and irrigation pumping [Randich and Hatchett, 1966]. The water table on terraces adjacent to rivers can respond rapidly to changes in river stage; however, the response decreases with increasing distance from the channel [Weist, 1971; Grannemann and Sharp, 1979].

Current releases from Garrison Dam are related primarily to generation of electricity. Peak demands occur during the coldest months and, to a lesser extent, the warmest months [U.S. Army Corps of Engineers, 1980], although the seasonal pattern is highly variable. It is difficult to determine the effect of changing river gauge height (flow) on water table depths at all distances from the river, although the greatest changes probably have occurred nearest the river channel. Unfortunately, we can find no data on pre-dam water table depths and seasonal fluctuations in the study area and can only speculate as to pre-dam water table conditions. However, irrigation and seasonal fluctuation in river stage have noticeably changed since completion of Garrison Dam. There has been increasing use of aquifers for pumped irrigation water, which would have lowered the water table during the growing season.

Several stands were located in areas flooded periodically from concentrated upland runoff. The highest of these (stand 16) was situated at the edge of the floodplain adjacent to the bedrock terrace. Three ravines draining a large upland area emptied into the stand. According to local reports, it is flooded most years in the spring at times of snow melt and heavy precipitation. Moisture conditions for this stand were markedly different from terraces of similar elevation that received no concentrated runoff. Not only did vegetation composition of this stand differ from drier terraces, but, as will be shown later, tree growth showed distinctly different patterns.

Soils in the study area are alluvial in origin and high in textural variability, not only between but also within stands. Past floods deposited lenses of sands, silts, and clays, varying in thickness throughout the floodplain. With the cessation of flooding, the deposition of silt on terraces and accompanying nutrient enrichment have been eliminated. Yet the cessation of flooding also allows for a build-up of organic matter on terraces where it was previously scoured and removed by flood waters. Changes in soil characteristics as a result of flood cessation are most likely not of as immediate importance to tree growth as the alteration in the hydrologic regimen. However, soils could have had an effect on the growth response of a tree to altered moisture conditions.

B. Inter-Period Comparisons of Cumulative Growth

Average cumulative growth of trees was compared between the immediate pre-dam (1935-1954) and post-dam (1955-1974) periods. All species on the Missouri River floodplain decreased in growth in the post-dam period *(Table 2),* comparing post-dam growth (adjusted for age) to growth in the pre-dam period. The trends are very similar to those of Johnson, Burgess, and Keammerer [1976], even though they are based on different sets of tree cores. In contrast, post-dam growth of oak (unadjusted) and cottonwood at the reference sites was greater than growth during the pre-dam period. Application of the Wilcoxon sign-rank test [Hollander and Wolfe, 1973] to growth during the pre- and post-dam periods showed that the decreases on the Missouri River floodplain were statistically significant for all species except cottonwood; the cottonwood reference site showed a statistically significant increase, but the increase in oak growth in the scarp woodland was not significant *(Table 2).*

In a separate analysis, the percent change between pre- and post-dam (adjusted for age) periods was computed for each core, and the median percent change computed for each species *(Table 3).* Percentages ranged from about a 25 percent decline to a 20 percent increase. Largest declines were for boxelder, elm, and ash, with moderate decreases for cottonwood and bur oak on the Missouri River floodplain. Comparatively large increases were exhibited by the two reference sites. Based on results from a multiple comparisons test [Hollander and Wolfe, 1973], the growth declines for boxelder and elm were significantly different from the increases on the reference sites, and ash was significantly different from oak on the scarp woodland reference site. Differences among species on the Missouri River floodplain were not statistically significant nor were the differences for bur oak and cottonwood between floodplain and reference sites.

An attempt was made to relate changes in growth to various environmental conditions such as soil characteristics and topographic position (for example, elevation above mean river level). Percent change in growth of all species was determined for each stand. The stands were then ranked into low/medium/high classes of change. This procedure was repeated for all three soil characteristics (available water capacity, organic matter, and soil texture) and for stand elevation. Frequency tables were constructed for growth classes and the classes for each environmental variable. No trends were found for the soil characteristics. Terrace elevation versus percent change in growth, however, showed a distinct trend *(Table 4).* On the uppermost terraces, growth was little changed; on the middle terraces, growth showed the greatest decline; and on the lowest terraces, growth decreased moderately.

Trees on low terraces (2-3 m above mean river level), which were flooded most frequently in the pre-dam period and are rarely flooded now, were expected to have shown the largest decrease in growth. However, growth decreased more on the middle terraces than on the lower terraces. The relative depth to the water table on a terrace may be more important for growth than flood frequency. Trees on low terraces are closer to the water table and to the river and could more effectively utilize pulses of high flow (for example, after heavy precipitation) compared to those of the upper terraces.

Tree growth on high terraces showed the least amount of change between the periods. Although the water table was likely at greater depths on these terraces and only occasionally accessible to trees (even in the pre-dam period), most of these stands received additional moisture from concentrated upland runoff. Many trees here showed increases, not decreases, in growth. For example, stand 16 reportedly was flooded most years by runoff from upland ravines. Elm in stand 16 showed no change in growth between pre- and post-dam periods compared to a decrease of 25 percent over the study area. Runoff is clearly important to the growth of trees on high terraces adjacent ot the uplands.

The observed decrease in the growth of elm was not caused by Dutch elm disease since trees in the Bismarck area have been infected only in the last several years. Johnson, Burgess, and Keammerer [1976] observed a decrease in growth of trees sampled in 1969, before the disease had spread to central North Dakota. The elms that we sampled 10 years after their study showed the same magnitude of decline in growth.

C. Patterns of Annual Radial Tree Growth

Cottonwood, elm, and oak were selected for multivariate analysis to examine year-to-year variation in growth in relation to environment. These species were selected because each is representative of a different stage in the development of the floodplain forest and therefore may be affected differently by the altered hydrologic regimen. Also, patterns of pre- and post-dam growth differed among these species. Percent change in the growth of bur oak and cotton was the smallest between the two periods, whereas elm showed a large decrease in growth in all but the most mesic stands.

Seven tree-ring chronologies were constructed from stands along the Missouri (two from stand 16), and two chronologies were constructed for the reference sites *(Table 5)*. Both unstandardized and standardized chronologies were constructed and smoothed [Tukey, 1977; 3RSSH 3RSSH3] for each site except for elm in stand 16, where just the unstandardized chronology was used *(Figures 6* through *9)*. Low growth during the 1930's (especially 1936-1937), in 1946, and in 1961 was common to all of the tree-ring chronologies. These were periods of low spring streamflow and AE *(Figure 10)*. During the pre-dam period, most chronologies exhibited two peaks in growth between 1938 and 1944. In the post-dam period, most chronologies showed peak growth in 1965 coincident with high spring AE. Thus, there was a close correspondence between macroclimate and the growth of floodplain trees.

But perhaps of more significance were the years 1952 and 1955. In April of 1952 one of the largest floods on record for the Missouri River inundated the entire floodplain. It was, however, a year of low AE. All chronologies except those from stand 13 *(Figure 6)* and the scarp woodland showed high growth in 1952. This illustrates the compensating effect that overbank flooding had on tree growth in years of low AE. In 1955, the reverse conditions prevailed; spring AE was high while streamflow (releases from the dam) was low. Growth in 1955 for all chronologies except in stands 13 *(Figure 6),* 16 *(Figure 7),* and the scarp woodland was low, which indicates the effect of low streamflow on growth. The growth of scarp woodland trees, not influenced directly by streamflow, generally followed AE patterns between 1928 and 1977.

The unstandardized series for elm sites that did not receive concentrated upland runoff (stands 12, 13, and 19) exhibited a systematic downward trend in growth rate through the post-dam period *(Figure 6),* which matched the general pattern of elm growth decline discussed earlier. In contrast, the unstandardized chronology for elm in stand 16, which continued to receive upland runoff since construction of the dam, showed no systematic, long-term decline in growth during the post-dam period and therefore was not standardized. This re-emphasizes the importance of topographic position on the magnitude of the growth decline of elm and other species during the post-dam period.

The cottonwood chronology from the Little Missouri reference site *(Figure 8)* showed similar trends in growth to that of cottonwood on the Missouri River *(Figure 9),* with lowest growth also occurring in the 1930's, 1946, and 1961. In contrast to the cottonwood chronology from stand 14 *(Figure 9),* the unstandardized chronology from the Little Missouri showed no systematic decline in growth. Trends in the Little Missouri streamflow data generally matched cottonwood growth patterns *(Figure 8).*

D. Multiple Regression Analysis

Fourteen environmental variables (fall AE plus those shown in *Table 6),* considered to be important for tree growth during certain months and seasons (for example, June flow), were used in stepwise multiple regression models. A fifteenth variable, tree growth during the previous year, was included because growth in one year may strongly affect growth in the following year (serial correlation; Fritts, 1976]. Thus, tree-ring index was the dependent variable, and the 15 aforementioned factors were independent variables. Regressions were determined separately for each stand for pre-and post-dam periods.

Several streamflow parameters correlated positively in the multiple regression models with annual patterns of cottonwood growth in the pre-dam period *(Figure 11).* April-May flow was important in models for both stands 5 and 14. In addition, spring precipitation and spring precipitation in the previous year (Y-1) were positively correlated in models for both stands. The analysis also indicated that growth may be suppressed when April precipitation is high (negatively correlated with growth, *Figure 11)* because it may prolong saturated soil conditions (low oxygen) after March-April floods. High June flow (negatively correlated, *Figure 11)* flooded low terraces near the river, such as stands 5 and 14, or raised the water table excessively during this important growing season month and therefore may have been responsible for decreased stem growth by limiting root oxygenation. High June flows were common in the pre-dam period *(Figure 2).*

Correlation patterns for cottonwood shifted markedly from streamflow and spring precipitation in the pre-dam period to AE and temperature in the post-dam period *(Figure 11).* Of the streamflow parameters, only June flow was positively correlated with growth (stand 5) in the post-dam period. Thus, very high flows in June in the pre-dam period could have reduced overall growth, but high flows within a much lower range in the post-dam period *(Table 3)* could have been beneficial. Growth in both stands was positively correlated with spring AE and spring temperature in the previous year and negatively correlated with fall temperature in the previous year. Low fall temperature in the previous year would have resulted in greater soil moisture storage over the winter. The negative correlation with spring precipitation in stand 14 appears to be spurious, a situation not uncommon in the application of multivariate techniques to ecological data [Pitt and Heady, 1978]. Overall, the general lack of correlation with streamflow suggests that moisture supplied by the river is now less important to the growth of cottonwood in the post-dam period.

Cottonwood presence has been used as an indicator of a high water table since it tends to be phreatophytic [Meinzer, 1927]. Hayes and Stoeckler [1935] classified cottonwood as a shallow-rooted tree (< 2 m); however, its roots may extend to much greater depths, especially on floodplains where the process of terrace development continually buries the trunks of trees [Everitt, 1968]. Older cottonwoods that grow on terraces 3 m above mean river level, yet that germinated on low terraces just above river level, may have roots that extend to the original depth of rooting.

With the alteration in flow regimen, especially during the growing season, there has likely been a corresponding change in depth to water table. For example, with a lower spring water table, the roots of trees may no longer extend to the capillary fringe; thus, growth might depend more on surface soil moisture from rainfall than on groundwater. This shift in response from one source of moisture to another indicated that the dam has indirectly affected cottonwood water relations. Cottonwood was perhaps less affected by altered streamflow than other species because of its deep root system, proximity to the river where the water table was most accessible, and possession of a root system more responsive to changes in water supply.

Most positive correlations with bur oak growth in stand 16 during the pre-dam period were with variables of the previous year, including growth, temperature, and AE *(Table 6).* Regression coefficients for the post-dam period increased considerably; positive correlations were for current year precipitation, AE, and temperature in the spring. The regression coefficients for the scarp woodland models were low (0.36, 0.41) and are therefore not discussed. With respect to the observed positive correlation between oak growth and streamflow variables, it should be recalled that post-dam streamflow was mainly a reflection of releases from the dam. However, high streamflow events were also caused in part by runoff from short, heavy rains or rapid snowmelt. The frequency of these events may have been independent of total monthly precipitation. For example, total monthly precipitation does not indicate whether there were many days of light rain or a few days of heavy rain with the rest of the month dry. For these reasons, the relationship between oak growth and streamflow was only correlative and not causal.

Regression coefficients for American elm were higher than the scarp woodland oak values but still considerably less than those of the cottonwood models. Patterns of correlation shown by at least two of the three elm stands during the pre-dam period were: positive correlation with April-May flow and spring precipitation in the previous year and negative correlation with spring temperature. The patterns are decidedly different in the post-dam period: April-May flow was negatively correlated, and June flow was positively correlated with growth. However, there was little pattern among stands with respect to the numerous other variables included in the regression models. The correlation pattern for elm appears to be highly variable among sites and between periods, and little can be generalized from the multiple regression analyses.

The chronologies were also used in a reduced model "growth = spring AE and spring streamflow" in a linear modeling procedure [Helwig and

Council, 1979] to more clearly define the contributions of these environmental factors to tree growth *(Table 7).* The results re-emphasize the shift in correlation between the periods from streamflow to AE for cottonwood. Bur oak growth correlated with AE in the pre-dam period, yet was more strongly correlated with AE and streamflow in the post-dam period. For American elm, correlations with growth in the reduced model were weak; one significant correlation with AE occurred in one elm chronology in the post-dam period.

Separate regression analyses were made for the Little Missouri cottonwood chronology corresponding to the pre- and post-dam periods on the Missouri. In the 15-variable stepwise regression procedure (using Little Missouri streamflow data from 1935-1977), there were no major differences in the variables selected for either pre- or post-dam period models. Using the reduced model "growth = spring AE and spring streamflow (Little Missouri)," there were again no shifts in correlations between the two periods. This is in distinct contrast to the shifts in correlations observed for cottonwood in stands 5 and 14 on the Missouri River, where the hydrologic regimen has been altered by Garrison Dam.

LAND USE AND RIVER HYDROLOGY

Johnson, Burgess, and Keammerer [1976] expected that because of reduced spring flooding (lower peak flows) and bank stabilization, the rate of river meandering had slowed since construction of the dam. This hypothesis is evaluated in this section by analyzing historic and present river meandering rates. Also in this section, the rates and directions of land use change since initial settlement are analyzed and discussed. Such an analysis is important since current vegetation patterns are closely linked to past land use.

I. Methods

A. River Meandering Rate

Historic and recent rates of meandering of the Missouri River were determined from channel change maps within the study area. Positions of the river over time were transferred to a common base map at a scale of 1:24,000. Several sources of information were used. General Land Office summary records describe the position of the river channel from 1872 to 1881. An additional set of archival maps was prepared in 1891 by the Missouri River Commission. The aerial photographic record of the study area began in 1938. Photographs recording channel position were available for several time periods up to the present. Additional information on pre-dam channel position was available from maps prepared by the U.S. Army Corps of Engineers in 1945.

The pre-dam meandering rate was determined from channel positions in 1881, 1891, and 1945. From the common base maps, an electronic digitizer was used to determine the amount of eroded and deposited land in each time interval. This total area was divided by the number of years in the time interval to compute average annual erosion and deposition for the period. Post-dam meandering rate was determined by comparing the position of the river compiled from U.S. Geological Survey photographs (1969) to current (1979) channel as shown by Corps of Engineers photographs. Meandering rates were independently determined for the period 1938-1972 by the Corps, which used aerial photogrammetric techniques and range line surveys.

Also, field surveys were conducted to assist in mapping historic channel positions. Five to 10 cottonwood trees on each terrace level on several large meanders in the study area were cored and aged. By plotting tree ages for a given terrace, "isochrones" or age contours could be drawn [Everitt, 1968]. Use of these maps improved the accuracy of the composite channel map.

B. Land Use Change

Land use was mapped for each period on a composite map at a scale of 1:24,000. Land use categories were: (1) marsh—treeless areas with emergent aquatic vegetation or open water; (2) non-forest—open land occupied by houses or farm buildings; (3) bare sand—non-forested bars and dunes along the river channel; (4) industrial—power plants and refineries; (5) agriculture (settlement to 1938)—cropland and pasture cleared before 1938; (6) agriculture (1938-1979)—cropland and pasture cleared 1938-1979; (7) cottonwood-willow—young stands of *Populus deltoides* and *Salix amygdaloides* up to approximately 40 years of age; (8) cottonwood—stands of *Populus deltoides* approximately 40-80 years of age; (9) cottonwood-ash-elm-boxelder—stands with at least 50 percent of the canopy composed of *Populus* with 20-50 percent an admixture of *Fraxinus, Ulmus,* and *Acer;* (10) ash-elm-boxelder—stands with at least 75 percent of the canopy composed of *Fraxinus, Ulmus,* and *Acer.* Many of these stands included a small component of *Populus* and/or *Quercus.*

Field surveys and tree aging also improved the accuracy of land use maps by providing general ground information and specifically enabling more accurate estimation of age classes of cottonwood forests. They also enabled accurate estimation of the area and age of young cottonwood-willow forests (less than 40 years), which are difficult to identify unambiguously from photography.

Because 1891 cover maps were very general, General Land Office Survey records were used to determine the proportional composition of the forest categories at the time of settlement. These records have been used by other researchers in determining pre-settlement vegetation [Stearns, 1949; Burgess, 1964]. Survey notes usually included a general description of each township, including details of forest, underbrush, soils, and relief. Points were established at each 1.6-km interval along the range and section lines of each township. In this manner, 36 sections were established within each township. At the common point between sections, as well as at quarter section corners (a point halfway between section corners), the species, diameter, and bearing of up to four witness trees were recorded. By examining the records for all trees on the 160 points occurring in the study area, the proportion of cover types could be estimated.

II. Results and Discussion

Between 1881 and 1891, approximately 1,650 ha. of land surface area were deposited as alluvial material *(Table 8)*. During this same period, approximately 1,328 ha. were eroded. The average annual erosion rate was 133 ha. per year. For the interval 1891-1945, approximately 5,464 ha. were deposited and 4,648 ha. eroded. Average annual loss rate during this interval was approximately 86 ha. per year. Thus, average annual erosion rate for the entire pre-reservoir period (1881-1945) was 93 ha. per year, while deposition rates averaged 111 ha. per year. Although there was a slight net accumulation of material (18 ha. per year) during the pre-dam period, losses and gains were relatively balanced.

In the post-dam period, both erosion and deposition rates decreased substantially. During 1969-1979, only 13 ha. of land were deposited, and most of that accumulated behind erosion control devices (wing-dikes) constructed along the bankline. During this same period, approximately 212 ha. of land were lost to erosion. This is an average annual rate of 21 ha. per year. Thus, erosion rates fell from the pre-dam average of 93 ha. per year to 21 ha. per year during the post-dam period (1969-1979). Accretion rates fell from 111 ha. per year to 1.3 ha. per year during the same period. Post-dam erosion rates were only 25 percent of pre-dam rates, and accretion rates only 1 percent of pre-dam rates.

While erosion and deposition rates were relatively balanced during the pre-dam period, they were decidedly unbalanced during the post-dam period. Deposition during the pre-dam period was 1.2 times greater than erosion; during the post-dam period, erosion was 16.2 times greater than accretion. This overall increase in erosion over deposition has resulted from increased bank cutting and destabilization. Thus, the channel is widening because material is being eroded from both banks with little concurrent accretion.

Meandering rates increased as floodplain width increased. Thus, where the floodplain was narrow, river meandering rate was small. In the portion of the study area below Garrison Dam *(Microfiche 1.7)*, the width of the floodplain averages about 1.6 km. Shifts in channel position since

1872 have averaged approximately 0.6 km. In the study area south of Bismarck *(Microfiche 1.1)*, the floodplain is approximately 11.6 km in width. Channel changes since 1872 have averaged approximately 2.4 km, resulting in redistribution of large amounts of alluvium.

The model of Schumm [1969] would predict that the reduction of flooding and bed-material load resulting from dam emplacement will lead to an increase in channel sinuosity and a decrease in meander wavelength. Thus, the natural response involves considerable lateral cutting until the channel reaches equilibrium with the new regimen. In the study area, however, an extensive series of bank-stabilization structures constructed by the Corps of Engineers since dam emplacement has prevented natural channel response and has actually led to a considerable post-dam reduction in lateral channel shifting. The Schumm model also predicts a decrease in channel width, but the actual channel has been widening. The cause of this anomalous response may be that the stream is expending energy in eroding and transporting sediment from both channel walls instead of unilateral channel shifting.

The dramatic decline in erosion and accretion rates since the construction of Garrison Dam and the change in the balance between the two are beginning to have an impact on natural rates of reforestation by cottonwood and willow. Currently, approximately 35 percent of the floodplain forest is composed of cottonwood forests less than 80 years old; forests with cottonwood trees less than 150 years old comprise 78 percent of the total. Thus, forests with cottonwood as the primary dominant currently make up the large majority of the floodplain forests.

On active floodplains, Everitt [1968] proposed a logarithmic decline in the area of the floodplain occupied by forests of increasing age, that is, young forests should occupy the largest proportion and old forests the smallest. If the meandering rate were to decline substantially, thereby decreasing the likelihood of erosion and increasing mean stand age, the pattern may at equilibrium become reversed, that is, old forests would occupy a larger area than young forests. This is the pattern now emerging on this protected floodplain; cottonwood forests less than 40 years of age now occupy only 8 percent of the total forest area, while forests of 40 to 80 years comprise 23 percent of the total. We expect the proportion of young cottonwood forests to decline in rough proportion to the decline in accretion rates. A new equilibrium composition would be reached in less than two centuries, and cottonwood forests will probably comprise, at the most, only 5-10 percent of the total forest area. The remainder would include forests of more advanced successional age dominated by green ash and boxelder, especially the former. Cottonwood stands of the future will be small in extent and primarily located behind wing-dikes and other erosion control devices. Few, if any, cottonwood forests will occupy broad terraces more than several meters above mean river level. The distribution of cottonwood should therefore become more restricted, that is, a "strand" species occurring in close proximity to the river.

Settlement has brought many significant changes in the extent and composition of the floodplain vegetation *(Microfiches 2.1* through *2.8).* The largest changes involved the clearing of forests for agricultural purposes. By 1938, approximately 38 percent of the floodplain forest had been cleared for agriculture, or about 0.7 percent per year over the 1881-1938 period *(Table 9).* Thus, clearing proceeded at a rapid rate after the General Land Office Survey of 1872-1881. No mention of agriculture on the floodplain was made in the Survey notes; however, some cultivation had occurred in the adjacent prairie uplands. An additional 18 percent of the forest was cleared for cultivation between 1938 and 1979, or about 0.5 percent per year.

Industrial development on the floodplain is a recent phenomenon, occurring mostly after the construction of Garrison Dam. Less than 1 percent of the land area is used by industry. Marshes and sand dunes also comprise less than 1 percent of the floodplain area. Marsh area has changed little since presettlement, but bare sand has decreased since the cessation of floods. Large floods in the pre-dam period scoured and deposited sand on low terraces near the river channel.

General Land Office Survey notes indicate that the presettlement floodplain was almost completely wooded. Young cottonwood forests less than 40 years old occupied about 14 percent of the floodplain forest. These may have occupied a larger proportion of the forest area because young trees were generally not used as witness trees in the land survey.

Approximately 53 percent of the forest was composed of cottonwoods 40-80 years old. Thirty percent of the forest was in the old cottonwood type, while only 3 percent of the forests were of advanced successional age. These included ash, elm, boxelder, and bur oak, with occasional large cottonwoods.

Presently, forest vegetation comprises about 44 percent of the floodplain area; about 8 percent of this total is composed of young stands of cottonwood and willow less than 40 years of age. Most of these have regenerated since the closing of Garrison Dam in 1954 on alluvium deposited during the 1952 flood. In many areas, these stands are severely browsed by beaver and scoured by ice in the spring, resulting in frequent damage to aboveground stems. Thus, individual plants are older than they appear. Because these stands are on low terraces with a high water table, are flooded occasionally, and are on soils unproductive for crops, only 6 percent of this forest type has been cleared since their establishment at various times during the past 40 years.

Approximately 23 percent of the existing floodplain forest was composed of stands of cottonwood ranging in age from 40 to 80 years. Forests in this age class generally occurred on more productive soils; however, they were still on low terraces with relatively sandy soils. Agricultural clearing has removed about 52 percent of these stands since their establishment. Clearing of forests of this age has increased since the 1930's because of floodplain protection and access to irrigation.

The most extensive forest category is age class 80-150 years—47 percent of the total forest area. These stands contain large cottonwood trees with young green ash, American elm, and boxelder. These forests are located on intermediate terrace elevations. About 43 percent of forests in this category have been cleared for agriculture.

The remaining forest type makes up 22 percent of the total forest area. These forests contain green ash, American elm, boxelder, and few scattered cottonwoods and/or bur oak. Since settlement, 75 percent of this forest type has been cleared for agriculture. This high rate of clearing is due to the location of these stands on high terraces removed from most floods and the presence of more productive soils for agriculture.

Overall, the rate of forest clearing was at its maximum during the early settlement period before 1938. Although the rate of clearing has been somewhat lower during the period after 1938, field observations indicate a surge in clearing since 1970 when irrigation became more widespread. Soils that were perhaps of marginal productivity and therefore left forested could be made more productive with additional water from irrigation. Deforestation continues at a rate that is probably greater than the average rate of 0.5 percent for the 1938-1979 period.

It is difficult to accurately estimate the forest type proportions on the presettlement floodplain primarily because the surveyors selected against choosing small trees as witness trees. Young witness trees less than about 12 cm diameter at breast height (dbh) did not occur in the data set, so the proportion of small cottonwood forests was significantly underestimated. The estimate of only 3 percent of the total forest area occupied by forests of advanced successional age is especially interesting, since the current proportion is about 22 percent, and these forests, which occurred on better soils, were preferentially cleared. We do not know with certainty the reasons for this, but we suspect that it is an artifact of past timber practices. Large cottonwood trees (50-100 years old) occurring with an understory canopy of ash, elm, and boxelder were preferred trees for lumbering. Selective cutting of these trees would have, in effect, shifted these stands from the mixed cottonwood forest type to the most advanced successional stage. Cottonwood does not reproduce in the tree gaps of older forests.

TREE POPULATION STRUCTURE

An underrepresentation of sapling-size reproduction of American elm and boxelder was observed by Johnson, Burgess, and Keammerer [1976]; however, they sampled only trees 12 cm dbh and larger and did not determine age, only size. Extrapolation from size to age is often inaccurate [Harcombe and Marks, 1978]. This research was designed to develop complete age structure diagrams in both treatment and reference stands to test the hypothesis that altered hydrologic regimen had affected tree population structure. The survey of Johnson, Burgess, and Keammerer indicated that the population structure of another important climax tree species, green ash, was unchanged from pre-dam conditions.

I. Methods

Four former stands of Johnson, Burgess, and Keammerer [1976] were selected for study (stands 7, 11, 13, and 19). In addition to these treatment stands, other stands or portions of treatment stands (7, 16, and 23) were included as control or reference sites. Because surface water occurred in the spring in these stands either from upland runoff or from rising groundwater, these reference stands represented an environment closest to that of flooded stands in the pre-dam period. If reproduction was as underrepresented in the wetter reference sites as in the treatment sites, then the initial hypothesis that underrepresentation was due to flood cessation would have to be rejected. Boxelder was a major species in stands 7 and 23, while American elm was dominant in stands 11, 13, and 19. Reference stand 7 (a section of treatment stand 7) was an abandoned channel of the Little Heart River on the Missouri River floodplain near Oahe Reservoir which fills with water in the spring. Reference stands 16 and 23 were flooded almost annually by concentrated upland runoff. All stands were on one terrace level and had undergone no significant cutting, grazing, or burning during the previous 30 years. Sampling occurred during the summer of 1979.

In each stand, parallel and equidistant lines were arranged perpendicular to the course of the river. Sample plots were located at random points within 25-m segments along each transect line. The sample unit consisted of nested circular plots: 250 m^2 for stems greater than 10 cm dbh (trees), 100 m^2 for stems less than 10 cm dbh but taller than 0.5 m (saplings), and 1 m^2 for stems less than 0.5 m tall (seedlings). Four 1-m^2 plots were randomly placed within each 100-m^2 plot. Twenty-one plots were sampled in stands 11 and 19, and 23 in stands 7 and 13. Because the reference stands were much smaller than the treatment sites, sample sizes were smaller: reference stand 7 (three plots), reference stand 16 (seven plots), and stand 23 (two plots).

Stem diameter at breast height was measured for all boxelder and elm trees and saplings that occurred in the quadrats. Ages of seedlings were determined by counting terminal bud scars or cutting and aging directly. Increment cores were collected from several saplings and trees in each plot, and age was determined in the laboratory. Small saplings were cored using a micro-increment borer. Ages for all stems were computed using the natural growth function $f(x, a, b) = a(1 - e^{-bx})$, where x = dbh and $f(x)$ = age [Parton and Innis, 1972]. The curve for each species was selected that minimized the residual sums of squares and yielded the greatest measure of fit [Helwig and Council, 1979]. For elm, $a = 143$, $b = 0.02956$ ($r^2 = 0.94$). For boxelder, $a = 106$, $b = 0.02388$ ($r^2 = 0.95$). All samples of each species were pooled for the age-size regressions.

Size and age structural diagrams were constructed separately by computing the density of stems in each size or age class. Because the relationship between age and size was close to being linear, the curves in both graphs exhibited the same basic form. Boxelder stems of sprout origin were tallied separately to show the contribution of sprouting to overall population structure. Data were divided into five-year age classes.

II. Results and Discussion

Age distributions for American elm *(Figure 12)* showed low densities of saplings and small trees and high densities of seedlings and large trees. Three of the four treatment stands showed a complete absence of stems in one of the two young age classes. The average of all four stands also showed lowest densities in the two sapling classes. The data clearly indicate that post-reservoir conditions allowed substantial germination and initial establishment of seedlings; seedling densities in the first age class averaged 110,000 per ha. However, seedlings must have thinned rapidly since stems from several years old to about 45 years old were relatively rare. High densities of elm seedlings were also noted during field surveys in 1969-70 by Keammerer [1972], and underrepresentation of saplings and small trees was observed by Johnson, Burgess, and Keammerer [1976]. Reduction in elm density occurred in stems from several years old to those that would have been approximately 20 years old when

Garrison Dam became operational.

Age distribution for boxelder also showed underrepresentation in the small age classes, but the reduction was less dramatic than for elm *(Figure 12).* Again, seedling reproduction was considerable, although at lower overall densities than elm. Mortality between seedlings and small tree classes was considerable, thereby resulting in fewer saplings than trees. Underrepresentation is most evident in stems several years old to about 25 years old. Thus, boxelder showed a somewhat narrower age gap than elm. Reduction in stem density appeared in age classes that corresponded closely to the time since flooding was eliminated by Garrison Dam.

Age distributions in reference stands showed different patterns *(Figure 13).* Age distributions for both species appeared to be more balanced [Meyer, 1952], that is, age classes between 5 and 45 years were considerably less underrepresented than in treatment sites. In our survey of reproduction on the floodplain, one observation held true—high sapling densities of American elm and/or boxelder were always associated with the few sites that received supplemental moisture either from a rising groundwater table near Oahe Reservoir or in areas that received upland runoff.

Therefore, the data suggest that moisture was the primary factor responsible for underrepresentation in the age structure of these two species. Supplemental moisture to these forests would, in the pre-reservoir years, have been provided by both a surface recharging of the rooting zone by overbank flooding and a high water table in the early growing season months when river height was generally maximum. However, in the absence of these sources of moisture, seedlings would now depend on precipitation alone to enable growth to the deeper post-reservoir water table. We believe that the reduction in available moisture was the likely cause of the extremely high seedling mortality and the movement of only a small fraction of elm and boxelder seedlings into the tree-size classes. The natural range of elm extends to only a few counties west of the study area in North Dakota, while boxelder extends west into the drier conditions of eastern and central Montana. Interestingly, the species less able to tolerate drier climatic conditions (elm), was also the species that showed the greatest underrepresentation in age structure in the drier post-dam floodplain.

Changes in the hydrologic regimen may have also caused greater mortality of established saplings in the years immediately following Garrison Dam. Thus, the observation in the age structural diagrams for elm *(Figure 12)* that increased mortality began two decades before Garrison Dam (that is, current 45-year-old age class) may be the result of increased mortality of saplings that were 20 years old or younger in the years following dam construction. Perhaps the root systems of saplings were too poorly developed to utilize groundwater or to persist on it alone. At the wetter reference sites, mortality of saplings of this age did not appear to have increased substantially over pre-dam levels.

In contrast, the mortality of established boxelder saplings appears to have continued at pre-dam levels; the change in hydrologic regimen appeared to increase only the mortality of young boxelder seedlings, that is, individuals established after 1954. The larger proportion of stems that had died and resprouted in treatment stands also indicates that these seedlings were under greater stress than those in reference sites.

Since livestock grazing could also have caused seedling-sapling mortality, the grazing history of the treatment stands was obtained from landowners. Stand 7 had not been grazed since the 1920's, stands 11 and 13 had not been grazed since 1950, and stand 19 had been grazed one year in the early 1970's but otherwise had not been grazed during the post-dam period. Grazing, therefore, has been light or nonexistent in the treatment stands and was probably not the reason for the gap in age structure. Furthermore, if the ingestion and trampling by cattle were responsible for increased mortality, other woody tree species would likewise also have been affected, yet green ash saplings of all age classes were numerous in treatment stands.

Browsing by deer has also been shown to affect the population structure of preferred species [Swift, 1948]. Although American elm is a preferred browse species in this region, damage to it from browsing was not noticeable in our treatment stands.

In streamside forests in the East, many large elms *(Ulmus americana* L. and *Ulmus rubra* Muhl.) have died from Dutch elm disease. We saw no evidence of diseased elms on the floodplain in our study area; however, the disease has killed many urban trees in Bismarck. Since elm trees are affected to a greater extent than seedlings and saplings [Stipes and Campana, 1981], the disease is not considered a cause for the low densities of elm saplings. Underrepresentation was already observed by Johnson, Burgess, and Keammerer [1976] during the 1969 and 1970 field seasons, about the time Dutch elm disease had spread to central North Dakota [Stipes and Campana, 1981].

Although the natural form of the age structure curve of "climax" or "equilibrium" tree populations had been thought to be negative exponential [Meyer, 1952], recent studies have indicated that underrepresentation in sapling size classes is a widespread phenomenon [Christensen, 1977; Harcombe and Marks, 1978]. Harcombe and Marks sampled forest stands in the Big Thicket of southeastern Texas that ranged from dry uplands, through mesic slopes, to wet river floodplains. They showed a high incidence of underrepresentation of saplings of climax tree species in wet and mesic forests but a lower incidence in dry upland forests. They argued that the cause of the underrepresentation was competition for light between the seedlings and saplings of overstory tree species and understory tree and shrub species. They suggested that underrepresentation in wet and mesic forests was natural and caused by increased mortality of seedlings because of shading by understory trees (for example, *Carpinus caroliniana).*

Patterns of underrepresentation in age structure for the Missouri River floodplain were nearly identical with those of southeastern Texas, except we believe that underrepresentation in our study was caused by lack of moisture, not light. The canopy of old floodplain forests along the Missouri River is relatively open. Hibbard [1972] showed that in these forests, canopy cover ranged from 65 to 80 percent. Also, neither boxelder nor elm is intolerant of shade [Baker, 1949]. Saplings of these species were no more abundant along stand edges or in large canopy gaps where light would have been more available.

In summary, our results indicate a significant decline in the abundance of American elm and boxelder on the Missouri River floodplain in the study area. Current overstory densities of these species cannot be maintained, given the low density of saplings. In the case of American elm, the decline will accelerate if Dutch elm disease begins to affect canopy trees. Assuming that current trends continue, the importance of these species in the overstory should consistently decline over time until only scattered trees remain or even become locally eliminated. Trees will become primarily restricted to the few small wet sites either near the backup of Oahe Reservoir or in places where intermittent streams flow onto the floodplain. Seedlings may continue to be numerous until affected by restricted seed dispersal from a dwindling number of canopy trees. Because green ash reproduction of all age classes was ubiquitous and dense, it should become an increasingly important canopy species.

Available evidence points to the altered hydrologic regimen as the cause of reduced recruitment of boxelder and elm trees; however, in the absence of pre-dam age structure and hydrologic information, this conclusion must be considered tentative. We clearly need additional information from other floodplains, both natural and altered, to solve the underrepresentation problem.

CONCLUSIONS

1. The hydrologic regimen of the Missouri River has been altered considerably by the construction of Garrison Dam. While precipitation and AE have shown no significant changes between pre- and post-dam periods, streamflow patterns have changed markedly. Peak flow no longer occurs early in the growing season and, consequently, is out of phase with the vernal growth pattern typical of floodplain trees. A larger proportion of the annual flow is now released in the non-growing season months and therefore is unavailable for growth. Now, flow in June is usually less than it was during the drought years of the 1930's. River flow data indicate a general lowering of the spring and early summer water table since Garrison Dam.

2. Flooding has been eliminated on terraces greater than 2 m above mean river level, thus decreasing the moisture available to floodplain ecosystems at the start of the growing season. The accompanying deposition of nutrient-rich silt has also ceased.

3. Both erosion and deposition rates by the river have decreased substantially since Garrison Dam. In effect, river meandering has all but ceased. Accretion rates have fallen to 1 percent of their pre-dam level and erosion rates to 25 percent of pre-dam levels. The net effect was a widening of the river channel by erosion on both banks and little concurrent deposition.

4. Results showed that decreases in radial tree growth in the post-dam period were not uniform throughout the floodplain but depended on species and location with respect to the river. Trees on terraces at the edge of the floodplain that received concentrated runoff from upland ravines (for example, bur oak) and those with deep root systems (for example, cottonwood) on low terraces close to the water table have been least affected by the altered hydrologic regimen. Growth of cottonwood and bur oak on reference sites unaffected by damming of the Missouri River increased significantly in the post-dam period. The most pronounced decrease in tree growth (for example, boxelder, American elm) occurred on higher terraces that received little or no upland runoff.

5. Lack of flooding and a lowered spring water table are implicated in the decline of radial tree growth. For example, with a lower spring

water table, the roots of established trees may no longer extend to the capillary fringe. Thus, growth might depend more upon spring AE than on groundwater. This shift in response from one source of moisture to another (from groundwater to precipitation) was exhibited in the regression analysis of cottonwood growth chronologies. The absence of overbank flooding may have had a greater effect on the growth of trees (for example, American elm) on dry upper terraces well above the water table that did not receive upland runoff. Although these terraces were only infrequently flooded before 1953, the supplemental moisture provided by floods just before the onset of growth could have augmented growth for several consecutive years and compensated for years of low precipitation.

6. Lack of accretion by the river in the post-dam period spells a decline in the proportion of the floodplain forest occupied by cottonwood-willow forests. The decline is already observable and will continue until, in a century or more, cottonwood forests will occupy only a fraction of their current proportion. Cottonwoods will be relegated to a river marginal position, being especially prominent behind wingdikes.

7. We believe that the decline in cottonwood abundance and ubiquity will be accompanied by a decline in American elm because of a rapidly declining growth rate, almost complete absence of seedling survivorship on most sites, and the impending effects of Dutch elm disease. Some remnant elm stands may persist on sites with an artificially elevated water table near the Oahe Reservoir and on high terraces that receive upland runoff. Boxelder, which exhibited greater survivorship but was still underrepresented in the sapling size classes, may exhibit a slower decline. Although growth rate of green ash has also declined, it exhibits balanced population structure and will likely increase its abundance and ubiquity in coming decades. Thus, the current observations foretell a drastic decline in cottonwood and elm abundance, a moderate-to-slow decline in boxelder prominence, and an increase in green ash. Overall, the alpha and beta diversities of the forest overstory should decline.

8. Clearing for agriculture has claimed slightly over half (55 percent) of the original floodplain forest. The rate appears to have accelerated during the last decade because of opportunities to irrigate croplands. Should these trends continue, future native forests may be maintained

only in protected areas such as the Riverdale and Oahe Game Management Areas and in private reserves (for example, Cross Ranch, The Nature Conservancy). However, forests protected from clearing and other disturbances remain unprotected from the ecological effects of altered river hydrology.

9. The effects of altered hydrology on floodplain ecosystem dynamics need further study on other forested floodplains, particularly where pre-dam biological information is available or where nearby wild rivers could serve as good controls. Where significant effects of floodplain protection are suspected, an index of impact could be derived by comparing pre-dam gauge height (flood frequency) and seasonal flow patterns to pre-dam patterns. Greater departure from pre-dam patterns would suggest greater potential impact on natural floodplain ecosystems.

LITERATURE CITED

Baker, F. S., 1949. "A Revised Tolerance Table." *Journal of Forestry* 47:179-81.

Baxter, R. M., 1977. "Environmental Effects of Dams and Impoundments." In *Annual Review of Ecology and Systematics, Vol. 8,* R. F. Johnson, editor, pp. 255-83. Palo Alto, California: Annual Reviews, Inc.

Bedinger, M. S., 1971. *Forest Species as Indicators of Flooding in the Lower White River Valley, Arkansas.* Professional Paper 750-C. U.S. Geological Survey, U.S. Department of the Interior, Washington.

Bell, D. T. and R. del Moral, 1977. "Vegetation Gradients in the Streamside Forest of Hickory Creek, Will County, Illinois." *Bulletin, Torrey Botanical Club* 104:127-35.

Bluemle, J. P., 1971. *Geology of McLean County, North Dakota.* North Dakota Geological Survey Bulletin No. 60, Pt. 1. North Dakota State Water Conservation Commission, Grand Forks.

Brockman, L. C. et al., 1974. *Soil Survey of McLean County, North Dakota.* Soil Conservation Service, U.S. Department of Agriculture, Washington.

Brown, D. E., C. H. Lowe, and J. F. Hausler, 1977. "Southwestern Riparian Communities: Their Biotic Importance and Management in Arizona." In *Importance, Preservation and Management of Riparian Habitats,* pp. 201-11. General Technical Report RM-43. U.S. Forest Service, U.S. Department of Agriculture, Washington.

Burgess, R. L., 1964. "Ninety Years of Vegetational Change in a Township in Eastern North Dakota." *Proceedings, North Dakota Academy of Science* 18:84-94.

Campbell, C. J. and W. Green, 1968. "Perpetual Succession of Stream-Channel Vegetation in a Semiarid Region." *Arizona Academy of Science Journal* 5:86-98.

Carlson, C. G., 1973. *Geology of Mercer and Oliver Counties, North Dakota.* North Dakota Geological Survey Bulletin, No. 56, Pt. 1. North Dakota State Water Conservation Commission, Grand Forks.

Christensen, N. L., 1977. "Changes in Structure, Pattern and Diversity Associated with Climax Forest Maturation in Piedmont, North Carolina." *American Midland Naturalist* 97:176-88.

Clayton, L., 1962. *Glacial Geology of Logan and McIntosh Counties, North Dakota.* North Dakota Geological Survey Bulletin No. 37. North Dakota State Water Conservation Commission, Grand Forks.

Everitt, B. L., 1968. "Use of the Cottonwood in an Investigation of the Recent History of a Floodplain." *American Journal of Science* 266:417-39.

———, 1980. "Ecology of Saltcedar—A Plea for Research." *Environmental Geology* 3:77-84.

Fenneman, N. M., 1931. *Physiography of the Western United States.* New York: McGraw-Hill Book Co.

Fritts, H. C., 1976. *Tree Rings and Climate.* New York: Academic Press, Inc.

Fritts, H. C., J. E. Mosimann, and C. P. Botroff, 1969. "A Revised Computer Program for Standardizing Tree-Ring Series." *Tree-Ring Bulletin* 29:15-20.

Gary, H. L., 1965. "Some Site Relations in Three Floodplain Communities in Central Arizona." *Arizona Academy of Science Journal* 3(4):209-12.

Grannemann, N. G. and J. M. Sharp, Jr., 1979. "Alluvial Hydrogeology of the Lower Missouri River Valley." *Journal of Hydrology* 40:85-99.

Greenman, D. W., 1953. "Reconnaissance of the Missouri River Pumping Units Between Garrison Dam and Bismarck, North Dakota." Unpublished paper compiled as part of a U.S. Department of the Interior program for development of the Missouri River Basin. Water Resources Division, U.S. Geological Survey, U.S. Department of the Interior, Washington.

Harcombe, P. A. and P. L. Marks, 1978. "Tree Diameter Distributions and Replacement Processes in Southeast Texas Forests." *Forest Science* 24:153-66.

Hayes, F. A. and J. H. Stoeckler, 1935. "Soil and Forest Relationships of the Shelterbelt Zone." In *Possibilities of Shelterbelt Planting in the Plains Region,* pp. 111-15. Special Bulletin. U.S. Forest Service, U.S. Department of Agriculture, Washington.

Helwig, J. T. and K. A. Council, editors, 1979. *SAS User's Guide.* Raleigh, North Carolina: SAS Institute Inc.

Hibbard, E. A., 1972. "Vertebrate Ecology and Zoogeography of the Missouri River Valley in North Dakota." Ph.D. dissertation. North Dakota State University, Fargo.

Hollander, M. and D. A. Wolfe, 1973. *Nonparametric Statistical Methods.* New York: John Wiley and Sons.

Keammerer, W. R., W. C. Johnson, and R. L. Burgess, 1975. "Floristic Analysis of the Missouri River Bottomland Forests in North Dakota." *Canadian Field-Naturalist* 89:5-19.

Kosler, J. A., 1979. "Regulating Critical Riparian Lands: A Challenge in Intergovernmental Cooperation." In *Strategies for Protection and Management of Floodplain Wetlands and Other Riparian Ecosystems,* R. R. Johnson and J. F. McCormick, editors, pp. 332-35. Symposium Proceedings, December 11-13, 1978, Calloway Gardens, Georgia.

Kroodsma, R. L., 1970. "North Dakota Species Pairs. I. Hybridization in Buntings, Grosbeaks and Orioles." Ph.D. dissertation. North Dakota State University, Fargo.

Kuchler, A. W., 1964. "Potential Natural Vegetation of the Conterminous United States" (map). Special Publication. American Geographical Society, New York.

Kujawa, M., 1974. "Plankton Studies on a Recently Impounded Reservoir." *Journal of Environmental Health* 37:252-55.

Johnson, W. C., R. L. Burgess, and W. R. Keammerer, 1976. "Forest Overstory Vegetation and Environment on the Missouri River Floodplain in North Dakota." *Ecological Monographs* 46:59-84.

Kume, J. and D. E. Hanson, 1965. *Geology and Water Resources of Burleigh County, North Dakota.* North Dakota Geological Survey Bulletin No. 42, Pt. 1. North Dakota State Water Conservation Commission, Grand Forks.

Lemke, R. W. and R. B. Colton, 1958. "Summary of the Pleistocene Geology of North Dakota." In *Midwestern Friends of the Pleistocene Guidebook.* 9th Annual Field Conference. Miscellaneous Serial No. 10. North Dakota Geological Survey, Grand Forks.

Lemke, R. W. et al., 1965. "Quaternary Geology of the Northern Great Plains." In *The Quaternary of the United States,* H. E. Wright, Jr. and D. J. Frey, editors, pp. 15-27. Princeton, New Jersey: Princeton University Press.

Leopold, L. B., M. G. Wolman, and J. P. Miller, 1964. *Fluvial Processes in Geomorphology.* San Francisco: W. H. Freeman.

McKenzie, M. A., 1936. "Flood Injury to Trees." *Science* 83(2154): 412-13.

Meinzer, O. E., 1927. *Plants as Indicators of Groundwater.* Water Supply Paper 577. U.S. Geological Survey, U.S. Department of the Interior, Washington.

Meyer, H. A., 1952. "Structure, Growth, and Diameter in Balanced, Uneven-Aged Forests." *Journal of Forestry* 50:85-92.

Parton, W. J. and G. S. Innis, 1972. *Some Graphs and Their Functional Forms.* Technical Report No. 153. Natural Resource Ecology Laboratory, Colorado State University, Fort Collins.

Pitt, M. D. and H. F. Heady, 1978. "Responses of Annual Vegetation to Temperature and Rainfall Patterns in Northern California." *Ecology* 59(2):336-50.

Randich, P. G. and J. L. Hatchett, 1966. *Geology and Groundwater Resources of Burleigh County, North Dakota. Part III: Groundwater Resources.* North Dakota Geological Survey Bulletin No. 42. North Dakota State Water Conservation Commission, Grand Forks.

Ridley, J. E. and J. A. Steele, 1975. "Ecological Aspects of River Impoundment." In *River Ecology,* B. A. Whitton, editor, pp. 565-87. Berkeley and Los Angeles: University of California Press.

Robertson, P. A., G. T. Weaver, and J. A. Cavanaugh, 1978. "Vegetation and Tree Species Patterns Near the Northern Terminus of the Southern Floodplain Forest." *Ecological Monographs* 48:249-67.

Schumm, S. A., 1969. "River Metamorphosis." *American Society of Civil Engineers Journal, Hydraulics Division* 95(HY1):254-73.

Stearns, F. W., 1949. "Ninety Years Change in a Northern Hardwood Forest in Wisconsin." *Ecology* 30:350-58.

Stokes, M. A. and T. L. Smiley, 1968. *An Introduction to Tree-Ring Dating.* Chicago: University of Chicago Press.

Stout, H. R. et al., 1974. *Soil Survey of Burleigh County, North Dakota.* Soil Conservation Service, U.S. Department of Agriculture, Washington.

Swift, E., 1948. *Wisconsin Deer Damage to Forest Reproduction Survey—Final Report.* Publication 347. Wisconsin Conservation Department, Madison.

Thornthwaite, C. W. and J. R. Mather, 1957. "Instructions and Tables for Computing Potential Evapotranspiration and Water Balance." *Publications in Climatology* 10:181-311.

Tukey, J. W., 1977. *Exploratory Data Analysis.* Reading, Massachusetts: Addison-Wesley Publishing Co.

U.S. Army Corps of Engineers, Omaha District, 1980. Personal communication.

U.S. Geological Survey, U.S. Department of the Interior, 1928-1977. *Water Resources Data for North Dakota, 1928-1977.* North Dakota State Geological Survey, Bismarck.

U.S. Weather Bureau, 1935-1974. *Climatological Data, North Dakota Annual Summary, 1935-1974.* Washington.

Weiser, P. K., 1975. *Soil Survey of Oliver County, North Dakota.* Soil Conservation Service, U.S. Department of Agriculture, Washington.

Weist, W. G., Jr., 1971. *Geology and Ground-Water System in the Gila River Phreatophyte Project Area, Graham County, Arizona.* Gila River Phreatophyte Project, Professional Paper 655-D. U.S. Geological Survey, U.S. Department of the Interior, Washington.

Wells, P. V., 1965. "Scarp Woodlands: Transported Grassland Soils and the Concept of Grassland Climate in the Great Plains Region." *Science* 148:246-49.

Wilhelm, F. J., 1978. *Soil Survey of Mercer County, North Dakota.* Soil Conservation Service, U.S. Department of Agriculture, Washington.

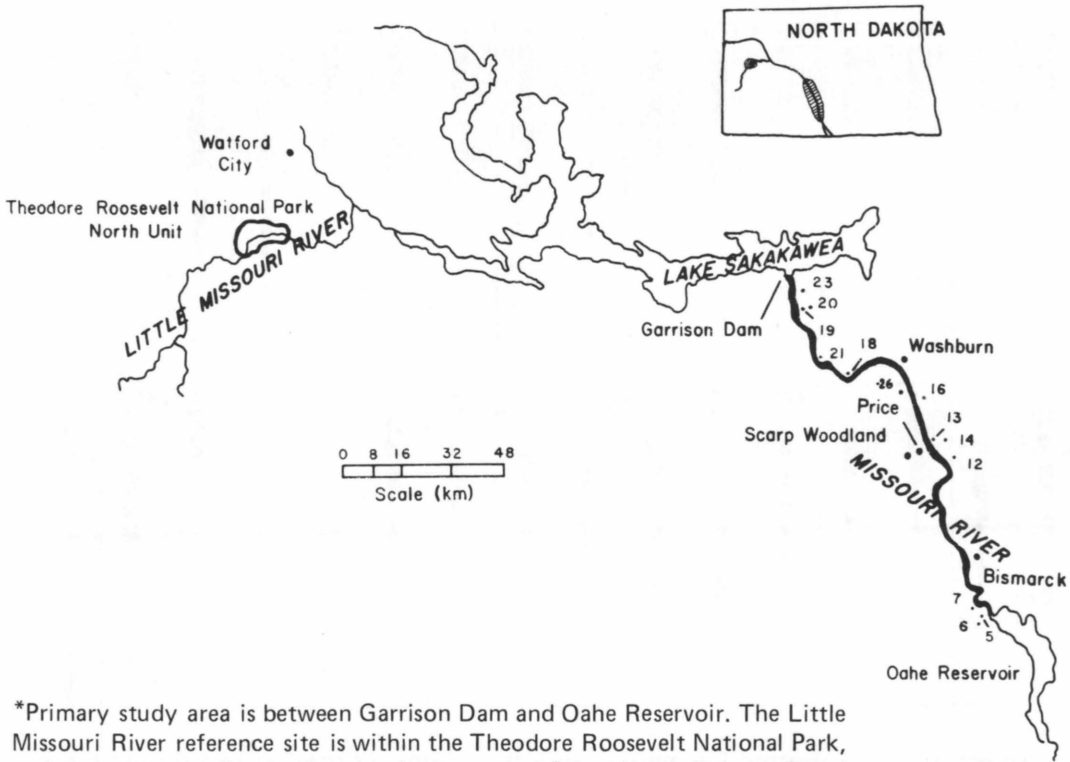
Wolman, M. G. and L. B. Leopold, 1957. *River Floodplains: Some Observations on Their Formation.* Professional Paper 282-C:37-107. U.S. Geological Survey, U.S. Department of the Interior, Washington.

Yeager, A. F., 1935. "Root Systems of Certain Trees and Shrubs Grown on Prairie Soils." *Journal of Agricultural Research* 51:1085-92.

Yeager, L. E., 1949. "Effect of Permanent Flooding in a River Bottom Timber Area." *Illinois Natural History Survey Bulletin* 25:33-65.

FIGURES

FIGURE 1
Location and Number of Study Sites in North Dakota*



*Primary study area is between Garrison Dam and Oahe Reservoir. The Little Missouri River reference site is within the Theodore Roosevelt National Park, and the scarp woodland reference site is west of Price, North Dakota. Stand numbers are those of Johnson, Burgess, and Keammerer [1976].

FIGURE 2

Monthly Streamflow (1928-1977) from the Bismarck Gauging Station on the Missouri River*

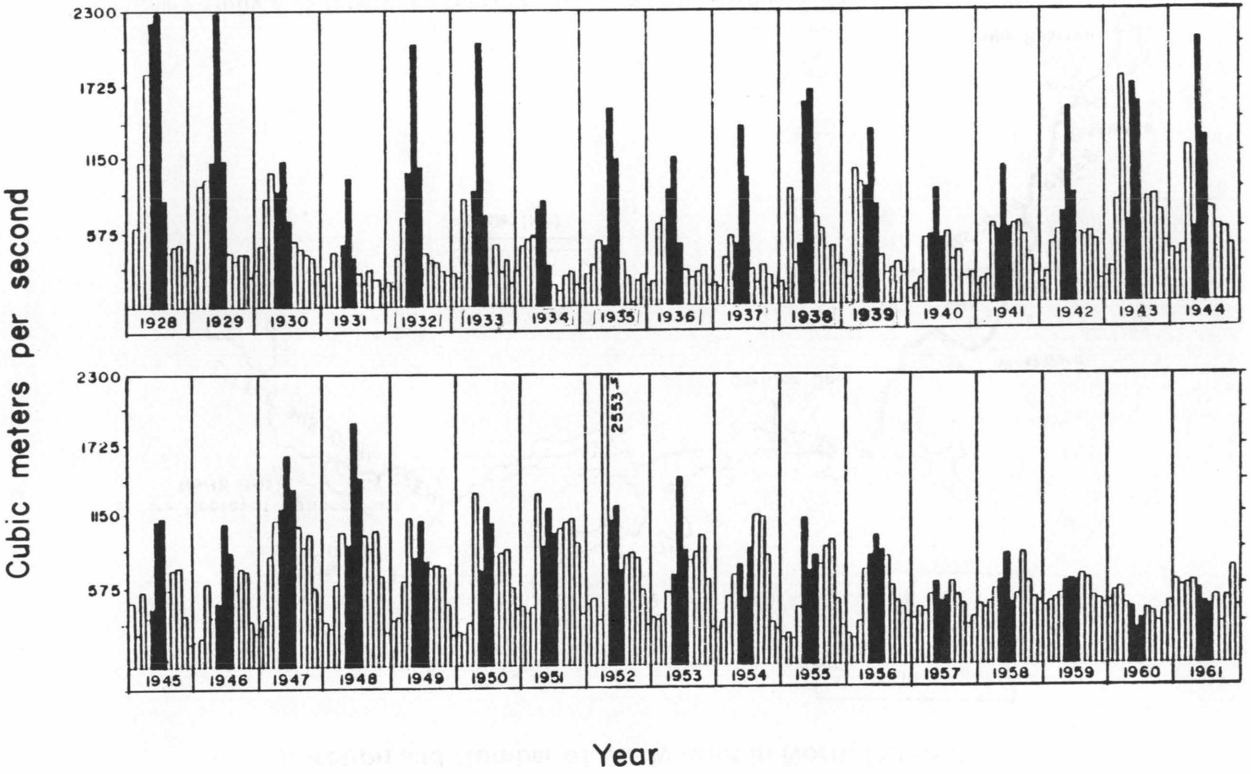
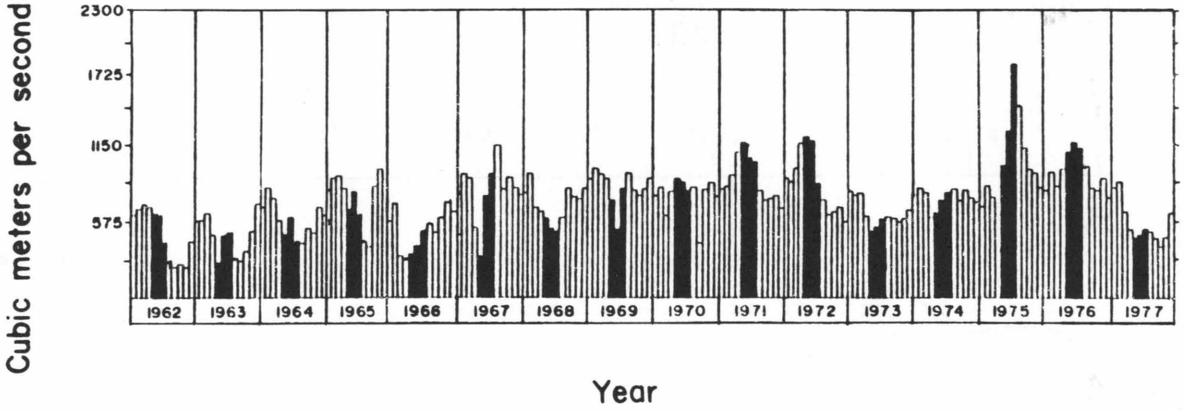


FIGURE 2 (continued)



*Source: U.S. Geological Survey, 1928-1977. The primary growing season months (May, June, and July) are represented by black bars. Garrison Dam was completed in April 1953. Streamflow is used here instead of gauge height since the latter data were not available for some years. There was usually a strong correlation between gauge height and streamflow (for example, for the month of October 1972: $R^2 = 0.9987$, $Y = 428.17x - 232.02$).

FIGURE 3

Streamflow for June and February 1928-1977, at the Bismarck Gauging Station on the Missouri River*

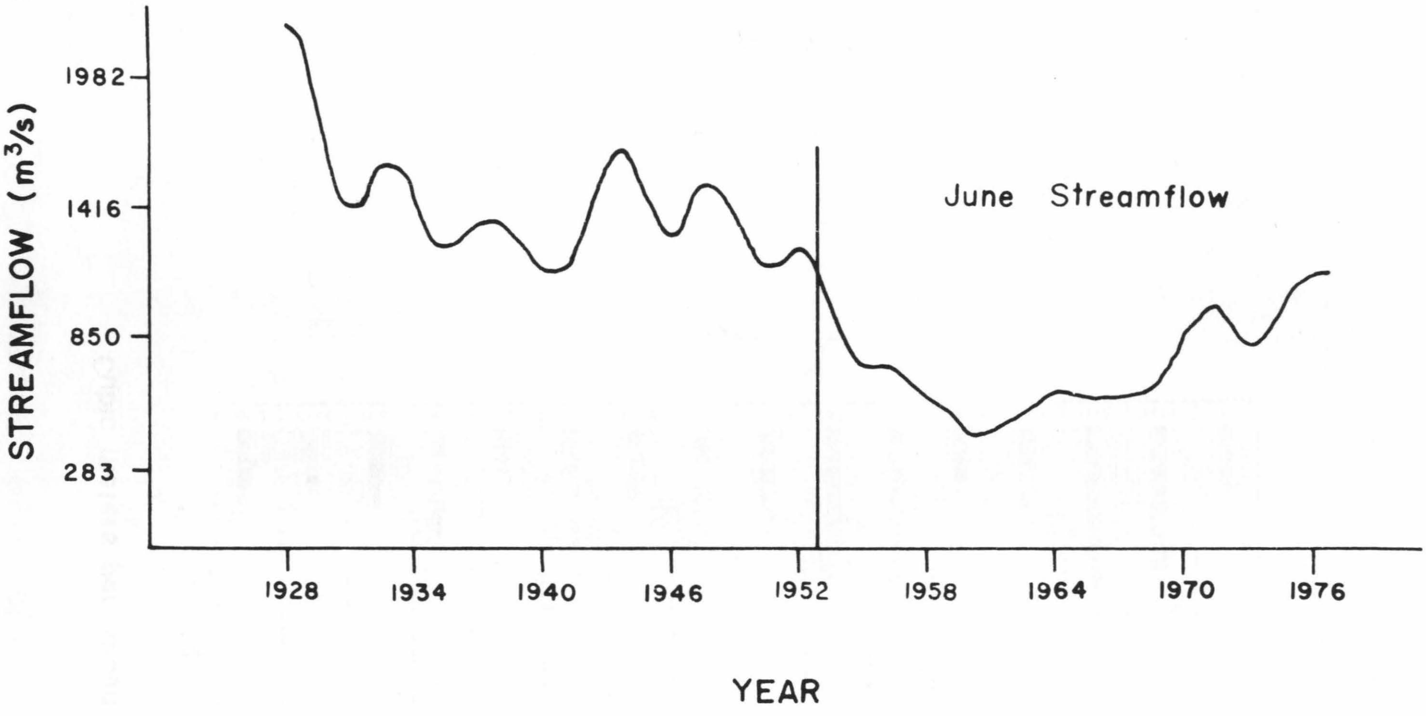
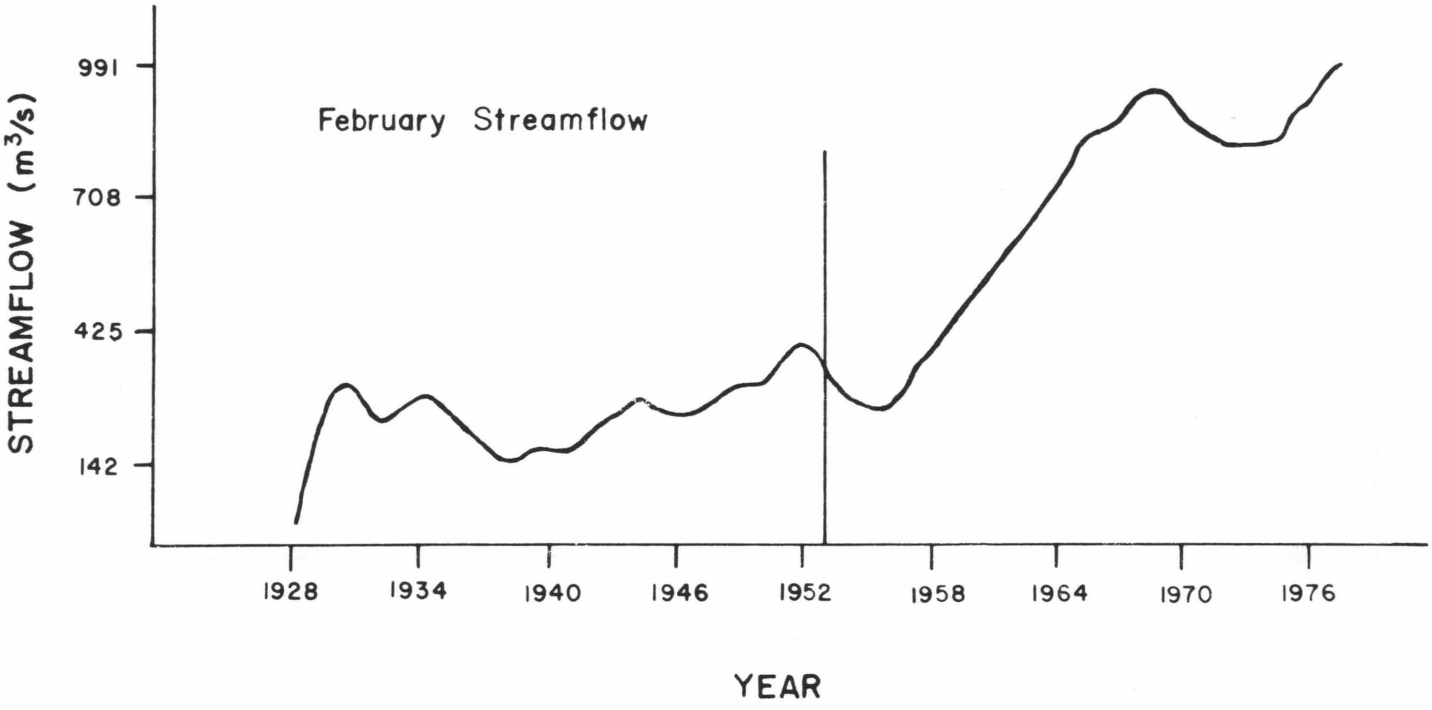


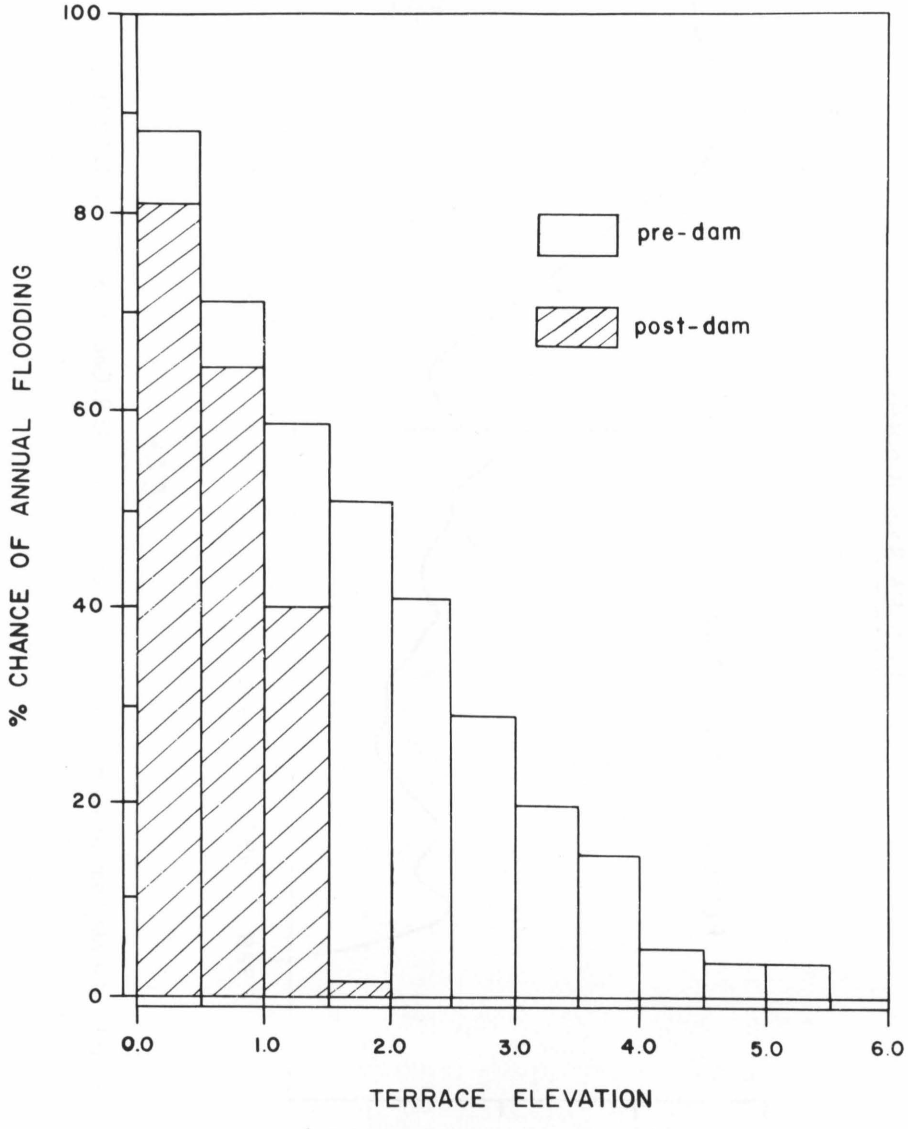
FIGURE 3 (continued)



*Vertical line indicates the year that Garrison Dam was completed. Source: U.S. Geological Survey, 1928-1977.

FIGURE 4

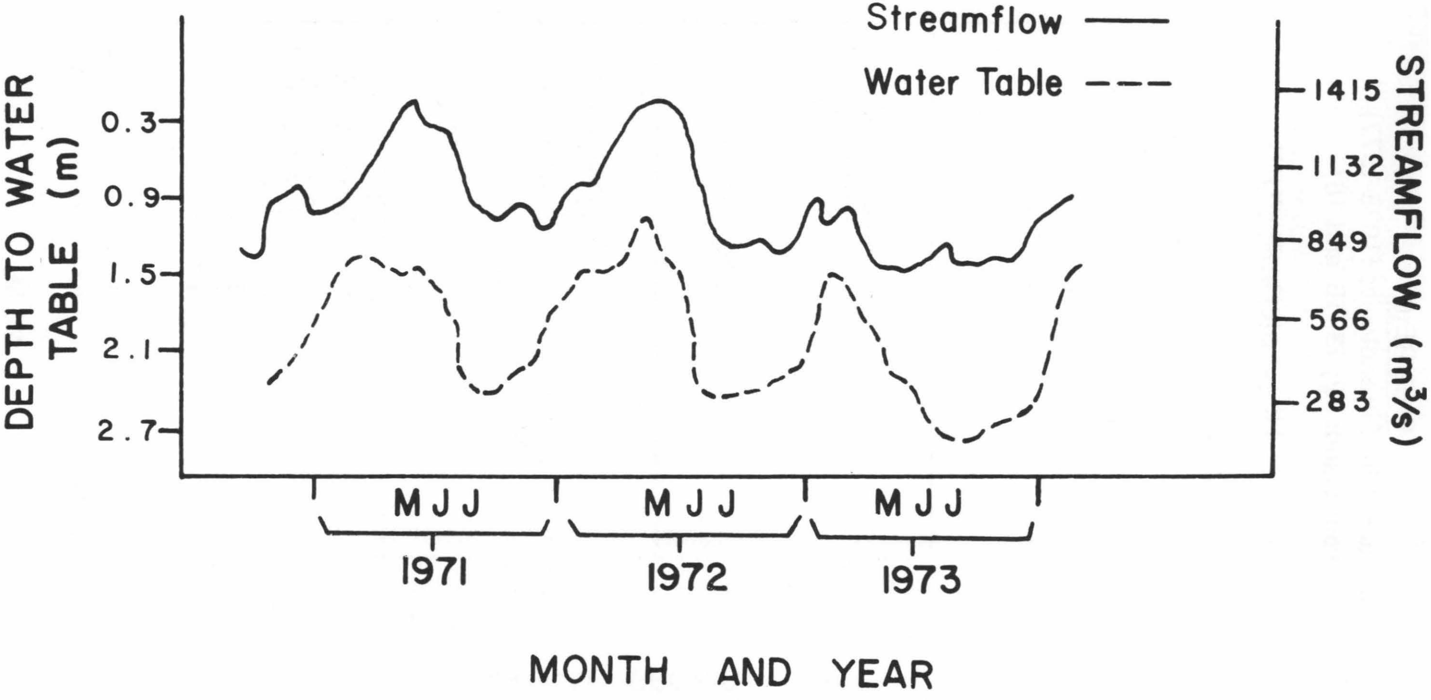
Percent Chance of Overbank Flooding at Different Terrace Elevations, Based on the Relationship Between Maximum Gauge Heights and Known Terrace Elevations*



*Source: U.S. Geological Survey, 1928-1977 (Bismarck gauging station on the Missouri River).

FIGURE 5

Groundwater and Streamflow Data (1971-1973) from the Missouri River near Bismarck*



*USGS test well no. 138-080-08-ABA1, located approximately 1 km from the Missouri River and approximately 2 km south of Bismarck. Primary growing season months of May, June, and July are represented by "MJJ." Streamflow data from Bismarck gauging station. Source: U.S. Geological Survey, 1928-1977.

FIGURE 6
American Elm Chronologies (1928-1977)
from Stands 12, 13, 19, and 16*

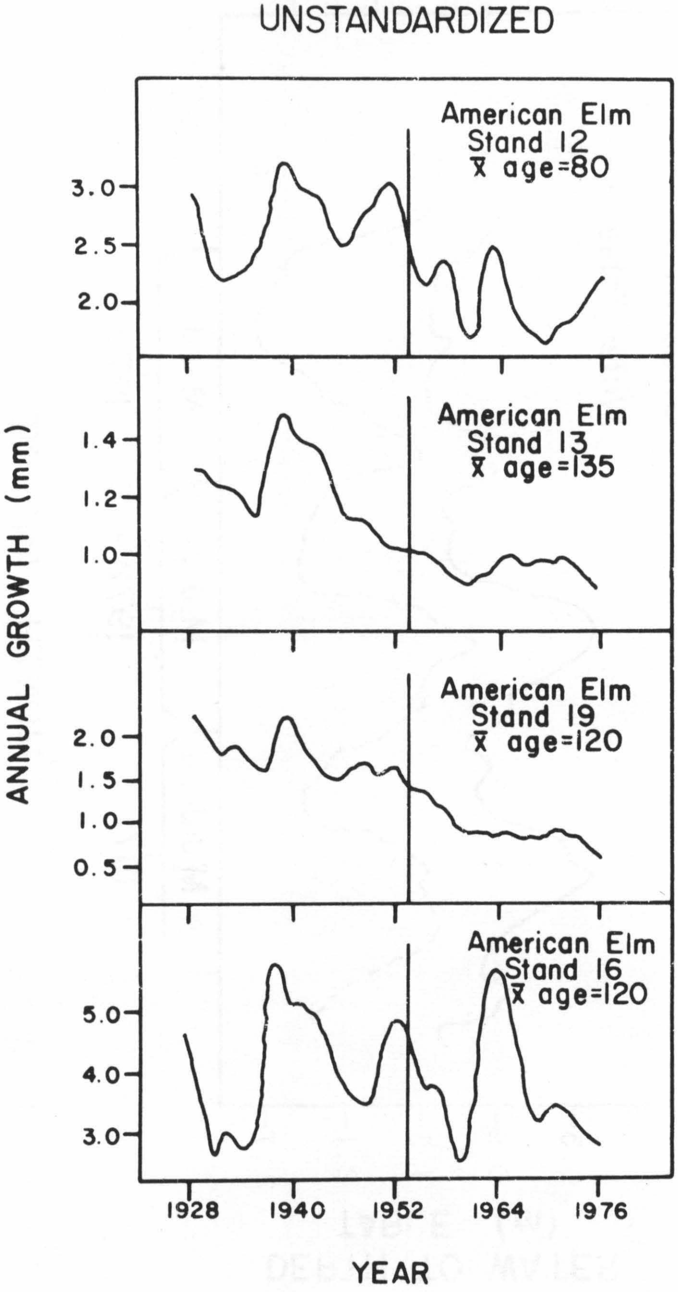
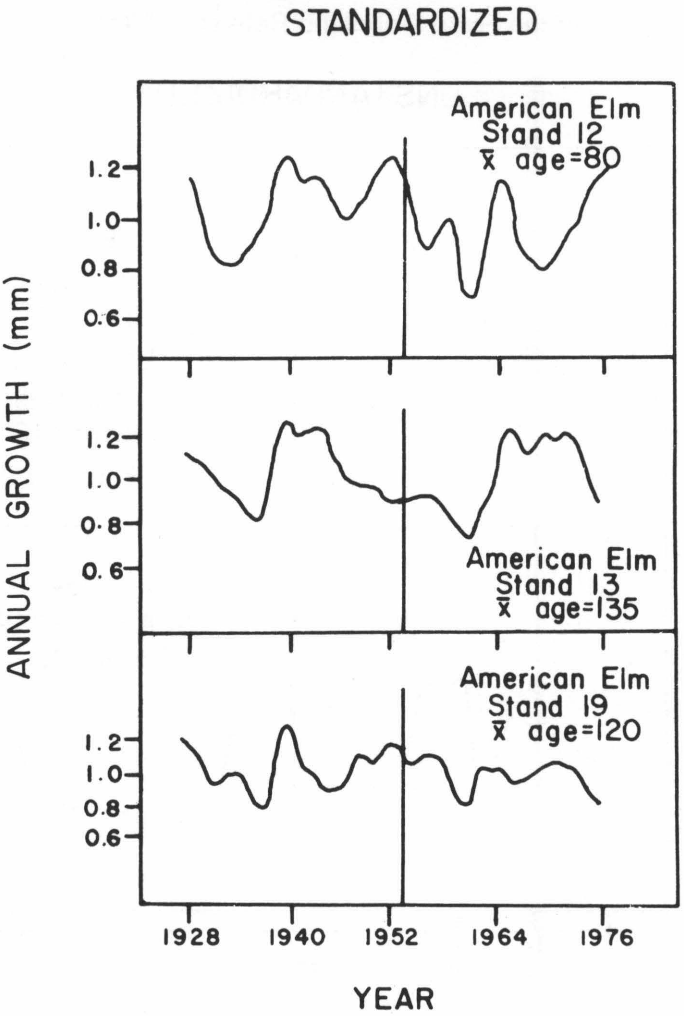


FIGURE 6 (continued)



*Figures on left are unstandardized (long-term trends not removed by standardization); figures on right have been standardized. Vertical lines indicate the year that Garrison Dam was completed.

FIGURE 7
Bur Oak Chronologies (1928-1977) from Stand 16
and the Scarp Woodland Reference Site*

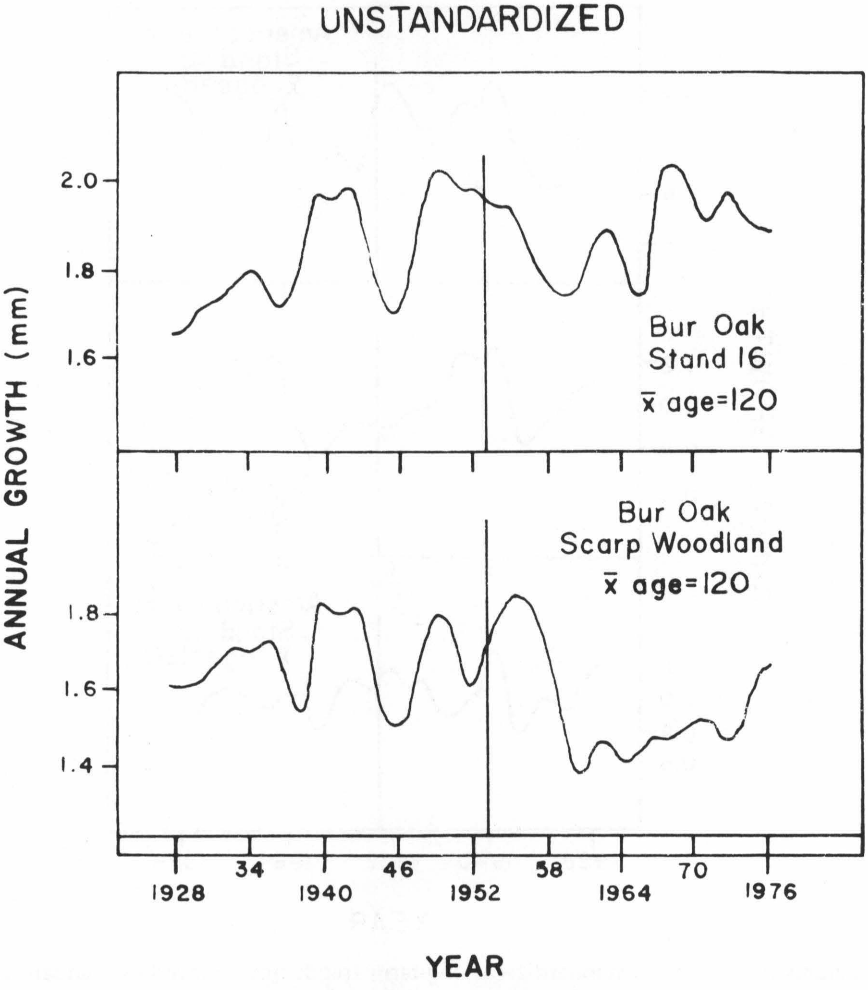
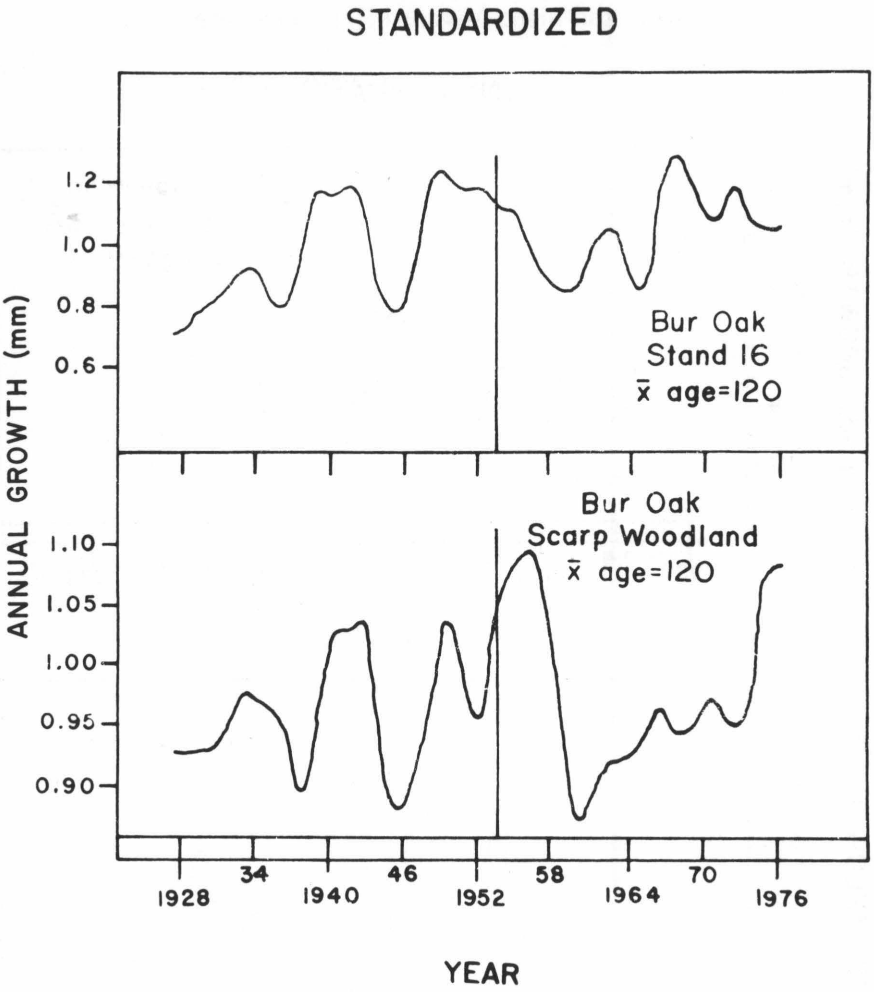


FIGURE 7 (continued)



*Figures on left are unstandardized; figures on right have been standardized. Vertical lines indicate the year that Garrison Dam was completed.

FIGURE 8
Cottonwood Chronology (1928-1977)
from the Little Missouri Reference Site*

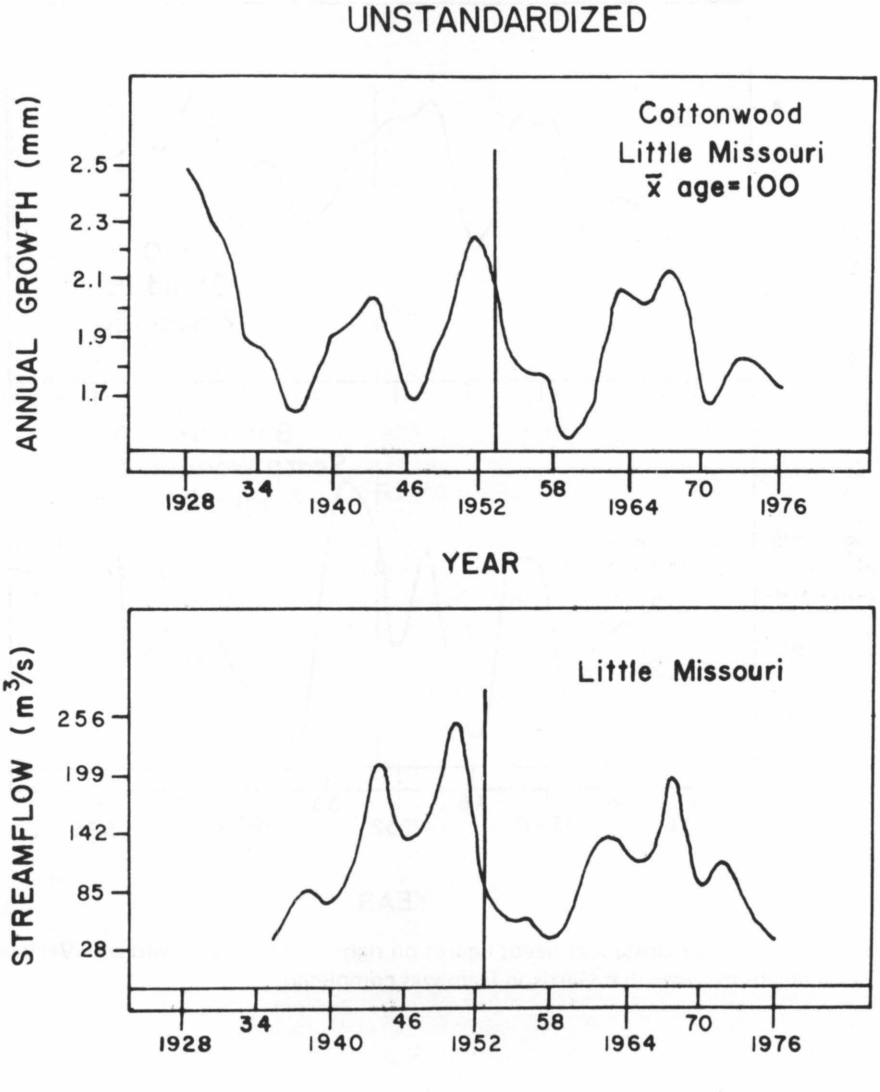
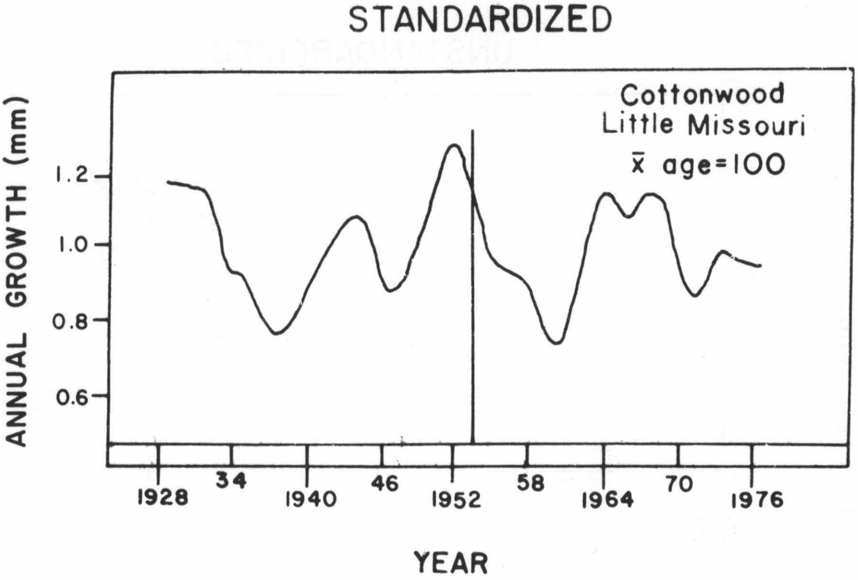


FIGURE 8 (continued)



*Unstandardized chronology is top left, standardized on right. Average streamflow for April to July (1935-1977) for the Little Missouri River is shown bottom left. Vertical lines indicate the year that Garrison Dam was completed. Source: U.S. Geological Survey, 1928-1977 (Watford City gauging station).

FIGURE 9

Cottonwood Chronologies (1928-1977) from Stands 5 and 14*

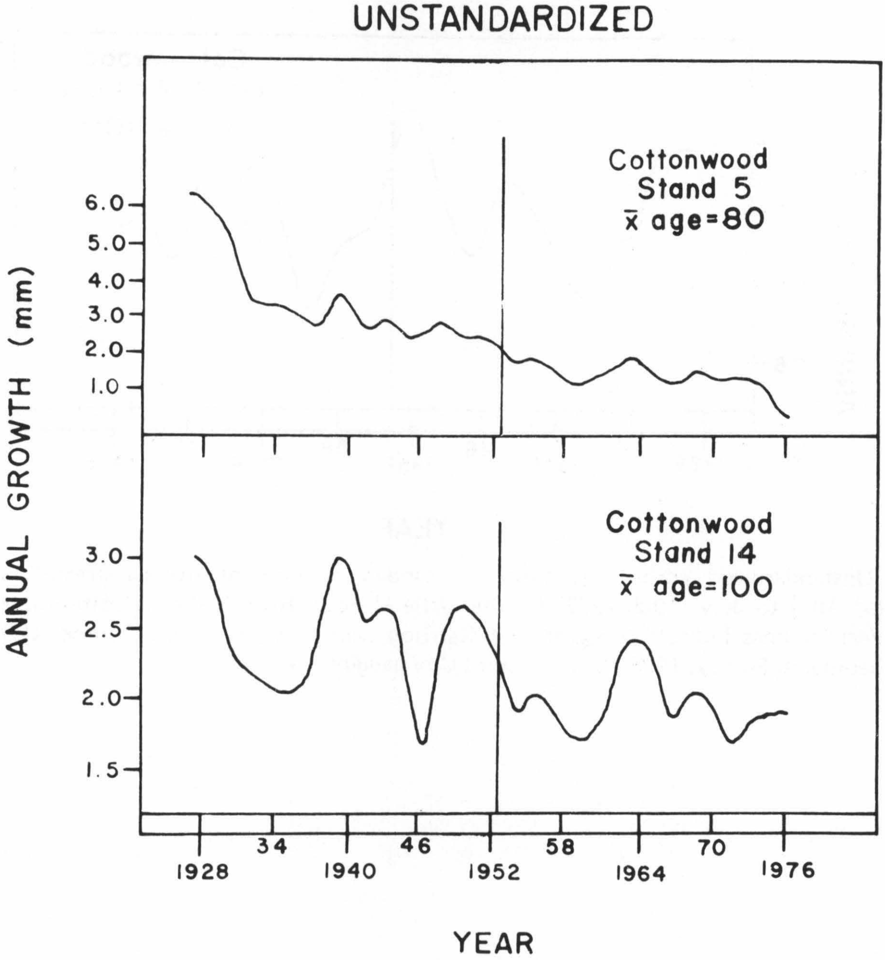
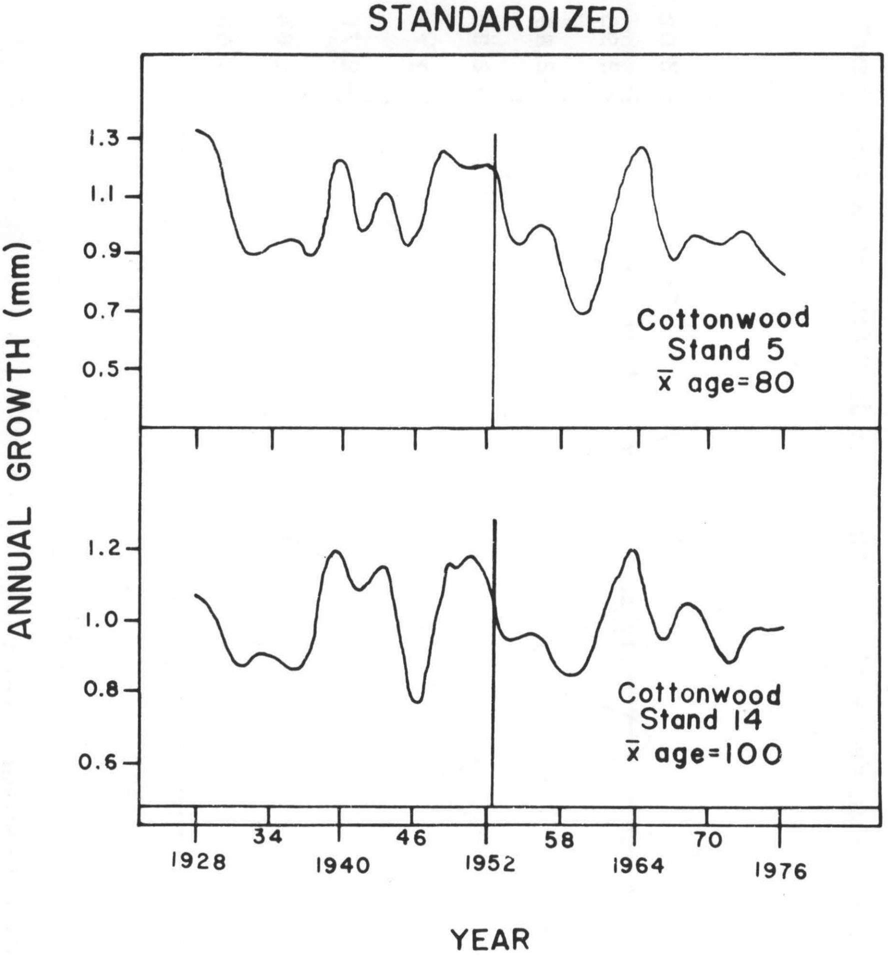
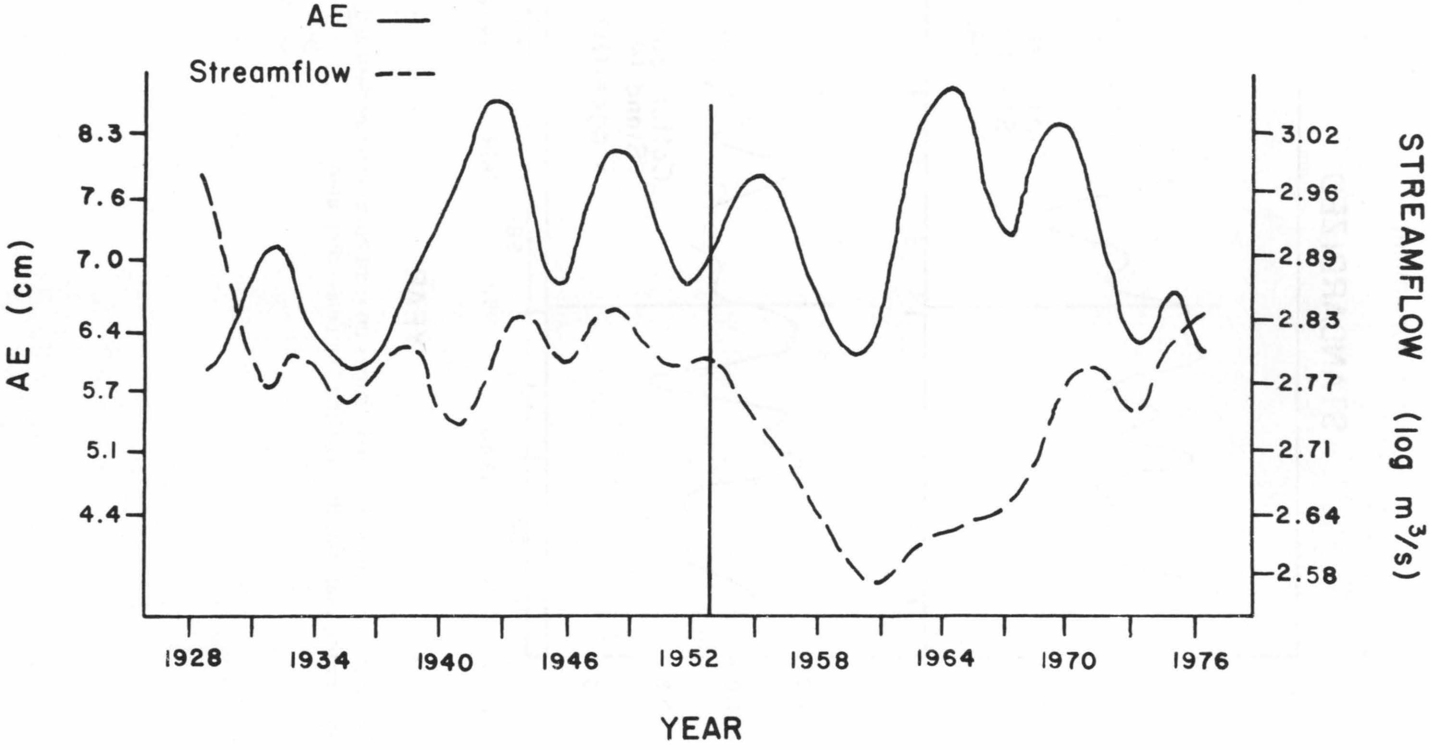


FIGURE 9 (continued)



*Figures on left are unstandardized; figures on right have been standardized. Vertical lines indicate the year that the Garrison Dam was completed.

FIGURE 10
Smoothed Plots of Spring AE Versus Year and Spring (May, June, July) Streamflow Versus Year*



*Vertical line indicates the year that Garrison Dam was completed.

FIGURE 11

Results of Stepwise [MAXR, Helwig and Council, 1979] Multiple Regression Analysis of Cottonwood from Stands 5 and 14 for Pre-Dam (1928-1952) and Post-Dam (1953-1977) Periods*

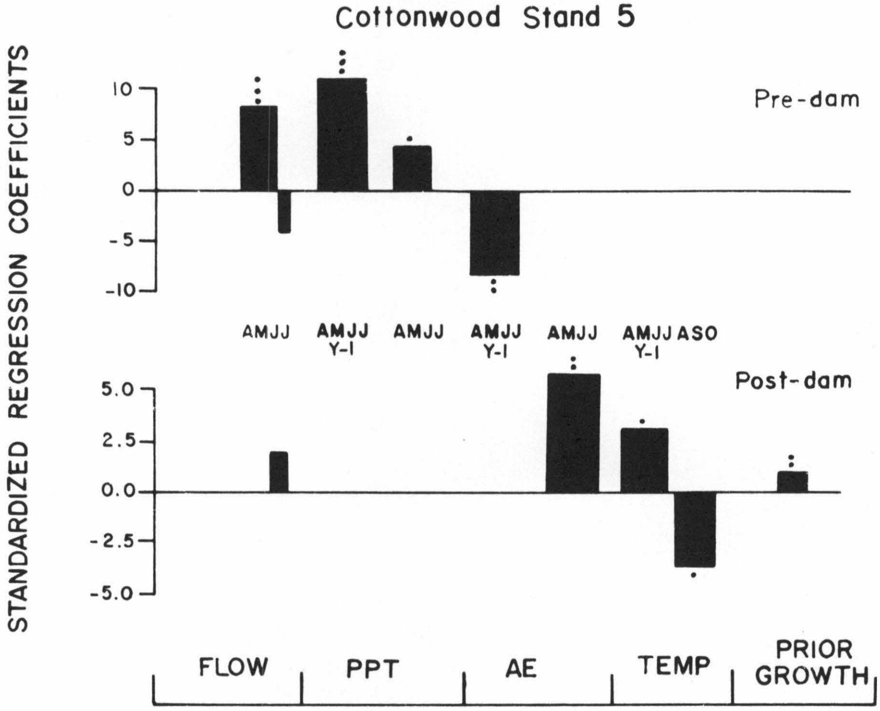
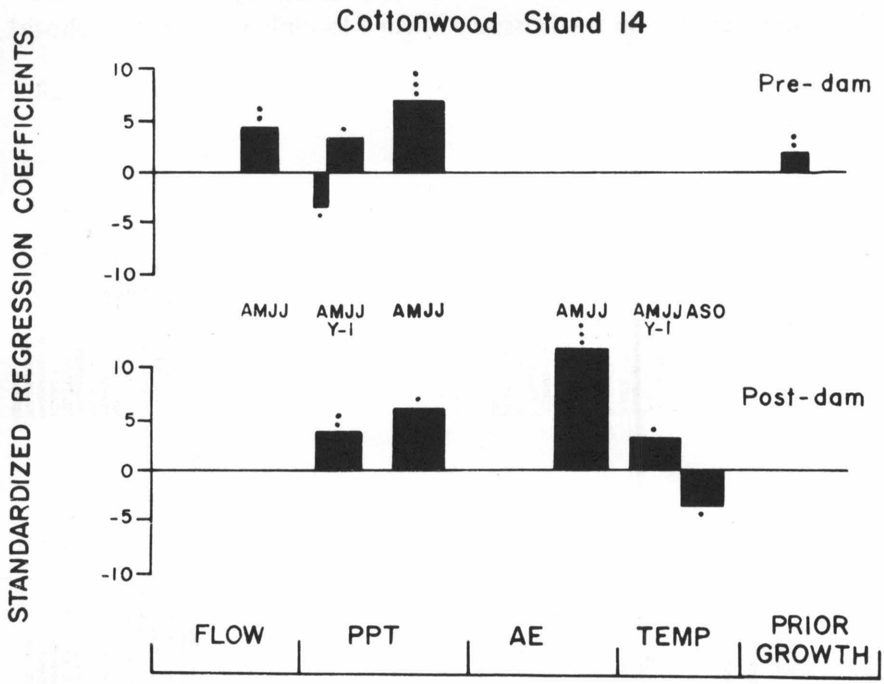


FIGURE 11 (continued)



Cottonwood Stand 14

*Fourteen environmental variables and a variable for the previous year's growth (shown in *Table 6* plus fall AE) were available to the stepwise selection process. Only those variables significant at the 0.100 level are shown. Bars represent standardization regression coefficient, and dots above or below bars indicate levels of significance: • ≤ 0.05, • • ≤ 0.01, • • • ≤ 0.001 [Fritts, 1976].

FIGURE 12

Age Structure of American Elm and Boxelder Populations in Four Treatment Stands on the Missouri River Floodplain in North Dakota*

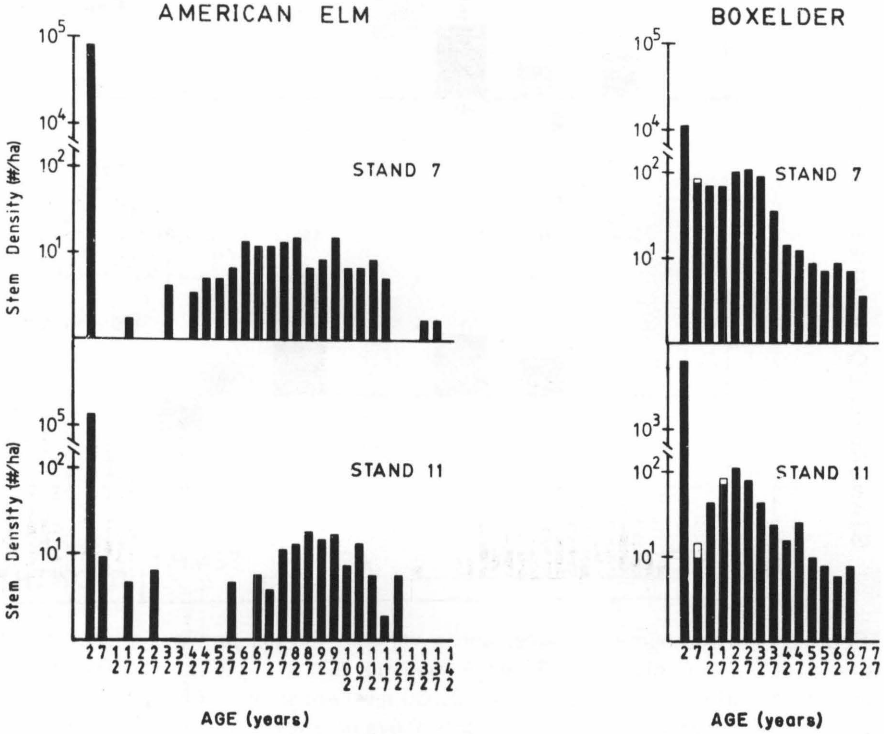
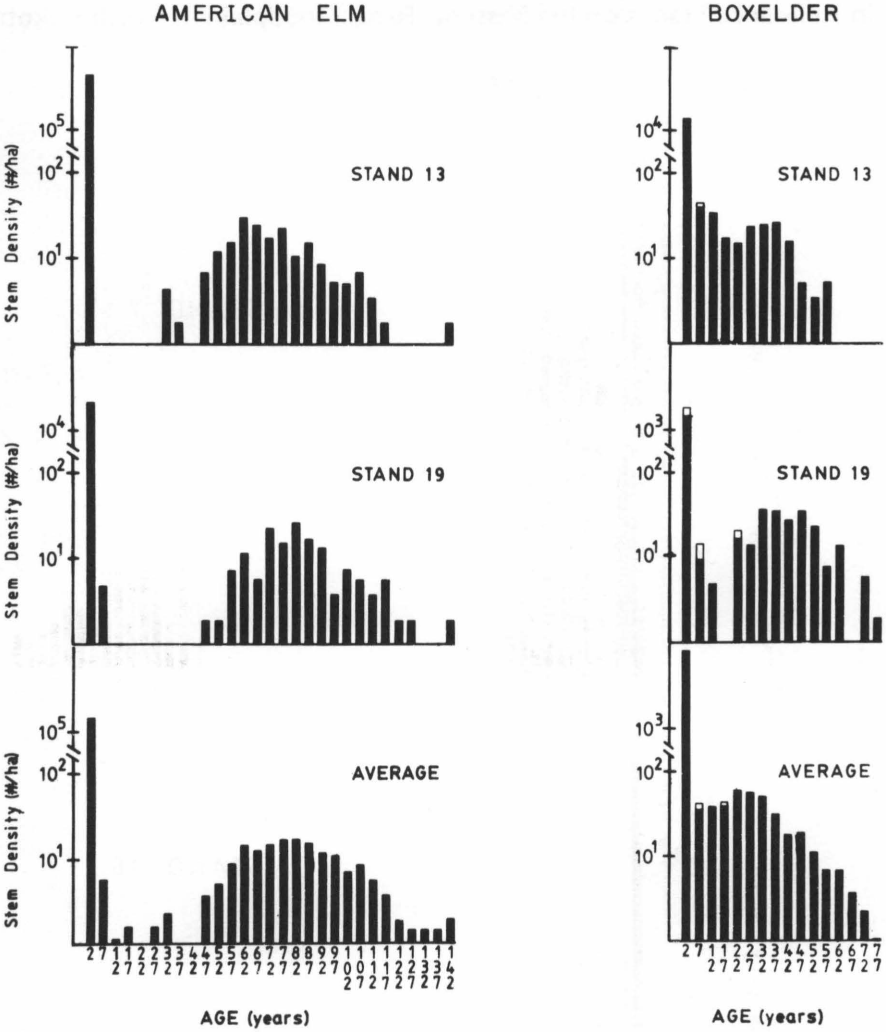


FIGURE 12 (continued)



*White bars denote proportion of stems of sprout origin.

FIGURE 13
Age Structure of American Elm and Boxelder Populations in Reference Stands on the Missouri River Floodplain in North Dakota

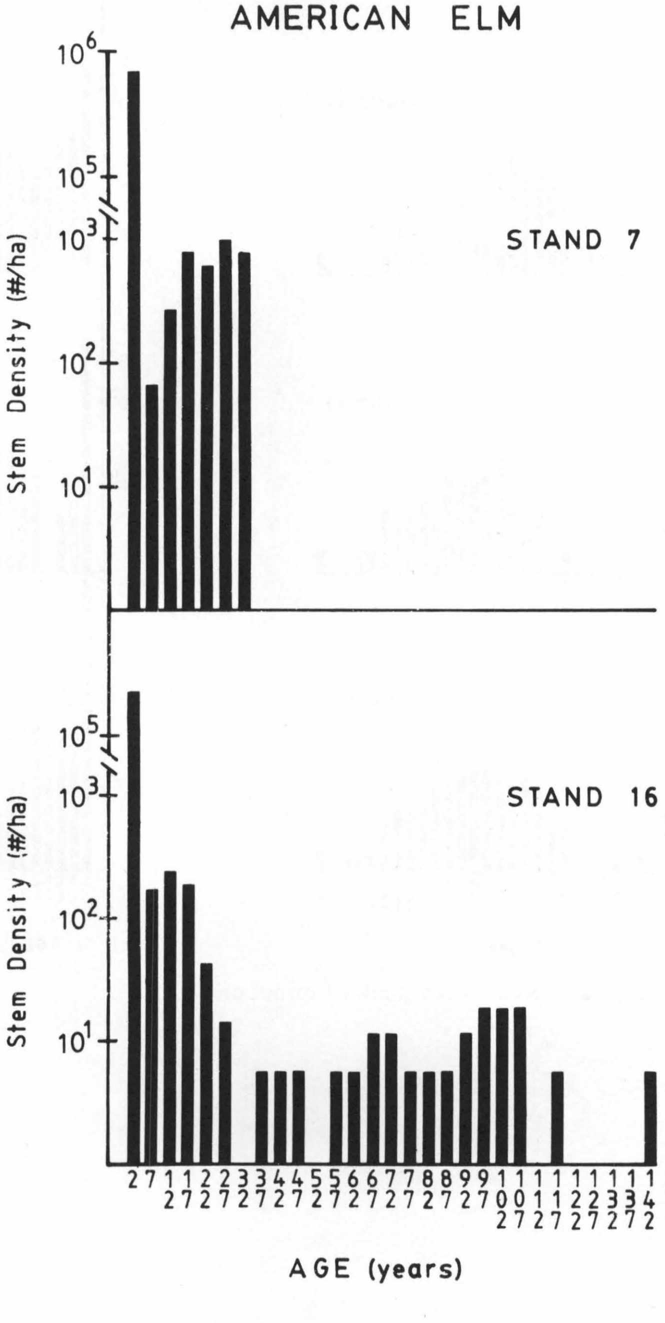
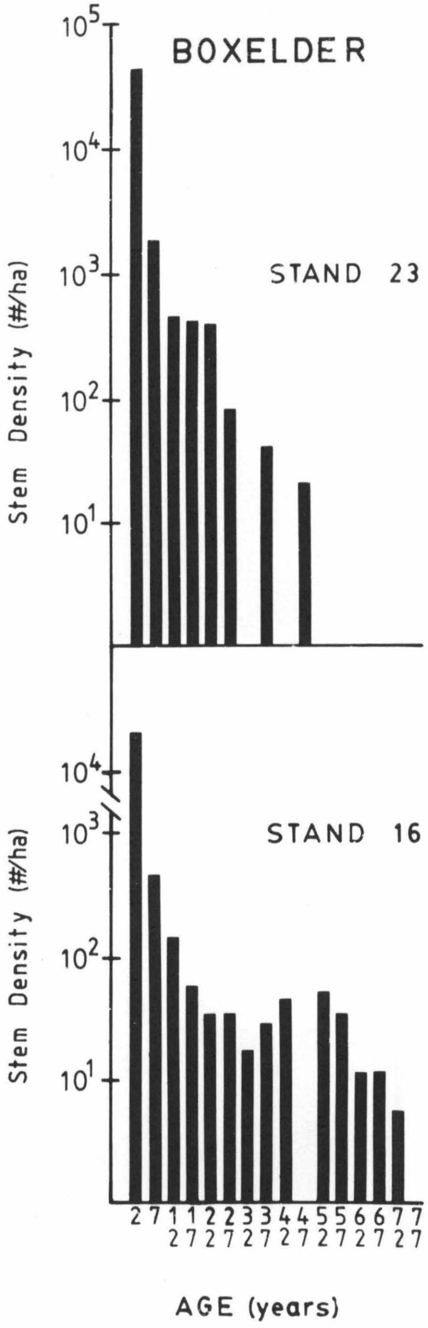


FIGURE 13 (continued)



TABLES

TABLE 1

Precipitation and AE Statistics for Pre-Dam (1935-1954) and Post-Dam (1955-1974) Periods*

	Mean		Maximum		Minimum	
	Total	April-July	Total	April-July	Total	April-July
Precipitation (cm)						
Pre-dam	40.3 (SD 9.1)	23.6 (SD 7.5)	51.6	34.4	15.2	2.7
Post-dam	38.2 (SD 7.2)	22.4 (SD 6.5)	54.7	33.0	27.1	12.6
AE (cm)						
Pre-dam	38.1 (SD 7.6)	29.6 (SD 6.4)	46.7	37.2	17.0	11.2
Post-dam	36.1 (SD 7.6)	29.2 (SD 6.6)	51.4	36.8	23.6	16.9

*Source: U.S. Weather Bureau Climatological Data.

TABLE 2

Mean Total Radial Wood Growth by Species and Site for 20-Year Pre-Dam (1935-1954) and Post-Dam (1955-1974) (Unadjusted and Adjusted for Age) Periods*

Species	Numbers of Cores and Stands Included†	(B1) Total Radial Wood Growth Per Core (mm) 1935-1954 $\overline{X}$	(B2) Unadjusted Total Radial Wood Growth Per Core (mm) 1955-1974 $\overline{X}$	(AB2) Adjusted Radial Wood Growth Per Core (mm) 1954-1974 $\overline{X}$	Wilcoxon Sign-Rank Z-Values‡ (B2-AB2)	(B1-B2)
Green ash	34 (8)	36.5	28.9	30.4	-3.21 ($p < 0.001$)	
American elm	48 (7)	36.1	23.5	26.4	-4.81 ($p < 0.0001$)	
Boxelder	29 (7)	41.0	26.4	31.6	-2.65 ($p < 0.008$)	
Cottonwood (Missouri River)	26 (5)	47.2	30.6	41.3	-1.24 (NS)	
Cottonwood (Little Missouri River)	25 (4)	38.3	35.5	47.2	+2.18 ($p < 0.03$)	
Bur oak (Missouri River)	20 (3)	32.0	29.6			-2.20 ($p < 0.03$)

TABLE 2 (continued)

Species	Numbers of Cores and Stands Included†	(B1) Total Radial Wood Growth Per Core (mm) 1935-1954 $\overline{X}$	(B2) Unadjusted Total Radial Wood Growth Per Core (mm) 1955-1974 $\overline{X}$	(AB2) Adjusted Radial Wood Growth Per Core (mm) 1954-1974 $\overline{X}$	Wilcoxon Sign-Rank Z-Values‡	
					(B2-AB2)	(B1-B2)
Bur oak						
(Scarp woodland)	10 (1)	17.1	19.3			-1.48 (NS)

*See text for method of adjustment. Post-dam growth of bur oak was not adjusted because most cases showed an increase in growth between the two pre-dam periods.

†Parentheses indicate stands included.

‡Source: Hollander and Wolfe [1973].

TABLE 3

Median Percent Change in Growth for Pre-Dam (1935-1954) and Post-Dam (1955-1974) Periods*

Species	Median Percent Change			
Boxelder	-26	│		
American elm	-25	│		
Green ash	-18	│	│	
Bur oak (Missouri River)	- 9	│	│	│
Cottonwood (Missouri River)	- 6	│	│	│
Cottonwood (Little Missouri River)	+13		│	│
Bur oak (scarp woodland)	+20			│

*Species connected by vertical lines are not significantly different (multiple comparisons test, $p < 0.05$; Hollander and Wolfe [1973].

TABLE 4

Frequency Table (Number of Stands) of Change in Growth Relative to Terrace Elevation

Classes of Percent Change in Growth*	Terrace Elevation Class†		
	Low	Medium	High
Low	1	0	3
Medium	3	2	0
High	0	3	1

*Low = less than 5 percent decrease; medium = 5-20 percent increase; high = greater than 20 percent increase.

†Low = approximately 3 m above mean river level; medium = approximately 4 m above mean river level; high = approximately 5 m above mean river level.

TABLE 5

Characteristics of Stands Sampled for Tree-Ring Chronologies*

Stand No.	Species Sampled and Mean Age	Texture	Soil Organic Matter (%)	NO_3-N (ppm)	Elevation Above Mean River Level (m)
Missouri River Floodplain					
5	Cottonwood (80 years)	sand	0.76	1.3	3.0
14	Cottonwood (100 years)	silty-clay	2.22	2.4	3.2
12	American elm (80 years)	silty-clay	2.92	1.6	3.5
13	American elm (135 years)	silty-clay	2.69	4.3	4.0
19	American elm (105 years)	silt	4.40	3.6	4.0
16	Bur oak (125 years)	silty-clay	4.07	3.2	5.0
Reference Sites					
Little Missouri River	Cottonwood (100 years)	––	––	––	2.8
Scarp woodland	Bur oak (120 years)	––	––	––	––

*Source for soil characteristics: Johnson, Burgess, and Keammerer [1976].

TABLE 6

Results of Stepwise Multiple Regression Analysis Using Tree-Ring Index as the Dependent Variable and 15 Independent Variables (Climate, Streamflow, Previous Year's Growth)

Species	Intercept	Standardized Regression Coefficient	Environmental Variables	r^2	F	p
Cottonwood						
Stand 5						
Pre-dam	-27.6	+8.28	April-May Flow (AMFL)	0.82	16.23	0.0001
		-2.03	June Flow (JUNEF)			
		+3.60	Spring Precip Y-1 (SPGP1)			
		+3.33	Spring Precip (SPGP)			
		-3.52	Spring AE Y-1 (SPGAE1)			
Post-dam	-6.48	+1.69	June Flow (JUNEF)	0.71	8.61	0.0003
		+5.76	Spring AE (SPGAE)			
		+2.62	Spring Temp Y-1 (SPGT1)			
		-3.73	Fall Temp Y-1 (FALLT1)			
		+0.42	Previous Growth (AVE 5-1)			
Stand 14						
Pre-dam	-21.7	+4.10	April-May Flow (AMFL)	0.73	9.86	0.0001
		+3.24	Spring Precip Y-1 (SPGP1)			
		-2.48	April Precip (AP)			
		+6.62	Spring Precip (SPGP)			
		+0.47	Previous Growth (AVE 14-1)			
Post-dam	-1.5	+4.20	Spring Precip Y-1 (SPGP1)	0.75	10.61	0.0001
		-5.44	Spring Precip (SPGP)			
		+11.71	Spring AE (SPGAE)			
		+2.99	Spring Temp Y-1 (SPGT1)			
		-3.49	Fall Temp Y-1 (FALLT1)			

TABLE 6 (continued)

Species	Intercept	Standardized Regression Coefficient	Environmental Variables	r^2	F	p
Bur oak						
Stand 16						
Pre-dam	-28.14	+3.80	April-May Flow (AMFL)	0.52	3.12	0.03
		+2.98	Spring AE Y-1 (SPGAE1)			
		+4.79	Spring Temp Y-1 (SPGT1)			
		+3.58	Fall Temp Y-1 (FALLT1)			
		-4.99	Spring Temp (SPGT)			
		+0.24	Previous Growth (AVE 16-1)			
Post-dam	-42.16	+3.95	April-May Flow (AMFL)	0.77	12.06	0.0001
		+3.61	June Flow Y-1 (JUNEF1)			
		+2.35	April Precip (AP)			
		+4.17	Spring AE (SPGAE)			
		+3.10	Spring Temp (SPGT)			
Scarp woodland						
Pre-dam	-18.9	-3.01	June Flow (JUNEF)	0.36	2.69	0.062
		+3.80	Spring Precip Y-1 (SPGP1)			
		+3.03	April Precip (AP)			
		+3.87	Spring AE (SPGAE)			
Post-dam	-7.37	+3.44	June Flow Y-1 (JUNEF1)	0.41	3.33	0.032
		+1.95	June Flow (JUNEF)			
		+2.27	Spring Precip (SPGP)			
		+0.41	Previous Growth (AVE 10-1)			

(continued)

TABLE 6 (continued)

Species	Intercept	Standardized Regression Coefficient	Environmental Variables	r^2	F	p
American elm						
Stand 12						
Pre-dam	+36.94	+3.96	April-May Flow (AMFL)	0.55	3.42	0.0211
		-4.83	June Flow (JUNEF)			
		+9.89	Spring Precip Y-1 (SPGP1)			
		+3.35	Spring Precip (SPGP)			
		-4.93	Spring AE (SPGAE)			
		-3.38	Spring Temp (SPGT)			
Post-dam	-13.77	-2.97	April-May Flow Y-1 (AMFL1)	0.47	2.55	0.06
		+5.47	June Flow Y-1 (JUNEF1)			
		-5.78	April-May Flow (AMFL)			
		+6.85	June Flow (JUNEF)			
		-2.45	Fall Temp Y-1 (FALLT1)			
		-3.72	Spring Temp (SPGT)			
Stand 13						
Pre-dam	+30.83	-5.00	April-May Flow Y-1 (AMFL1)	0.63	6.18	0.0017
		+3.13	June Flow Y-1 (JUNEF1)			
		+5.21	Spring Precip Y-1 (SPGP1)			
		+2.85	Spring Temp Y-1 (SPGT1)			
		-6.28	Spring Temp (SPGT)			
Post-dam	+52.51	-6.98	Spring Precip Y-1 (SPGP1)	0.54	5.52	0.004
		+10.09	Spring AE Y-1 (SPAE1)			
		-3.64	Spring Temp Y-1 (SPGT1)			
		-4.15	April Temp (AT)			

TABLE 6 (continued)

Species	Intercept	Standardized Regression Coefficient	Environmental Variables	r^2	F	p
Stand 19						
Pre-dam	+19.98	+3.95	April-May Flow (AMFL)	0.51	3.70	0.0176
		+11.06	Spring Precip Y-1 (SPGP1)			
		-9.94	Spring AE Y-1 (SPGAE1)			
		-4.91	Spring Temp (SPGT)			
Post-dam	-11.34	+4.57	April-May Flow Y-1 (AMFL1)	0.67	7.38	0.0006
		-5.44	April-May Flow (AMFL)			
		+6.29	June Flow (JUNEF)			
		-1.97	April Precip (AP)			
		+3.47	Spring AE (SPGAE)			

TABLE 7
Results from the Modified Regression Model[*]

Stand	Pre-Dam	Post-Dam
Cottonwood		
5	Streamflow (0.004)[†]	AE (0.01)
14	Streamflow (0.02)	AE (0.01)
Elm		
12	––	––
13	––	––
19	––	AE (0.03)
Oak		
16	AE (0.05)	AE (0.006) Streamflow (0.006)
Scarp woodland	AE (0.05)	

[*] Growth = growing season AE and growing season streamflow, using the GLM procedure in SAS [Helwig and Council, 1979]. Growing season is May, June, and July.

[†] Parentheses indicate levels of significance.

TABLE 8
Missouri River Erosion and Deposition Rates at Various Time Intervals

Time Interval	Time (yr)	Total Erosion (ha.)	Erosion Rate (ha./yr)	Total Deposition	Deposition Rate (ha./yr)
1881-1891	10	1,328	133	1,650	165
1891-1945	54	4,648	86	5,464	101
1945-1969	22	1,704	77	937	43
1969-1979	10	212	21	13	1.3

TABLE 9
Missouri River Land Use Changes Since Early Settlement

Category	Time Period	Percentage of Coverage	
		Pre-settlement	Post-settlement
Agriculture	1872-1938	––	38
Agriculture	1938-1979	––	18
Cottonwood, willow	< 40 years of age	14	3
Cottonwood	40-80 years of age	53	10
Cottonwood, ash, elm, boxelder	80-150 years of age	30	21
Ash, elm, boxelder	> 150 years of age	3	10

MISSOURI RIVER CHANNEL & LAND-USE CHANGES

MISSOURI RIVER CHANNEL & LAND-USE CHANGES