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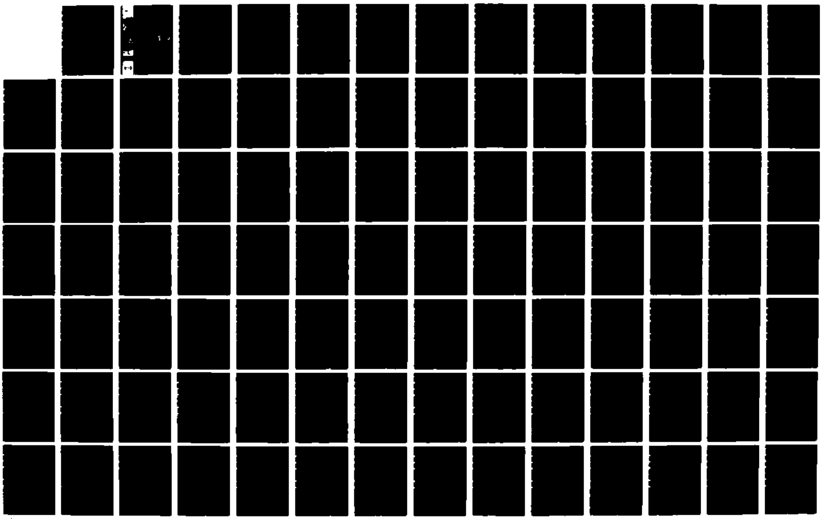

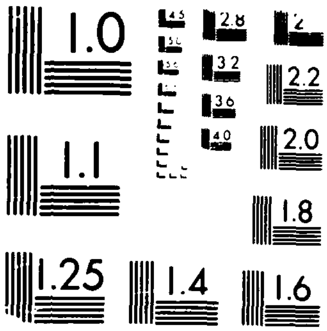

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AD-A190 426

MISCELLANEOUS PAPER EL-87-12

MANAGEMENT OF ENVIRONMENTAL RESOURCES OF CUTOFF BENDS ALONG THE TENNESSEE-TOMBIGBEE WATERWAY

by

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Environmental Laboratory

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Construction of the Tennessee-Tombigbee Waterway (TTW) involved construction of a navigation channel across the necks of 35 meander bends of the Tombigbee River. The cutoff bends, or bendways, constitute a valuable resource that the Corps of Engineers is committed to maintain. This study was conducted to provide a rational basis for refinement of the management strategy for the 30 TTW bendways located downstream of Aberdeen Lock and Dam. The five bendways in Aberdeen Pool were not considered in this study.

Bendway sedimentation may be conceptually divided into two phases: blockage and infilling. Sedimentation during the blockage phase is primarily deposition of bars of bed material in the upstream and downstream bend entrances. The infilling phase begins when the upstream bend entrance is blocked to top bank elevation and is characterized by deposition of fine sediment more or less uniformly along the length of the bend.

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19. ABSTRACT (Continued).

Discharge, suspended sediment concentration, and repetitive hydrographic survey records for 20 man-made cutoff bends and associated cut channels and for one natural chute cutoff were used to study the rate of sedimentation during the blockage phase. Cutoff bend volume was found to be a log-decay function of cumulative water discharge in the main channel. Regression functions show that the log-decay constant is inversely proportional to the average bed-material concentration in the master stream during the period of interest divided by either the sine of the angle between the cut channel and the bend entrance or by the average difference in mean bed elevations of the cut and bend entrances. The derived regression functions may be used to predict log-decay constants for cutoff bends along river reaches similar to those studied.

The variation of bendway channel cross-sectional area with both time and distance along the bend showed that for most bends, deposition patterns tend to be bimodal, with a primary location for deposition just below the upstream entrance and a secondary location just above the downstream entrance. Extrapolation of trends observed in blockage-phase bends showed that the TTW bends will experience large losses of channel volume during the blockage phase if allowed to block naturally.

Sequential aerial photographs of seven cutoff bends were used to study infilling rates. The perimeter of the treeline and the area enclosed by the treeline around each lake were measured for each photography coverage date. Area decreased rapidly at the end of the blockage phase and then stabilized and mildly fluctuated about a value 40 to 60 percent of the initial value. Perimeter declined only slightly or remained constant over the same time period.

Specific recommendations are provided for management of each of the 30 TTW bendways downstream of Aberdeen Lock and Dam. Construction of blockage embankments at the upstream end is recommended for 27 of the bendways. Three of these 27 blocks were constructed in 1985.

PREFACE

This report was prepared by the Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES), in fulfillment of Reimbursable Order Nos. FC 84-0076, FC 85-0060, and FC 86-0025. Mr. Thomas A. Lightcap of the US Army Engineer (USAE) District, Mobile, was the District point of contact. Messrs. Max L. Yates, Norman Connell, and F. Dewayne Imsand of the USAE District, Mobile, provided assistance. The report was written by Dr. F. Douglas Shields, Jr., of the Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), EL.

Technician support was provided by Ms. Cheryl Lloyd and Ms. Kathy Smart; computer support was provided by Messrs. Anthony Gibson and Richard Ladner. Ms. Monette Ward proofread portions of the draft report while working under an Intergovernmental Personnel Act agreement. Ms. Lloyd edited the draft report. Messrs. Thomas Schaefer and Porter Rivers III and Mses. Cindy Cox and Anita Zitta worked on the project as contract students. All support personnel were members of the WREG except for Mr. Ladner, who was first a member of the Computations and Analysis Unit of the WES Geotechnical Laboratory and, later, an employee of Hilton Systems, Vicksburg, Miss. Mr. Mark Walters of Hilton Systems assisted with preparation and analysis of the maps of oxbow lakes. The report was edited for publication by Ms. Jessica S. Ruff of the WES Information Technology Laboratory.

Technical reviews of the draft report were provided by Dr. S. R. Abt of the Department of Civil Engineering, Colorado State University; Dr. Paul Schroeder of the WREG; Dr. Jim Pennington of the Aquatic Habitat Group, EL; and Mr. Charles Elliott of the USAE Division, Lower Mississippi Valley.

The work was accomplished under the direct supervision of Dr. Michael R. Palermo, Chief, WREG, and under the general supervision of Dr. Raymond L. Montgomery, Chief, EED; Dr. John Keeley, Acting Chief, EL; and Dr. John Harrison, Chief, EL.

COL Dwayne G. Lee, CE, was the Commander and Director of WES. Dr. Robert W. Whalin was Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acre-feet	1,233.489	cubic metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
cubic yards per mile	0.47507	cubic metres per kilometre
feet	0.3048	metres
feet per mile	0.1893935	metres per kilometre
miles (US statute)	1.609347	kilometres
pounds (mass) per acre	0.000112	kilograms per square metre
square feet	0.09290304	square metres
square miles	2.589998	square kilometres
tons (2,000 pounds, mass)	907.1847	kilograms

MANAGEMENT OF ENVIRONMENTAL RESOURCES OF CUTOFF BENDS ALONG THE TENNESSEE-TOMBIGBEE WATERWAY

PART I: INTRODUCTION

Background

1. Construction of the River Section of the Tennessee-Tombigbee Waterway (TTW) involved excavation of cutoff channels across some 35 meander necks along the Tombigbee River, thereby creating 35 cutoff bends (bendways). In addition, the construction of Aberdeen, Columbus, and Gainesville Locks and Dams involved cutting off three additional meanders. At two of these structures, the locks were placed in the cut channels, and flow is maintained in the bendways by minimum flow structures that release water from upstream impoundments. At Gainesville the entire flow is passed through the bendway.

2. Throughout development of the TTW project, the Corps of Engineers made commitments to the public and to other agencies that appropriate measures would be taken to maintain the resources of the bendways. Commitments concerning these resources are contained in the Environmental Impact Statement (EIS) (US Army Engineer District, Mobile 1971*), the Final Supplement to the EIS (Mobile and Nashville Districts 1982), and the Record of Decision for the TTW, which was signed on 30 June 1982. In addition to these commitments, the Corps' interest in the condition of the bendways was reinforced when several recreation areas were located along the banks of the bendways.

3. To address concerns regarding management of the severed bends, the Mobile District formed a multidisciplinary task force and conducted a bendway management study (Mobile District 1984). Results of this effort included a specific plan of action for managing each of the 30 bendways downstream of Aberdeen Lock and Dam (Table 1). The five bendways in Aberdeen Pool are not included in Table 1 and are not considered in the remainder of this report because they are of such recent construction and are located deep enough in the navigation pool that they were not thought to be immediately threatened by

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* Hereinafter, publications of US Army Engineer Districts will be cited by giving the name of the District and the date.

Table 1

Management Plan for TTW Bendways (from Mobile District 1984)

Pool	Site No.	Bendway	Recommended Management Plan
Demopolis	101	Rattlesnake	No action
Gainesville	202	Warsaw	No action
Gainesville	203	Cooks Bend	No action
Gainesville	204	Windham Landing	No action
Gainesville	205	Cochrane	No action
Gainesville	206	Lubbub Creek	No action
Gainesville	207	Owl Creek	Dredged material dam
Gainesville	208	Big Creek	Full channel with sump
Aliceville	309	Pickensville	No action
Aliceville	310	Coalfire	No action
Aliceville	311	Hairston	Full channel with sump
Aliceville	312	Columbus	Full channel with sump
Columbus	413	Waverly Ferry	No action
Columbus	414	Waverly	No action
Columbus	415	Waverly Mansion	No action
Columbus	416	Stinson Creek	No action
Columbus	417	Town Creek	No action
Columbus	418	Barton Ferry	No action
Columbus	419	Buttahatchee River	No action
Columbus	420	Vinton	No action
Columbus	421	Denmon Creek	No action
Columbus	422	Cane Creek	No action
Columbus	423	McKinley Creek	Full channel with sump
Columbus	424	Richardson Lake	Dredged material dam
Columbus	425	New Hamilton	Dredged material dam
Columbus	426	Lockridge Creek	Dredged material dam
Columbus	427	Hickelson Lake	Dredged material dam
Columbus	428	Dead River	Dredged material dam
Columbus	429	James Creek	Full channel with sump
Columbus	430	Morgan Landing	Dredged material dam

sediment deposition. In addition, requisite data for the Aberdeen Pool bendways were not available for this study.

4. A program to monitor fish populations, water quality, and sediment deposition in selected bendways was suggested by the Mobile District (1984). In addition, the study recommended that the overall bendway management policy be evolutionary in nature due to the dynamic set of circumstances acting on the bendways. It was recommended that a review study be conducted every 3 years after implementation of management measures to assess the accuracy of the initial study effort and the effectiveness of the management measures implemented. This report is a major component of the first review study.

Objective and Overview

5. The objective of this study was to provide a rational basis for future decisions regarding management of the TTW bendways. More specifically, relationships were developed between hydrologic and geometric variables and the rate of bendway blockage and filling. These relationships will allow Mobile District personnel to make decisions regarding the allocation of scarce resources for bendway management and to select the most effective management approach for a given bend.

6. Results of this study have potential application to the important problem of management of cutoff bends and backwaters along other projects in addition to the TTW, and this sort of application is a useful by-product of this study, although not a primary objective. The ecological value and importance of backwaters such as cutoff bends along stabilized rivers are well documented (Funk and Robinson 1974; Schramm and Lewis 1974; Kallemeyen and Novotony 1977; Environmental Science and Engineering 1982; Conner, Pennington, and Bosley 1983; Pennington, Baker, and Bond 1983; Atchison et al. 1986; Beckett and Pennington 1986).

Approach

7. Environmental conditions in river reaches that are cut off undergo changes due to many factors, but the primary factor operative for most of the TTW bendways is sediment deposition. The basic hypothesis of this study is that the rates and patterns of sediment deposition in cutoff bends are

controlled by hydrology and site geometry and are thus subject to management by understanding and, in some cases, altering these independent variables.

8. The first step in this study was the identification of the important independent variables that influence bendway sedimentation. Variables were identified by literature review and by consideration of the physical situation. As described in Appendix A, dimensional analysis was then used to formulate dimensionless groups of the independent variables. Relationships between these groups and bendway sediment deposition were then explored using hydrologic records and repetitive hydrographic surveys from 21 cutoff bendways located along four rivers.

9. The 21 study sites included 14 of the 30 bendways in the TTW study reach. No hydrographic survey data were available for the remaining 16. In addition, in order to include a wide range of the important variables involved, data were included from one man-made bendway on the Mississippi River, one natural cutoff bend on the Mississippi River, four Arkansas River bendways, and one Red River bendway.

10. Results of the data analysis described in Appendix A are discussed in Part II. Available management techniques are evaluated, and a procedure is proposed for design and long-term management of cutoff bends. Specific recommendations for the 30 bendways in the River Section of the TTW downstream of Aberdeen Lock and Dam are provided in Part III.

PART II: LITERATURE REVIEW

11. The search of literature for this study proceeded along two separate but related lines. The first part of the search addressed the fate of cutoff bendways--whether severed naturally or by man. The term "fate," as used here, encompasses both the physical dimensions of cutoff bendways and other characteristics such as water quality that influence habitat suitability. The second line of inquiry for the literature search identified various techniques for cutoff bendway management in order to conserve their environmental resources. Both employed and proposed management techniques were evaluated.

12. The literature dealing with both the fate of cutoff bends and management techniques for them is limited. Most engineering literature on bendway cutoffs tends to emphasize the design and construction of cuts, the response of the main channel geometry, and effects on flood hydrographs rather than management of severed bendways. This literature is summarized briefly in Table 2. A number of authors (Anderson 1974, Weihaupt 1977, Kalkomey 1979, Mobile District 1983) have noted the lack of information on cutoff bendways and oxbow lakes in the literature, despite the abundance of these features.

Fate of Cutoff Bendways

13. A major assumption of the work that follows is that the primary objective of bendway management is to conserve environmental resources but not necessarily to preserve severed bendways in some phase of their natural cycle or to prohibit all types of environmental change. Many of the environmental changes that occur in cutoff bends are beneficial to the resources involved. Even if some types of change are undesirable, halting all change is not a feasible form of management from an economic standpoint.

14. In general, cutoff bends will be filled with sediment. Sediments deposited in bends may originate primarily from the channel and watershed of the stream or from erosion of pilot cuts upstream (Ferguson 1940, Matthes 1948, Schega 1951). In some cases, cutoff bends have been deliberately used as disposal locations for sediment excavated from the main channel (Savannah District 1976). Cutoff bends along smaller streams may dewater as the straightened channel degrades or may be deliberately filled to create land for cultivation.

Table 2

Cutoff Construction and Main Channel Response

River	No. of Cutoffs Discussed	Effects: Flood Stage Elevation	Effects: Stability	Reference
Arkansas	15	Minimal	Minimal	Petersen (1963)
Arkansas	2	--	--	Bush (1962)
Arkansas	1	--	--	Buffington (1962)
Mississippi	16	Greatly lowered initially	Detrimental in long term	Clemens (1936), Ferguson (1940), Matthes (1948), Odom (1951), Shulits (1951), Carey (1966), Winkley (1977)
Savannah	31		Some detrimental	Wall (1962), Savannah *District* (1976)
Papaloapan	6	Lowered 1.5-6 ft (0.4-1.8 m)	--	Schega (1951)
Rhine	18		Very detrimental	Shulits (1951)

Conceptual model

15. Gagliano and Howard (1984) present a conceptual model of bendway sedimentation that relies heavily on the work by Fisk (1944, 1947, 1951). Bendway sedimentation proceeds in two distinct phases: blockage and infilling. The blockage phase extends from the time the bendway is cut off until one or both junctions are blocked, thus preventing flow through the old bendway except during floods. Current velocity in the cutoff bend during the blockage phase is minimal except at high flow. However, after the entrances to the old bend are blocked, conditions in the old bend, now an oxbow lake, become lacustrine. The infilling, or lacustrine, phase gradually gives way to a terrestrial phase in which all that remains of the old bend is a swampy meander scar on the floodplain.

Blockage phase

16. Blockage occurs due to the deposition of bars of bed material (War Department 1932). Blockage rates tend to be quite rapid, ranging from 2 to 10 years for Lower Mississippi River neck cutoffs (Clemens 1936, Gagliano and Howard 1984) and about 5 years for Arkansas River cutoffs (Petersen 1963). Schega (1951) reported that one of the six Papaloapan River cutoffs was blocked by a major flood only 15 months after it was cut off. Blockage rates are affected by hydrographic variations.

17. Gagliano and Howard (1984) note that blockage rates are controlled by the supply of bed load, the ratio of cutoff length to bendway length ("length ratio"), and the angle of incidence between the cutoff and the old bendway ("diversion angle"). More quantitative information is available from physical model studies (War Department 1932) and prototype (Odom 1951a) studies of the movement of water and sediment at forks (or bifurcations) of alluvial channels. A good summary of this work is presented by Lindner (1953) and in discussions of his paper (Blench 1953, Leliavsky 1953, Thomas 1953). Although these studies focused on conditions at the entrances of diversions constructed either for intake of water to irrigation canals or as cutoff pilot channels, some of their findings are useful. In particular, these investigations revealed that fine suspended sediments tend to divide between a main channel and a branch in roughly the same proportion as water discharge. Conversely, most of the bed-load and coarse suspended sediments moving near the bottom tend to move into the channel, which makes the greatest angle with the

upstream bed-load path. The influence of the diversion angle is discussed further below.

18. When there are typical vertical distributions of velocity and sediment upstream of a bifurcation, the faster moving upper region of flow has greater momentum than the lower region and is less likely to be diverted from a straight path. The slower moving lower region of flow, which carries the most coarse sediment, is more easily turned into the diversion channel. This tendency is modified and influenced by a number of factors: the ratio of the slopes of the two channels, the ratio of velocities in the two channels, and the relative elevation of the inverts of the two channels.

19. Upstream junctions become blocked with sediment before downstream junctions, and it is not uncommon for a small channel to persist at the downstream end of the bendway (Lindner 1969). Blockage of downstream junctions is probably the result of transport of bed material into the old bendway by secondary currents, mainly during flood events.

20. Curran (1932) noted that the amount of bed material that is moved into the mouth of a diversion or side channel will progressively decrease as the bar builds because the mean force per unit area the flowing water exerts on and parallel to the channel bottom is reduced as depth is reduced. In addition, the upstream face of the bar will slope upward, which also decreases the rate of bed-load transport. This suggests that the cross-sectional area of the mouth of the old bend (and the total volume of the old bend) is a log-decay function of the total volume of bed material transported through the reach.

21. Diversion entrance location. The location of a diversion entrance is important because the helicoidal flow pattern in bends tends to carry coarse sediment to the inside; therefore, diversion intakes are best located on concave banks with the axis of the diversion tangent to that of the river. However, locations of cutoff bendway entrances relative to the new main channel are usually dictated by navigation or flood control channel design constraints. Also, pilot channel alignments usually do not have sufficient curvature to affect lateral sediment distribution. However, when pilot channels may be curved, concavity in the same direction as the old bendways will reduce sediment movement into the old bend.

22. Diversion angle. Vanoni (1975) and Richards (1982) present graphs of flume data showing the effect of diversion angle on the amount of sediment diverted into a branching channel. Figure 1 is based on flume data presented by Lindner (1953), which indicate that the fraction of bed load diverted is greatest for a diversion angle of 30 deg and least for angles between 90 and 120 deg. Vanoni's (1975) graphs are based on independent model studies by Bulle and Schoklitsch. Vanoni notes that the effects of diversion angle vary with the ratios of water discharge and the location of the diversion intake in a river bend.

23. Length ratio. The length of the bendway divided by the length of the pilot (or cutoff) channel, hereafter referred to as the "length ratio," is also the ratio of the cut channel slope to bend channel slope. Since stream power is directly proportional to slope, the rate of cutoff channel development and flow capture should vary directly with length ratio. Flow will persist in the old bendway longer for lower length ratios (Gagliano and Howard 1984).

24. Petersen (1963) presents hydrographic surveys of four cutoff bendways along the Arkansas River. The rate of sedimentation in the old bendways was observed to be directly proportional to the length ratio for several years after construction. However, as shown in Figure 2, after about 5 years, all four bendways were filled about the same amount, regardless of the length ratio.

25. On the other hand, Wolff (1978) found the longevity of Missouri River oxbow lakes to be directly proportional to the length ratio. Bends with a high length ratio tended to have greater initial depths and have bottom sediments with thicker layers of silt and clay, thus hindering ground-water outflow.

26. Proximity to dams. Blockage rates for three of the Tombigbee River bendways (Rattlesnake, Cooks, and Big Creek) were found to be influenced by the distances from the bends to upstream navigation dams (Mobile District 1984). The bend closest to an upstream dam blocked most rapidly due to higher rates of sediment transport in the upstream portion of the navigation pool and smaller storage available below normal pool elevation. Conversely, McHenry et al. (1984) found that backwater lakes in the upper portion of the Upper Mississippi River navigation pools filled more slowly than similar areas just above dams.

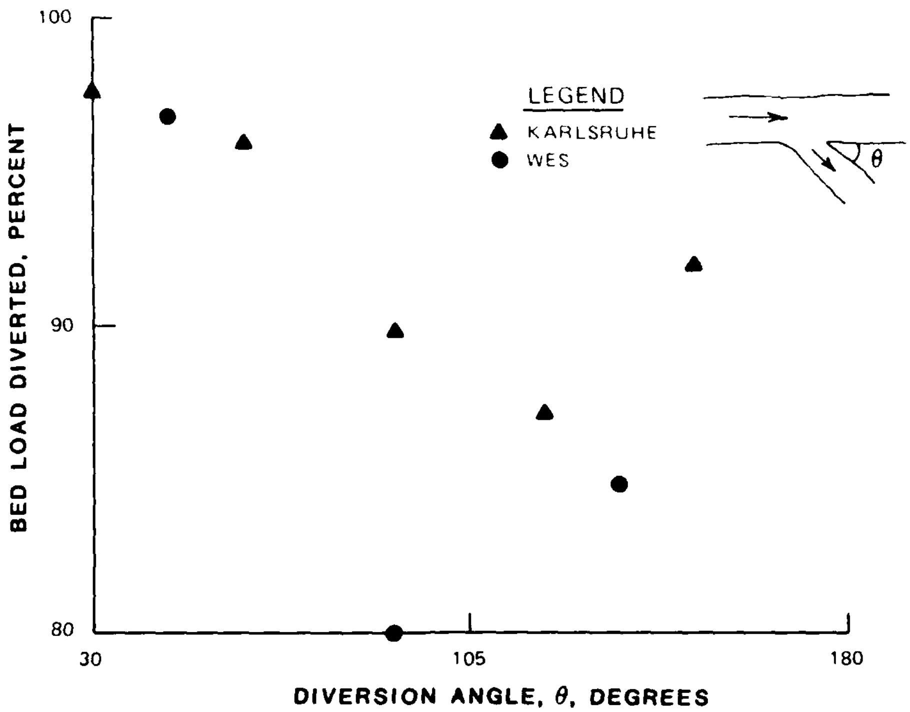

Figure 1. Effect of angle of incidence between a diversion and a straight main channel on the fraction of bed load diverted. (Data from Lindner 1953. WES data are measurements by Vogel at the US Army Engineer Waterways Experiment Station. Karlsruhe data were measured at the Karlsruhe hydraulic laboratory by Freeman. Both sets were tabulated by Linder.)

They reasoned that these areas are subjected to a lesser input of sediment because of less direct flow.

Infilling phase

27. After the junctions of the old bendway are blocked by bars of bed material, bendway sedimentation is dominated by deposition of finer sediments during overbank flows. Gagliano and Howard (1984) list five factors that control the rate of infilling of oxbow lakes: (a) river flooding history, (b) river migration history, (c) lake size, (d) number and size of outflow channels to the backswamp, and (e) artificial levee construction.

28. The literature contains scattered information on infilling rates for floodplain water bodies as portrayed in Table 3. Infilling rates tend to be one to two orders of magnitude slower than blockage rates (Gagliano and Howard 1984) but in some cases can be rapid enough to cause significant resource reductions in a few decades. Jauron (1974) describes the dramatic effects of

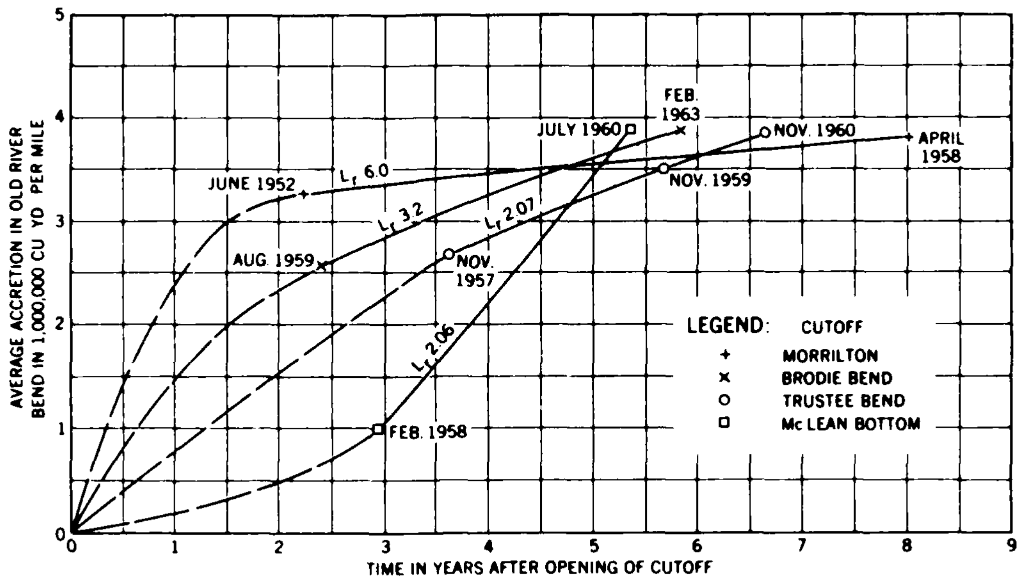

Figure 2. Relationship between L_r, the ratio of cutoff bend length to cut channel length, and the rate of sediment deposition per unit length of cutoff bend for four Arkansas River bends (from Petersen 1964). (To convert cubic yards per mile to cubic metres per kilometre, multiply by 0.47507)

a few floods on 17 man-made oxbow lakes along the Missouri River. Doris (1958) reports that a single flood deposited a layer of silt several inches thick in four Middle Mississippi River floodplain lakes after levee failure. Cooper and Knight (1978) document the detrimental effects on fish and water quality of sediment input to several Mississippi Delta lakes and sloughs by local drainage. Sedimentation rates ranged from 1.7 to 7 cm per year, but the water bodies studied were not subject to overbank flooding from a master stream. Eckblad, Peterson, and Ostlie (1977) state that the floodplain lake they studied could completely fill in 43 to 61 years at current rates (1964-1974) of infilling. McHenry, Ritchie, and Cooper (1980) and McHenry et al. (1984) predict that Upper Mississippi River backwater lakes will become marshes in 50 to 100 years if present sedimentation rates continue.

29. Since oxbow lakes are floodplain features, infilling is a part of the overall process of floodplain formation. Leopold, Wolman, and Miller (1964) state that floodplain formation is the result of two related processes: deposition on point bars and vertical accretion due to overbank flows. It is the latter process that is of interest here. A study of overbank sediment deposition resulting from a 1958 flood in Japan revealed irregular patterns of

Table 3

Published Data on Sedimentation of Floodplain Lakes

Site	Infill Rate	Reference	Remarks
Raccourci - Old River, Miss.; Miss. River	0.263% bendway length/year	Gagliano and Howard (1984)	Man-made cutoff, 1847
False River, La.; Miss. River	0.449% bendway length/year	Gagliano and Howard (1984)	Natural cutoff, 1699-1722
Swan Lake, Miss.; Miss. River	0.10-0.07% bendway length/year	Weinstein (1981), Gagliano and Howard (1984)	Natural cutoff, A.D. 100-200. History determined using archaeological evidence.
17 man-made cutoff bendways, Iowa, Mo. River	1-50% surface area/year	Jauron (1974)	Man-made cutoffs, 1950s and '60s. Infilling usually occurred only during rare events, but very rapidly then.
4 Missouri River oxbow lakes, Iowa	0.4% surface area/year, 0.01-0.04 ft/year*	Lohnes et al. (1977); Lohnes, Bachmann, and Austin (1979)	Natural cutoffs formed in mid- to late-1800s. Area reduced due to declining water levels and sedimentation.
Lake Manawa, Iowa, Mo. River	20 acre-feet/year (24,670 cu m/yr)	Omaha District (1979)	Natural cutoff, 1881. Rate shown does not reflect flooding from river, which is prevented by levees.
28 man-made cutoff bendways, La., Red River	0.6% surface area/year	New Orleans District (1983)	A projection based on history of existing cutoff bendways on the Red and Arkansas Rivers.

(Continued)

* Average vertical deposition (to convert feet to metres, multiply by 0.3048).

Table 3 (Concluded)

Site	Infill Rate	Reference	Remarks
Big Lake, Iowa; Miss. River	0.03-0.06 ft/year*	Eckblad, Peterson, and Ostlie (1977)	Backwater lake adjacent to navigation pool.
Small, natural and man-made chute channels, Middle Miss. River	1-3 ft/year*	Simons, Schumm, and Stevens (1974)	
"Backwater channels"; Middle Miss. River	0.08-0.42 ft/year*	Simons, Schumm, and Stevens (1974)	
Lake Pepin	0.08 ft/year* since 1954	McHenry, Ritchie, and Cooper (1980)	25-mile-long (40-km) reach of Upper Miss. River
Upper Miss. River	0.03-0.17 ft/year*	McHenry et al. (1984)	Various locations

* Average vertical deposition (to convert feet to metres, multiply by 0.3048).

scour and deposition. However, the general trend indicated that the thickness of sediment deposition first increased in the downstream direction from the headwaters and then decreased in a reach in which the channel gradient flattened appreciably (Aramaki and Takayama 1960). Conversely, a similar study of the effects of a 1955 flood on channels and valleys of several Connecticut streams indicated that deposition was generally related to gradual slopes (Wolman and Eiler 1958). Patterns of scour and deposition were complex and tended to reflect local variation in the velocity and direction of flow. Deposition is also related to the quantity and size of available sediment (Wolman and Eiler 1958, Gregory and Walling 1973).

Environmental conditions

30. Little information is available regarding the ecology and water quality of cutoff bends in the blockage phase. Intuition would indicate that biological and chemical conditions would be relatively unchanged from their

precutoff states as long as significant currents persist. Shipp and Hemphill (1974) studied two cutoff bends and two unaltered bends on the Alabama River for 2 years. The cutoff bends had been severed 3 to 4 years prior to the study and remained in the blockage phase.

31. Shipp and Hemphill (1974) found that the overall catch was greater and game fish were more numerous in the cutoff bends. However, greater numbers of minnows were captured in the unaltered bends. Fish generally benefited from the greater accumulation of shoreline structure, such as brush, logs, and willows in the cutoff bends. The absence of point bars of coarse sand in the cutoff bends was viewed as a negative factor because large numbers of fish were collected from the sandy flats in the unaltered bends by seining at night. Pennington et al. (1981) observed similar trends in Big Creek cutoff bend on the Tombigbee River before and after the upstream end was blocked by natural deposition.

32. Cutoff bends in the infilling phase (oxbow lakes) tend to be highly productive eutrophic floodplain lakes. In warm weather, thermal stratification occurs. Deeper strata (below 6 to 9 ft*) often become anaerobic, while upper layers exhibit pH and dissolved oxygen fluctuations typical of waters with algal blooms (Mathis and Butts 1981; Sabol, Winfield, and Todczydlowski 1984; Tennessee Valley Authority 1987).

33. Bed material and suspended solids concentrations are sensitive to the presence or absence of local inflows from tributaries and hydraulic connections with the master stream. Most oxbow lakes tend to be characterized by clay and silt in the bed and extremely low suspended solids concentrations relative to the master stream.

34. Literature citations were found regarding macroinvertebrate, larval fish, and adult fish populations of cutoff bends. Benthic macroinvertebrate communities tend to be dense and often diverse assemblages of burrowing-type organisms typical of lentic eutrophic systems (Mathis et al. 1981, Beckett et al. 1983). Larval fish collections from a variety of habitats along the lower Mississippi River showed that abandoned channels similar to cutoff bends provide spawning and nursery habitat for several species of forage and sport fishes (Conner, Pennington, and Bosley 1983). Larval fish diversity in these

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

habitats tends to be low, but densities can be quite high (Schramm and Pennington 1981).

35. Several investigators have noted the value of backwater habitat such as oxbow lakes to adult fish. For example, Lambou (1959) sampled adult fish populations of seven backwater lakes in Louisiana and found an average density of 397 lb/acre including 103 lb of game fish and 169 lb of commercial fish per acre. This compares with an average density of only 73 lb/acre of fish in various Louisiana impoundments. Lambou (1959) described the sport fishery of the backwater lakes as excellent and reasoned that periodic flooding from adjacent streams had a salutary effect on their ecology. The Tennessee Valley Authority (1987) studied several lower Mississippi River floodplain lakes, including site 701 (described in Appendix A, paragraphs 16-21), and arrived at similar conclusions. Pennington et al. (1980) and Pennington, Baker, and Bond (1983) reported results of sampling adult fish in a variety of lower Mississippi River habitats with a variety of gear types. Abandoned channels, like cutoff bends, were found to have intermediate levels of fish density and diversity. However, at low river stages these areas provided scarce habitat for lentic species and juvenile fish. Pennington et al. (1981) found that the fish populations of the Tombigbee River cutoff bends reflected the influence of downstream dams and the formation of upstream blocks in bendway entrances in a similar fashion: when current velocities were greatly reduced or eliminated, fish communities changed from suckers, minnows, and catfishes to shad and sunfishes.

36. Atchison et al. (1986) sampled water quality, benthic macroinvertebrates, and fish in a variety of habitats along a 17-mile-long reach of the Missouri River upstream of Omaha, Nebraska. Samples were collected from three abandoned channels as well as dikefields, revetted banks, and main channel locations. The abandoned channels were found to be important fish habitat, especially as spawning and nursery areas. However, Atchison et al. (1986) found this type of backwater habitat to be especially scarce along the Missouri River. During the course of the study, one of the three abandoned channels selected for sampling became too shallow for access by boat. The abandoned channel habitat was described as "endangered," and protection and enhancement were recommended.

37. Throughout the period of the Missouri River study (summer and fall 1983), the abandoned channels supported the highest densities of benthic macroinvertebrates of all the areas sampled. Furthermore, the abandoned channels yielded the greatest fish species richness and overall greatest numbers of fish. It was speculated that a loss of interaction with the main channel due to sedimentation or drainage of connecting channels would reduce the production of river fish species in the abandoned channels (Atchison et al. 1986).

38. Cutoff bends in the infilling phase share many of the same characteristics of other floodplain lakes and abandoned channels. Borrow pits are plentiful on the river side of the main stem levee system of the lower Mississippi River. These borrow pits tend to be smaller and shallower than the old cutoff bends along the same reach but are subject to the same environmental influences. Cobb et al. (1984) reported results of biological and water quality sampling of 25 of these pits distributed along 250 miles of the river. The borrow pits were found to constitute a significant resource with regard to production of fish, aquatic habitat, and sport and commercial fisheries. The total standing stock of fish in the borrow pits averages 595 lb/acre, which is higher than levels for most water bodies in the southern United States.

39. Cobb et al. (1984) studied the relationships between biological and physical characteristics of the borrow pits. Borrow pit size and volume had little effect on abundance of fishes and benthic macroinvertebrates. On the other hand, the data did strongly suggest that population densities, number of species, and standing stocks of fish and macroinvertebrates were directly related to the average number of days that borrow pits were flooded annually, shoreline sinuousity, and depth.

Bendway Management Techniques

40. Techniques for controlling sediment and water movement in cutoff bendways have been identified by various authors. These techniques and their major limitations are listed in Table 4. Discussion of each major category of management follows.

Table 4

Management Alternatives for Severed Bendways

Management Alternative	Existing Installations	Limitations	References
No action	16 cutoffs on the lower Mississippi Kateland Bend, Red River, La.	Large amounts of bed material may deposit in the bendway during the riverine phase and shorten or eliminate the lacustrine phase.	New Orleans District (1983)
Construction of embankments (blocks) in one or both bendway entrances	Red River, La. Kaskaskia River, Ill.	Blocks eliminate or severely hamper recreational boat access. Exchange of aquatic organisms and water with main channel reduced. Water quality degradation may occur.	Mathis and Butts (1981)
Blocks with culverts or water control structures	Crow Creek, Ala. Little Blue River, Mo. Verdigris River, Okla.	High maintenance costs due to sediment and debris clogging. Hydraulic gradient required for flow.	Winger et al. (1976) Shields (1982) Tulsa District (1970)
Construction of training works to modify flow patterns at bendway entrance	Downstream entrance, physical model of cutoff bendway; canal intakes	Unfavorable sedimentation patterns may result in main channel. Some structures partially obstruct main channel, perhaps causing navigation problems.	Foster, O'Dell, and Franco (1982) Vanoni (1975, pp 546-582)
Low weirs or grade control sills placed in cutoff channel to force low to normal flow through cutoff bendway and to limit cut degradation	Souris River, Minot, N. Dak. Little Blue River, Mo. Prairie Creek, Ind. Stanefer Creek, Miss.	Use limited to small streams not used for commercial navigation. Cutoff bendway may experience aggradation since dominant discharge is shared with cutoff channel.	Nunnally and Shields (1985) USDA SCS (1975) Shields (1982)
Dredging	Big Creek Bendway, Tombigbee River, Ala. Blue Lake, Iowa	Must be repeated periodically. If bendway is in lacustrine phase, dredging may expose more permeable bottom sediments and increase outward flow to ground water.	Pennington, Baker, and Bond (1983) Sorge (1981) Lohnes, Bachmann, and Austin (1979)
Placement of brush or gravel structure to improve aquatic habitat	Tombigbee River, Miss.	The artificial riffle requires a large, steady supply of relatively supply of relatively sediment-free water.	Miller, King, and Glover (1983)
Control of inflow water quality and/or quantity	Eagle Lake, Miss. Lake Manawa, Iowa Snyder-Winnebago Complex, Iowa	Some schemes are limited to bendways isolated from overbank flooding from master streams.	Omaha District (1979) Mobile District (1983)

Blocks and culverts

41. Construction of blocks or embankments to completely isolate the severed bendway is the most commonly employed and suggested bendway management technique (Grant 1934; Carey 1964, 1966; Tulsa District 1970; New Orleans District 1972; Anderson 1974; Mahloch 1978; Mathis and Butts 1981; Foster, O'Dell, and Franco 1982; Mobile District 1983; Office, Chief of Engineers (OCE) 1983; Nunnally and Shields 1985). Complete blockage to top bank elevation promptly after cutoff pilot channel opening was required to prevent rapid bendway infilling at a site along the Red River (New Orleans District 1983). A disadvantage of blocks or closures is that they eliminate or severely hamper access by recreational boats. In addition, bendway blockage reduces or eliminates exchange of water and aquatic organisms between the master stream and the old bendway. A modification of this basic concept is to place culverts or control structures in one or both embankments to allow water exchange and fish passage (Tulsa District 1970, Anderson 1974, Nunnally and Shields 1985). Water control structures may be used to stabilize water levels and improve aquatic productivity (Miller, Wihry, and Lee, Inc. 1981) or to exclude local inflows during periods of poor water quality (Omaha District 1979). Water control structures can be a disadvantage due to high costs for construction and maintenance (New Orleans District 1983).

Training works

42. Use of river training structures such as constricting dikes made of stone and/or pilings to keep bendway entrances open was investigated as part of a larger physical model study by Foster, O'Dell, and Franco (1982). They concluded that cutoff bendway preservation in their study reach of the Red River would be best achieved by closing the upper ends with an embankment and either periodically dredging the lower end or constructing training dikes to block sediment-carrying bottom currents.

43. Training works have also been used to exclude sediments from canal intakes. Vanoni (1975) and Scheuerlein (1986) review the structural techniques used to control sediment at diversion intakes. Most of the structures described are expensive and/or require a larger hydraulic gradient in the main channel than is normally available at cutoff bendways. However, methods similar to guide vanes, skimming weirs, and settling basins could be used at cutoff bendways.

44. Carlson and Enger (1963) describe model tests of a series of four submerged guide vanes placed at a 45-deg angle with the flow upstream of a canal entrance. The model vanes were effective in creating a pattern of secondary flow that excluded coarse sediment from a canal intake that made a 90-deg angle with the main channel.

45. Remillieux (1966) and the War Department (1933) describe the use of guide vanes to direct sediments into a secondary channel. The latter reference reports mixed results with a physical model of a reach of the lower Mississippi River, but the former reports rapid closure of a Brahmaputra side channel using impermanent guide vanes made of iron sheets supported by bamboo stakes.

46. Garde and Raju (1977) describe the use of submerged deflecting vanes, King's vanes, and pitched islands to produce flow curvature and resultant exclusion of sediment from canal intakes. Mushtaq (1973) and Rao (1973) also mention the use of pitched islands and training dikes, respectively. Pitched islands could possibly be constructed of dredged material just upstream of a cutoff bendway entrance if there were sufficient width in the main channel.

47. Schoklitsch (1937) suggests that in order to exclude sediment, diversions should be at right angles to the main flow with a relatively narrow, high inlet. The inlet sill should be sloped or stepped from upstream to downstream.

Sills

48. Apmann and Blinco (1969) provide design details for sills to be placed in cutoff channels on smaller streams to limit degradation. Nunnally and Shields (1985) and the US Department of Agriculture Soil Conservation Service (1975) describe the use of sills placed in cutoff channels along channelized streams. These sills serve a dual purpose: they divert low to normal flows through the old bendway, and they stabilize the cutoff channel against degradation. A recent cutoff on the Cumberland River at Barbourville, Ky., is designed so that low to normal flows will follow the old channel, and only high flow will flow through the cutoff. Mathematical modeling during design indicated that the diversion channel would be stable without construction of sills (Nashville District, undated) and that sediment deposition in the bendway would be negligible during the project life. Nunnally (1982) observed flow diverted through unblocked cutoff bendways by sheet-pile weirs

in the cut channel of Stanefer Creek in Mississippi. These two aforementioned sites evidently experience atypically low rates of bed sediment transport and attendant low rates of bendway sedimentation.

Dredging

49. Mahloch (1978), OCE (1983), and Smith (1984) suggest the use of periodic dredging to maintain cutoff bendways and the construction of sediment traps or sumps at bendway entrances to localize sediment deposition. Dredging was evaluated as a management alternative for several bendways along the Tombigbee River. Although dredging is expensive, use of the dredging-and-sump technique was recommended by the Mobile District (1983) for maintenance of five of the Tombigbee River cutoff bendways. Simons, Li, and Associates (1982) suggested that gravel could be mined (dredged) from some of the Tombigbee River bendways. Lohnes, Bachmann, and Austin (1979) caution against indiscriminate dredging of perched lakes along the Missouri River in Iowa. Dredging could destroy the clay seal under the lakes, thereby increasing outward flow to ground water. Sorge (1981) monitored the water quality effects of dredging a Missouri River oxbow. Suspended sediment and nutrient concentrations were elevated temporarily in the immediate vicinity of the dredge. Dredging did not impair concurrent recreational use of the lake.

Structures to improve aquatic habitat

50. Structural measures for restoration or enhancement of aquatic habitat in cutoff bends have also been proposed. Smith (1984), in a report on fish populations of Verdigris River cutoff bendways, recommends installation of brush fish attractors in the bendways to provide cover for fish. Miller, King, and Glover (1983) describe the design of a series of artificial riffles or gravel bars to be placed downstream of a minimum-flow structure in a Tombigbee River cutoff bendway. The artificial riffle habitat design requires that there be a significant change in head through the bendway to ensure continuous flow. This condition is provided at the site in question by directing flow into the bendway from an upstream impoundment through the minimum-flow structure.

Ground-water controls

51. Several Missouri River floodplain lakes in western Iowa have been studied by Iowa State workers (Huggins 1968; Wolff 1978; Johnson 1979; Lohnes, Bachmann, and Austin 1979) and the Omaha District (1979). These lakes have experienced reductions in depth and surface area. However, these reductions

have been caused primarily by a lack of ground and surface water supply. Sedimentation from local inflows and shoreline erosion has been only a secondary cause of lake decline, while flooding by the master stream (Missouri River) has been largely eliminated in the last few decades. Management techniques suggested and/or employed have included dredging, exclusion of local inflows during periods of high sediment load, aquatic plant control, shoreline protection, and utilization of ground water for supplemental water supply. These lakes tend to be perched above a water table that is falling due to Missouri River degradation. Lohnes, Bachmann, and Austin (1979) noted that wells for supplemental inflows must be located to avoid recycling lake water.

Conclusions from Literature Review

52. Relatively little information is available in the literature regarding cutoff bendways or oxbow lakes. After cutoff, bends are usually blocked off from the main channel by deposition of bars of bed material. Blocked bends are then gradually filled by deposition of fine sediments during floods.

53. Bendway blockage rates are influenced by local geometric and hydraulic variables. Reported times from cutoff to blockage are on the order of a few (i.e., 5 to 10) years. There appears to be only limited potential for significant reduction of blockage rates for cutoff bendways on streams carrying capacity loads of coarse bed material. Infilling of blocked bendways should be similar to infilling of any type of floodplain water body. Variables influencing the rate of infilling at a given site include the quantity and size of sediment supplied, valley slope, valley width, vegetation, and local topographic features that affect flow patterns.

54. A wide range of techniques has been proposed for control of cutoff bendway environmental characteristics. Presently there is no well-developed, rational approach for selection and implementation of a management technique for a given site or a given waterway project. However, the remainder of this report documents an effort to provide criteria for the selection of management approaches for given cutoff bendways.

PART III: RECOMMENDATIONS FOR MANAGEMENT OF CUTOFF BENDS ON THE TOMBIGBEE WATERWAY

55. This part is an application of the results of this study to the problem of managing the 30 cutoff bends located in the lower four navigation pools of the River Section of the TTW. The five cutoff bends located in the upstream navigation pool (Aberdeen) were not included in the analysis and are not considered here.

56. The management recommendations below are intended to supplement and update the management plan previously formulated and presented by the Mobile District (1984). An update of that plan is warranted because of the large body of data collected and analyzed subsequent to the Mobile District study. This management plan is based on the information in the Mobile District (1984) study, the analysis of hydrographic and hydrologic data (see Appendix A), and notes from field inspections of several of the bendways conducted in October 1984 and July 1985. The sections that follow summarize information from these sources. Results of an ongoing study of the fish populations of several of the bends being conducted for the Mobile District by the US Fish and Wildlife Service (FWS) were not available for inclusion in this study but should be incorporated in future studies.

Field Inspections

December 1983

57. Mobile District (1984) presents results of a 12 December 1983 inspection of 15 of the TTW bendways in the Aliceville and Columbus Pools by FWS personnel (Table 6, Appendix B, Mobile District 1984). Water surface elevations were near normal pool elevations at the time of inspection, and mean daily discharges ranged from 27,000 cfs at Columbus to 82,000 cfs at Gainesville. Four of the eight bendways located in the upper portion of Columbus Pool were completely blocked to flow (sites 430, 429, 427, and 425). One of the other four of this group of eight (site 424) was nearly blocked, with only 1 ft of water in the upstream entrance. The remaining seven bendways that were inspected were passing some flow, with velocities ranging from 3.0 ft/sec in the upper portion of Hairston Bend to 0.0 ft/sec in the lower portion of Big Creek Bend. However, five of these seven sites had water

depths of 5 ft or less in their upstream entrances (sites 422, 311, 208, 207, and 206). Bed material in the 15 inspected bends was classified as sand in the upstream portion of 10 of the bendways and as combinations of sand and silt elsewhere.

58. Special problems were detected at three of the bendways. Sewage inflow caused water quality degradation at site 430. Local sediment inflows caused extensive shoaling in the middle portions of site 427 (from bentonite mines) and site 428 (from a headcutting drainage ditch). The shoaling problem was extreme at site 427, with virtually all of the bendway channel below normal pool elevation filled.

October 1984

59. Aerial inspection of all of the bendways below Aberdeen Lock and Dam was conducted on 3 October 1984, and 25 of the 30 bendways were inspected by boat on 3-5 October 1984. Water surfaces were at normal pool elevations, and mean daily discharges at Columbus, Aliceville, and Gainesville ranged from 400 to 1,340 cfs. Six of the bendways were entirely blocked to flow at their upstream entrances (sites 430, 429, 428, 427, 425, and 208). Significant shoaling was noted in the upstream entrances of six additional bendways (sites 426, 424, 423, 421, 311, and 207). The special problems at sites 430, 428, and 427 were still very much in evidence. Dense stands of pioneer terrestrial vegetation were growing on sediment deposits at sites 430, 429, 428, 427, and 311, and some of the other sites as well.

July 1985

60. Fourteen of the bendways were inspected by boat on 23-24 July 1985. Water surface elevations were at normal pool elevation, and mean daily discharges at Columbus, Aliceville, and Gainesville ranged from 800 to 3,300 cfs. Blockage structures had just been completed at sites 430 and 429, and a blockage structure was under construction at site 208. At least 7 of the remaining 11 bends were either completely blocked (425, 427 and 428) or had upstream entrance thalweg depths of less than 5 ft (311, 420, 422, and 426). Once again, special problems at sites 430, 428, and 427 were evident. The blockage structure at site 430 was composed of two parallel embankments perpendicular to the bend channel near its midpoint. A diversion channel for the wastewater effluent was excavated between these two embankments to allow the wastewater to empty directly into the navigation cut.

Prognosis for Bendways

61. The current (November 1986) management plan calls for blockage of 15 of the 30 cutoff bends. When these bendways are blocked (as is planned for FY87), they will enter the infilling morphologic phase, and sediment deposition rates will be greatly reduced. The prognosis for the other 15 bends may be examined by first using the regression equations from Appendix A, Part II, to predict decay constants for each bend, and then using these constants to predict the bend volume remaining after a given interval of time.

Determination of decay constants

62. Regression equations for prediction of decay coefficients for the TTW bends as a function of geometric variables are developed in Appendix A, Part II. These decay constants can be used along with projected flow rates to predict the amount of deposition that will occur in a cutoff bend between cutoff completion and the time when the upstream entrance is blocked to top bank elevation. The equation for the volume of a cutoff bend below normal pool elevation at time t after cutoff is:

$$V_{b_{pl}}(t) = V_{b_{pl}}(0) \exp (K_{d_{pl}} t^*) \tag{1}$$

where

$$t^* = \int_0^t Q_w \, dt / V_b(0) \tag{2}$$

and

$V_{b_{pl}}(t)$ = volume of cutoff bend below normal pool elevation at time t after cutoff, cu ft

$V_{b_{pl}}(0)$ = volume of cutoff bend below normal pool elevation at time of cutoff

$K_{d_{pl}}$ = decay coefficient

Q_w = water discharge in main channel just upstream of cutoff, cfs

$V_b(0)$ = volume of cutoff below normal pool elevation at time of cutoff, cu ft

63. Observed and predicted values for the bend volume decay coefficient for TTW bends are shown in Table 5. The decay constants for bends located in Columbus Pool were predicted using Equation A34:

$$K_{d_{pl}} = -0.00001(3.41 - 6.86 \sin \psi_2) \qquad (3)$$

where $\sin \psi_2$ is as shown in Figure A1. Decay constants for bends located in Aliceville, Gainesville, and Demopolis Pools were calculated using Equation A33:

$$K_{d_{pl}} = -0.00001(3.55 - 7.31W_c/r_c - 4.67 \sin \psi_2) \qquad (4)$$

where W_c/r_c is the top-bank width of the cut channel just downstream of the upstream bend entrance divided by the radius of the cut channel.

64. The W_c values were not available for five of the seven Gainesville Pool bendways because survey ranges were not located in the cuts. Since the objective of using the regression equations for predicting $K_{d_{pl}}$ is to estimate approximate magnitudes of the decay coefficients rather than to generate precise values, use of an average W_c value for the unsurveyed locations was considered. However, the top-bank cut channel widths varied widely from site to site as shown in Table 6. Widths of the cut channel measured at normal pool elevation were much less variable. Therefore, a regression equation for $K_{d_{pl}}$ in terms of $\sin \psi_2$ and W_c(at normal pool)/r_c was developed:

$$K_{d_{pl}} = -0.00001(3.64 - 12.47W_{c_p}/r_c - 4.56 \sin \psi_2) \qquad (5)$$

where W_{c_p} is the width of the cut channel at normal pool elevation.

Table 5

Predicted and Observed Values of $K_{d_{pl}}$ for TTW Bendways

Site Number	Bendway	Predicted $K_{d_{pl}} \times 10^5$	Observed $-K_{d_{pl}} \times 10^5$
101	Rattlesnake	3.67	3.40
202	Warsaw	0.90	--
203	Cooks Bend	1.99	2.64
204	Windham Landing	0.95	--
205	Cochrane	2.23	--
206	Lubbub Creek	-0.56	--
207	Owl Creek	1.96	--
208	Big Creek	4.81	3.78
309	Pickensville	3.55	--
310	Coalfire	3.55	--
311	Hairston	3.47	2.78
312	Columbus	2.48	15.7
413	Waverly Ferry	3.41	--
414	Waverly	3.41	--
415	Waverly Mansion	2.46	--
416	Stinson Creek	3.41	2.82
417	Town Creek	1.63	1.04
418	Barton Ferry	2.10	--
419	Buttahatchee River	2.46	2.43
420	Vinton	3.41	3.24
421	Denmon Creek	3.41	2.64
422	Cane Creek	1.63	2.27
423	McKinley Creek	3.17	4.65
424	Richardson Lake	1.98	--
425	New Hamilton	3.41	--
426	Lockridge Creek	1.40	--
427	Hickelson Lake	0.73	26
428	Dead River	3.05	--
429	James Creek	3.05	2.83
430	Morgan Landing	1.87	--

Table 6

Cut Channel Widths at Top Bank and Normal Pool Elevations

Site Number	Bendway	Top Bank Width, ft	Normal Pool Width, ft
101	Rattlesnake	592	356
202	Warsaw		395
203	Cooks Bend	416	395
204	Windham Landing		395
205	Cochrane		395
206	Lubbub Creek		395
207	Owl Creek		395
208	Big Creek	960	440
309	Pickensville	470	
310	Coalfire	470	
311	Hairston	721	389
312	Columbus	451	383
413	Waverly Ferry	410	
414	Waverly		
415	Waverly Mansion	400	
416	Stinson Creek	838	578
417	Town Creek	529	359
418	Barton Ferry	432	
419	Buttahatchee River	410	358
420	Vinton	524	381
421	Denmon Creek	730	380
422	Cane Creek	390	373
423	McKinley Creek	682	401
424	Richardson Lake	475	
425	New Hamilton	500	
426	Lockridge Creek	583	
427	Hickelson Lake		
428	Dead River	525	345
429	James Creek	602	
430	Morgan Landing	588	
	Mean	470	309
	Std. Deviation	238	169

65. Values of $K_{d_{pl}}$, W_c/r_c, W_{c_p}/r_c, and $\sin \psi_2$ are presented in Table 7. Two of the predicted values of $K_{d_{pl}}$ are questionable. Sites 202 and 206 had values of $\sin \psi_2$ that fall outside the range of values used to produce Equations 4 and 5. Furthermore, W_{c_p}/r_c for site 206 is larger than any of the values used to produce Equations 4 and 5. The unusual values of $\sin \psi_2$ and W_{c_p}/r_c arise because these bendways are located on the outsides of relatively tight bends in the main channel. These out-of-range values for the independent variables resulted in predicted values of $-K_{d_{pl}}$ for sites 202 and 206 that are probably too low. The negative value of $-K_{d_{pl}}$ for site 206 is unreasonable, because it indicates that the bendway would scour instead of fill. The 1983 field inspection revealed that site 206 was "approximately 50 percent filled at the bendway entrance." However, the sediments deposited in this bendway may be from a local tributary, Lubbub Creek, rather than the main channel. Mobile District (1976) estimated that the 339-square-mile drainage area of Lubbub Creek contributes an average of 76,600 tons of suspended sediment to Gainesville Pool annually. The value of $K_{d_{pl}}$ reflects the propensity of a bend to divert bed-material from the main channel and ignores tributary inflows.

Bend volumes in 1990

66. The $K_{d_{pl}}$ values for each of the 15 "no-action" bendways were used to estimate bend volume below normal pool elevation remaining in 1990. The 1990 volumes were also estimated for sites 311 and 419, although current plans call for them to be blocked. The year 1990 was chosen as a date for projection of bendway volumes because it is 6 years after the first bendway management study and thus is the date for the second 3-year reevaluation. Observed $K_{d_{pl}}$ values were used for the bendways where survey data were available (sites 101, 203, 311, 312, 416, 417, and 419), while $K_{d_{pl}}$ values calculated using Equation 3, 4, or 5 were used for the unsurveyed bendways (sites 202, 204, 205, 206, 309, 310, 413, 414, and 415).

67. To calculate bendway volume remaining in 1990, t^* values were also required. The surrogate time, t^*, is equal to the total volume of water discharged through the reach containing the cutoff bend during the period of

Table 7

Predicted Values of $K_{d_{pl}}$

Site Number	Bendway	W_c/r_c	W_{c_p}/r_c	$\sin \Psi_2$	Predicted $-K_{d_{pl}} \times 10^5$
101	Rattlesnake	-0.275		0.017	3.67
202	Warsaw		0.2150	0.500	0.90
203	Cooks Bend	0.0170		0.309	1.99
204	Windham Landing		0.1448	0.375	0.95
205	Cochrane		0.4306	0.122	2.23
206	Lubbub Creek		2.3289	0.588	-0.56
207	Owl Creek		0.1786	0.292	1.96
208	Big Creek			0.052	4.81
309	Pickensville	0.0000		0.000	3.55
310	Coalfire	0.0000		0.000	3.55
311	Hairston	0.0000		0.017	3.47
312	Columbus	0.0027		0.225	2.48
413	Waverly Ferry			0.000	3.41
414	Waverly			0.000	3.41
415	Waverly Mansion			0.139	2.46
416	Stinson Creek			0.000	3.41
417	Town Creek			0.259	1.63
418	Barton Ferry			0.191	2.10
419	Buttahatchee River			0.139	2.46
420	Vinton			0.000	3.41
421	Denmon Creek			0.000	3.41
422	Cane Creek			0.239	1.63
423	McKinley Creek			0.035	3.17
424	Richardson Lake			0.208	1.98
425	New Hamilton			0.000	3.41
426	Lockridge Creek			0.292	1.40
427	Hickelson Lake			0.391	0.73
428	Dead River			0.052	3.05
429	James Creek			0.052	3.05
430	Morgan Landing			0.225	1.87

interest divided by the bendway volume at the time of cutoff. Initial bend volumes for unsurveyed bendways were estimated using a nonlinear regression function for bendway volume as a function of bend length. This regression function is presented in Figure 3. Cumulative streamflow volumes for the period between cut completion and 1990 were calculated by adding the streamflow volume between cut completion and the 1985 survey date to five times the mean annual discharge volume. The surrogate time, t^* , for each bend was thus computed as follows:

$$t^* = \int_0^{1985} Q\, dt + (5 \text{ yr} \times 31{,}557{,}600 \text{ sec/yr} \times Q_m)/V_{b_{pl}}(0) \qquad (6)$$

where $V_{b_{pl}}(0)$ is the bendway volume below normal pool elevation at the time of cutoff in cubic feet and Q_m is the average flow in cubic feet per second for the river just upstream of the bendway in question. The fraction of initial bend volume remaining in 1990, $V_{b_{pl}}/V_{b_{pl}}(0)$, was calculated for each of the 15 no-action bendways as follows:

$$V_{b_{pl}}/V_{b_{pl}}(0) = \exp\,(K_{d_{pl}}\, t^*) \qquad (7)$$

where t^* is as determined from Equation 6. The results of these calculations, presented in Table 8, indicate that if the 15 bendways are left open until 1990, they will undergo enough natural deposition to be filled 15 to 96 percent. If flows between 1985 and 1990 exceed the average levels, Q_m , used in Equation 6, the 1990 values of $V_{b_{pl}}/V_{b_{pl}}(0)$ will be smaller.

Management Recommendations

Comments on original plan

68. The original management plan (Mobile District) was formulated with two conflicting goals in mind. The first goal was to minimize the loss of bendway aquatic habitat due to sediment deposition. The second goal was to maintain flow through the bendways in order to preserve lotic rather than

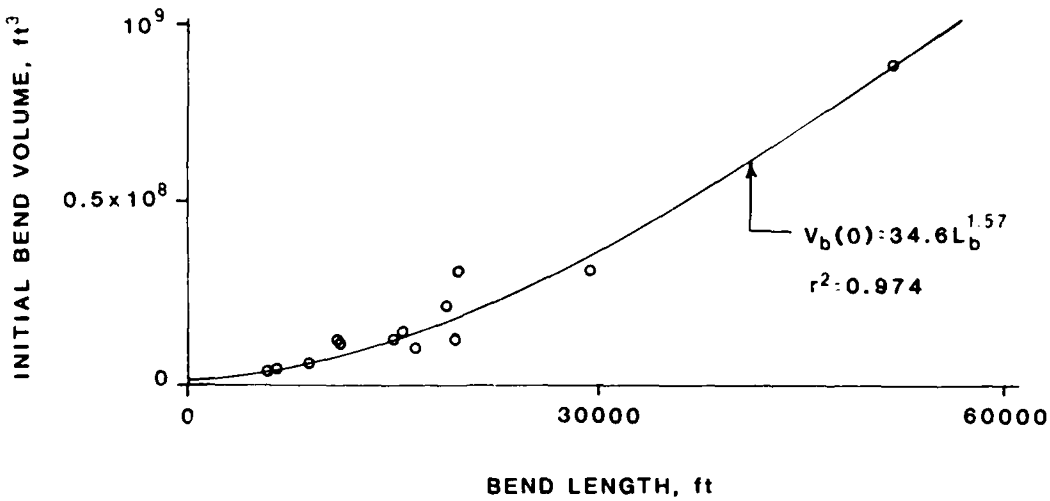


Figure 3. Initial volume of TTW bendways as a function of bend length

lentic habitat and thereby maintain the cutoff reaches in as near their pre-project condition as possible. This dual emphasis resulted from statements in the EIS (Mobile District 1971) and in the decision of the US Fifth Circuit Court of Appeals which referred to measures to avoid siltation in the bendways and the undesirability of stagnant, eutrophic conditions. In addition, recommendations by the FWS regarding design of the River Section basically emphasized maintaining the bendways in a manner that would keep them opened to flow (FWS 1981, in Mobile District 1983). The FWS (1981) also suggested the Corps "take appropriate steps to protect gravel bar substrates to protect the associated fauna." The Coordination Act report for the bendway management study (FWS 1984, in Mobile District 1984) recommended "maintaining maximum flow throughout the longer bendways" to prevent water quality degradation and aquatic resource deterioration.

69. The results of this study clearly show that the goal of maintaining sufficient flow through the bendways to maintain gravel bars and other coarse substrate is not economically or technically feasible. Diversion of sufficient flow through the bendways to prevent sediment deposition in them would result in sediment deposition in the navigation channel. Furthermore, diversion of significant flows into the bendways would necessitate building structures at the bendway entrances to divert flow from the main channel.

Table 8

Projected Status of No-Action Bendways in 1990

Site Number	Bendway	Initial Volume, 10^7 ft^3	$V_b/V_{b_{pl}}(0)$ in 1985	Mean Flow, cfs	t* in 1985	t* in 1990	$-K_{d_{pl}} \times 10^5$	$V_b/V_{b_{pl}}(0)$ in 1990
101	Rattlesnake	89.390	0.863	18,132	5,387	8,588	3.40	0.747
202	Warsaw	2.071		10,383	113,578	192,686	0.90	0.177
203	Cooks Bend	30.410	0.830	10,383	7,735	13,122	2.64	0.707
204	Windham Landing	1.395		10,383	168,617	286,059	0.95	0.065
205	Cochrane	4.147		10,383	56,721	96,227	2.23	0.117
206	Lubbub Creek	22.430		10,383	10,487	17,791	-0.56	1.104
309	Pickensville	14.460		8,715	9,383	18,893	3.55	0.511
310	Coalfire	4.622		8,715	29,355	59,107	3.55	0.123
311	Hairston	30.340	0.896	8,715	4,472	9,004	2.78	0.779
312	Columbus	20.900	0.869	8,715	528	7,108	15.65	0.329
413	Waverly Ferry	1.721		5,243	36,377	84,446	3.41	0.056
414	Waverly	4.147		5,243	15,096	35,045	3.41	0.303
415	Waverly Mansion	1.095		5,243	57,173	132,724	2.46	0.038
416	Stinson Creek	11.280	0.884	4,964	5,550	12,494	2.82	0.703
417	Town Creek	10.148	0.944	4,964	6,188	13,906	1.04	0.865
418	Barton Ferry	2.444		4,964	25,615	57,664	2.10	0.298
419	Buttahatchee River	11.390	0.884	3,425	3,795	8,540	2.43	0.813

Tremendous volumes of sediment (Table 8) would have to be dredged from the cut channels or the bendways to maintain immediate postconstruction dimensions.

70. Attempts to maintain flow through the bendways by leaving them open to the main channel have not resulted in sufficient velocities in the bends to provide lotic habitat. Instead, leaving the bends open has allowed considerable amounts of lentic aquatic habitat to be transformed into terrestrial habitat due to sediment deposition.

General recommendations

71. Results of this study indicate that more of the TTW bendways should be blocked to top of bank at their upstream entrances rather than left open. Construction of blockage embankments will end the blockage phase with a minimum of bend volume lost. If blocks are allowed to form naturally rather than constructed, more bendway volume will be lost during the blockage phase (see Table A32). Sediment deposition will continue during the infilling phase, but at a slower rate.

72. A major objection to construction of blocks in bendway entrances has to do with the effect of such blockage on water quality. It is true that eutrophic conditions are likely to result. However, eutrophic oxbow lakes on the floodplains of the Mississippi and other major rivers have been found to be major ecologic and recreational resources to the river systems, particularly if some type of channel remains to provide access for aquatic organisms and recreational vessels from the main channel to the lake. Water quality in blocked bends should be safeguarded by eliminating point sources of pollution such as wastewater inflows (sites 312 and 423) and discharges from dredged material disposal areas (sites 427 and 429). Water quality conditions should be periodically monitored in selected bendways, and if oxygen depletion occurs in the top 3 to 4 ft, consideration should be given to supplemental supply of sediment-free water.

Specific recommendations

73. Table 9 presents the specific management recommendations developed in this study for each bend. All of the bends, with the possible exception of site 417, should be blocked to top bank at their upstream entrances. The TTW hydrographic survey data analyzed for this study indicate that the quantity of sediment deposited in the bendways and the rapidity of deposition make other management approaches, such as maintenance dredging, economically infeasible.

Table 9

Recommendations for Management of TTW Cutoff Bendways

Site Number	Pool	Bendway	Bendway Length, ft	Recommended Management Actions
101	Demopolis	Rattlesnake	51,744	Block with connecting channel
202	Gainesville	Warsaw	4,752	Dredged material dam
203	Gainesville	Cooks Bend	19,536	Block with connecting channel
204	Gainesville	Windham Landing	3,696	Dredged material dam
205	Gainesville	Cochrane	7,392	Block with connecting channel
206	Gainesville	Lubbub Creek	21,648	Block with connecting channel
207	Gainesville	Owl Creek	4,224	Dredged material dam
208	Gainesville	Big Creek	15,312	Block constructed in 1985
309	Aliceville	Pickensville	16,368	Block with connecting channel
310	Aliceville	Coalfire	7,920	Block with connecting channel
311	Aliceville	Hairston	29,356	Block with connecting channel
312	Aliceville	Columbus	18,480	Block with connecting channel
413	Columbus	Waverly Ferry	4,224	Dredged material dam
414	Columbus	Waverly	7,392	Block with connecting channel
415	Columbus	Waverly Mansion	3,168	Dredged material dam
416	Columbus	Stinson Creek	10,349	Block with connecting channel
417	Columbus	Town Creek	10,560	Block with connecting channel
418	Columbus	Barton Ferry	5,280	Block with connecting channel
419	Columbus	Buttahatchee River	14,573	Block with connecting channel

(Continued)

Table 9 (Concluded)

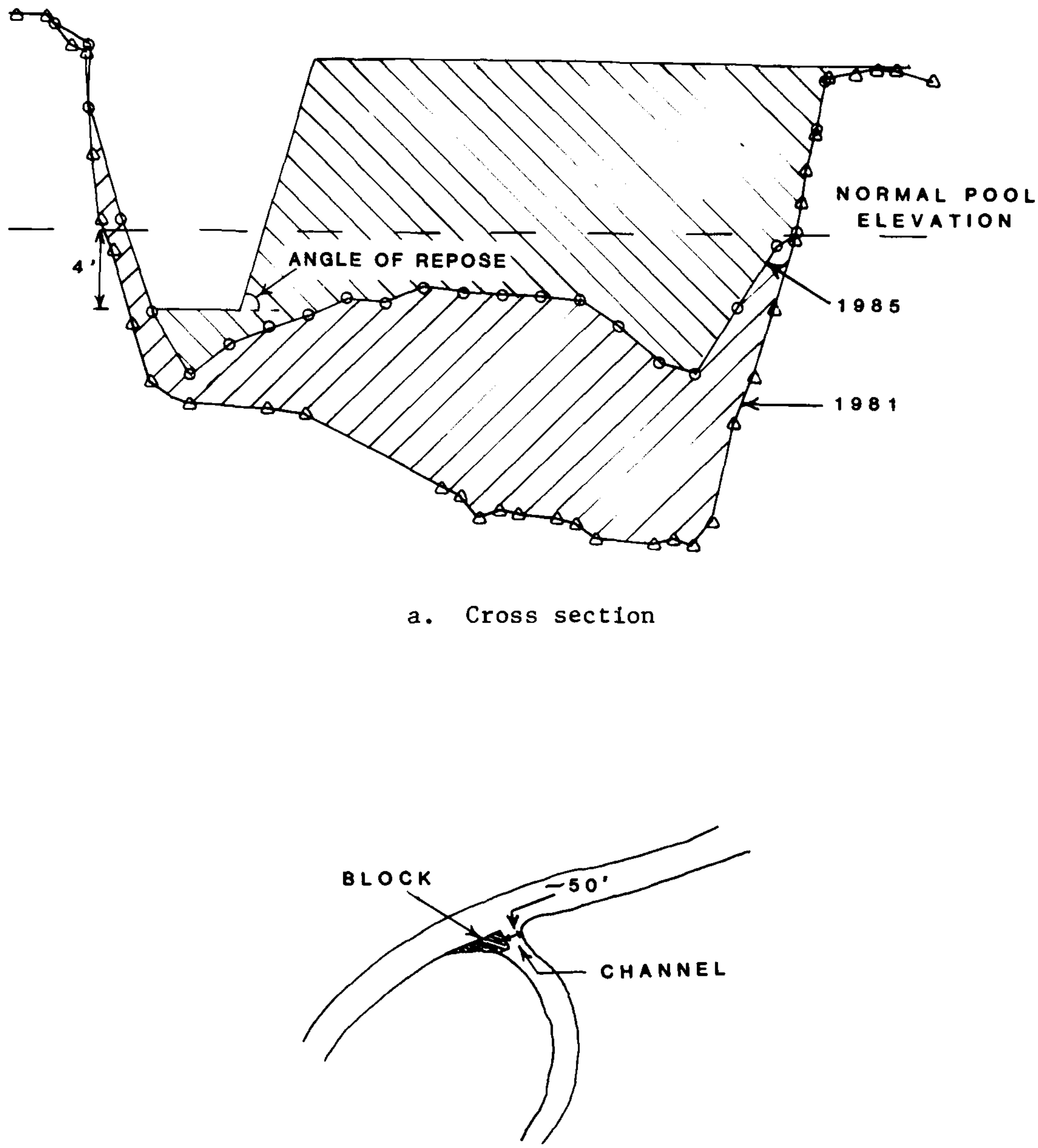
Site Number	Pool	Bendway	Bendway Length, ft	Recommended Management Actions
420	Columbus	Vinton	8,184	Block with connecting channel
421	Columbus	Denmon Creek	5,068	Dredged material dam
422	Columbus	Cane Creek	5,808	Block with connecting channel
423	Columbus	McKinley Creek	16,157	Block with connecting channel
424	Columbus	Richardson Lake	3,168	Dredged material dam
425	Columbus	New Hamilton	4,224	Dredged material dam
426	Columbus	Lockridge Creek	4,752	Dredged material dam
427	Columbus	Hickelson Lake	9,715	No action until sediment is removed
428	Columbus	Dead River	5,280	No action until grade control is established on ditch
429	Columbus	James Creek	19,325	Block constructed in 1985
430	Columbus	Morgan Landing	4,224	Block and diversion constructed in 1985

74. Blockage structures for bends longer than 1 mile should have channels connecting the bendway and the main channel to provide access for recreational vessels and aquatic organisms. A schematic of a typical channel is shown in Figure 4. The connecting channel should be no wider or deeper than necessary to provide access when water surface elevations are at normal pool elevation. Dimensions of 4 ft deep by 50 ft wide are suggested. Narrower widths (30 to 40 ft) may be used if they are constructible with ordinary equipment. A key requirement for the access channels is that the angle of incidence with the main channel be 90 deg or slightly greater. These design criteria are intended to minimize the passage of sediment through the access channel into the bendway.

75. The study of seven oxbow lakes, described in Appendix A, indicated that bendways in the infilling phase tend to lose surface area more by narrowing than shortening. This tendency indicates that, in the absence of major local inputs of sediment, deposition of sediments is fairly uniform throughout the length of the bendway. Accordingly, it appears little would be gained by dredging a sump to trap sediments at the upstream entrance of a blocked bendway. Such a sump would trap sediments that move into the bendway through the small access channel, but the volume of these should be quite small. If sumps are constructed, they should be as long as feasible, and they should generally follow the center line of the bendway.

76. Maintenance dredging to maintain bendway dimensions is not recommended. However, after the downstream ends of bendways are blocked by natural deposition, annual or biannual dredging to maintain access channels of the size discussed above is recommended. Furthermore, access channels through upstream entrance blockage embankments should also be maintained annually or biannually. Dredging of site 427 is also recommended if the party legally responsible for the deposition of sediments from the bentonite mining operation can be forced to pay for it, or if other types of non-Federal funding become available.

77. Point sources of pollution and suspended sediment should be diverted from all of the bends. In particular, every effort should be made to eliminate wastewater inputs to sites 423 and 312. Actions should be taken, in cooperation with other agencies if necessary, to prevent future point sources from discharging into the bendways and to minimize nonpoint source pollution



a. Cross section

b. Plan

Figure 4. Schematic of blockage embankment for upstream entrance of site 311 modified to retain a small connecting channel. Connecting channels should be at right angles with navigation cut

loads entering the bendways. Dredged material containment area weirs discharging into sites 427 and 429 should be relocated or not used.

78. No action should be taken to manage sites 427 or 428 until steps are taken to reduce the magnitude of the local inputs of sediment. This includes relocation of the dredged material containment area discharge at site 427. Furthermore, site 427 should be at least partially restored by excavating or dredging before any new effort is expended there. Further study of site 428 should occur before corrective action is taken. Installation of a grade control structure to stabilize the ditch that is contributing so much sediment to the bend will likely prove to be the most cost-efficient corrective action.

79. Construction of artificial gravel bars in the bendways immediately below Aberdeen and Aliceville similar to those placed in the bendway below Columbus Pool is strongly recommended. Only by this sort of action, and by careful planning of future water resources projects in the Tombigbee River basin, can even a fragment of lotic habitat for certain species of mussels and darters be preserved.

PART IV: SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH

Summary

80. Man-made cutoff meander bends undergo a morphologic sequence similar to natural neck cutoffs. This sequence consists of an active meander bend phase, a blockage phase, an infilling phase, and a terrestrial phase. Cutoff bends in either the blockage phase or the infilling phase located along channelized or stabilized streams are extremely valuable ecological and recreational resources. Their value is increased for streams that have been so stabilized into fixed alignments that new cutoff bends and other types of abandoned channels cannot be formed to replace those gradually lost due to sedimentation.

81. Sediment deposition in cutoff bends occurs in two stages or phases. The blockage phase lasts from the time the bend is cut off until the upstream entrance is blocked to top-bank elevation. Deposition during the blockage phase is primarily deposition of bed material in the upper limb of the old bend. The bar that forms in the mouth of the old bend has morphology similar to a point bar growing from the upstream side of the bend entrance toward the downstream side. A smaller amount of deposition also occurs in the lower bend entrance, probably due to secondary current patterns in the new main channel. When the bar of bed material in the upper limb of the old bend is high enough to force flood flows overbank, bend deposition enters the infilling phase. Deposition during the infilling phase is primarily deposition of fine-grained material (wash load), ultimately resulting in formation of a clay plug. The clay plug will underlie a low, swampy swale or meander scar on the floodplain.

82. During the blockage phase, the volume of the cutoff bend will decrease as a log-decay function of cumulative water discharge in the main channel just upstream of the cutoff:

$$V_b(t) = V_b(0) \exp (K_d t^*) \tag{8}$$

where

V_b = the volume of the bend

K_d = a constant for each bend

$t^* = [1/V_b(0)] \int_0^t Q_w \, dt$

83. This log-decay relationship results from the negative feedback produced by the formation of a bar in the bend entrance. The bend volume decay constant, K_d, tends to fall within a rather narrow range for a given river reach. Observed K_d values for cutoff bends on the Mississippi, Arkansas, Red, and Tombigbee Rivers ranged from about -10^{-6} to -10^{-4}. The value of K_d was found to be functionally related to C_s, the average concentration of bed material in the master stream during the period of interest (0 to t), and to the geometry of the upstream junction of the bend and cut channels.

84. Since the geometry of a cutoff bend can be quite complex, at least 12 dimensionless variables are required for an adequate description. Dimensional analysis for the decay constant, K_d, indicates that K_d is a function of these geometric variables and two others: C_s and K_g, a cut channel growth coefficient defined similarly to K_d. Examination of the data reveals that sediment deposition during the blockage phase is directly related to C_s and inversely related to the sine of the angle between the cut and bend channel entrances and to the vertical distance between the average bed elevations of the bend and cut entrances. In addition, the rate of deposition is reduced if the new main channel is laid out so that the upstream entrance of the old bend is on the outside of a bend. Stepwise multiple regression analysis using data from 19 cutoff bends produced a prediction equation for K_d with only C_s and one of the geometric variables as independent variables:

$$10^5 K_d = \frac{-0.681 \, C_s^{0.9291}}{(Z/\bar{y}_c + 2)^{1.8627}} \qquad (9)$$

$$r^2 = 0.6963$$

85. The blockage phase can be quite brief (1 to 2 years) if a cutoff bend is located on a stream with high C_s and if a period of high flow follows cut

completion. Conversely, the blockage phase for Rattlesnake Bend on the Tombigbee River (site 101) has lasted 10 years and will probably last many decades more in the absence of human intervention (see Table A32). If entrance geometry is favorable for diversion of sediment into the old bend, as much as 100 percent of the bend volume can be lost during the blockage phase. The infilling phase is typically two to three orders of magnitude longer than the blockage phase.

86. Patterns of deposition in cutoff bends during the blockage phase vary widely from site to site. In this study, the longitudinal location of most rapid deposition was at or near the extreme upstream end for several bends but was almost at the midpoint of one site.

87. Study of sequential aerial photographs of seven man-made cutoff bends on the Arkansas and Mississippi Rivers showed that permanent changes in lake surface area and perimeter occur slowly during the infilling phase. Surface areas exhibited rapid decline at the end of the blockage phase, but then leveled off and fluctuated slightly about average values that were 10 to 60 percent of the area observed at the end of the blockage phase. Lake shoreline lengths showed little change during the period of observation, indicating that the lakes tended to reduce their areas more by narrowing than by shortening. The persistence of shoreline length is a positive factor in regard to the habitat value of the old bends.

Conclusions

88. The following conclusions can be drawn from this study:

a. Deposition of sediments in cutoff bends can be described by a log-decay function of cumulative water discharge in the master stream during the period between cut completion and blockage of the upstream bend entrance to approximately top-bank elevation.

b. The rate of sediment deposition during the period before blockage varies from site to site and is related to the average concentration of bed material in the master stream, the erosivity of the cut, and the site geometry. The rate of deposition can be reduced by modifying bend and cut entrance geometry.

c. Several techniques for conserving the resources associated with cutoff bends have been incorporated into various stream modification projects. These techniques include training structures to modify bend entrance conditions, embankments to completely block bend entrances, dredging to remove sediments, and various types of habitat enhancement and water control structures. Results of this study may be used to evaluate the range of potential techniques and to select and design the most appropriate management strategy for a given cutoff bend. In particular, the regression equations for the bend volume decay constant, K_d, can be used to gage the effects of using training structures or partial blocks to modify the plan and vertical geometry of the upstream bend entrance.

d. The pattern of sediment deposition during the blockage phase tends to be bimodal. The primary location of deposition is in the upper limb of the bendway, usually in the first 25 percent of bend length. A secondary locus for deposition often occurs just upstream of the downstream bend entrance.

e. The rate of blockage phase sediment deposition in cutoff bends along streams carrying average concentrations of bed material greater than about 50 ppm is sufficiently great that in many cases complete blockage of the upstream bend entrance is the most prudent strategy. In some cases only partial blockage of the upstream entrance may be desirable to preserve access for recreational vessels. In such cases, the access channel should be at a right angle to the main channel and should be no deeper or wider than necessary. A small access channel will have to be maintained by dredging but will limit the inflow of sediment to the cutoff bend.

f. After the upstream entrance is blocked to top-bank elevation, deposition occurs more uniformly along the length of the bend. Deltas may form at points of local inflow to the bend during both the blockage and infilling phases.

g. The great volume of sediment naturally deposited in cutoff bends adjacent to alluvial streams makes maintenance of original bend channel dimensions by dredging economically impractical in all but the most unusual cases.

h. Cutoff bends along modified, stabilized streams often constitute a valuable ecological, recreational, and aesthetic resource.

i. The resource value of bendways usually declines after cutoff due to a variety of factors. Sediment deposition in the bend by the master stream is most frequently the dominant cause of decline.

j. A number of techniques have been employed to manage cutoff bends, but selection and design of these measures have largely been based on intuition and qualitative observation.

k. Management strategy for all bends in a river reach should be formulated simultaneously to facilitate trade-offs.

l. Long-term benefits resulting from management of cutoff bends along the Tennessee-Tombigbee Waterway will be increased if the bends are promptly blocked to top-bank elevation at their upstream entrances. A small channel for passage of aquatic organisms and recreational boats should be maintained at the upstream entrance of bends longer than a mile. Bendway management should include a program of biological and water quality monitoring.

Future Research

89. Future research in this area should deal with verification of the regression equations derived in Appendix A for the rates and patterns of deposition in cutoff bends. Additional data for the infilling phase should be collected, and factors controlling the shape and longevity of oxbow lakes should be more clearly identified. Results of studies of the morphologic response of bends to cutoff should be compared with studies of biological response of the same or highly similar bends. Finally, the long-term prognosis for backwater areas on specific major river systems should be elucidated, and techniques for managing the backwater resource that may be incorporated into existing project management procedures should be developed.

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APPENDIX A: DEVELOPMENT OF PREDICTIVE RELATIONSHIPS

PART I: METHODS AND MATERIALS

Introduction and Overview

1\. Meander bends pass through several morphologic stages or phases: active bend, blockage phase, infilling phase, and, finally, terrestrial phase. The primary objective of the analysis below is to ascertain the factors that control the rate of deposition in cutoff bends during the blockage phase to allow resource managers to make rational decisions regarding management strategies. The study has three main components: (a) determination of a functional relationship for estimating the rate of sediment deposition in a cutoff bend during the blockage phase, (b) characterization of the patterns of deposition in a cutoff bend during the blockage phase, and (c) determination of a range of values for the rate of change of infilling-phase cutoff bend surface area.

2\. The approach taken for the first two study components is to use dimensional analysis to form dimensionless groups of variables involved and then to study the functional relationships among these groups using field data. The field data consist of repetitive hydrographic surveys of 21 cutoff bends along four rivers, associated streamflow records, and suspended bed material records. Time and money constraints limited the data set to 21 sites. The approach for the third component is more qualitative. Surface areas and perimeters of selected oxbow lakes are plotted against time.

3\. The first study component deals with the rates of volumetric change of cutoff bends during the blockage phase. The data show that cutoff bend volume is a log-decay function of the cumulative volumetric water discharge through the reach containing the cutoff bend:

$$V_b(t)/V_b(0) = \exp\ (k_d t') \tag{A1}$$

where

$V_b(t)$ = bend volume at time t after cutoff

$V_b(0)$ = bend volume at time of cutoff

k_d = decay constant for a given bend

and

$$t' = \int_0^t Q \, dt \tag{A2}$$

where Q is the water discharge just upstream of the cutoff. The first component of the study is therefore concerned with prediction of k_d as a function of site conditions.

4. Since the pattern of sediment deposition along a cutoff bend is nonuniform, the second component of the study involves characterizing the pattern of deposition along a given bend by generating regression functions for bend cross-sectional area in terms of the surrogate time variable (cumulative discharge) and the longitudinal distance along the bend. Results of the first two study components allow estimation of the rate and pattern of sediment deposition in cutoff bends during the blockage phase. These results may be used for design of cutoff bends or for formulation of a management strategy for cutoff bends, chutes, and secondary channels along waterway projects already constructed.

5. The third element of the study addresses morphologic changes of bends in the infilling phase. Data are presented showing changes in the surface areas and perimeters of seven oxbow lakes over several decades. Lake surface area and perimeter are measured from repetitive aerial photographs. Definite linkage between the rate of surface area reduction and hydrologic inputs is not possible using the approach employed for the infilling phase because many of the simplifying assumptions are no longer valid. However, the resultant information about the longevity of oxbow lakes is useful in estimating the long-term effects of waterway construction and other types of channel modification on floodplain backwater habitats. These estimates can be used in formulation of long-term resource management plans and associated economic analyses.

Dimensional Analysis

Assumptions

6. In order to simplify the analysis, the following assumptions are made regarding cutoff bends in the blockage phase.

a. Reduction of bend volume through time is due to deposition of bed material. As previously noted, work by Fisk (1944, 1947,

1951) and Gagliano and Howard (1984) shows that deposition in cutoff bends during the blockage phase is dominated by deposition of bed material. Field inspection of several cutoff bends along the Tombigbee River and data from four of these bends reported by Pennington et al. (1981) have also shown that sediments deposited in these bends tend to be primarily fine sand until the upstream end of the bend is blocked to top bank.

b. Velocities in the old bends are sufficiently low that all of the bed material transported into the upstream entrance of the bend is deposited in the bend.

c. The volume of sediments transported into and deposited in the bend from local drainage and small tributaries is negligible relative to the contribution from the master stream.

d. Consolidation of deposited sediments is negligible since bed material in the streams of interest is primarily sand and gravel. The reduction in bend volume is therefore directly proportional to the weight or volume of bed material transported into the bend.

Volume-decay function

7. Curran (1932) noted that the rate of bed material movement into the mouth of a diversion progressively decreases as the bar in the inlet builds. This decrease is attributed to two factors: (a) the mean shear stress is reduced as the depth is reduced, and (b) the upstream face of the bar slopes upward, decreasing bed-load movement over the bar. Therefore, the volume of a cutoff bend in the blockage phase is given by Equation A1. Dimensions for k_d are L^{-3} and L^3 for t'. The surrogate time t' may be nondimensionalized by dividing by the initial bendway volume $V_b(0)$:

$$t* = t'/V_b(0) \tag{A3}$$

The log-decay constant, K_d, may also be nondimensionalized using $V_b(0)$:

$$K_d = k_d V_b(0) \tag{A4}$$

Therefore

$$V_b(t) = V_b(0) \exp (K_d t*) \tag{A5}$$

Identification of variables

8. Given the stated assumptions, the log-decay constant, K_d, will be a function of the initial geometry of the cutoff, the average bed material concentration in the master stream above the cutoff reach between time 0 and t, and the rate of enlargement of the cut channel. Figure A1 is a schematic depicting a typical cutoff bend. Based on the findings of the literature review and consideration of the physical situation, a description of the initial geometry should include:

$V_b(0)$	initial bendway volume below top-bank elevation, L^3
L_b	bendway length, L^1
$A_b(0)$	initial cross-sectional area of bendway mouth below top-bank elevation, L^2
$\bar{y}_b(0)$	initial mean depth of bendway mouth below top bank elevation, L^1
S_b	bendway water surface slope, L^0
$V_c(0)$	initial cut volume below top-bank elevation, L^3
L_c	cut length, L^1
$A_c(0)$	initial cross-sectional area of cut just below bendway mouth, L^2
S_c	cut water surface slope, L^0
$\bar{y}_c(0)$	initial mean depth of cut below top-bank elevation, L^1
r_c	radius of cut, L^1
ψ_1	angle between approach channel and bendway, L^0

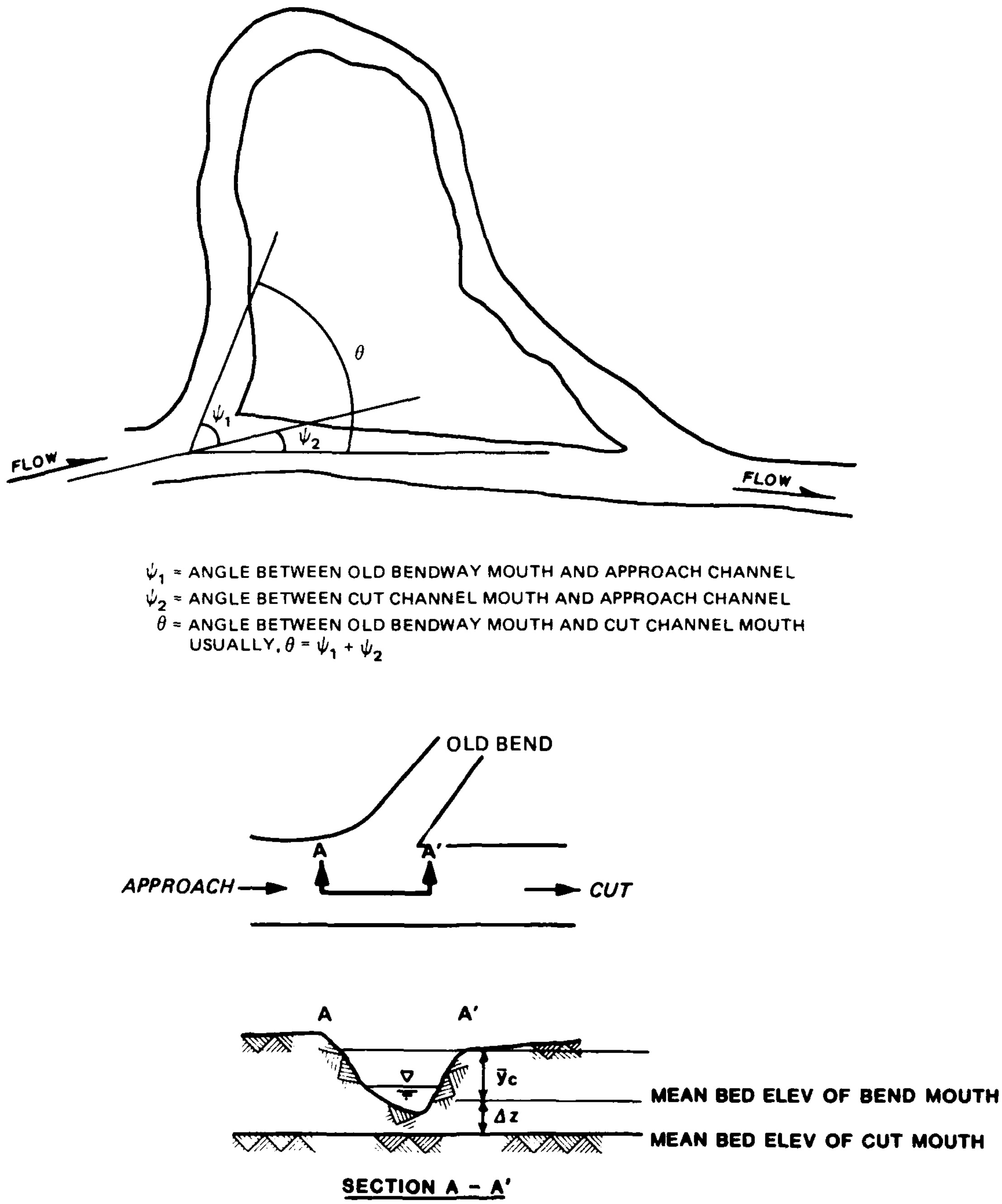


Figure A1. Definition of geometric variables for cutoff bend entrance

ψ_2 angle between approach channel and the cut, L^0

ΔZ initial difference between the mean bed elevation of the mouth of the bend and the mean bed elevation of the mouth of the cut, L^1

9. The water and sediment inputs to the system may be described by t^* and C_s, where C_s is the average concentration of bed material in the master stream above the reach containing the cutoff during the time period 0 to t in units of weight per weight. Variable C_s is defined as:

$$C_s = \frac{\int_0^t Q_s \, dt}{\gamma_w \int_0^t Q \, dt} \tag{A6}$$

where γ_w is the specific weight of water and Q_s has dimensions of weight per unit time. The rate of enlargement of the cut channel may be characterized by the dimensionless exponent K_g, where

$$V_c(0)/V_c(t) = \exp\,(K_g t^*) \tag{A7}$$

Variable K_g is dimensionless because t^* is dimensionless. Therefore,

$$K_d = f[V_b(0),\ L_b,\ A_b(0),\ \bar{y}_b(0),\ S_b,\ V_c(0),\ L_c,\ A_c(0),\ S_c,\ \bar{y}_c(0),\ r_c,\ \psi_1,\ \psi_2,\ \Delta Z,\ C_s,\ K_g] \tag{A8}$$

Elimination of excess variables

10. Since the bend and cut have the same endpoints, $S_b L_b = S_c L_c$. Thus, S_b may be dropped from the analysis since it is not independent. Similarly, if the cut channel section is fairly uniform, $A_c(0)$ may be omitted:

$$A_c(0) = V_c(0)/L_c \tag{A9}$$

Channel widths are not included in Equation A9 since area and mean depth are included, and area divided by mean depth equals width. With these deletions,

$$K_d = f[V_b(0),\ L_b,\ A_b(0),\ \bar{y}_b(0),\ V_c(0),\ L_c,\ S_c,$$
$$\bar{y}_c(0),\ r_c,\ \psi_1,\ \psi_2,\ \Delta Z,\ C_s,\ K_g] \qquad \text{(A10)}$$

11. Equation A10 indicates that K_d is a function of at least 14 variables in only one dimension, length. If angles are treated as dimensionless length ratios, then 5 of the 14 variables are dimensionless (S_c, ψ_1, ψ_2, C_s, K_g). The number of independent variables may be reduced to 13 by selecting $V_b(0)$ as the repeating variable and dividing each of the other 9 dimensional variables in Equation A10 by the appropriate power of $V_b(0)$ to produce a dimensionless quantity. More meaningful dimensionless groups may be obtained by dividing and/or multiplying some of the terms by one another:

$$K_d = f[\ L_r,\ A_r,\ \bar{y}_r,\ V_r,\ L_c/r_c,\ S_c,\ \sin\theta,\ \sin\psi_2,$$
$$Z/\bar{y}_c,\ C_s,\ K_g,\ \bar{y}_b/L_b,\ W_c/r_c] \qquad \text{(A11)}$$

where the subscript r denotes the ratio of bendway to cut dimension, and Z is equivalent to the quantity heretofore referred to as ΔZ.

Study Approach

12. A large number of variables is required to describe the complex geometry of a cutoff bendway reach in general terms. Most authorities indicate that regression analyses require a total number of observations at least as great as four or five times the number of variables (Herzberg 1969). Ideally, each of the variables should be normally distributed with respect to each of the other variables (bivariate normal distributions). Furthermore, determination of a single value of K_d requires several repetitive hydrographic surveys of a cutoff bend, preferably separated in time by several months or years, and each such hydrographic survey consists of hundreds or even thousands of discrete topographic measurements. Exact definition of the function of Equation A11 was therefore beyond the scope of this study.

13. The approach taken in this study was to build a data base that describes 21 cutoff bends from four rivers. The data base was then input to stepwise multiple regression. Stepwise multiple regression provided equations for K_d as a function of only the independent variables that, when combined, were the most important determinants of K_d for this data base.

Site Selection

Description of river reaches studied

14. Reaches of four large rivers in the southeastern United States were used as data sources. All four streams have beds of sand and gravel and mature drainage basins. The reaches studied were typical of large alluvial rivers usually developed by channel stabilization and/or canalization. Thus, the data collected are representative of the most important class of cutoff bends, if not all cutoff bends.

15. Table A1 shows the major physical descriptors of the studied reaches. Only the Tombigbee River was simultaneously affected by dam construction and cutoffs during the period of record, although dams have been constructed on the Arkansas and Red Rivers subsequent to the periods of data acquisition. Additional details regarding each of the study reaches follow.

Mississippi River

16. The portion of the Mississippi River considered in this study is the reach between Memphis, Tenn., and Natchez, Miss., shown in Figure A2. The study period is 1930 to 1984. This reach is highly sinuous with river length about twice the valley length. The differential between extreme high and low stages is about 60 ft, and the differential between stages associated with the average minimum discharge and the average maximum discharge is about 27 ft. Velocities are typically 3 to 6 fps (Haas 1964, Robbins 1976).

17. The floodplain contains recent alluvial deposits composed of silt, sand, and clay ranging from 5 to 25 ft thick. Soil patterns provide ample evidence of natural levees, point bar deposits, backswamp deposits, and frequent clay plugs that are the remnants of old, naturally cutoff meanders. The recent alluvium is underlain by Pleistocene fluvial sand and gravel deposits 80 to 100 ft thick. The river is confined to a floodplain bordered by levees and bluffs. The leveed floodplain ranges from 2 to 6 miles wide (Miller, Wihry, and Lee, Inc. 1981). The morphology and stability of the Mississippi River channel have been significantly influenced during the period of interest by construction of articulated concrete mattress revetments and stone training dikes. In addition, the sediment load has gradually decreased due to reservoir construction and channel stabilization activities throughout the basin (Keown, Dardeau, and Causey 1981).

Table A1

Description of Study Reaches

Reach	No. of Study Bendways	Channel Slope ft/mile	Difference Between Extreme Stages, ft	Suspended Sediment Percent by Weight	Estimated Ratio of Bed Load to Total Load	Annual Bank Erosion ft*	Discharge, cfs Maximum	Average	Minimum
Lower Mississippi	4	0.40	60	0.07	-	500	2,080,000	573,900	99,400
Arkansas	4	0.8-1.0	40	0.27	5-10	300	855,000	46,000	200
Red	1	0.50	50	0.14	2-8	800	233,000	31,500	873
Tombigbee									
Columbus Pool	9	1.40	32	0.005	-		148,800	6,991	939
Aliceville Pool	2	~0.65	34	0.008	-		158,300	8,715	966
Gainesville Pool	2	~0.65	37	0.008	-		165,800	10,383	1,001
Demopolis Pool	1	~0.65	47	-	-		-	-	-

Additional Information on Bank Erosion

Mississippi --

Arkansas — Bank recession of 200 to 300 ft during a single rise is a common occurrence. Bank caving is negligible during prolonged periods of low flow (Tulsa, Little Rock, and Vicksburg Districts 1960).

Red — Bank recession of 200 to 400 ft during a single rise is a common occurrence (New Orleans District 1972).

Tombigbee — A 1969 study showed less than 1 percent of the bank-miles had erosion rates greater than 0.5 ft/year (Mobile and Nashville Districts 1982).

NOTE: Numbers tabulated above are general figures for long periods of time that do not correspond exactly to periods of interest for this study. In general, though, these figures are for the riverine phase. Descriptors for Arkansas and Red Rivers are for the periods preceding completion of main stem dams and most channel stabilization works. for Slopes for Mississippi, Arkansas, and Red are low-water slopes; slopes for Tombigbee are channel slopes. Other descriptors for Tombigbee are estimated postproject conditions. Sources: ASCE Task Committee (1965); Peterson (1964); New Orleans District (1972); Tate et al. (1982); Yu and Wolman (1986); New Orleans District (1980); Causey (1966); Mobile District (1977); Simons, Li, and Associates (1982).

* Bank erosion rates from ASCE Task Committee (1965). Figure for Red River is "maximum total recession in one year at one location."

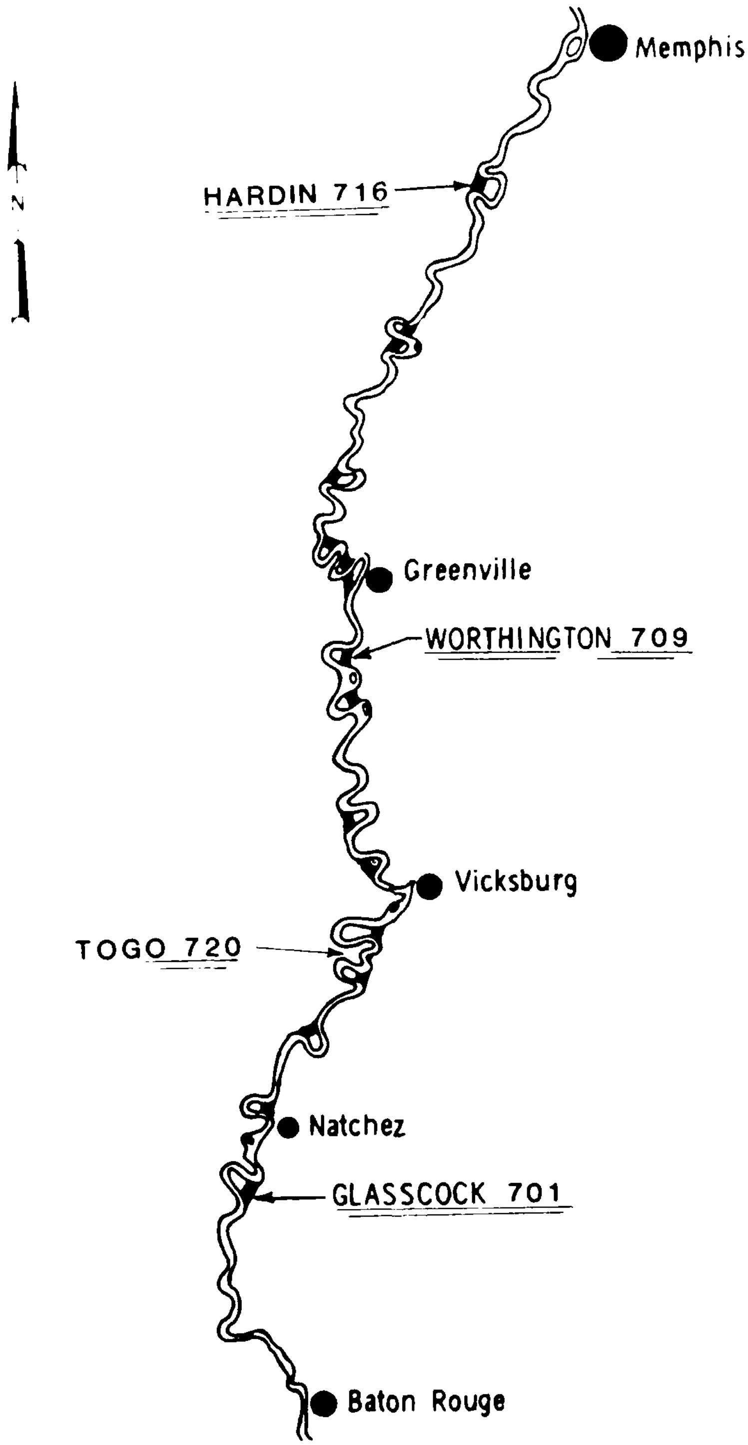


Figure A2. Mississippi River study sites

18. Sixteen man-made meander cutoffs were constructed for flood control on the lower Mississippi River between 1933 and 1942. All of the cutoffs were located in a reach beginning just upstream of Helena, Ark., and ending just downstream of Natchez, Miss. This reach of the river was shortened by approximately 151.9 miles, or about 30 percent, by the cutoffs. Three of these cutoff bends were selected for inclusion in the third component of this study: Glasscock, Worthington, and Hardin (sites 701, 709, and 716, respectively). In addition, Glasscock (site 701) is included in the study of the blockage phase.

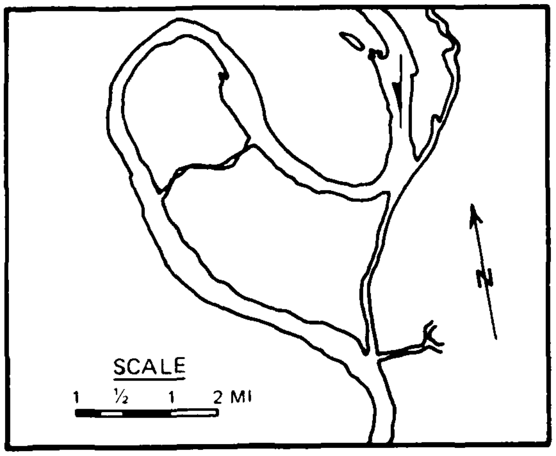
19. Three main criteria were used in selecting these bends from the 16 available. First, the selected sites had to have existing oxbow lakes inside the levee. Second, reaches where two consecutive bends were cut off (for example, the cut downstream of Hardin cutoff in Figure A2) were avoided because the response of such "compound" reaches might be more complex. The third criterion for site selection was the length ratio. The three sites selected had a wide range of values for the ratio of bend length to cut length, L_r. Values for the length ratio were 2.1, 3.3, and 9.9 for Worthington, Glasscock, and Hardin, respectively.

20. The Mississippi River cutoffs were constructed by dredging small pilot channels with slight concavity in the same direction as the bendway. Glasscock cut (see Figure A3) was initially constructed as a shallow dragline cut in early 1933. The cut was then enlarged by dredging in April 1933. "Developmental dredging" continued sporadically through 1938 (Ferguson 1940, Winkley 1977).

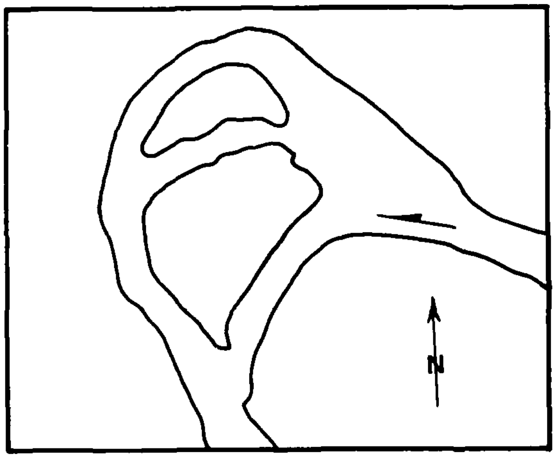
21. In addition to the man-made cutoffs, data were also obtained for a natural chute cutoff just downstream of Vicksburg, Miss. The Togo Island cutoff, site 720, developed from a broad swale across a point bar in 1964 to capture the entire normal flow of the river by 1984 (see Figure A3). The morphology of this chute cutoff is radically different from the other sites considered in the study. The cut developed from a very wide, shallow swale across a point bar rather than a man-made pilot channel or navigation channel. The natural swale was initially much higher than the old bend.

Arkansas River

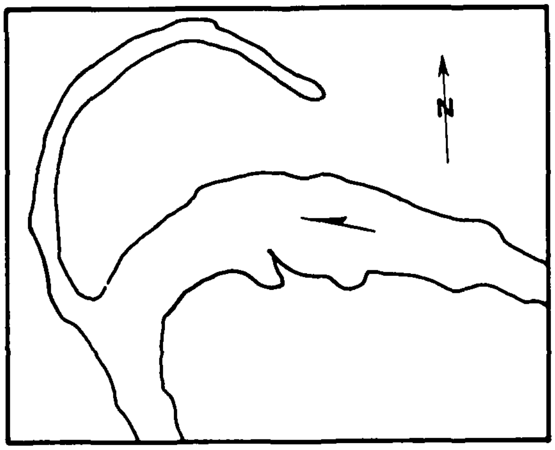
22. The reach of the Arkansas River of interest lies roughly between Fort Smith, Ark., and Pine Bluff, Ark., as shown in Figure A4. (For more detail see Figure A5.) The period of interest is between 1950 and 1984.



GLASSCOCK (701)



TOGO (720) IN 1970



TOGO (720) IN 1983

Figure A3. Mississippi River study sites 701 and 720. Togo (site 720) is a natural chute cutoff

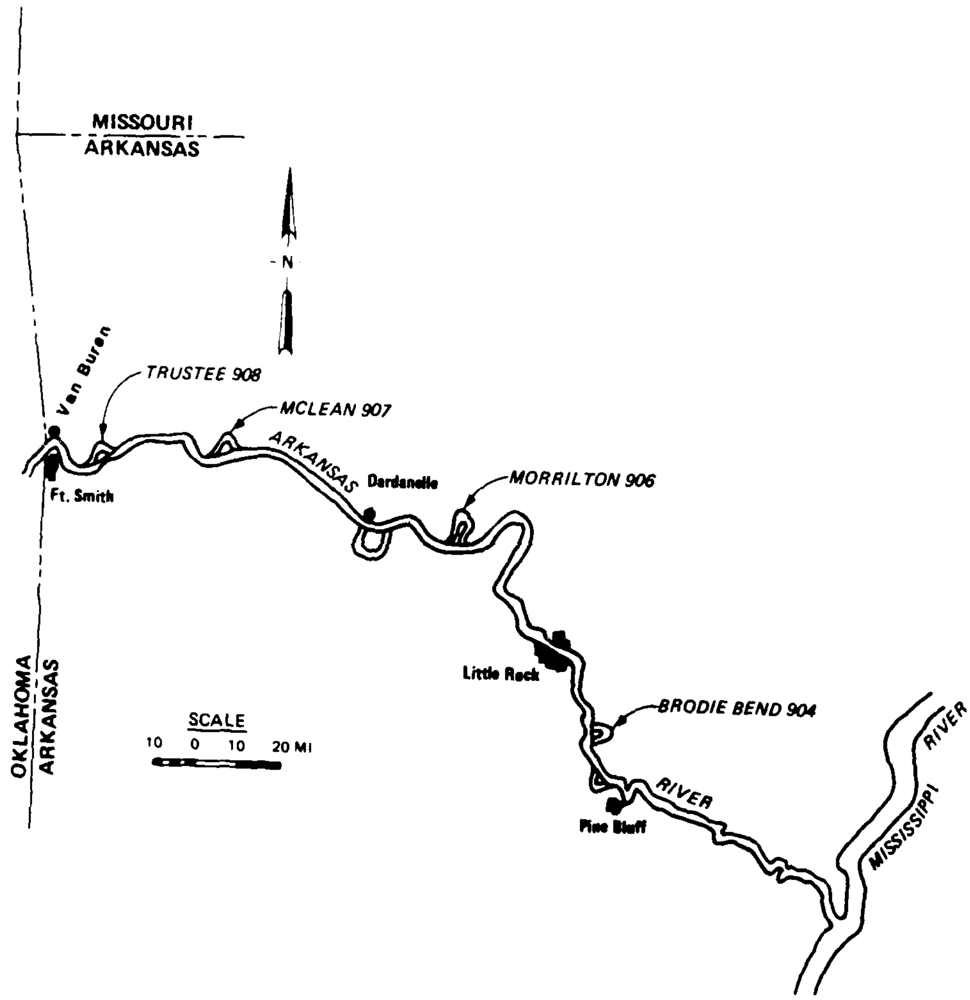


Figure A4. Arkansas River study sites

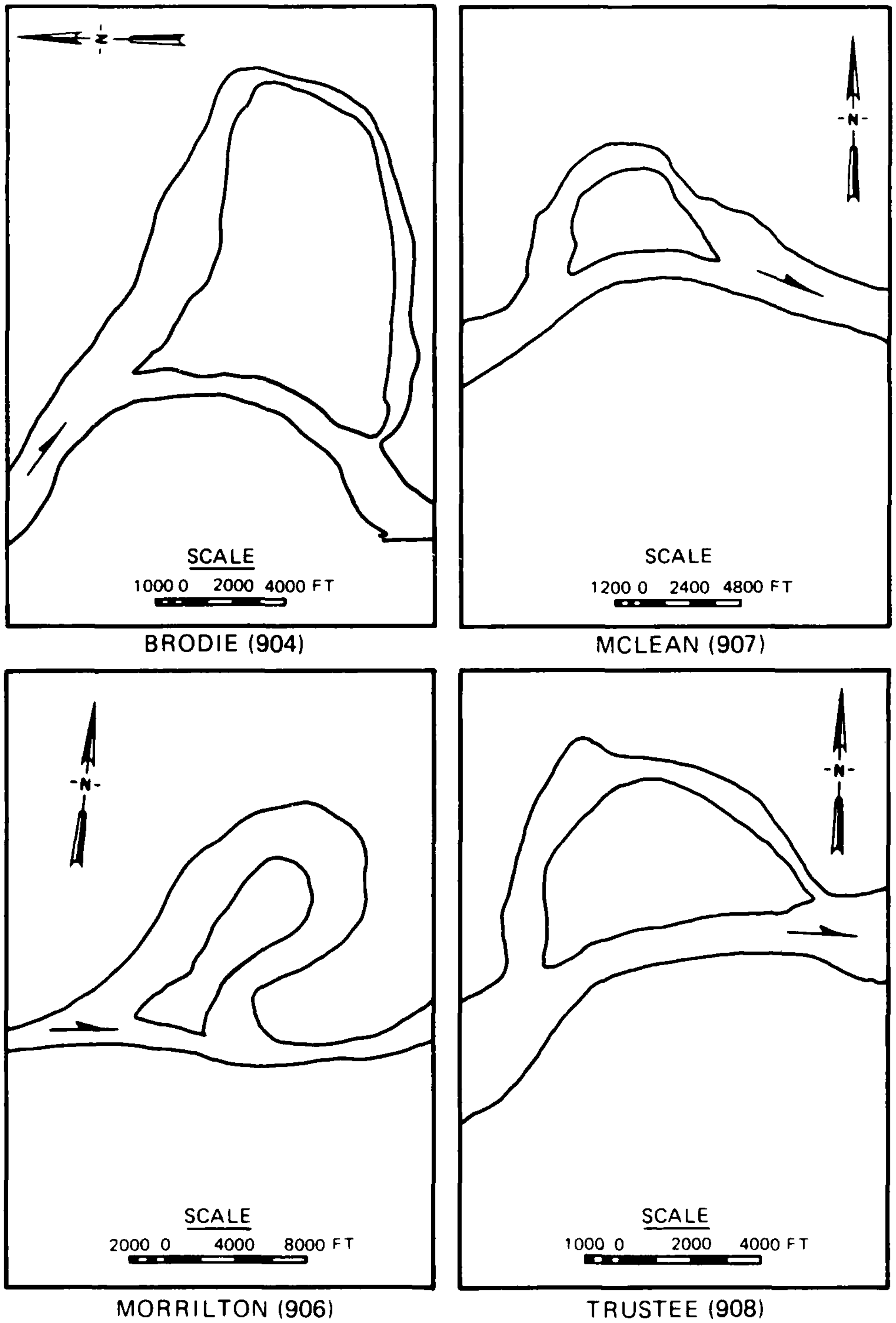


Figure A5. Arkansas River study sites 904, 906, 907, and 908

Above Little Rock, the Arkansas River flows through a mountainous region. The 2- to 6-mile-wide floodplain is bounded by shale and sandstone bluffs. During low-water periods, bedrock is approximately 5 to 30 ft below the thalweg. The channel slope ranges from 0.8 to 1.0 ft per mile. Just below Little Rock, the river enters the Mississippi River alluvial valley, and slopes decrease to 0.8 to 0.6 ft per mile. Depth to bedrock increases to more than 100 ft and, except for a few deposits of marine clay, the channel is underlain by easily erodible materials. Three of the bends are located upstream of Little Rock and one downstream.

23. A multipurpose project was completed on the Arkansas River about 1970 (Clements 1984). Major elements of the project included extensive channel stabilization with stone dikes and revetments, and construction of at least 12 bendway cutoffs. Channel stabilization and cutoffs were constructed primarily between 1960 and 1964, while main stem dams were completed primarily between 1964 and 1968. Completion of the project was expected to result in a decrease in sediment load of 70 to 90 percent, primarily due to closure of storage reservoirs and channel stabilization (Petersen 1963, Madden 1964).

24. Hydrographic survey data were found for only 4 of the 12 cutoff bends (Petersen 1963, 1964), and all of these data were included in the study of the blockage phase. Petersen (1963, 1964) also presents some design and construction data and plan maps for each of the four sites.

25. Aerial photos were also obtained for the four sites for use in the study of the infilling phase. All of the hydrographic survey data were collected prior to main stem dam construction, while aerial photos cover both predam and postdam periods.

26. All four of the Arkansas River cutoffs were constructed by excavating pilot channels 30 to 50 ft wide at the bottom, to a depth 1 to 10 ft below the water surface elevation for a flow of about 10,000 cfs. Plugs were left in the upstream end of the pilot cuts that were designed to be washed out during the first major flood. Additional excavation was performed at site 907 to speed cut development. At this site, the pilot channel was deepened 6 to 10 ft about 18 months after initial cutoff.

27. A unique characteristic of the Arkansas River sites is that permeable blockage structures of piling and stone were constructed at the upstream ends of the old bends 1 to 3 years after cutoff. Typically, these structures were

initially at midbank elevation or lower and were gradually raised. In one case (site 907), the blockage structure was initially built to extend only halfway across the mouth of the old bend, but was later completed. The purpose of these structures was to accelerate development of the cut channel.

Red River

28. Only one cutoff bend from the Red River was included in this study. Shown in Figure A6, Kateland Bend (site 601) is located about 30 river miles upstream of Alexandria, La. Kateland Bend was cut off by dredging a small pilot channel in November 1972 and was filled rapidly. The blockage phase lasted only about a year. The rapid deposition in the bend was in part due to high flows during the winter of 1972-73.

29. The study reach of the Red River flows over recent deposits of alluvial sands, silts, and clays which are in most instances easily eroded. Although there are a number of stable clay points along the river, for the most part, banks mainly consist of sand and silt and erode rapidly. Accordingly, the channel meanders freely and migrates rapidly (New Orleans District 1972). Active bends have an average migration rate of 20 ft per year (Yu and Wolman 1986), and bank recession of 200 to 400 ft during a single rise is a common occurrence (New Orleans District 1972).

30. Yu and Wolman (1986) showed that the primary source of fine sediment in the Red River is derived from channel erosion rather than erosion of the land surface. This is presumably due to the completion and operation of large storage reservoirs in the upper part of the basin. The primary trap for upstream fine sediment appears to be Lake Texoma, which was completed in 1944. There has been no significant increase or decrease in sediment yield over the last 30 years. Since the fine sediments originate in the channel, fine sediment transport is unusually highly related to local flow conditions. Prior to construction of Kateland Bend cutoff, only isolated bank stabilization measures and a few cutoffs were constructed to protect floodplain structures such as levees, roads, and bridges from channel migration. The work was piecemeal and was not based on a comprehensive plan. Kateland Bend cutoff was one of the initial items of work in a comprehensive channel stabilization and navigation project now under construction. Locks or dams were not constructed during the period of interest for this study, however.

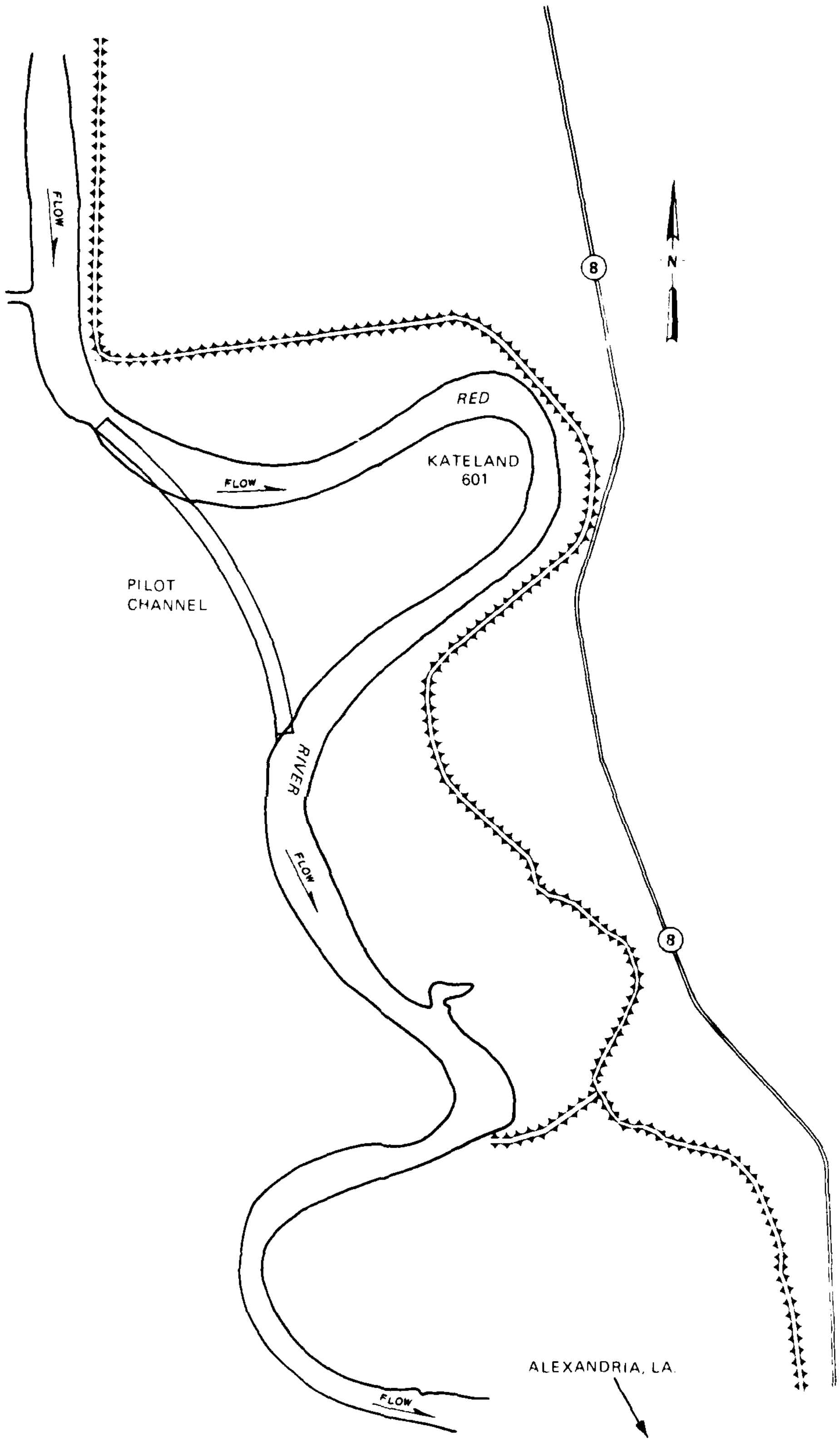


Figure A6. Kateland Bend, Red River study site

Tombigbee River

31. The portion of the Tombigbee River of interest lies between Aberdeen Lock and Dam and Demopolis Lock and Dam as shown in Figure A7. (For more detail see Figures A8 and A9.) This reach is part of the River Section of the Tennessee-Tombigbee Waterway completed in 1985. The period of interest is 1976 to 1986. Demopolis Lock and Dam was completed several years prior to 1976, while Gainesville, Aliceville, Columbus, and Aberdeen Pools were raised in 1979, 1979, 1981, and 1984, respectively. Low-to-normal stages and discharges are controlled by operation of the five River Section dams, but these structures are operated to have minimal effects on large flood flows (Simons, Li, and Associates 1982):

> The reservoirs (pools) will be operated to provide suitable navigation depths. No flood protection or power generation is contemplated. The reservoirs will be maintained at normal pool elevation, except during low-flow periods when evaporation and leakage requirements exceed the inflow, and during floods. During floods, the spillway gates will be operated to hold the pool at the normal pool elevation by passing the inflow until full spillway capacity is reached; and thereafter, free outflow conditions will prevail until the pool peaks and returns to the normal pool elevation.

32. Burkett (1986) further discusses the effect of the Tennessee-Tombigbee project on river hydraulics. Construction of the navigation channel superimposed a navigation channel 300 ft wide and 9 ft deep on a natural river channel 100 to 200 ft wide and several feet deep. Furthermore, the navigation channel is much straighter and freer of snags than was the natural channel. As a result of these changes, the capacity of the present channel near the upper end of the study area is equal to the 5- to 20-year frequency flows. However, stages for floods larger than channel capacity are not affected as much because overbank storage and flow area have been reduced by the placement of numerous dredged material containment areas in the floodplain.

33. Tombigbee River discharge varies significantly throughout the year with an average of 66 percent of the annual streamflow occurring during the four wet months of January through April. Approximately 79 percent of the sediment transport occurs during these months as well. As shown in Table A1, the average discharge increases in the downstream direction as several major tributaries join this reach. Accordingly, the variation of flow decreases downstream as the river becomes larger and less influenced by small, intense rainfall events.

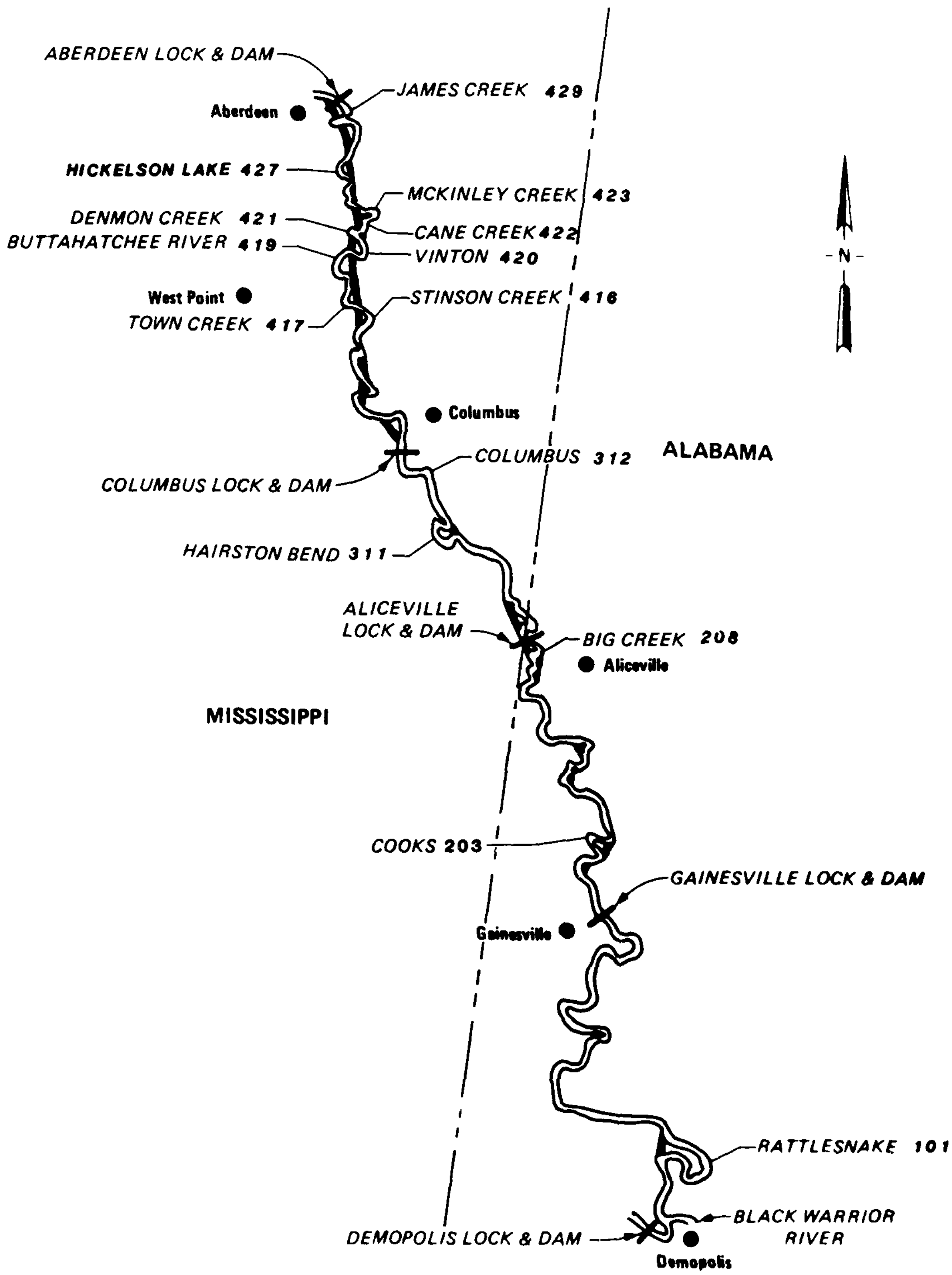


Figure A7. Tombigbee River study sites. Data from numbered cutoffs were used in this study

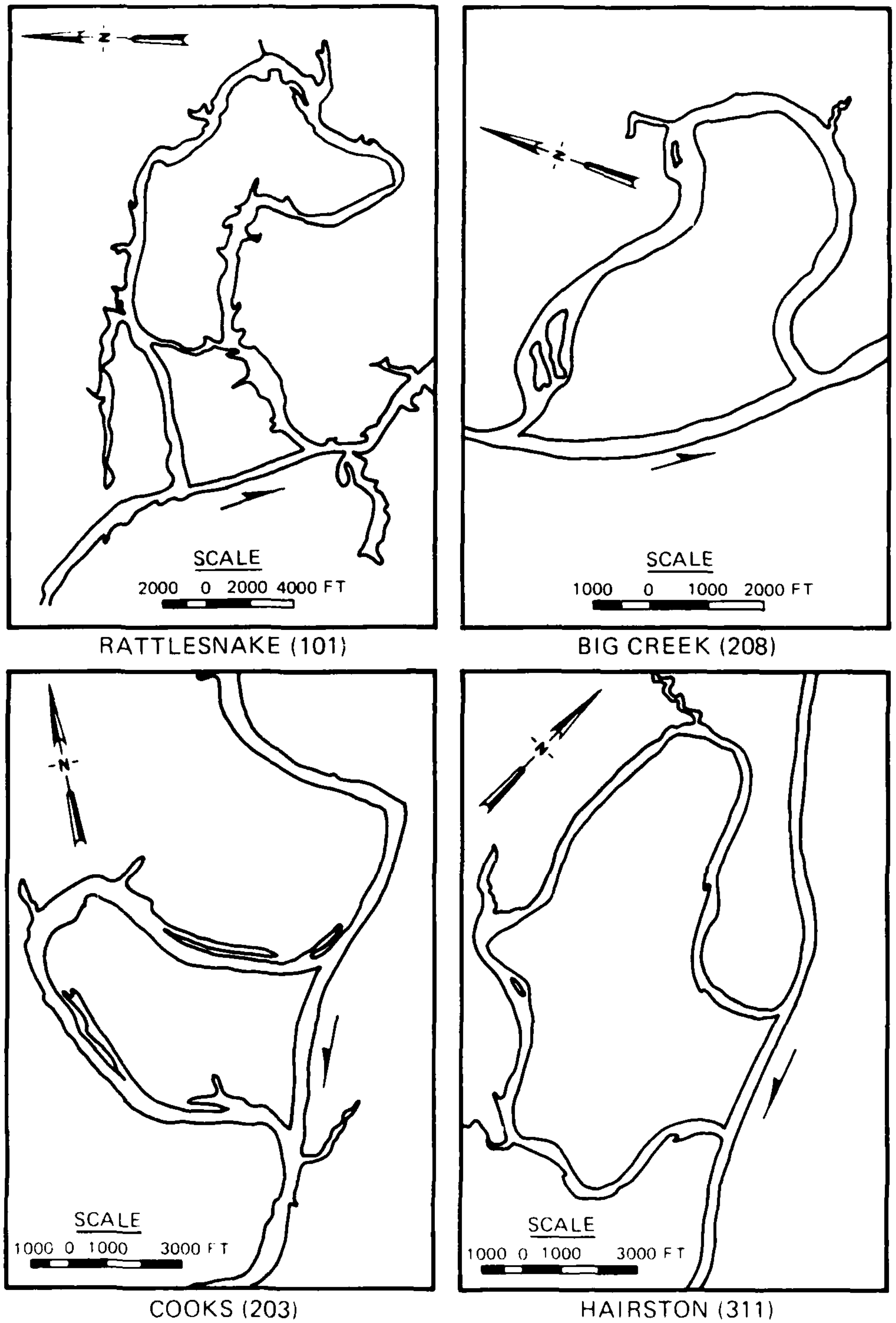


Figure A8. Tombigbee River study sites 101, 203, 208, and 311 (from Pennington et al. 1981)

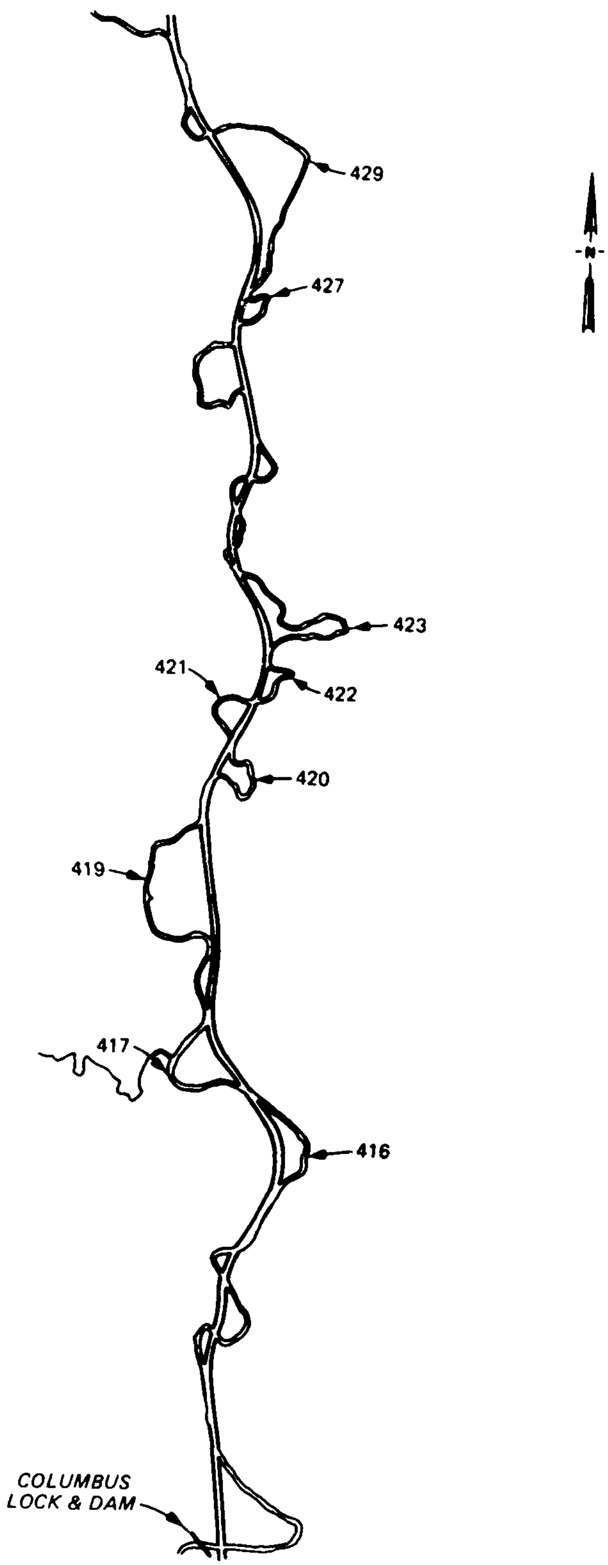


Figure A9. Tombigbee River study sites in Columbus Pool

34. Above Columbus, the Tombigbee River bed has a slope of about 1.4 ft per mile and flows through hilly terrain. Downstream of Columbus, the slope decreases to about 0.65 ft per mile, and the floodplain is 1 to 3 miles wide (Mobile District 1977). Bank erosion along the river was not rapid prior to waterway construction. Data collected for a national survey in 1969 showed that less than 1 percent of the total miles of bank in the Warrior-Tombigbee basin had erosion rates greater than 0.5 ft per year. Steep, unvegetated banklines are evident along much of the navigation channel, particularly in the Columbus Pool, but erosion rates continue to be slow to moderate. Natural levees flank the lower reaches of the river, and point bars were visible along the river prior to dam construction.

35. Of the four river reaches studied, the Tombigbee is the most highly modified during the period of interest, with four navigation dams and 30 cutoffs. As shown in Figure A7, the frequency of cutoffs increases upstream, with 18 of the 30 cutoffs occurring in the Columbus Pool. Bank protection is largely limited to short reaches immediately downstream of the navigation dams, and there are no training dikes.

36. The Tombigbee River cutoffs were constructed by dredging the cut channels to full dimensions with hydraulic dredges after the navigation pools were raised. In the upper portion of the study reach, the river channel had to be widened with dredges to accommodate the navigation channel. Since their construction, the cutoff channels have remained fairly stable because of the navigation dams and because of local geologic conditions. For much of its length, the Tombigbee River channel flows over a relatively thin (10- to 40-ft-thick) layer of alluvial deposits underlain by highly resistant late Cretaceous material. For site 101, the Cretaceous material is calcareous siltstone of the Selma chalk Formation while the slightly older Eutaw Formation outcrops along much of the navigation channel in Columbus Pool. The Eutaw material is so resistant to erosion that marks made by the dredge cutterheads remain visible on the sides of cuts in the Columbus Pool 3 years after construction.

37. Annual hydrographic survey data were available for 14 of the 30 cutoff bends in the Tombigbee River study reach. All of these data were used in the study of the blockage phase. However, data from two sites were of limited utility because one received large amounts of sediment from a nearby

surface mine (Hickelson Lake, site 427) and another (Columbus Bend, site 312) had a short postcutoff record (only two surveys).

Data Collection

Hydrographic surveys

38. Repetitive hydrographic surveys were performed in all of the study bends and cut channels by the Corps of Engineers or surveyors under contract to the Corps. Before about 1940 on the Mississippi and about 1960 on the Arkansas, subaqueous portions of cross sections were sounded with lead lines or weighted piano wires. Survey boat operators maintained their station by sighting on flags on the bank, or in some cases transits were used to maintain stationing. Soundings were taken at permanently monumented cross sections, hereinafter referred to as "survey ranges" or just "ranges." Overbank areas were surveyed by transit or plane table. Since about 1940 on the Mississippi and 1960 on the Arkansas, subaqueous ranges have been surveyed using acoustic fathometers. Survey instruments have been used to determine survey boat location in the x-y plane. Also in the more recent Mississippi River surveys, overbank mapping has relied heavily on stereoscopic interpretation of aerial photographs (personal communication, 1986, C. M. Elliott, Lower Mississippi Valley Division, US Army Corps of Engineers; Elgia Howe, Vicksburg District (ret.); Jim Baker, Little Rock District). All of the Tombigbee River survey data used in this study were collected along permanently monumented ranges using acoustic fathometers for subaqueous areas and transits for extremely shallow areas and overbanks. Sources for survey data are presented in Table A2.

Streamflow data

39. Streamflow records for each bendway site were obtained from the US Geological Survey (USGS) National Water Data Exchange in Reston, Va., or, in some cases, the appropriate USGS District office. Streamflows were always tabulated as mean daily discharges in cubic feet per second. Some of the discharge data had to be adjusted for differences between bend and gage location. Sources for discharge data and adjustments made are tabulated in Table A3.

Table A2

Sources of Hydrographic Survey Data for Study of Blockage Phase

Site	No. of Surveys	Period of Postcutoff Record	Source of Data
101	8	1976-85	Mobile District files
203	6	1979-85	Mobile District files
208	6	1979-85	Mobile District files
311	4	1981-85	Mobile District files
312	2	1984-85	Mobile District files
416	3	1982-85	Mobile District files
417	3	1982-85	Mobile District files
419	4	1982-85	Mobile District files
420	4	1982-85	Mobile District files
421	4	1982-85	Mobile District files
422	3	1983-85	Mobile District files
423	4	1982-85	Mobile District files
427	4	1982-85	Mobile District files
429	4	1982-85	Mobile District files
601	9	11/72-11/73	Vicksburg District files
701 720	6 3	1933-84* 1964-84	Vicksburg District files and Mississippi River comprehensive hydrographic surveys
904	3	1957-63	Petersen (1963, 1964)
906	3	1950-58	Petersen (1963, 1964)
907	3	1955-60	Petersen (1963, 1964)
908	4	1954-60	Petersen (1963, 1964)

* Only first four surveys (1933-64) used in riverine phase study.

Table A3

Sources for Streamflow Data

Site No.	USGS Station	Adjustments
101	Tombigbee R. at Demopolis Lock and Dam	Flow from Black Warrior R. at Warrior Lock and Dam, lagged by 1 day, was subtracted.*
203	Tombigbee R. at Gainesville Lock and Dam	None
208	Tombigbee R. at Aliceville Lock and Dam	None
311	Tombigbee R. at Aliceville Lock and Dam	None
312	Tombigbee R. at Columbus Lock and Dam	None
416	Columbus Lock and Dam	None
417	Columbus Lock and Dam**	Multiplied by 0.71 (ratio of drainage areas)
419	Columbus Lock and Dam**	Multiplied by 0.71 (ratio of drainage areas)
420	Columbus Lock and Dam**	Multiplied by 0.49 (ratio of drainage areas)
421	Columbus Lock and Dam**	Multiplied by 0.49 (ratio of drainage areas)
422	Columbus Lock and Dam**	Multiplied by 0.49 (ratio of drainage areas)
423	Columbus Lock and Dam**	Multiplied by 0.49 (ratio of drainage areas)
427	Columbus Lock and Dam**	Multiplied by 0.49 (ratio of drainage areas)
429	Columbus Lock and Dam**	Multiplied by 0.49 (ratio of drainage areas)
601	Red R. at Alexandria	None
701	Mississippi R. at Vicksburg	None
720	Mississippi R. at Vicksburg	None
904	Arkansas R. at Little Rock	None
906	Arkansas R. at Dardanelle	None
907	Arkansas R. at Van Buren	None
908	Arkansas R. at Van Buren	None

* The Black Warrior River flows into the Tombigbee just downstream of Rattlesnake Bend but upstream of Demopolis Lock and Dam (Figure A7). The gage at Warrior Lock and Dam is 49.6 river miles above the confluence with the Tombigbee, so flows from there were lagged by 1 day before subtracting them from the discharge at Demopolis Lock and Dam to obtain estimated discharges for Rattlesnake Bend.

** Discharge records for the Tombigbee River upstream of Columbus Lock and Dam (Tombigbee River at Aberdeen and Tombigbee River at Aberdeen Lock and Dam) were not available for the period of interest. The gage on the Tombigbee at Aberdeen was destroyed in a 1982 flood. Measurements have since been collected at Aberdeen Lock and Dam, but are presently stored in unreduced form because rating curves for the dam have not been formulated.

Suspended bed material

40. The average concentration of suspended bed material, C_s , in the master stream above the cutoff is an important variable in Equation A11. As shown in Table A4, suspended sand data were obtained from various published sources for the sites on the Mississippi, Arkansas, and Red Rivers. Suspended sediment data were obtained from the Mobile District for four of the Tombigbee River sites (101, 203, 208, 311).

41. Suspended sediment samples and measurements of velocity and discharge were collected during high-flow events at the Tombigbee River sites. Velocities were measured using a Price AA current meter from a boat at three or more verticals at 0.2 and 0.8 depths. Velocities were measured at three cross sections at each site: upstream of the cutoff, within the cut channel, and in the upstream limb of the old bendway. Depth-integrated suspended sediment samples were collected at the same times and locations as the velocity measurements. Most of the suspended sediment samples were later split into fractions finer and coarser than 0.062 mm. Discharges were measured in the cut channel and upstream of the cut using the moving-boat procedure (Smoot and Novak 1969) with two to five replications. Discharge was not measured upstream of site 208. Instead, the discharge from Aliceville Lock and Dam, which is just upstream of site 208, was obtained and tabulated. Measurements of discharge, velocity, and suspended sediment for the Tombigbee River sites are tabulated in Table B1, Appendix B.

Table A4

Sources of Suspended Sediment Data

Sites	Source
101, 208, 203, 311	Mobile District files
601	New Orleans District (1980)
720	Robbins (1976)
904, 906, 907, 908	Little Rock District (1959)

Aerial photographs

42. Photographic collections of the USGS, the US Department of Agriculture, and the Vicksburg and Little Rock Districts were searched for aerial photographs of the study sites on the Mississippi, Arkansas, and Red Rivers. Specifications used to select aerial photos are presented in Table A5. Photographic coverage was often incomplete in either the specified temporal or spatial domains. However, reasonably good coverage was identified and obtained for the four sites on the Arkansas River and three Mississippi River sites. Details of the set of aerial photographs obtained and used are given in Table A6. In addition to the photographs listed in Table A6, color infrared (IR) photographs of several of the Tombigbee River sites were obtained and used in a qualitative fashion. For example, photos of bends in the upper portion of Columbus Pool were helpful in verifying construction dates, locating unusual sediment sources, and observing vegetal invasion of sediment deposits in the cutoff bends.

Table A5

Specifications Used to Select Aerial Photographs*

Sites	River	Minimum Scale	Dates
701, 709, 716	Mississippi	1:62,500	1930-1986
904, 906, 907, 908	Arkansas	1:20,000	1950-1986
601	Red	1:20,000	1972-1986

* Positive prints of any type of film (color, color IR, black and white) fitting the specifications were ordered.

Table A6

Scales and Sizes of Aerial Photos Obtained for Study

Site	Date	Scale	Print Sizes, in.
701	1959	1:20,000	9 × 9
	1964	1:20,000	9 × 9
	1969	1:20,000	9 × 9
	1975	1:40,000	9 × 9
	1982	1:40,000	9 × 9
709	1949	1:20,000	9 × 9
	1966	1:20,000	9 × 9
	1984	1:24,000	22 × 22*
716	1950	1:20,000	9 × 9
	1962	1:20,000	9 × 9
	1979	1:40,000	9 × 9
904	1958	1:20,000	9 × 9
	1965	1:12,000	18 × 18*
	1968	1:12,000	9 × 9
	1973	1:12,000	15 × 15
	1984	1:12,000	9 × 9
906	1955	1:12,000	20 × 16**
	1964	1:12,000	20 × 16**
	1966	1:12,000	20 × 16**
	1971	1:12,000	16 × 16**
	1973	1:12,000	33 × 25**
907	1960	1:12,000	9 × 9
	1963	1:12,000	9 × 9
	1972	1:20,000	15 × 9
	1975	1:12,000	9 × 9
	1981	1:12,000	9 × 9
908	1960	1:12,000	9 × 9
	1963	1:12,000	9 × 9
	1968	1:12,000	9 × 9
	1972	1:12,000	15 × 15*

NOTE: All photos were black and white positive prints except for 1984 photos of site 709, which were color IR positive prints.

* Enlargement of 9 × 9 original.

** Mosaic obtained from Little Rock District.

PART II: DATA ANALYSIS

43. The procedures used to reduce a large quantity of hydrographic survey data and hydrologic records to form a data set of the dimensionless variables listed in Equation A11 are presented herein. Hydrographic survey data, which were obtained in either graphical or digital form, were used to compute the geometric descriptors of cutoff bends and cut channels. The volumes of these channels and streamflow records were used to determine values of the channel volume decay and growth coefficients, K_d and K_g. Regression analyses were then employed to relate the decay coefficient to the growth coefficient and other dimensionless variables that describe initial geometry and average sediment input. Additional analyses focused on the longitudinal distribution of deposition along the cutoff bend and on the changes in surface area of cutoff bends in the infilling phase.

Reduction of Graphical Data

44. Hydrographic surveys of cutoff levels on rivers other than the Tombigbee were obtained in graphical form. Tombigbee data were obtained both in graphical form and on magnetic media. Table A7 presents the form of the data obtained for each site. Data reduction procedures were tailored to the format of the data.

Stage-area curves

45. Data for the cutoff bends and cut channels on the Mississippi, Red, and Arkansas Rivers were extracted from contour hydrographic survey charts, maps with elevations (soundings) shown in digital form, or cross-section plots. Bend volumes for site 701 for 1933 and 1938 were determined by measuring areas enclosed by contours on contour charts with a Calcomp 2000 digitizer. These areas were then used to draw hypsometric (stage-area) curves (Vanoni 1975). Areas enclosed by the hypsometric curves shown in Figure A10 were then digitized to yield bendway volume. Digitization of each area was repeated until consecutive results were within 5 percent of one another, and then the last two measurements were averaged to reduce operator error. An appropriate constant elevation was used for the upper limit of the bend

Table A7

Format of Survey Data

Site (date)	Form	Remarks
101-429	Large-scale, computer-generated cross-section plots and computer files containing x-y coordinates for each range survey.	All Tombigbee River data. About 75,000 discrete points.
601	Hand-plotted cross sections.	Extracted from fathometer scrolls.
701 (1933, 1938)	Highly detailed surveys. Soundings at ranges shown in numerical form. Contours drawn.	
(1948)	Soundings at ranges shown in numerical form. Contours drawn.	
(1964)	Soundings at ranges shown in numerical form. Contours down to +10 ALWP.*	
(1975)	Soundings at ranges shown in numerical form. No contours.	
720	Contour maps.	
904-908	Cross-section plots from Petersen (1963, 1964)	

* Annual Low Water Plane. A sloping datum based on the average of annual minimum stage elevations for a certain period of record.

channel when measuring the area enclosed by the hypsometric curves. Volumes for site 720 were computed using areas digitized from contour charts and the average end-area formula.

Regeneration of cross-section plots

46. When soundings were printed on maps, the lateral distances between sounding points were measured using either the Calcomp 2000 digitizer or an engineer's scale. The lateral distances and corresponding soundings were then tabulated and entered into a microcomputer, and cross-section plots were generated. Even when hyposometric curves were used to determine channel volumes, cross sections at the bend and cut channel entrances were generated to

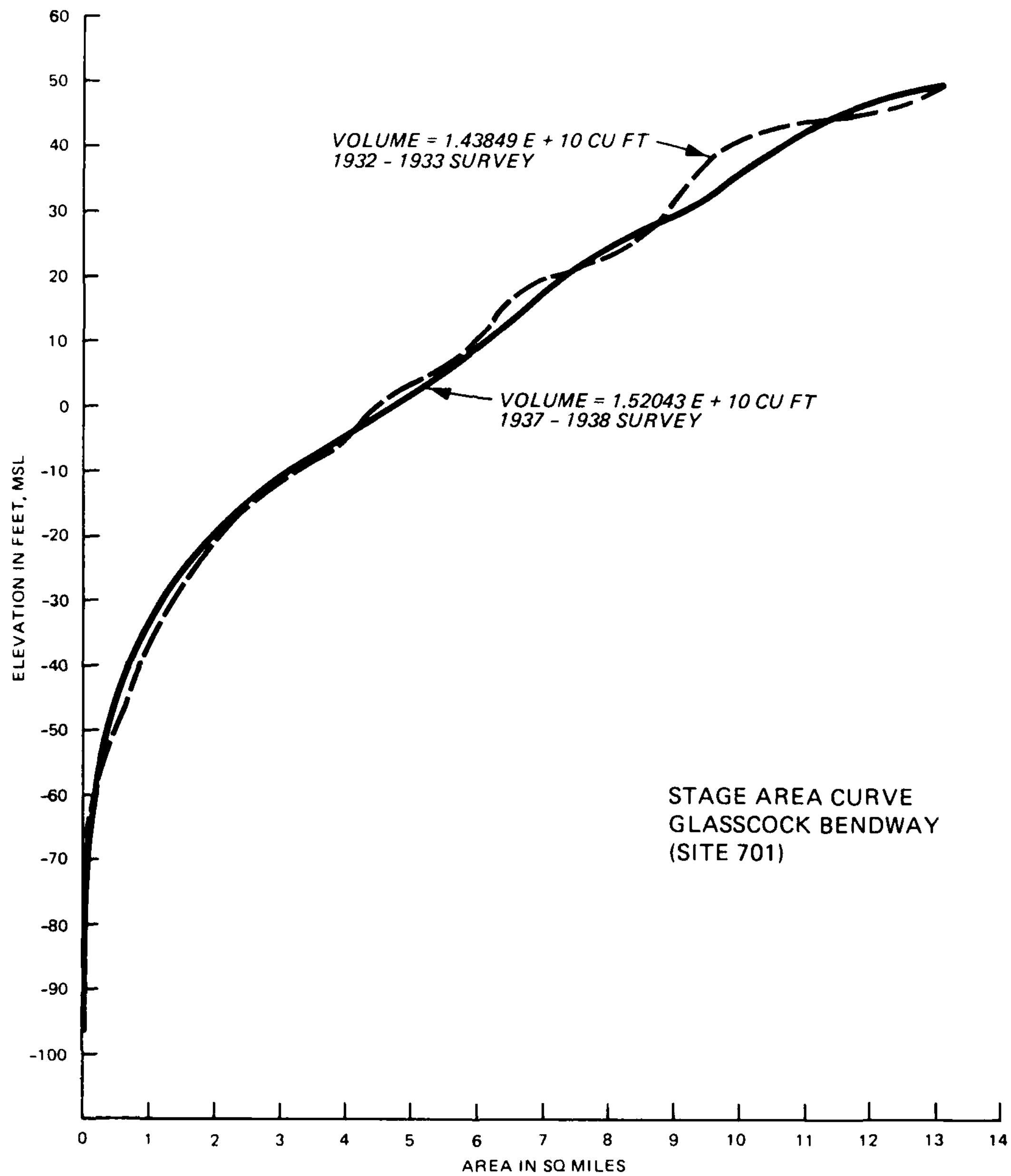


Figure A10. Hypsometric curves for site 701 define entrance geometries. Latitude and longitude coordinates for end points of these entrance ranges were determined to ensure unchanging locations from survey to survey.

Top-bank and thalweg elevations

47. The first step in extracting data from the hydrographic surveys obtained in graphical form was to examine each cross-section plot. Cross-section plots generated from survey maps or charts and cross-section plots obtained directly from files or published sources (such as those for sites 601, 904, 906, 907, and 908) were treated in an identical fashion. First, the thalweg elevation and top-bank elevation were determined by visually inspecting the plot. Top-bank elevation was determined as shown in Figure A11. Bank elevations for the left and right sides of the cross section were compared, and the local maximum on the low bank was selected as top-bank elevation. If there was no local maximum on the low bank, the maximum low-bank elevation was used as top bank. Variation of top-bank elevation from range to range within a given bend or cut was usually minor for these sites.

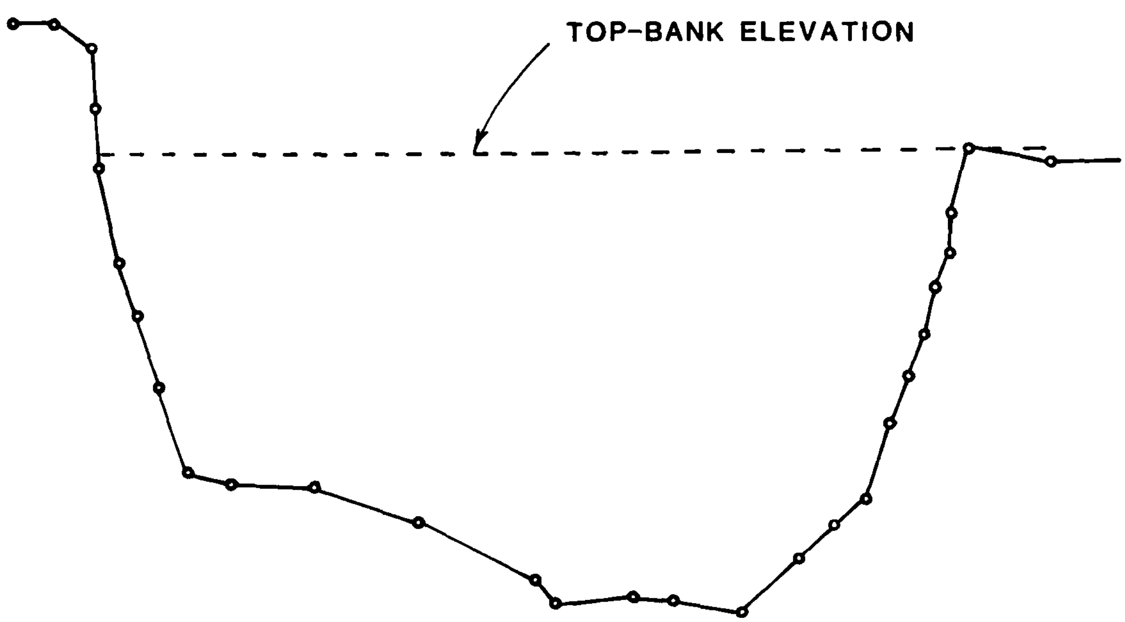


Figure A11. Definition of top-bank elevation

Channel width and area

48. After the top-bank elevation was determined, top-bank width and cross-sectional area below top-bank elevation were measured using the Calcomp 2000 digitizer. Area measurements were replicated and averaged. The descriptors of bend geometry (top-bank width, thalweg elevation, cross-sectional area, etc.) were tabulated and entered onto spreadsheets on a microcomputer. Table A8 is an example of the data extracted from cross-section plots. A complete tabulation of all data used in this project is in project files at the US Army Engineer Waterways Experiment Station, Environmental Laboratory.

Table A8

Example of Data Extracted from Cross-Section Plots

Range	River Mile	Date (YYMMDD)	Area ft^2	Top-Bank Elev. ft, msl	Thalweg Elev. ft, msl	Top-Bank Width, ft
601008	134.23	721010	32,000	96.4	47.0	1,090
601007	133.97	721006	30,280	97.8	47.5	1,130
601006	133.79	721020	29,200	94.4	47.2	1,050
601005	133.59	721006	26,800	95.5	44.0	1,210

Interpolation for missing data

49. Not all of the ranges established in a given bend or cut channel were surveyed on each survey date. To minimize error associated with uneven survey coverage, missing cross-sectional areas were interpolated using linear regression functions. An example of the interpolation procedure is presented in Table A9, which shows cross-sectional areas computed from hydrographic surveys of site 203 on the Tombigbee River. Although 11 ranges were established in the bend, complete temporal coverage was available for only one range. The missing cross-sectional areas were estimated using linear regression. Channel cross-sectional area for the year with the missing value was the dependent variable, and cross-sectional area for the previous year was the independent variable. Interpolations were generally based on regressions with coefficients of determination (r^2) of 0.81 or greater, and interpolated areas were never included in subsequent regressions for interpolation. The minimum value of r^2 was set at 0.81 because it is significantly greater than zero at the 95-percent confidence level with as few as three points in the regression.

Table A9

Interpolation for Missing Cross-Sectional Areas, Site 203

	Cross-Sectional Areas, 10^4 ft^{2*} (Interpolated Areas Are Shown in Parentheses)						
Range	1978	1979	1980	1981	1983	1984	1985
CB1	1.53	1.60	1.56	1.49	1.48	(1.46)	1.47
2	2.38	2.44	2.38	(2.23)	2.28	(2.04)	2.19
3	1.29	1.30	1.24	1.24	(1.09)	1.27	1.23
4	1.72	1.67	1.57	(1.51)	1.52	1.49	1.50
5	1.71	1.68	1.63	1.61	1.47	(1.48)	(1.45)
6	1.92	1.90	1.86	(1.77)	1.63	(1.55)	1.58
7	1.57	(1.53)	1.61	1.52	1.46	1.39	1.39
8	1.52	1.48	1.42	1.37	1.24	(1.27)	1.23
9	1.60	1.42	1.37	1.33	1.13	(1.21)	1.15
10	1.64	1.52	1.45	1.40	1.16	(1.28)	1.24
11	1.27	1.26	1.09	1.07	0.93	(1.06)	0.96

Prediction of Missing Values
(Interpolated Value = ax + b)

Missing Value Date	Missing Value Range	Intercept, a, 10^3 ft^2	Slope, b	Independent Variable, x	Coefficient of Determination, r^2
1979	CB7	-1.08	1.05	1978 survey	0.978
1981	2	1.16	0.89	1980	0.991
	4	1.16	0.89	1980	0.991
	6	1.16	0.89	1980	0.991
1983	3	-3.43	1.15	1981	0.939
1984	1	2.95	0.797	1985	0.999
	2	2.95	0.797	1985	0.999
	5	6.22	0.501	1978	0.992
	6	2.95	0.797	1985	0.999
	8	2.95	0.797	1985	0.999
	9	2.95	0.797	1985	0.999
	10	2.95	0.797	1985	0.999
	11	2.95	0.797	1985	0.999
1985	5	1.45	0.888	1983	0.996

* Actual computations were performed to the nearest square foot. Only three significant figures are shown here for simplicity.

Mean depths

50. Mean channel depths were determined by dividing channel cross-sectional area by top-bank width:

$$\bar{y} = A/W \tag{A12}$$

where

$\bar{y}$ = mean depth, ft

A = channel cross-sectional area, ft^2

W = top-bank width, ft

Mean channel depths computed for the upstream entrances in each bend and each cut channel were used to compute the difference in average channel bed elevations, Z , shown as ΔZ in Figure A1:

$$Z = (TBB - \bar{y}_b) - (TBC - \bar{y}_c) \tag{A13}$$

where

TBB = bend top-bank elevation

$\bar{y}_b$ = average channel depth at bend entrance

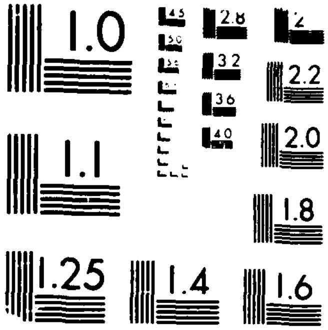
TBC = cut top-bank elevation

$\bar{y}_c$ = average channel depth at cut entrance

The value of Z determined for the initial survey after cutoff was used in the analysis described below.

51. Surveys were available for only one of the Arkansas River cut channels, Morrilton Bend cutoff, site 906. However, bottom widths, side slopes, and bottom elevations for the trapezoidal pilot channels were available for each of the Arkansas River sites (Tulsa, Little Rock, and Vicksburg Districts 1960). Cross-sectional areas, top widths, and mean bed elevations for each of the three unsurveyed pilot elevations were determined by assuming that the top-bank elevation for the upstream entrance to the pilot cut was [illegible] top-bank elevation for the bend entrance. These calculations [illegible] in Table A10.

AD-A190 426 MANAGEMENT OF ENVIRONMENTAL RESOURCES OF CUTOFF BENDS 2/3
ALONG THE TENNESSEE (U) ARMY ENGINEER WATERWAYS
EXPERIMENT STATION VICKSBURG MS ENVIR F D SHIELDS
UNCLASSIFIED NOV 87 WES/MP/EL-87-12 F/G 13/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

Table A10

Computation of Geometric Characteristics of Arkansas River Cut Channels

Site	Top-Bank Elevation ft, msl*	Cut Channel Area, ft^2	Cut Channel Width, ft	Mean Depth of Cut $\bar{y}_c$, ft	Z, ft	$Z/\bar{y}_c$
904	222.0	2,125.0	123.5	17.2	3.5	0.203
906	277.0	1,824.0	112.0	16.3	5.3	0.325
907	338.0	1,284.0	101.0	12.7	7.0	0.551
908	385.0	1,284.0	101.0	12.7	6.2	0.488

* Top-bank elevation of cut assumed to be the same as for the bend.

Channel volumes

52. Volumes of bends and cuts for which cross-section surveys were available were determined from channel cross-sectional areas using the average end-area method:

$$\text{Channel volume} = \sum_{i=1}^{n-1} \frac{(A_i + A_{i+1})(x_i - x_{i+1})}{2} \qquad \text{(A14)}$$

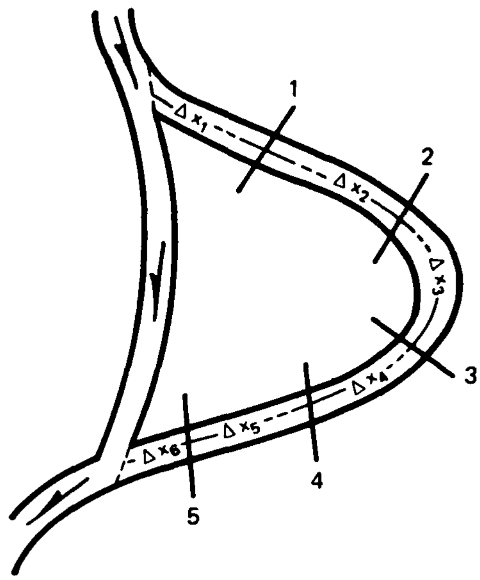
where

n = number of ranges in bend

A_i = cross-sectional area of the i^{th} cross section

X_i = distance along channel center line from channel endpoint to i^{th} cross section

53. In several cases, there were no ranges located at bend or cut channel endpoints. In these cases, the cross-sectional area of the channel at each endpoint was assumed equal to the adjacent range in the bend or cut as shown in Figure A12. Since the upstream entrance is the primary location for deposition, this approach may have slightly underestimated the initial deposition in the bends. Since the bend entrances are primary deposition locations, though, the approach used was more accurate than ignoring the segments of channel between the established ranges and bend end points.



$$\text{VOLUME OF BEND} = A_1\,\Delta x_1 + \left(\frac{A_1 + A_2}{2}\right)\Delta x_2 + \left(\frac{A_2 + A_3}{2}\right)\Delta x_3 + \left(\frac{A_3 + A_4}{2}\right)\Delta x_4 + \left(\frac{A_4 + A_5}{2}\right)\Delta x_5 + A_5\,\Delta x_6$$

Figure A12. Calculation of channel volumes using cross-sectional areas

Angles of incidence

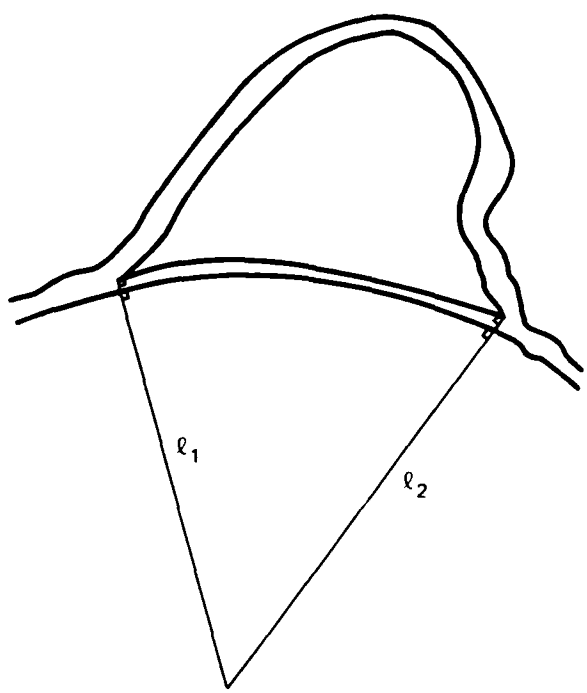
54. The angles between the approach channel and the cutoff bend, ψ_1, the approach channel and the cut channel, ψ_2, and the cutoff bend and the cut channel, θ, were carefully measured from plan maps of all sites as illustrated in Figure A1. Clear sheets of mylar were laid over the plan maps, and the center lines of all three channels were plotted for three channel widths along each channel starting at the points of intersection and moving into each channel. Lines were drawn through these points, and the angles, as shown in Figure A1, were measured using a protractor. All measurements were checked.

Radii of curvature

55. In a similar fashion, radii of curvature of cut channels, r_c, were determined from plan maps by drawing lines perpendicular to both bank lines of the cut channels at their upstream and downstream end points on mylar overlays. The distances along each of the two lines from their intersection to the cut channel center line were measured with an engineer's scale and averaged as shown in Figure A13.

Channel lengths

56. Cut and bend channel lengths were determined from river mileages associated with survey ranges or by scaling distances along channel center lines from plan maps.



$$r_c = \frac{\ell_1 + \ell_2}{2}$$

$r_c > 0$ IF CUT CURVATURE IS IN THE SAME DIRECTIONS AS BEND CURVATURE

$r_c <$ IF CUT CURVATURE IS IN THE OPPOSITE DIRECTION **FROM** BEND CURVATURE

$r_c = \infty$ IF CUT CHANNEL IS STRAIGHT

Figure A13. Determination of radius of curvature, r_c

Reduction of Data on Magnetic Media

Data checking and reformatting

57. Hydrographic surveys of the same 14 cutoff bends and associated cut channels on the Tombigbee River were obtained from the Mobile District both in digital form on magnetic tape and on paper as cross-section plots. Computer-generated plots of all the surveys (taken at roughly annual intervals) for a given survey range were drawn on the same sheet for ease of comparison.

58. Each of the large-scale plots was visually inspected. In a few cases, the magnitude and direction of bed changes were inconsistent with both prior and subsequent surveys, and with other surveys in the same bend or cut. In cases where these changes could not be explained, the range survey for the year in question was removed from the data base. Thirty-five of the 37 range surveys removed from the data base in this manner were 1984 surveys. Mobile District personnel have indicated that the 1984 survey contractor did poor quality work (Max Yates, personal communication).

59. Raw data from the magnetic tape were then reformatted into a series of computer data files for input into a FORTRAN computer program. The primary components of each of the input files were the hydrographic survey data expressed as coordinate pairs (lateral distance, elevation). Range locations were included on header records that included the following data:

- a. Normal pool elevation and the top-bank elevation.
- b. The total number of range surveys stored in the file.
- c. Range locations in river miles. Ranges in cutoff bends were located using preproject river miles, while cutoff channel ranges were designated using navigation channel miles.
- d. An identification code for each range.
- e. The dates the range was surveyed.
- f. The total number of hydrographic survey points for each range.

60. The hydrographic survey data pairs (distance, elevation) were tested to verify consistency through all years for which the ranges were surveyed. This testing occasionally required changes to the range survey data as copied from the data tape. All such changes were clearly noted in the data files and are shown in Table B2 in Appendix B.

61. The circumstances that required editing or changing the data copied from the original tape acquired from the Mobile District were as follows:

a. <u>Data entry error.</u> Occasionally a survey point was entered twice, or a survey point may have been entered in the wrong order. Normally data points for each range survey were tabulated with x-values in ascending order. Occasionally a point was entered out of sequence. Out of some 75,000 data points, less than 50 had to be changed due to data entry error.

b. <u>Inconsistent range length.</u> This was the most common reason for editing the data. Range end points always lay on the same line as the established range but at varying points along that line. Coverage of overbank areas was inconsistent. However, annual variation in range length was less than 10 percent and never involved the main channel. Sometimes a few points at one end of the range would be omitted; other times, some additional distance along the range would be surveyed. All of the surveys of each range for all years were forced to begin and end at the same point using the following procedure:

   (1) All surveys of the same range were compared, and the most frequently occurring start of range point and the most frequently occurring end of range point were selected.

   (2) When a survey was terminated more than 50 ft short of the selected end points, elevations from the previous year's survey were used to extend the survey to the selected end points. If no previous survey contained the end points, the supplemental data were extracted from a subsequent survey.

   (3) When a survey stopped less than 50 ft from a selected end point, a dummy end point was added with x-coordinate value equal to that of the selected common end point and a y-coordinate value equal to that of the nearest real survey point.

   (4) When real survey points were located landward of the selected common end point, the "extra" survey points were deleted. The distance truncated was typically less than 50 ft.

c. <u>Range intersected both bend and cut.</u> The navigation cut was nearly parallel to the cutoff river channel at three range locations. Figure A14 shows maps of each of these. In two cases, range 8A in Stinson Bend and 19A in Town Creek Bend (sites 416 and 417, respectively), postconstruction surveys were edited by inserting preconstruction points for one bank line. As shown in Figure A14, this was performed by plotting and superimposing preconstruction and postconstruction surveys of these ranges. Postconstruction data points landward of the preconstruction bank line were then replaced with data points from the preconstruction survey. The third case involved range 38A in the Vinton Cut (site 420), which is depicted in Figure A15. Postconstruction surveys were edited to eliminate the old river channel portion of the section. The left bank of the surveyed section was replaced with a steep line to create a typical cross section for the cut channel in this reach. The overbank on the

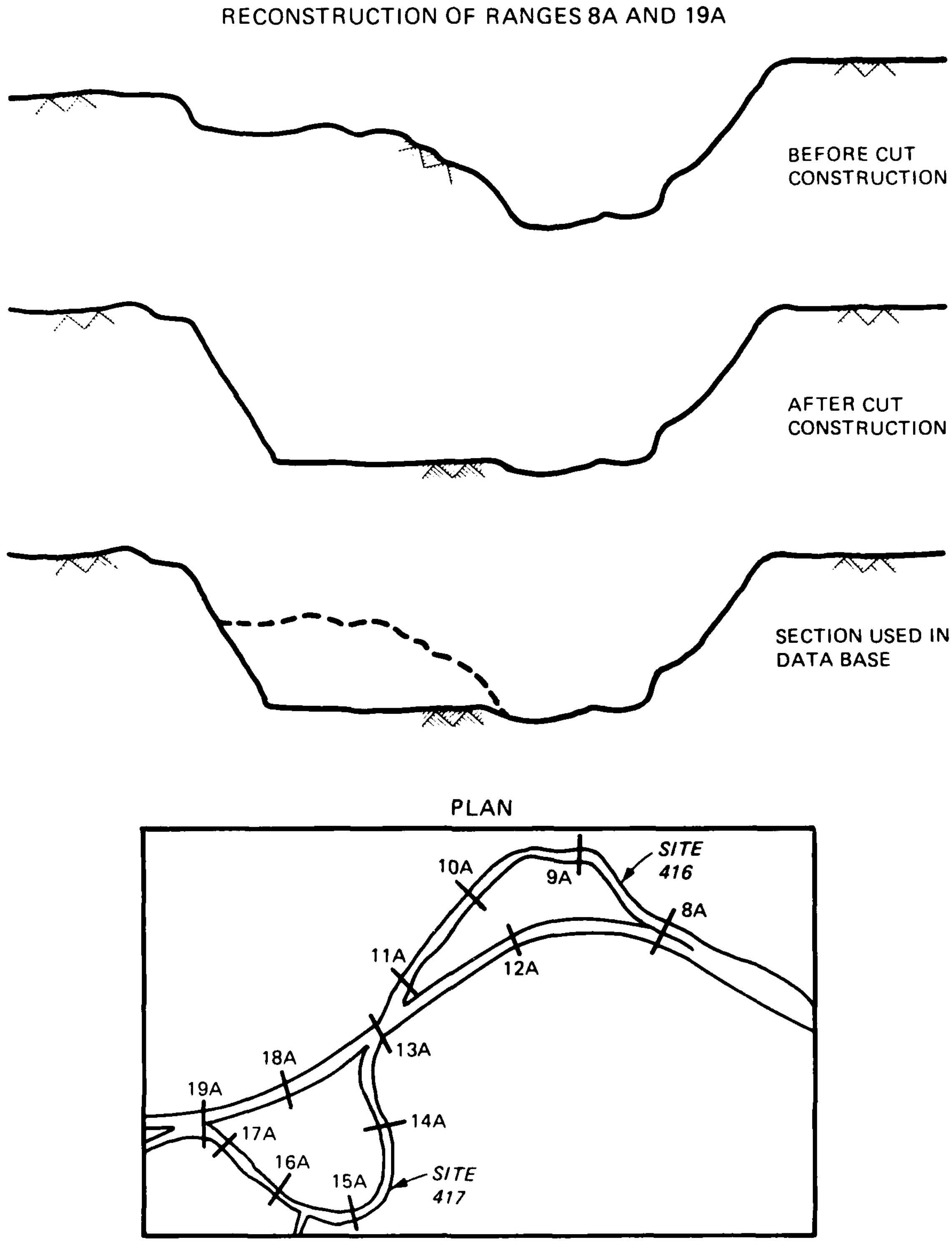


Figure A14. Schematic showing the procedure used to edit data from ranges 8A (site 416) and 19A (site 417)

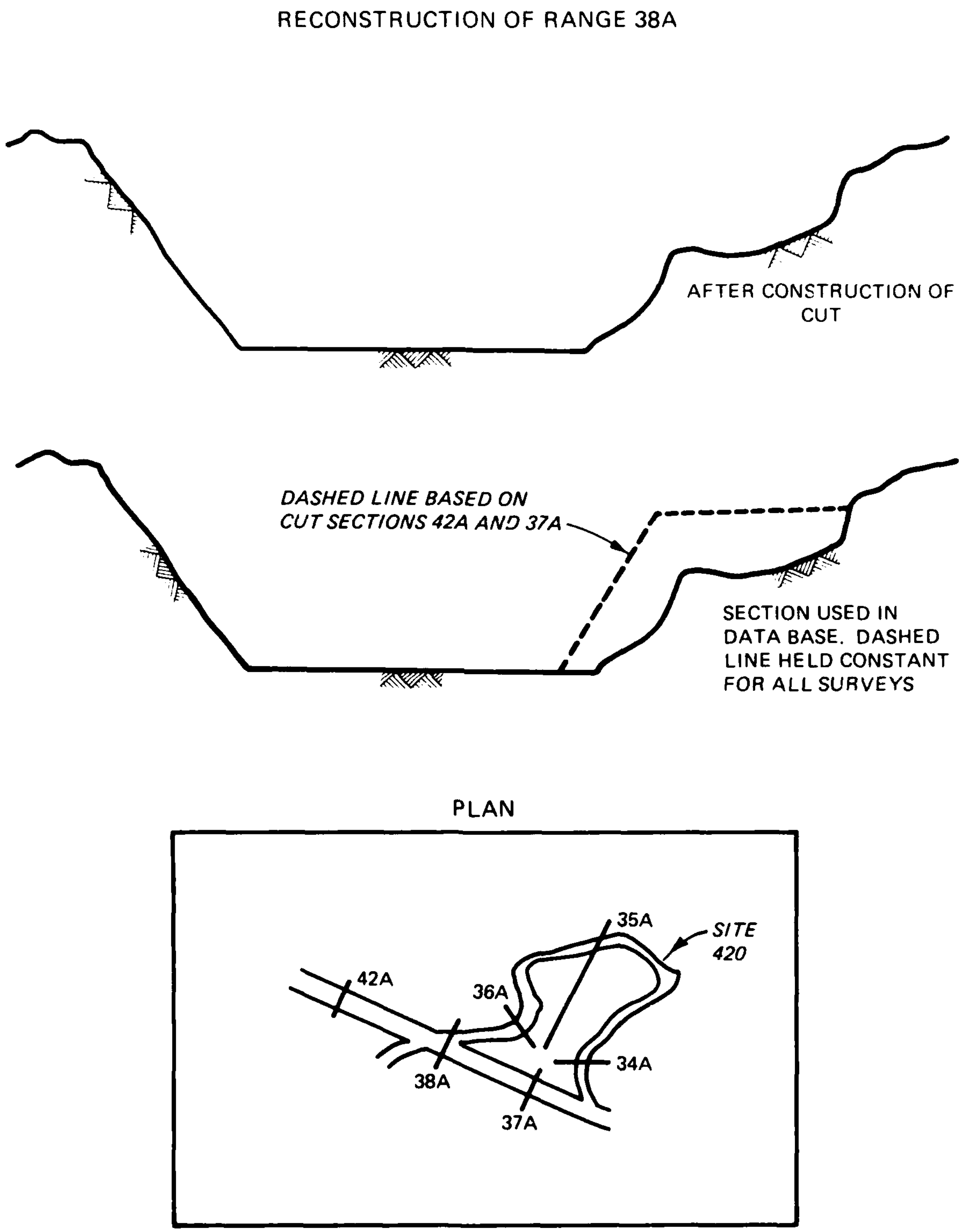


Figure A15. Schematic showing the procedure used to edit data from range 38A (site 420) left side was assigned a constant elevation selected based on surveys of left bank ranges immediately upstream and downstream.

Calculations

62. After the data files were edited, they were used as input for a computer program designed to mimic the manual procedure described above that was used for the sites from rivers other than the Tombigbee. The program selected top-bank elevations for each cross-section survey using the criteria shown in Figure A11. Variation of top-bank elevations between Tombigbee River ranges in the same bend or cut was occasionally large (i.e., 5 to 10 ft). For this reason, constant top-bank elevations were selected for each of the 14 Tombigbee River bends and each of the 14 cuts. Frequency distributions of the top-bank elevations that were produced by the procedure for each bend and each cut were examined. The selected top-bank elevations are presented in Table A11.

Table A11

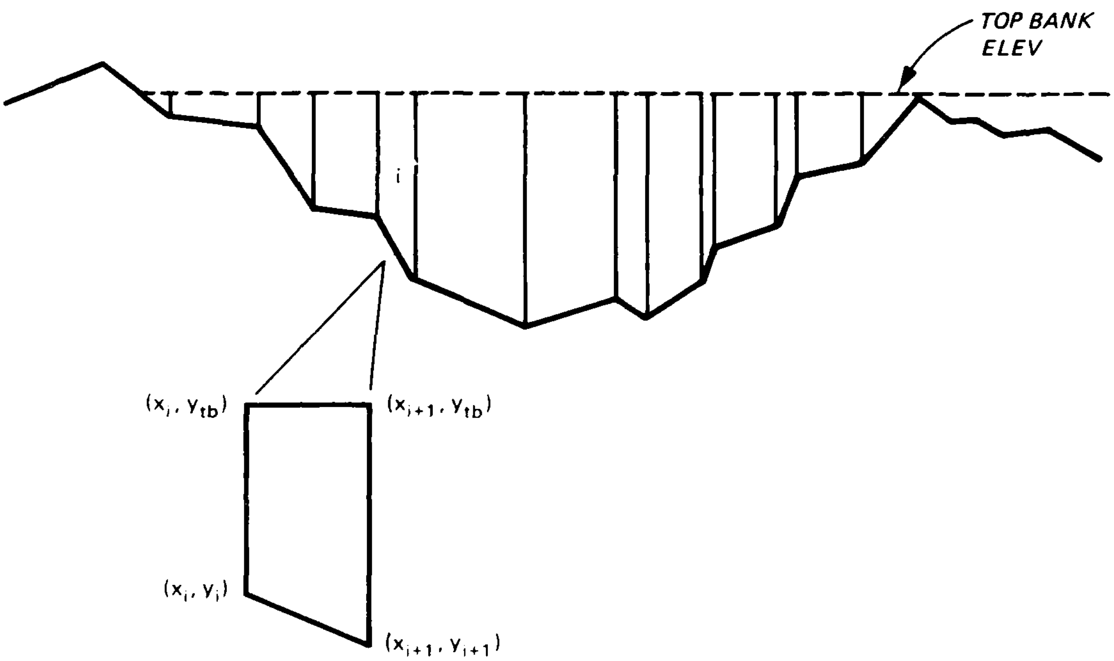
Top-Bank Elevations for Tombigbee River Bends and Cuts (in feet, MSL)

Site	Selected Elevation for Bend	Mean	Median	Selected Elevation for Cut	Mean	Median
101	85.4	85.4	85.4	85.4	86.2	85.4
203	115.0	115.6	115.1	116.0	116.5	117.1
208	126.0	125.9	126.5	130.0	130.2	130.7
311	142.8	143.0	142.8	146.3	146.3	146.4
416	173.6	173.7	173.6	174.9	174.9	174.9
417	175.2	175.3	175.9	175.8	175.8	176.0
419	174.6	174.6	177.2	176.7	176.8	176.7
420	172.0	172.1	170.6	170.7	170.8	170.7
421	173.3	173.7	173.9	168.8	168.8	168.8
422	173.7	173.7	173.9	170.7	170.9	171.0
423	175.0	176.2	174.7	175.8	176.5	175.8
427	178.5	178.5	179.0	178.8	179.4	178.8
429	183.1	185.4	183.1	184.0	184.0	184.4

63. Data files prepared as described above were used as input to a FORTRAN computer program that calculated geometric characteristics of the surveyed bends and cuts. The computer program first located the minimum elevation in each cross section and recorded it as the thalweg elevation. Next, the cross-sectional area, which was the area enclosed by the channel and a

horizontal line drawn at top-bank elevation, was determined. Areas were calculated by computing and summing incremental areas of trapezoids and triangles enclosed by survey points, as shown in Figure A16.

64. Channel volumes were calculated using the average end-area approach. The computer program performed two complete sets of computations for each bendway and each cut: one using top-bank elevation as the vertical upper limit of the cross sections and another using normal pool elevation. The second set of calculations was performed since the volume of deposition below normal pool elevation was of interest. The quantity and quality of available aquatic habitat are reflected by depths and water surface areas present when the water surface is at normal pool elevation. Water surface elevations along



$$\text{AREA OF SUBSECTION } i = (x_{i+1} - x_i)\left[(y_{tb} - y_i) + \frac{(y_i - y_{i+1})}{2}\right]$$

FOR TRIANGULAR SUBSECTIONS, EITHER $y_i = y_{tb}$ OR $y_{i+1} = y_{tb}$

Figure A16. Procedure used by computer program to compute cross-sectional areas this reach of the Tennessee-Tombigbee Waterway are maintained at normal pool elevations except during extreme events.

Reduction of Hydrologic Data

65. Streamflow records for each of the 21 cutoff bends were obtained from the USGS. Gaging stations for each site are listed in Table A3. These data were obtained on magnetic tape and placed in files on a microcomputer. The data were then reformatted using a simple FORTRAN program, and the adjustments described in Table A3 were performed using spreadsheet software on the microcomputer. Finally, t^* was computed for each survey of each cutoff bend:

$$t^* = (86{,}400 \text{ sec/day}) \times \sum_{i=0}^{t} Q \, \Delta t / V_b(0) \qquad \text{(A15)}$$

where

t^* = dimensionless time surrogate

Q = mean flow for day i, cfs

$V_b(0)$ = bend volume at time 0 in cubic feet. Time 0 was defined as either the date of the first survey or the date when the cut was completed, whichever was later. As shown in Table A12, these two dates were separated by less than a year for all of the sites except one (site 906).

Determination of Average Sediment Concentration

66. Available suspended bed material concentration data were used to determine coefficients a and b for power functions of the form

$$Q_s = a(Q - Q_c)^b \qquad \text{(A16)}$$

where

Q_s = sediment discharge, tons/day

Q = mean daily discharge, cfs

Q_c = critical discharge, cfs

a and b = coefficients

Table A12

Dates for Initial Survey and Cut Completion

Site	Initial Survey	Cut Complete
101	2/77*	5/76
203	8/79*	1/80
208	8/79*	4/79
311	7/81*	3/81
416	10/82*	11/82
417	10/82*	10/82
419	11/82*	11/82
420	12/82*	12/82
421	12/82*	12/82
422	12/82*	12/82
423	12/82*	12/82
427	12/82*	12/82
429	4/81**	12/82
601	11/3/72*	11/7/72
701	3/33*	3/26/33
720	2/64*	gradual process
904	7/50*	5/13/50
906	54	5/57*
907	54	3/55*
908	3/53	5/54*

* This date used for $t = 0$ in computing t^* : $t^* = \sum_{i=0}^{t} Q\ \Delta t/V_b(0)$.

** The April 1981 date was used as the initial survey for site 429 because the 1982 survey was of poor quality and had very limited coverage. This probably resulted in a higher value of $-K_d$ for site 429 since the bend probably experienced some aggradation prior to cutoff due to closure of Columbus Dam downstream (January 1981).

67. The variable Q_c was assumed to be zero for the open-river systems (Arkansas, Mississippi, Red). Suspended bed material data and power curve fits to the data are shown in Figure A17 for the Mississippi, Red, and Arkansas Rivers. Equations for these curves are given in Table A13.

68. Plots of bed material concentration versus discharge for stations just upstream of four of the Tombigbee River bendways (sites 101, 203, 208, and 311) are shown in Figure A18. These plots indicated nonzero values of Q_c , which seems reasonable for a canalized river. Run-of-river impoundments along canalized rivers generally exhibit hydraulic characteristics that are more similar to lakes than rivers at low to moderate discharges. At higher discharges, they become more similar to rivers, and sediment transport rates

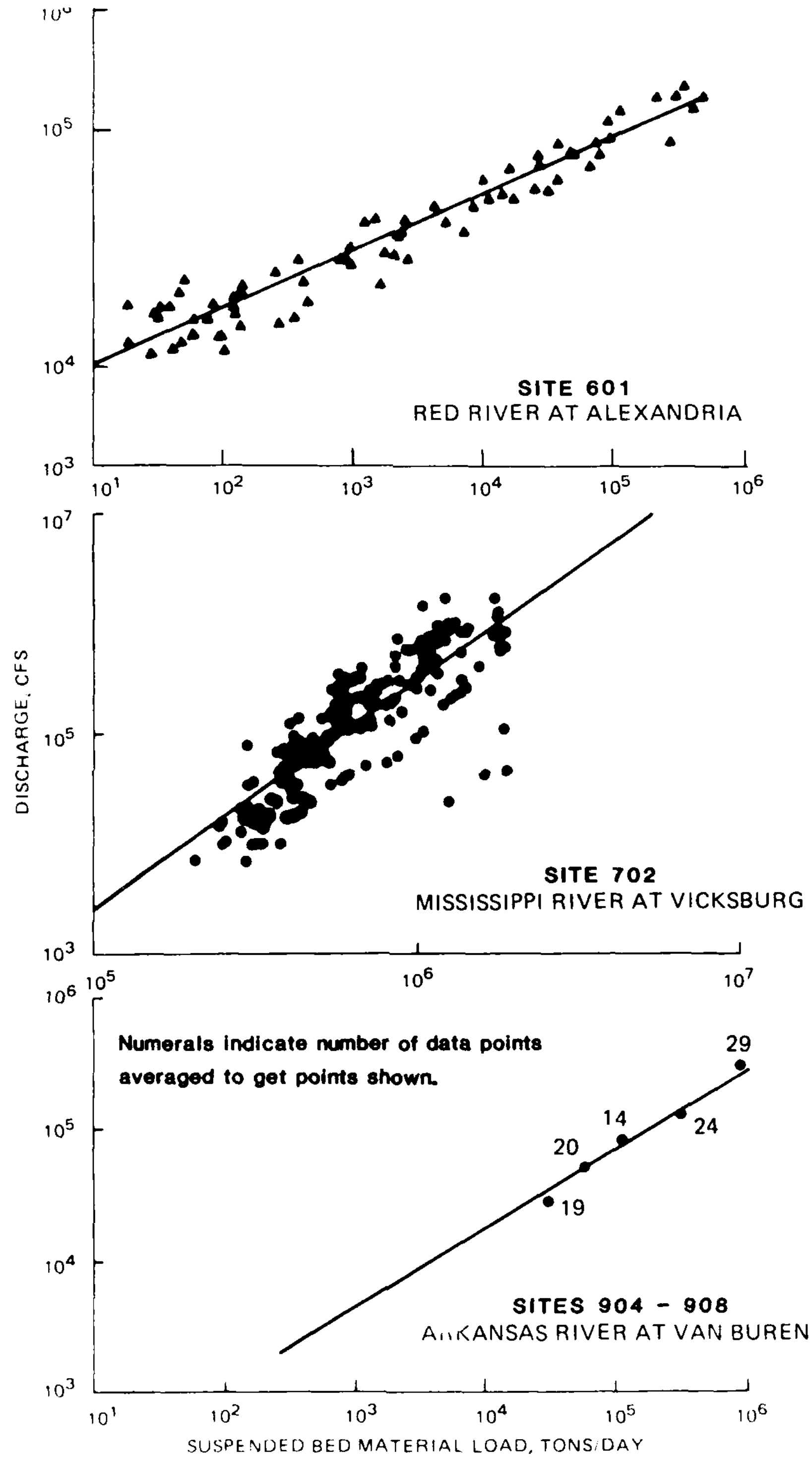


Figure A17. Suspended bed material curves for open-river systems

Table A13

Constants for Bed Material Transport Functions*

Site	$Q_c \times 10^{-4}$	$a \times 10^{-9}$	b	r^2	n**
101	4.28	1,260	2.23	0.658	7
203	2.02	5.23	2.67	0.874	8
208	2.72	9.01	2.73	0.947	5
311	2.73	163.	2.51	0.696	6
601	0	1,510	2.20	--	70
720	0	98.6	2.08	0.704	191
904-908	0	100,000	1.67	0.977	123

* Q_s (tons/day) $= a(Q - Q_c)^b$; Q and Q_c in cubic feet per second.

** Number of points.

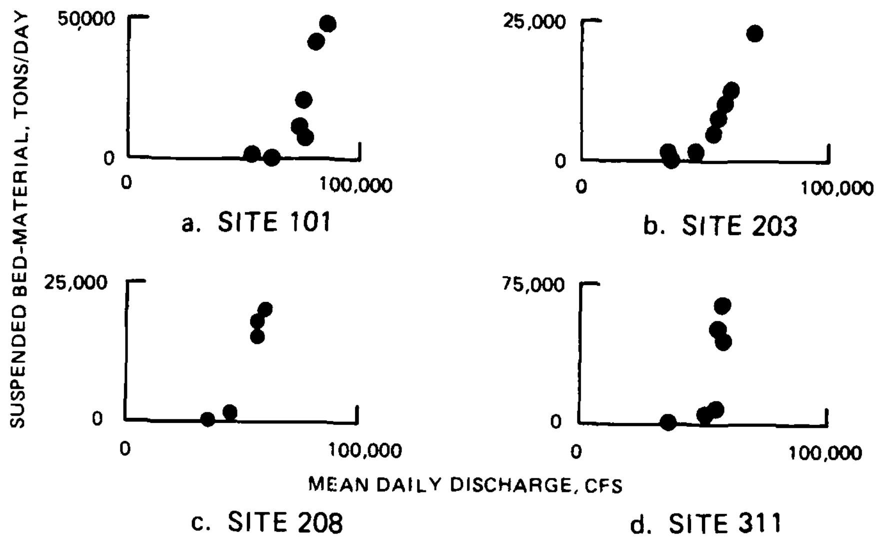


Figure A18. Suspended bed material concentration versus discharge for stations just upstream of four Tombigbee River sites

respond accordingly. The Q_c values were therefore determined by fitting linear regression functions of the form

$$\log C_s = a + b \log Q \tag{A17}$$

where C_s = bed material concentration, ppm. These functions were then used to estimate the critical discharge as the mean daily flow for $C_s = 1.0$ ppm. Plots of these functions are shown in Figure A19. Since $\log 1.0 = 0$, Q_c was determined from the functional regression coefficients as $Q_c = 10^{-a/b^c}$. The Q_c values ranged from 20,200 to 42,800 cfs as shown in Table A13.

69. Coefficients for the power function of Equation A17 were determined using linear regression on log-transformed values of Q_s and $Q - Q_c$:

$$\log Q_s = A + B \log (Q - Q_c) \quad \text{(A18)}$$

$$\log Q_s = \log (10^A)(Q - Q_c)^B \quad \text{(A19)}$$

$$Q_s = (10^A)(Q - Q_c)^B \quad \text{(A20)}$$

Therefore, $a = 10^A$ and $b = B$. (A21)

Linear regression of log-transformed data was used instead of nonlinear regression because nonlinear regression was too heavily influenced by large

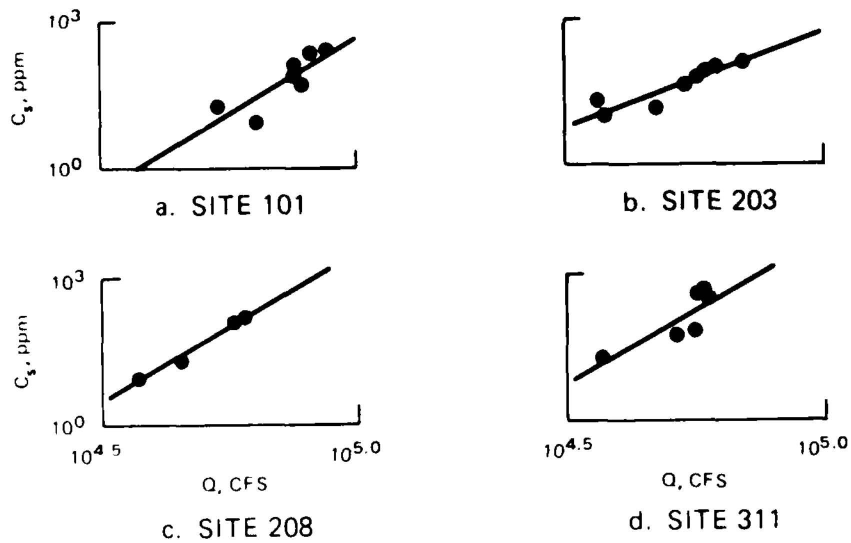


Figure A19. Log-log plots of suspended bed material concentration, C_s , versus mean daily discharge, Q , for Tombigbee River sites 101, 203, 208, and 311

Q_s outliers. Values of a and b are presented in Table A13, and the resulting functions are plotted in Figure A20.

70. Suspended bed material data were unavailable for the nine Tombigbee River study sites in Columbus Pool depicted in Figure A7. Values of a , b , and Q_c for the Columbus Pool sites (416-429) were estimated. First, Q_c for the lower reach of Columbus Pool was estimated to be 1,000 cfs by incipient motion analysis (Simons, Li, and Associates 1982). The Q_c values for each bend in Columbus Pool were computed by multiplying 1,000 cfs by the ratio of the drainage area upstream of the bend in question to the drainage area upstream of the damsite as shown in Table A14.

71. Values for coefficients a and b were assigned based on the following reasoning. Bed material transport at a given cross section along the Tombigbee River is controlled by the local hydraulics and hydraulic geometry. Due to backwater effects, local hydraulic conditions are heavily influenced by the distance downstream to the next dam. Mobile District (1984) divided each of the impoundments into three reaches, categorized as upper, middle, or lower based on local hydraulics. Accordingly, the values of coefficients a and b calculated for site 208 were used for the upstream portion of Columbus Pool (sites 429-419), and those computed for site 203 (a midpool location in Gainesville Pool) were used for the middle portion of Columbus Pool (sites 416-417).

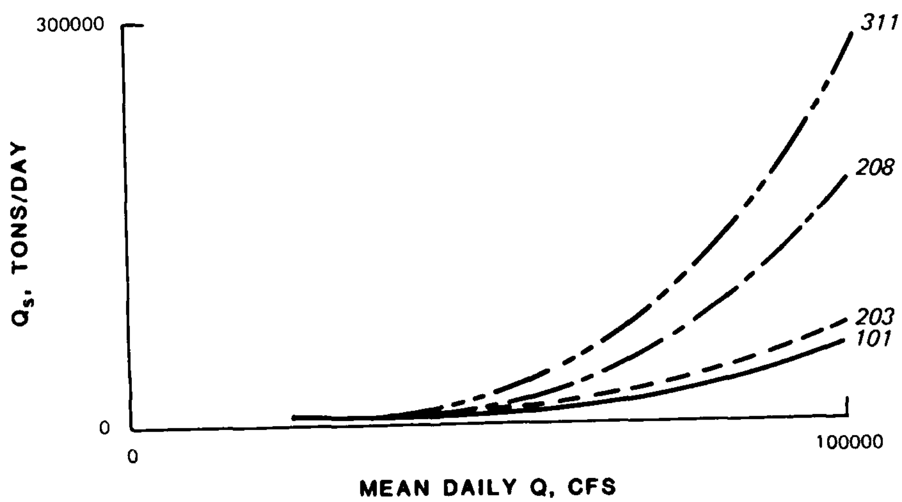


Figure A20. Regression functions for Q_s

Table A14

Columbus Pool Q_s Relations

Site	Upstream Drainage Area*	Location in Pool	Formula for Q_s, tons/day**
Columbus L&D	4,440	Low	
416-417	3,171	Mid	$5.23 \times 10^{-9} \times (0.71Q_{w_{columbus}} - 1,000)^{2.67}$
419-429	2,171	High	$9.00 \times 10^{-9} \times (0.49Q_{w_{columbus}} - 1,000)^{2.73}$

* Expressed in square miles.

** $Q_{w_{columbus}}$ = mean daily flow at Columbus Lock and Dam, cfs.

$Q_s = 0$ when the quantity in parentheses is <0.

72. Suspended bed material data were also unavailable for the period of time coinciding with the blockage phase at site 701 (Glasscock Bend, Mississippi River, 1933-1964). Average C_s for this site was estimated to be 240 ppm based on information presented by Keown, Dardeau, and Causey (1981, pp F51-F53). They estimated the annual suspended sediment load of the lower Mississippi River mainstream prior to 1963 to be 434 million tons, about 30 percent of which was coarser than 0.062 mm. Dividing 30 percent of 434 million, or 130 million tons, by the weight of the mean annual water discharge for the 31 years of hydrographic survey record for site 701 (1933-64) yields an average suspended bed material concentration, C_s, of 240 ppm. This value was about three times greater than the value of 75 ppm that was calculated for the period 1964-84 at site 720 using suspended sediment measurements. The relative size of these values for C_s is sensible in light of the observed reduction in sediment load in the lower Mississippi River over the last 50 years (Keown, Dardeau, and Causey 1981).

73. Average bed material concentration was computed for each bend other than site 701 by first using the regression functions for Q_s to determine daily mean Q_s values in tons per day. The Q_s values were then summed over

the period of record. The sum was divided by the weight of water discharged for the same time period:

$$C_s = \sum_{t=0}^{t} (Q_s CF) / \sum_{t=0}^{t} Q \ \Delta t \tag{A22}$$

where

C_s = dimensionless ratio of weights, ppm

CF = conversion factor to convert both numerator and denominator to pounds

74. The C_s values estimated for sites 208a,* 427, and 429 using Equation A22 are probably too low. As shown in Figure A7, these sites are located in the upper portions of navigation pools and received inflow from uncontrolled drainage areas upstream. For example, Big Creek Bend was cut off in April 1979, and Aliceville Lock and Dam was completed and closed in December 1979. The C_s data for site 208 were collected in 1984 when the Aliceville Pool was trapping a significant fraction of the sediment load. Furthermore, during construction of Aliceville Dam (1973-79), the Tombigbee River was diverted around the damsite in an unlined channel that eroded during high flows. Aggradation in the upper limb of Big Creek Bend is evident on sequential aerial photographs taken prior to cutoff during construction of Aliceville Dam.

75. Similarly, sites 429 and 427 are located in the upper portion of Columbus Pool, which was raised in 1981. Aberdeen Pool, located just upstream of sites 429 and 427, was not raised until January 1984. During the intervening 3 years, sediment loads in this reach reflected no significant upstream impoundments in the drainage basin.

Decay and Growth Curves

76. Hydrographic survey records and hydrologic records were reduced to ordered pairs of the dimensionless variables $V_b/V_b(0)$ and t^* for 21 cutoff bends. These reduced data were used to generalize the unit response in cutoff bend or cut channel volume to a unit hydrologic input. Results of

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* See paragraph A77 for discussion of sites 208a and 208b.

hydrographic and hydrologic data reduction are presented in Table B3 of Appendix B. Functions of the form

$$V_b/V_b(0) = e^{K_d t^*} \tag{A23}$$

where

V_b = volume of bend at time t, ft^3

$V_b(0)$ = volume of bend at time 0, ft^3

K_d = dimensionless bend volume decay constant

t^* = surrogate time defined above

were fit to the data in Table B3 for each bend using nonlinear regression. Results of decay curve fitting are shown in Figure A21 and Table A15.

77. Two decay curves were fit for site 208, which is Big Creek Bend on the Tombigbee River. Cut off in April 1979, this bendway experienced rapid deposition and was reopened by dredging 145,000 cu yd from the upstream entrance in August 1981. Entrance conditions were thus "reset," necessitating two separate curves. The data for 1979-81 are hereinafter referred to as 208a and for 1981-85 as 208b.

78. In a similar fashion, equations of the form

$$V_c(0)/V_c = e^{K_g t^*} \tag{A24}$$

where

$V_c(0)$ = volume of cut channel at time 0, ft^3

V_c = volume of cut channel at time t, ft^3

K_g = dimensionless cut channel growth constant

were fit for each cut channel. The cut channel growth curves resulting from this analysis are presented in Figure A22.

79. Hydrographic surveys were available for only one of the Arkansas River cut channels (site 906). The K_g for this site was computed to be -8.97×10^{-5}. Arkansas River cutoff designers noted that the rate of cut channel enlargement was related to the "bed shear ratio," which is the ratio of average boundary shear stress in the cut channel to the average boundary shear stress in the bend. This bed shear ratio may be computed as the ratio of depth-slope products:

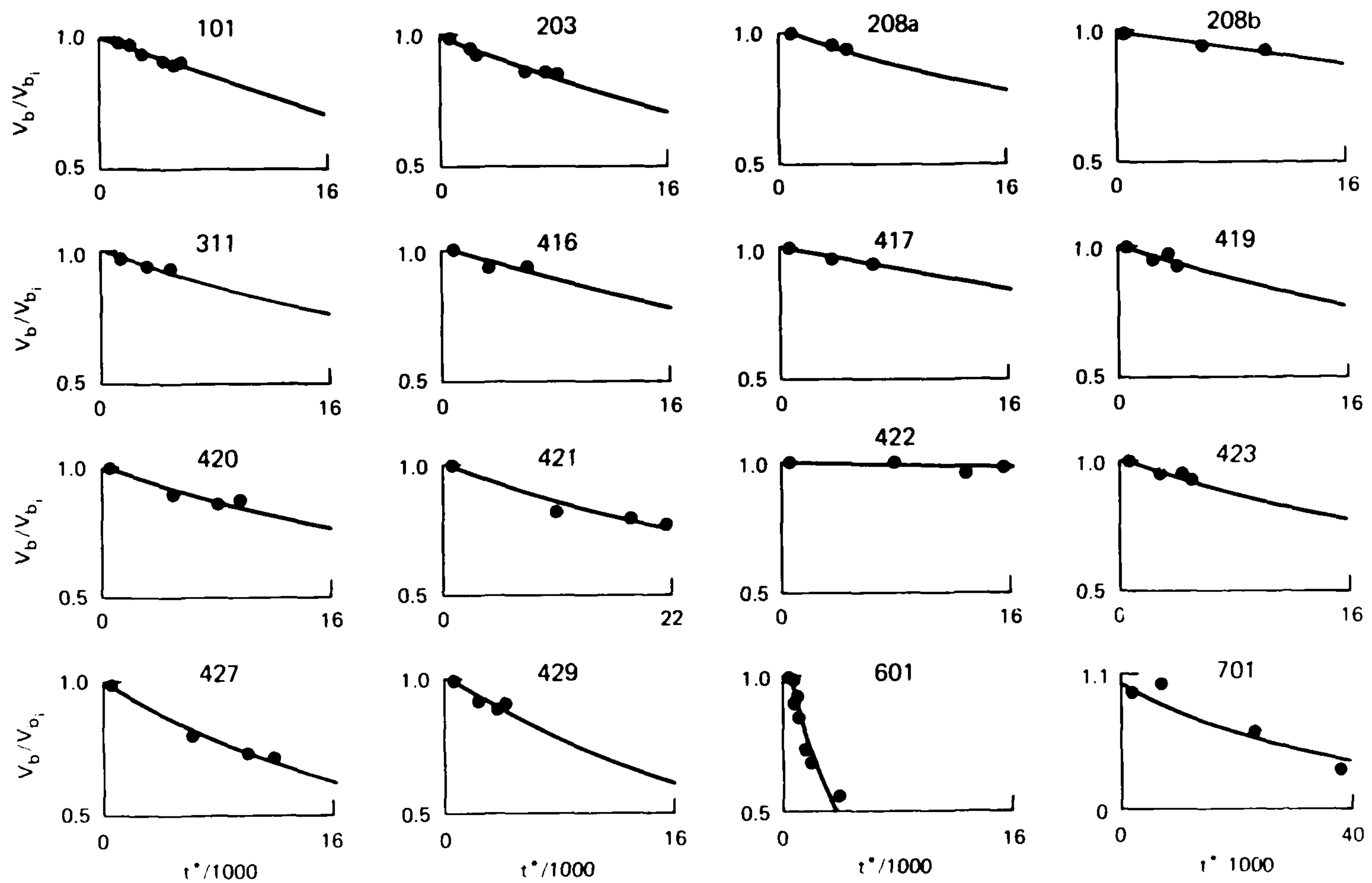


Figure A21. Decay curves for cutoff bends (Continued)

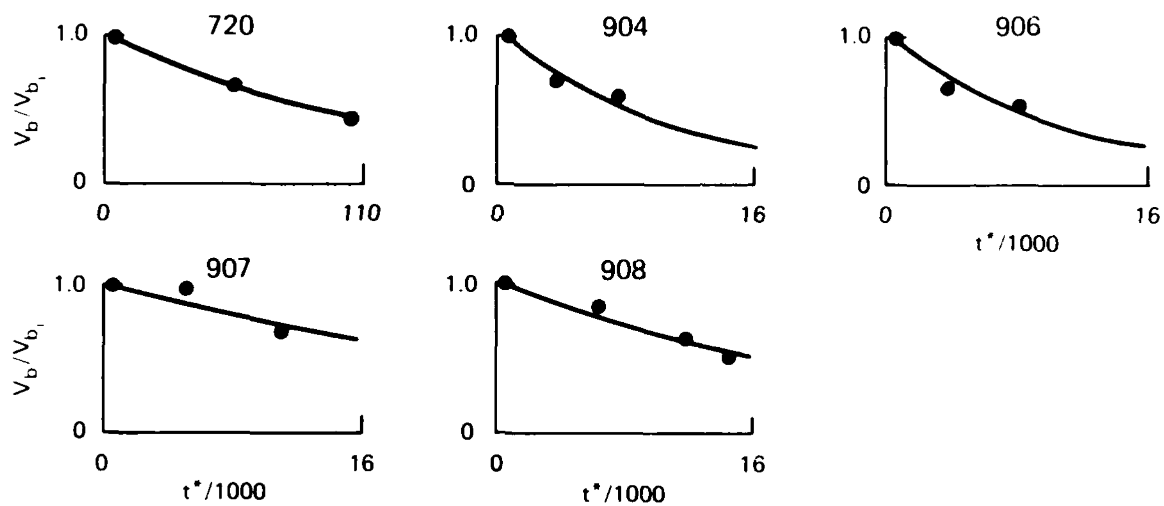


Figure A21. (Concluded)

Table A15

Values of K_d , K_g , and $K_{d_{pl}}$

Site*	$K_d \times 10^6$	n	r^2	$K_g \times 10^6$	n	r^2	$K_{d_{pl}} \times 10^6$	n	r^2
101	-22.4	8	0.917	-0.938	4	0.615	-34.0	8	0.906
203	-21.5	6	0.893	-10.7	4	0.868	-26.4	6	0.848
208a	-17.0	3	0.999	3.22	2	1.00	-64.9	3	0.980
208b	-8.64	3	0.901	22.2	2	1.00	-37.8	3	0.958
311	-17.0	4	0.949	-39.0	3	0.915	-27.8	4	0.915
416	-16.2	3	0.770	18.2	4	0.035	-28.2	3	0.637
417	-11.6	3	0.879	-11.6	3	0.916	-10.4	3	0.266
419	-17.2	4	0.568	-5.55	3	0.381	-24.3	4	0.350
420	-17.4	4	0.913	-18.3	3	0.732	-32.4	4	0.877
421	-14.5	4	0.921	-2.05	2	1.00	-26.4	4	0.944
422	-2.22	4	0.567	-0.142	3	0.174	-22.7	4	0.911
423	-16.5	4	0.836	-20.3	3	0.962	-46.5	4	0.861
427	-31.2	4	0.968	-29.7	3	0.894	-260.	4	0.992
429	-32.9	4	0.756	-5.65	3	0.603	-28.3	4	0.944
601	-233.	9	0.910	-468.	5	0.853			
701	-23.2	4	0.917	-383.	4	0.995			
720	-7.84	3	0.998	-4.88	3	0.884			
904	-93.8	3	0.931	-89.7	-	-			
906	-93.0	3	0.934	-79.5	5	0.590			
907	-31.0	3	0.828	-32.0	-	-			
908	-44.2	4	0.966	-34.3	-	-			

* Only two postcutoff surveys were available for Columbus Bend, site 312. Therefore, K_d and K_g values for that site were not included in this data set.

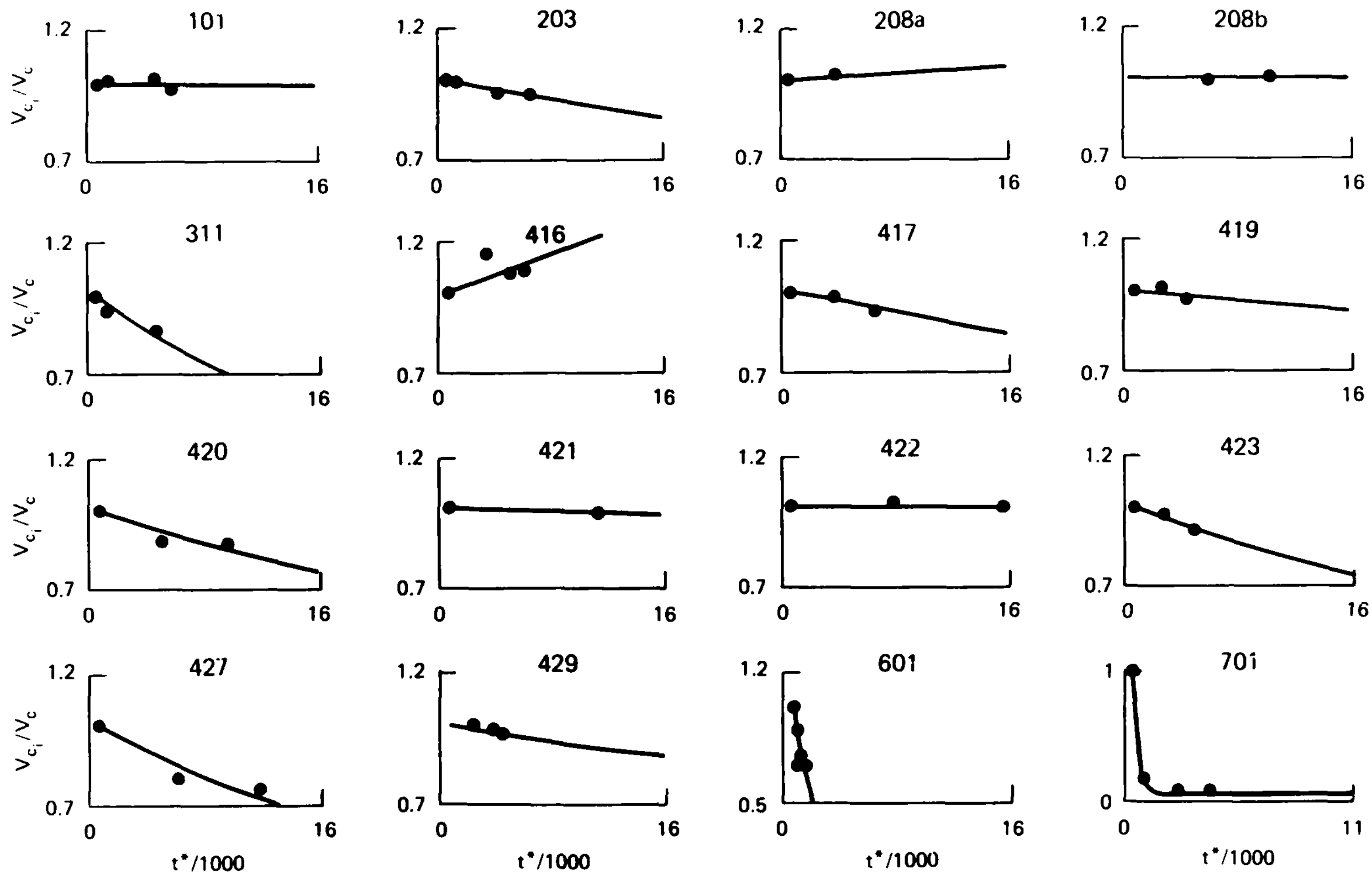


Figure A22. Growth curves for cut channels (Continued)

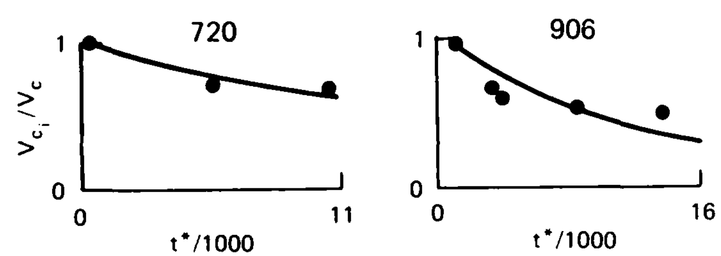


Figure A22. (Concluded)

$$\text{Bed shear ratio} = y_c S_c / y_b S_b \tag{A25}$$

where

y = depth

S = slope

c = cut

b = bend

80. Since cut channel growth is related to the bed shear ratio, K_g values were estimated for the three unsurveyed Arkansas River cut channels by multiplying the K_g value for site 906 by the ratio of bed shear ratios as shown in Table A16. The resulting K_g values agreed well with qualitative observations presented by Petersen (1963, 1964) and the Tulsa, Little Rock, and Vicksburg Districts (1960).

81. Bend channel volume decay coefficients were also generated using volumes below normal pool elevation for the Tombigbee River sites. These coefficients are defined as follows:

$$V_{b_{pl}} / V_{b_{pl}}(0) = e^{K_{d_{pl}} t^*} \tag{A26}$$

where

$V_{b_{pl}}$ = volume of bend below normal pool elevation

$K_{d_{pl}}$ = bend volume decay coefficient based on normal pool volume

Bend volume below normal pool elevation is equal to the volume of water in a cutoff bend except during high flows. The $K_{d_{pl}}$ values are therefore of interest for management of Tombigbee River bends. The normal pool volume decay curves are shown in Figure A23, and the related coefficients are presented in Table A15.

Table A16

Estimation of K_g for Sites 904, 907, and 908

Site	Character of Material Excavated for Pilot Cut Channel	L_r	Bottom width ft	Bottom Elev. ft CRP	Maximum Experienced Bed-Shear Ratio*	Ratio to Site 906	$-K_g \times 10^4$**
904	Sand bottom, moderately cohesive sides	3.2	50	-3.5 to 0	3.4+	3.4/3.0	0.897
906	Sand bottom, sides mostly erodible except for localized clay lenses	4.5	40	-6 to -4	±3.0	3.0/3.0	0.795
907	Predominantly sand bottom and sides	2.06	50	-1	1.21	1.21/3.0	0.320
908	Sand bottom, fairly resistant material in sides over half of total length	2.07	50	-1	1.30	1.3/3.0	0.343

* The "bed shear," or average boundary shear stress, τ_o, is roughly proportional to the product of depth and slope. The designers of the Arkansas River cutoffs noted that for the pilot channel to be self-scouring, the ratio of the bed shear in the cut channel to that in the bend had to be greater than about 1.5 for a channel excavated in sand and greater than about 2.0 for a channel excavated in relatively resistant material.

** K_g was computed for site 906 using surveys and hydrologic data. The other three K_g values were determined by multiplying the value for site 906 by the ratio of bed-shear ratios.

Qualitative Notes on Cut Channel Development

Site	US Army Engineer Districts, Tulsa, Little Rock, and Vicksburg (1960)	Petersen (1963, 1964)
904	Developed rapidly under very favor-	Subjected to high discharge able flow conditions. shortly after being opened.
906	Developed rapidly (very favorable flow conditions and large bed-shear ratio).	Subjected to high discharge shortly after being opened.
907	Channel widened but shoaled in the bottom, especially in upstream portion. After some additional excavation, channel widened and deepened satisfactorily.	Relatively slow development can be attributed to the gravelly material in the cutoff area and to the fact that caving of the right riverbank upstream of the pilot channel entrance produced flow patterns that tended to transport sediment into the cut channel rather than the old bend.
908	Some development during initial 205,000-cfs flow; little additional development in subsequent rises at 100,000 cfs.	Subjected to high discharge shortly after being opened.

Descriptive Statistics

82. A dimensionless data set describing 21 cutoff bends was assembled as shown in Table A17. Each of the dimensionless quantities in Equation A11 except for S_c , K_d , K_g , C_s , L_r , A_r , $\bar{y}_r$, V_r , L_c/r_c , $\sin\theta$, $\sin\psi_2$, $\bar{y}_b/L_b$, and W_c/r_c was determined for each of the 21 sites. Exploratory data analysis indicated that several of the dimensionless independent variables describing the geometry of the Togo Island natural chute cutoff (site 720) were extreme outliers to the rest of the data set. Maximum and minimum values for each of the dimensionless groups are shown in Table A18. Values for $\sin\psi_2$, A_r , $\bar{y}_r$, $Z/\bar{y}_c$, and W_c/r_c from site 720 were all extremes. Values of A_r , $\bar{y}_r$, $Z/\bar{y}_c$, and W_c/r_c for site 720 were all more than an order of magnitude larger or smaller than the next nearest value in the data set. However, the value of K_d for site 720 was not an outlier, and values of independent variables for site 720 other than those mentioned above were within the ranges observed for the other site. The extreme values for site 720 highlight the morphological differences between this natural chute cutoff and the other sites, which were all man-made. Additional remarks on this matter are found in Part III of this appendix.

83. In addition, data for site 427 (Hickelson Lake bendway) were not included in the regression analysis because it receives a significant input of sediment from a nearby surface mine, thus violating one of the key assumptions enumerated in Part I of this appendix. The sediment source is evident on aerial photographs and was noted by the Mobile District (1984) and the US Fish and Wildlife Service (in Mobile District 1984). The large negative values of K_d and $K_{d_{pl}}$ (Table A15) for site 427 confirm the magnitude and importance of the local sediment source.

Observed ranges

84. Maximum and minimum values for each variable from Table A17 are tabulated in Table A18. Estimated extreme values for each of these variables for man-made or natural neck cutoffs on US rivers are also presented in Table A18. Although the data set for this study is from only four rivers in the south- eastern United States, the range of conditions likely to be encountered in the field (as estimated by this investigator) are well represented by the data set.

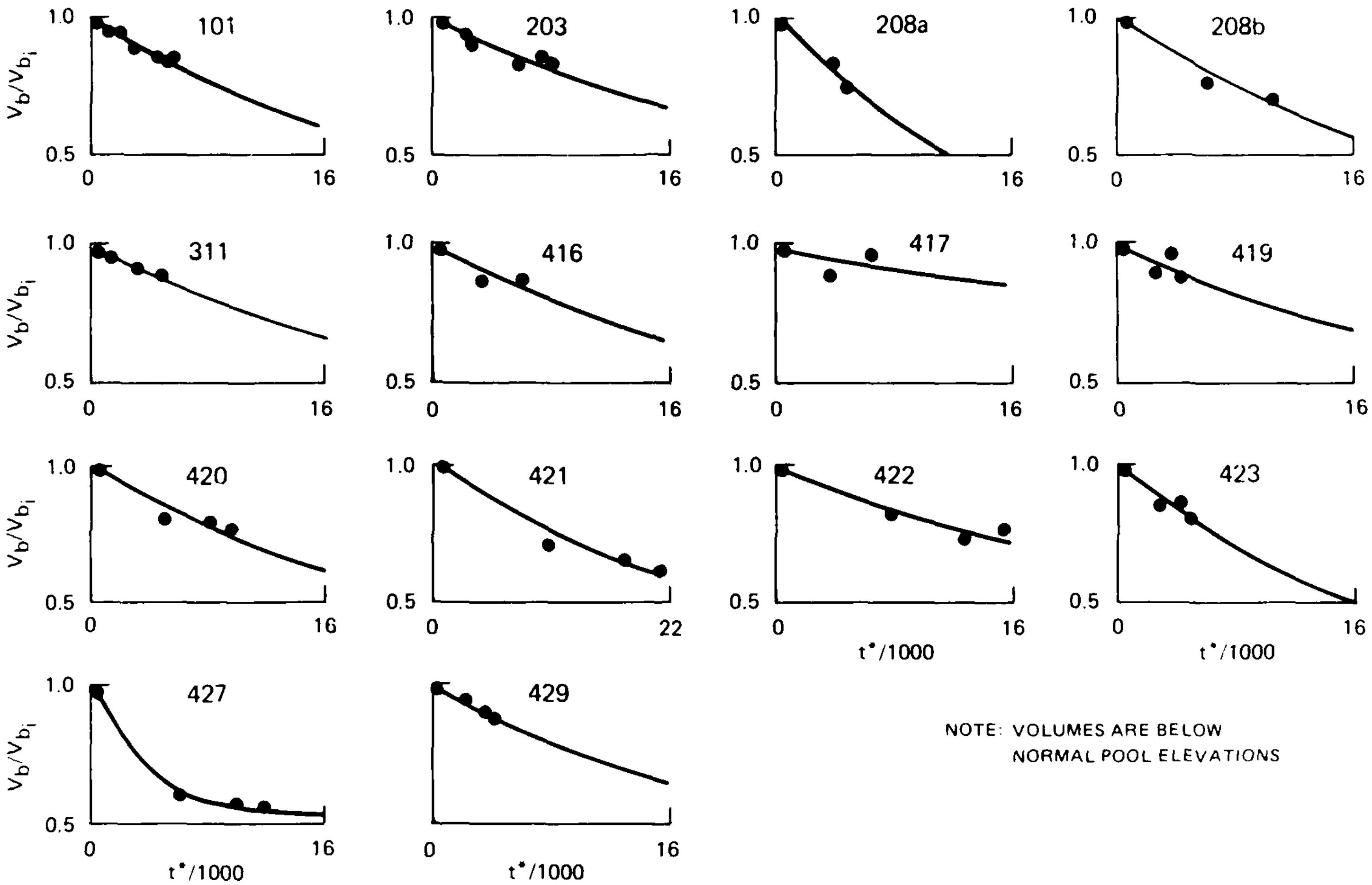


Figure A23. Decay curves using bend volume below normal pool elevation, Tombigbee River

Table A17

Dimensionless Data Set

Site No.	K_d	L_r	A_r	$\bar{y}_r$	V_r	L_c/r_c	$K_{d_{p1}}$	sin θ	sin ψ_2	$Z/\bar{y}_c$	C_s	K_g	$\ddot{y}_b/L_b$	W_c/r_c
101	-2.240E-05	8.921	1.489	1.493	25.84	-0.269	-3.40E-05	0.988	0.017	-0.493	82	-9.38E-07	5.00E-04	-0.028
203	-2.149E-05	3.552	1.424	1.288	6.68	0.225	-2.64E-05	0.656	0.309	-0.335	76	-1.07E-05	1.40E-03	0.017
208a	-1.700E-05	2.595	0.285	0.727	1.96	-1.124	-6.49E-05	0.809	0.017	0.052	64	3.22E-06	9.00E-04	-0.183
208b	-8.640E-06	2.595	0.383	0.976	1.89	-1.124	-3.78E-05	0.809	0.017	-0.200	133	2.22E-07	1.10E-03	-0.183
311	-1.700E-05	8.043	0.713	0.978	15.54	0.000	-2.78E-05	0.777	0.017	-0.253	207	-3.90E-05	4.00E-04	0.000
416	-1.624E-05	1.327	0.680	1.090	1.01	0.975	-2.82E-05	0.485	0.017	-0.177	69	1.82E-05	1.60E-03	0.105
417	-1.161E-05	1.821	0.960	0.882	1.89	0.637	-1.05E-05	0.829	0.259	0.083	68	-1.16E-05	1.40E-03	0.058
419	-1.720E-05	1.584	0.598	0.591	1.49	0.000	-2.43E-05	0.978	0.139	0.311	117	-5.55E-06	9.00E-04	0.000
420	-1.740E-05	3.148	0.710	0.666	5.36	0.000	-3.24E-05	0.469	0.017	0.416	124	-1.83E-05	1.30E-03	0.000
421	-1.446E-05	1.584	0.611	0.633	0.86	0.000	-2.65E-05	0.961	0.017	0.253	124	-2.05E-06	1.40E-03	0.000
422	-2.220E-06	1.936	0.736	0.531	1.46	0.444	-2.27E-05	0.978	0.259	0.628	124	-1.42E-07	1.70E-03	0.058
423	-1.650E-05	2.606	0.521	0.664	0.71	0.670	-4.65E-05	0.629	0.017	0.287	124	-2.03E-05	7.00E-04	0.074
427	-3.120E-05	2.491	0.391	0.644	1.70	0.095	-2.60E-04	0.956	0.174	0.342	124	-2.97E-05	1.30E-03	0.010
429	-3.290E-05	1.578	0.364	0.807	0.64	1.000	-2.83E-05	0.970	0.052	0.153	124	-5.65E-06	9.00E-04	0.049
601	-2.330E-04	2.696	3.383	1.340	8.78	0.536		0.208	0.017	-1.162	398	-4.68E-04	1.90E-03	0.040
701	-2.320E-05	3.960	8.669	1.199	121.09	0.492		0.743	0.242	-0.199	240	-3.83E-04	4.00E-04	0.011
720	-7.838E-06	1.928	126.80	44.480	0.90	0.943		0.974	0.857	-43.402	75	-4.88E-06	1.40E-03	0.099
904	-9.382E-05	3.539	22.520	1.237	73.08	1.117		0.707	0.707	0.204	568	-8.97E-05	6.73E-04	0.013
906	-9.303E-05	8.410	21.337	1.327	112.01	0.229		0.755	0.326	0.325	535	-7.95E-05	6.59E-04	0.006
907	-3.103E-05	2.400	16.0047	0.981	36.35	0.517		0.921	0.122	0.551	578	-3.20E-05	7.91E-04	0.008
908	-4.423E-05	1.810	24.4626	0.838	23.95	0.604		0.906	0.122	0.488	540	-3.43E-05	7.22E-04	0.007

Table A18

Observed and Estimated Possible Ranges for Dimensionless Variables

Dimensionless Variables	Observed Range Min	Observed Range Max	Probable Extremes* Min	Probable Extremes* Max
K_d	-10^{-4}	-10^{-6}	-10^{-3}	0
K_g	-5×10^{-4}	2×10^{-5}	-10^{-3}	10^{-4}
C_s	70	600	0	1000
$\sin \theta$	0.2	0.99	0	1
$\sin \psi_2$	0.02	0.86** (0.707)	0	1
L_r	1.3	8.9	1.2	12
A_r	0.36	130** (22.8)	-1.5	10
V_r	0.64	120	0.5	200
$\bar{y}_r$	0.37	44** (1.49)	0.1	10
L_c/r_c	-1.1	1.1	-1.5	11.5
$Z/\bar{y}_c$	-43** (-1.16)	0.63	-10	1.0
W_c/r_c	-0.183	0.105	-0.25	0.25
$\bar{y}_b/L_b$	0.000400	0.00190	0	0.1
S_c	unknown	unknown	-	-

* Estimate of maximum and minimum values for man-made or natural neck cut-offs on meandering rivers in the continental United States.

** Extreme value from site 720. Values in parentheses are extreme values from data set without site 720.

NOTE: All sites are from Table A16 except 427.

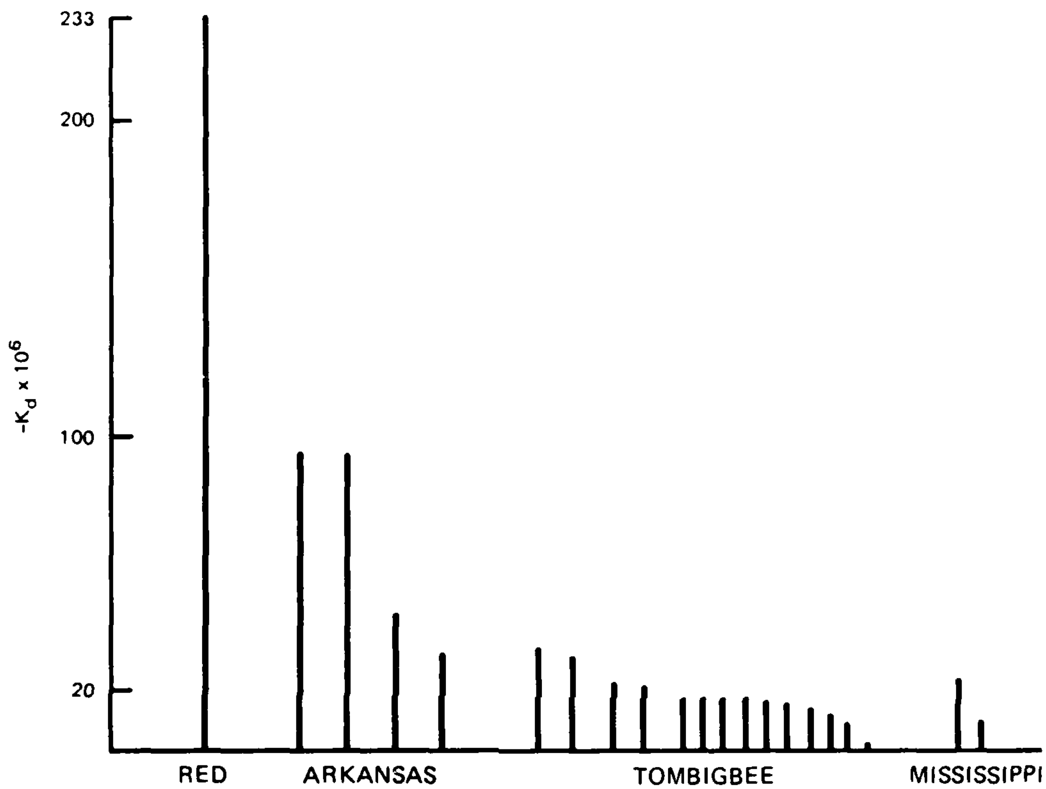
Variation in K_d values

85. The distribution of values for the decay constants K_d and $K_{d_{pl}}$ are shown in Figure A24. Variation of $K_{d_{pl}}$ values was slightly less than variation of K_d values. The coefficients of variation for K_d and $K_{d_{pl}}$ for the Tombigbee River sites were -0.4360 and -0.4142, respectively. The coefficient of variation (c.v.) is equal to the mean divided by the standard deviation. The coefficient of variation is thus a unitless measure of the scatter of a group of numbers with small values of the c.v. corresponding to groups clustered closely about their means. The bend decay constants evidently vary little from site to site along the Tombigbee River.

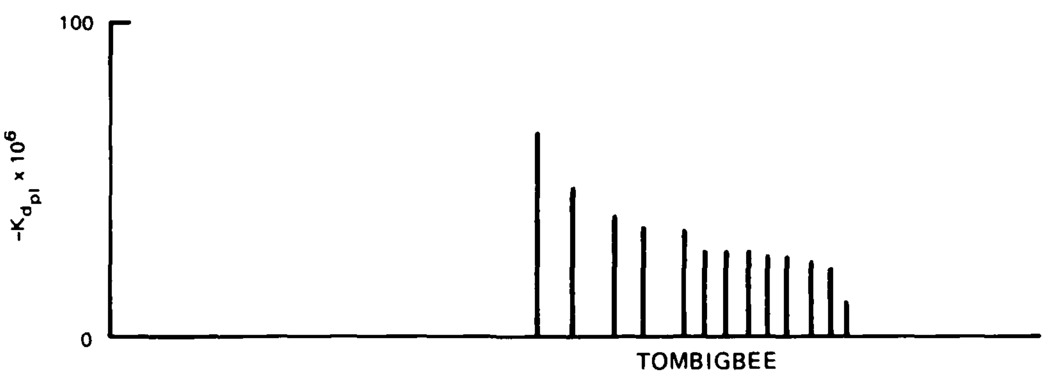
86. Examination of Figure A24 reveals that the observed K_d values tended to cluster about rather narrow ranges for each river, but these typical ranges varied substantially from river to river. Since the C_s also tends to vary about a typical value for a given river, the distribution of K_d suggests C_s would be a good predictor variable. The value of $-K_d$ for site 601 on the Red River was twice as great as for any other site, and C_s for this site was higher than all others except the Arkansas River sites. The quantity $C_s/\sin\theta$ was greatest for site 601.

87. The variation in K_d for the four Arkansas River sites (-31 to -94 $\times 10^{-6}$) appears partially related to the time elapsed between pilot channel completion and construction of low training structures across the upstream entrances of the cutoff bends. The difference in K_d values for the two Mississippi River sites (-8 and -23 $\times 10^{-6}$) seems to be related both to the lower C_s value for the more recent site (720) and to the radically different geometry of these two sites. Site 701 (Glasscock Bend) was cut off by repeated dredging of a very narrow, deep pilot channel across a meander neck, while site 720 was cut off by gradual natural development of a wide, shallow swale across a point bar.

88. Tombigbee River values of K_d are clustered around a mean of about -20×10^{-6}. Five of the 14 values are between -16.2×10^{-6} and -17.4×10^{-6}. Outlying values for sites 427, 429, and 422 may be explained, respectively, as the result of local sediment input from a surface mine (as previously described), aggradation in the upper portion of a recently raised reservoir pool, and both a large positive value for $Z/\bar{y}_c$ and location of the upstream



a. DISTRIBUTION OF DECAY CONSTANTS $-K_d$



b. DISTRIBUTION OF DECAY CONSTANTS $-K_{d_{pl}}$

Figure A24. Distribution of bend volume decay coefficients K_d and $K_{d_{pl}}$

bend entrance on the outside of a bend in the main channel. These observations on K_d variation are summarized in Table A19.

89. Examination of individual values of the independent variables as well as the decay constants shows that the data set is rather strongly divided into two subsets: Tombigbee River data and data from other rivers. Means and extremes for these two subsets are compared in Table A20. Cutoff bends from the Mississippi, Arkansas, and Red Rivers tended to have larger values of $-K_g$, C_s , V_r , and A_r , and smaller values of W_c . These values resulted in generally higher $-K_d$ values.

Regression Analyses

Data from rivers other than Tombigbee

90. A correlation matrix was computed for all 13 of the dimensionless variables of Equation A11 using only the data from the six man-made cutoffs on the Mississippi, Arkansas, and Red Rivers (601, 701, 904, 906, 907, 908). Only $\sin \Theta$, $Z/\bar{y}_c$, $\bar{y}_b/L_b$, and W_c/r_c were significantly correlated with K_d . A correlation matrix for these five variables is shown in Table A21. The correlation coefficients were little changed by the inclusion of data from the natural chute cutoff, except for pairs including $Z/\bar{y}_c$ or W_c/r_c . The difference in regression results obtained for these two independent variables when the observation for site 720 was used underscores the basic morphological difference between this natural chute cutoff and the six man-made cutoffs. Simple linear regression equations for K_d as a function of each of the four independent variables are shown in Table A22. Plots of selected equations from Table A22 are shown in Figure A25.

91. Multiple regression analysis was not attempted for this subset of the data because of the small number of points available. However, several simple combinations of the independent variables were used as predictor variables in linear regression in an effort to study their interaction and to find a good K_d predictor. The following relationship was obtained using $C_s/\sin \Theta$ as the independent variable:

$$K_d = 0.00001 \times [1.791 - 0.0129(C_s/\sin \Theta)] \tag{A27}$$

$$r^2 = 0.9452$$

Table A19

Variation of Bend Volume Decay Coefficients

Site	River	$-K_d \times 10^6$	C_s	Remarks
601	Red	233	400	Max observed $C_s/\sin\theta$
904	Arkansas	94	570	Closure constructed 3 years after cutoff
906		93	540	Closure constructed 3 years after cutoff
907		31	580	Closure constructed 1-2 years after cutoff. Also note comments by Petersen (1963, 1964), Table A16.
908		44	540	Closure constructed 3 years after cutoff
701	Mississippi	23	240	
720	Mississippi	8	75	
101-429	Tombigbee	All but 422 lie between 9 and 33	65-210	422 has maximum observed $Z/\bar{y}_c$ and the bend entrance is on the outside of a bend in the new channel

This function is also plotted in Figure A25. Variable $C_s/\sin\Theta$ was a particularly attractive combination because of its apparent physical meaning: the rate of volume reduction is related to the fraction of C_s diverted through the angle Θ into the old bend. As shown in Table A20, C_s seems to explain some of the variation in K_d between rivers. Flume data published by Lindner (1953), which are shown in Figure 1 of the main text, indicate that the fraction of bed material load moved into a diversion is inversely proportional to $\sin\Theta$.

Tombigbee River data

92. A stepwise multiple linear regression computer program (Press 1985) was used to generate a regression function for K_d for the Tombigbee River. After checking the data for normality, values for all 12 of the independent dimensionless variables for all 13 sites were input to the program (all

Table A20

Comparison of Means and Extremes of Data from Tombigbee River with Data from Other Rivers

Variable	Tombigbee* Min	Tombigbee* Mean	Tombigbee* Max	Other Rivers ** Min	Other Rivers ** Mean	Other Rivers ** Max
$K_d \times 10^6$	-32.9	-16.5	-2.22	-233	-86.4	-23.2
L_r	1.33	3.18	8.92	1.81	3.8	8.41
A_r	0.285	0.729	1.49	3.38	16.1	24.5
$\bar{y}_r$	0.531	0.871	1.49	0.838	1.15	1.34
V_r	0.639	5.02	25.8	8.78	62.5	121.1
L_c/r_c	-1.12	0.110	1.00	0.229	0.583	1.18
$\sin \theta$	0.469	0.795	0.988	0.208	0.707	0.921
$\sin \psi_2$	0.0174	0.0891	0.309	0.0174	0.256	0.707
$Z/\bar{y}_c$	-0.493	0.0557	0.628	-1.16	0.0346	0.551
C_s	64	110	207	240	480	578
$K_g \times 10^6$	-39.0	-7.12	18.2	-468	-181	-32.0
$\bar{y}_b/L_b \times 10^4$	4.00	10.9	17.0	4.00	8.57	119.0
$W_c/r_c \times 10^4$	-1830	-25.3	1050	59.0	140	395.

* n = 13. All sites but 427.
** n = 6. All sites but 720.

Table A21

Correlation Matrix, Data for Rivers Other Than Tombigbee*

Variable	$\sin \theta$	$Z/\bar{y}_c$	$\bar{y}_b/L_b$	W_c/r_c
K_d	0.9403	0.8174	-0.9156	-0.9034
$\sin \theta$		0.9600	0.7275	-0.6989
$Z/\bar{y}_c$			-0.7804	0.9285
$\bar{y}_b/L_b$				0.3360

* With $n = 6$, critical value for r at the 0.05 probability level = 0.8116.

Table A22

Linear Regressions for K_d , Rivers Other Than Tombigbee

Independent Variable	n	r^2	Intercept × 10^5	Slope × 10^5
sin θ	6(7)	0.8842(0.9012)	-28.6(-28.7)	28.2(28.4)
$Z/\bar{y}_c$	6(7)	0.6682(0.1278)	-8.98(-8.55)	9.91(-0.168)
$\bar{y}_b/L_b$	6(7)	0.8383(0.3929)	2.97(1.12)	-13530(-9240)
W_c/r_c	6(7)	0.8161(0.0061)	-0.858(-7.93)	-554(17.7)
C_s/sin θ	6(7)	0.9483(0.9452)	2.69(1.79)	-0.0137(-0.0129)

NOTE: Values in parentheses were derived using data from site 720.

14 surveyed TTW bends except Hickelson Lake and Columbus Bend; Big Creek counts as two sites, before and after dredging). An F-test (Neter and Wasserman 1974) was used to determine the order in which variables were entered. The F-statistic is the ratio of the regression mean square to the error mean square (Neter and Wasserman 1974). The higher F, the more significant the relationship is between the dependent variable and the independent variable being tested. The critical value of F (F to enter) was set at 2.70, which corresponds to a confidence level near 90 percent. The resulting regression function was

$$K_d = 0.00001(-2.534 + 805.5\ \bar{y}_b/L_b) \tag{A28}$$

$$r^2 = 0.2130$$

The C_s values for sites 429 and 208a were probably lower than the actual values because the methods used to estimate C_s did not account for the higher sediment load prior to closure of upstream dams. The effect of these low values was explored by doubling C_s for these two sites and then again running the stepwise regression program. However, C_s remained uncorrelated with K_d , and the resultant regression equation was unchanged. A linear regression plot showing K_d as a function of $\bar{y}_b/L_b$ for the Tombigbee River data is shown in Figure A26.

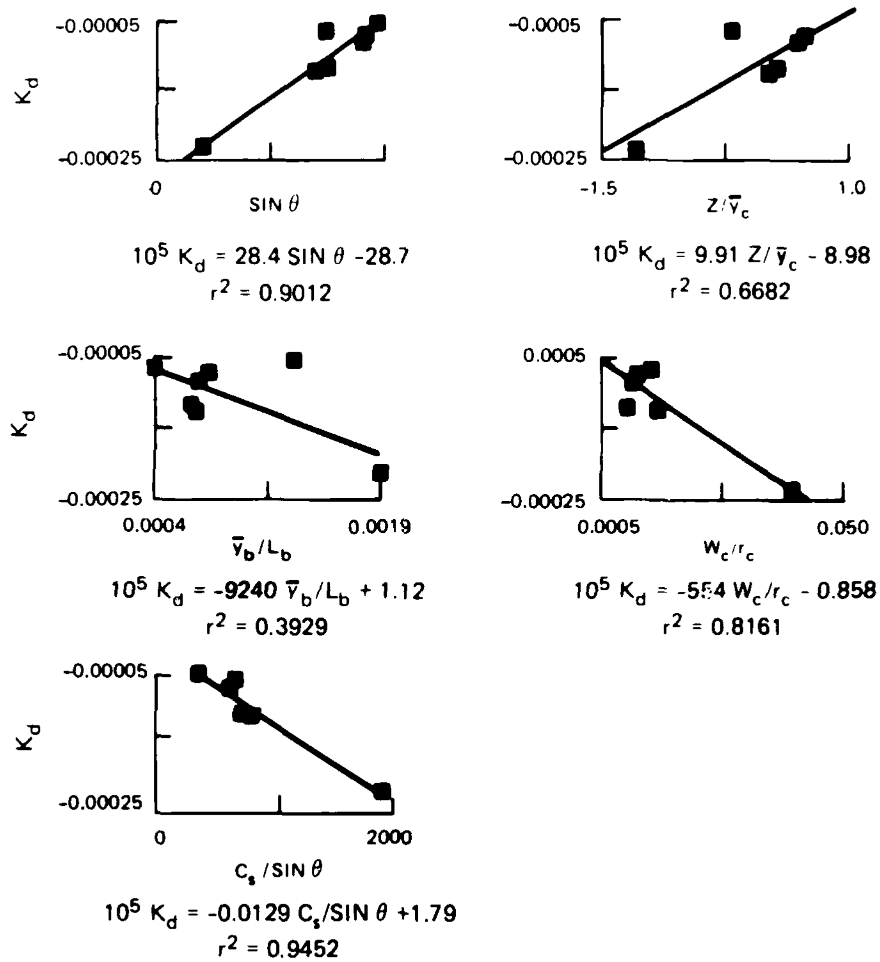


Figure A25. Regression functions for K_d, data from Mississippi, Arkansas and Red Rivers

93. When only data from the Columbus Pool sites (except 427) were input, the stepwise program yielded:

$$K_d = 0.00001(-4.23 + 3.51\ A_r + 1.51\ Z/\bar{y}_c) \tag{A29}$$

$$r^2 = 0.6932$$

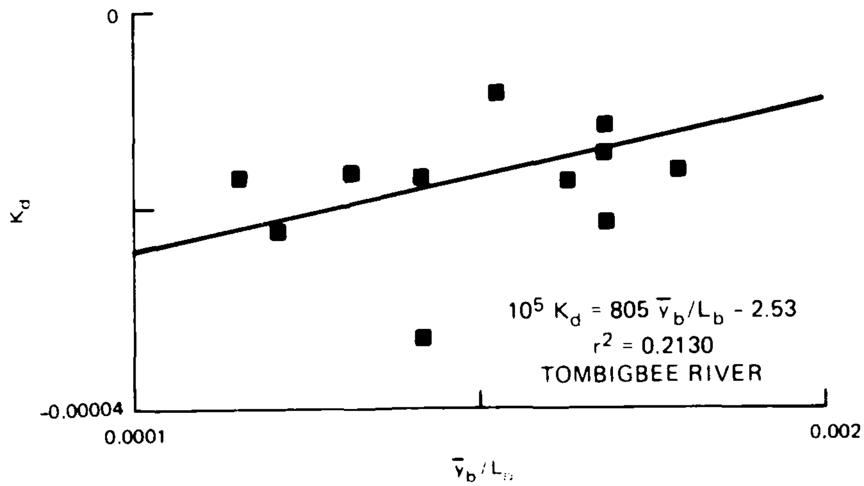


Figure A26. Variable K_d versus $\bar{y}_b/L_b$, Tombigbee River data

Composite data set

94. Descriptive statistics for the abbreviated data set are shown in Table A23. This subset of the data consists of 19 observations: site 701 from the Mississippi River, all four Arkansas River sites, site 601 from the Red River, and the 13 TTW observations identified in paragraph 92. Coefficients of skewness, as well as histograms like those in Figure A27, and Q-Q plots revealed that 9 of the 13 variables have distributions that depart significantly from normality. One of the assumptions underlying the theory behind using regression analysis to generate a function to make predictions is that the data are normally distributed. In order to generate more nearly normal variate distributions and to produce a regression function that consisted of a ratio of powers of C_s and variables describing entrance geometry, all of the data were log-transformed (natural logs). This procedure is suggested by Johnson and Wichern (1982) and Sokal and Rohlf (1981). Linear transforms, such as multiplying by -1 or adding a positive constant, were performed on variables with nonpositive data values prior to taking logarithms. Descriptive statistics for the transformed data are presented in Table A24, and

Table A23

Descriptive Statistics for Dimensionless Data

Variable	n	Mean	Variance
K_d	19	-3.86×10^{-5}	2.84×10^{-9}
L_r	19	-3.37	5.68
A_r	19	5.57	73.5
$\bar{y}_r$	19	0.960	0.0846
V_r	19	23.2	1400
L_c/r_c	19	0.259	0.380
$-K_{d_{pl}}$	13	-3.16×10^{-5}	1.71×10^{-10}
$\sin \theta$	19	0.767	0.0435
$\sin \psi_2$	19	0.142	0.0315
$Z/\bar{y}_c$	19	0.049	0.187
C_s	19	222	37,500
K_g	19	-6.21×10^{-5}	1.73×10^{-8}
$\bar{y}_b/L_b$	19	1.02×10^{-3}	2.04×10^{-7}
W_c/r_c	19	2.70×10^{-3}	5.30×10^{-3}

coefficients of skewness for the untransformed and log data are shown in Table A25. Examples of frequency distributions of the untransformed and log data are shown in Figure A27.

95. A correlation matrix for the log-transformed data is shown in Table A26. Only the transforms of K_g , C_s , $\sin \Theta$, $\bar{y}_r$, A_r , and V_r were significantly correlated with $\ln(-K_d)$ (correlation coefficient $r > 0.4542$ for two-tailed test with 95-percent confidence). The transforms of $\bar{y}_r$, A_r , and V_r were collinear. Their positive correlation with $\ln(-K_d)$ is probably due to the use of small pilot cut channels on the Red and Arkansas

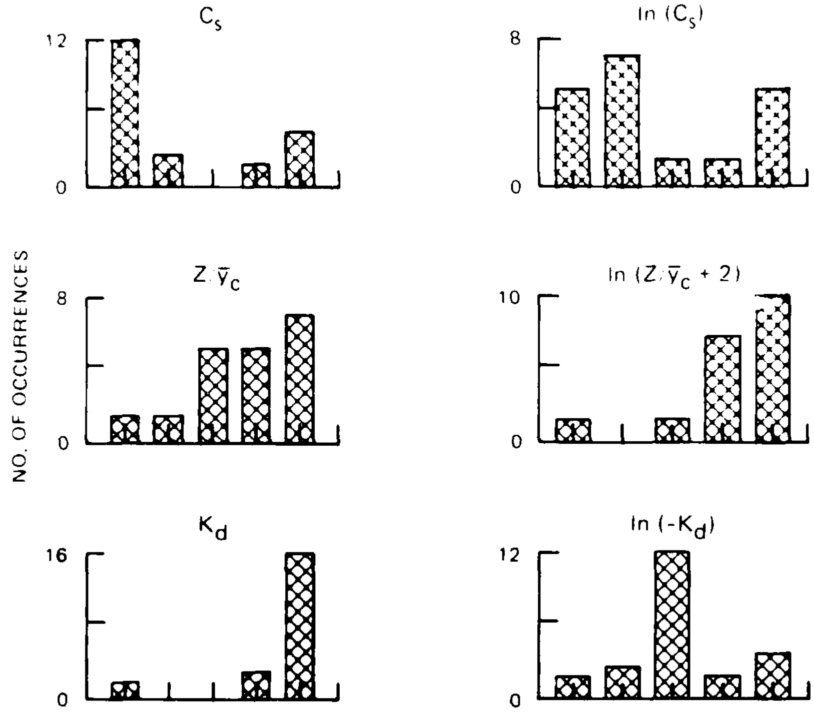


Figure A27. Example of distributions of dimensionless variables, untransformed and natural log of data

Rivers which had the highest C_s values. With all other independent variables held constant, it would seem that $\ln(-K_d)$ would be negatively correlated with $\ln(A_r)$ since a smaller bend entrance would admit less sediment. However, extremely large values of A_r coupled with large negative values for $Z/\bar{y}_c$ would probably lead to relatively low values of $\ln(-K_d)$ since these conditions would cause almost all flow to pass through the bend rather than the cut. The extremely large negative value of $Z/\bar{y}_c$ at site 720 probably accounts for its relatively low $-K_d$ value. The large negative value of $Z/\bar{y}_c$ at site 720 occurred because the cut channel was a wide, shallow natural chute across a point bar.

96. The transformed data for the 19 sites were input to the stepwise multiple linear regression computer program. The critical F-value was again equal to 2.70. The resulting regression equation was

Table A24

Descriptive Statistics, Natural Logs of Dimensionless Variables

Log base e of	n	Mean	Variance
$-K_d$	19	-10.78	0.979
L_r	19	1.04	0.333
A_r	19	0.467	2.113
$\bar{y}_r$	19	-0.230	0.145
V_r	19	1.80	3.14
L_c/r_c	19	2.33	0.00385
$-K_{d_{pl}}$	13	-10.44	0.178
$\sin\theta$	19	-0.317	0.141
$\sin\psi_2$	19	-2.75	1.85
$Z/\bar{y}_c + 2$	19	4.61	1.56×10^{-5}
C_s	19	5.11	0.610
$K_g + 0.001$	19	-6.98	0.030
$\bar{y}_b/L_b$	19	-6.99	0.220
$W_c/r_c + 1$	19	-2.68×10^{-5}	0.00601

$$K_d = 0.000001 - \left[1.09\ C_s^{0.8385}/\left(Z/\bar{y} + 2\right)^{1.7973}\right] \tag{A30}$$

$$r^2 = 0.6405$$

When C_s values for sites 208a and 429 were doubled, the coefficient of determination increased slightly:

Table A25

Comparison of Distributions, Untransformed Data and Natural Log Data

Variable	Coefficient of Skewness Untransformed	Coefficient of Skewness Log	Q-Q correlation Coefficient* Untransformed	Q-Q correlation Coefficient* Log
K_d	-2.83	0.230	0.746	0.950
L_r	1.52	0.832	0.856	0.947
A_r	1.56	0.764	0.805	0.919
$\bar{y}_r$	0.486	-0.140	0.980	0.982
V_r	1.80	0.366	0.807	0.962
L_c/r_c	-0.949	-1.09	0.949	0.938
$K_{d_{pl}}$	-1.16	-0.550	0.926	0.941
$\sin\theta$	-1.11	-2.13	0.942	0.859
$\sin\psi_2$	1.81	0.265	0.852	0.903
$Z/\bar{y}_c$	-1.14	-1.10	0.955	0.954
C_s	1.08	0.534	0.870	0.937
K_g	-2.44	-2.55	0.731	0.705
$\bar{y}_b/L_b$	0.379	-0.264	0.974	0.977
W_c/r_c	-1.61	-1.79	0.872	0.851

* If the Q-Q correlation coefficient <0.948, we may reject the null hypothesis that there is no difference between the sample distribution and normality at a 0.05 level of significance (number of points, n = 19). For $K_{d_{pl}}$, the critical value is 0.930 (n = 13).

$$K_d = 0.000001 \left[-0.681\ C_s^{0.9291} / \left(Z/\bar{y}_c + 2\right)^{1.8627}\right] \qquad \text{(A31)}$$

$$r^2 = 0.6963$$

Table A26

Correlation Matrix for Log-Transformed Dimensionless Variables

	$\ln(-K_d)$	$\ln(L_r)$	$\ln(A_r)$	$\ln(\bar{y}_r)$	$\ln(V_r)$	$\ln(L_c/r_c)$	$\ln(\sin\theta)$	$\ln(\sin\psi_2)$	$\ln(Z/\bar{y}_c + 2)$	$\ln(C_s)$	$\ln(K_g + 0.001)$	$\ln(\bar{y}_b/L_b)$
$\ln(-K_d)$	1.0000											
$\ln(L_r)$	0.2736	1.0000										
$\ln(A_r)$	0.6167	0.3009	1.0000									
$\ln(\bar{y}_r)$	0.6165	0.5918	0.5150	1.0000								
$\ln(V_r)$	0.5397	0.6794	0.8590	0.6651	1.0000							
$\ln(L_c/r_c)$	0.3106	-0.2356	0.4208	0.1193	0.1255	1.0000						
$\ln(\sin\theta)$	-0.5105	-0.0144	-0.0532	0.3265	-0.0397	-0.1836	1.0000					
$\ln(\sin\psi_2)$	0.1067	0.0273	0.6013	0.1525	0.4578	0.4370	0.2951	1.0000				
$\ln(Z/\bar{y}_c + 2)$	-0.3909	-0.2992	0.1139	-0.6455	-0.0967	0.1349	0.6159	0.3557	1.0000			
$\ln(C_s)$	0.6445	0.2413	0.8576	0.3089	0.7079	0.3398	-0.1356	0.3734	0.1324	1.0000		
$\ln(K_g + 0.001)$	-0.5561	-0.1515	-0.3663	-0.4231	-0.4087	-0.1994	0.6506	-0.0453	0.6032	-0.4161	1.0000	
$\ln(\bar{y}_b/L_b)$	-0.1627	-0.6175	-0.3369	-0.2763	-0.5797	0.0551	-0.4051	-0.0881	-0.0611	-0.3182	0.0324	1.000
$\ln(W_c/r_c + 1)$	-0.1232	-0.1767	0.2143	0.0115	-0.0166	0.9069	-0.2120	0.2778	0.0871	0.1232	-0.1379	0.1467

The difference between the correlation coefficients for Equations A30 and A31 was tested using the Fisher Z-transformation as described by Till (1974). The difference was found to be statistically insignificant ($\alpha = 0.293$), and therefore the equations have about the same predictive capability.

97. Observed values of K_d are plotted against values predicted by Equation A31 in Figures A28a and b. Figure A28c shows all of the bend volume decay curves plotted on a common axis. The points in Figure A28c are observed values of $V_b/V_b(0)$ plotted against the product of predicted $-K_d$ (from Equation A31) and observed t^*. The relative importance of the two independent variables in Equation A31 can be seen in scatter plots of predicted and observed values of $\ln(-K_d)$ versus $\ln(C_s)$ and $\ln(Z/\bar{y}_c + 2)$ as shown in Figure A29. Evidently, C_s has much greater influence on K_d than $Z/\bar{y}_c$. In fact, this data set may even overestimate the influence of $Z/\bar{y}_c$ because of the outlying values of K_d and $Z/\bar{y}_c$ for site 601. When data for site 601 are removed from the data set, multiple regression yields

$$K_d = 0.000001\left[-0.679\ C_s^{0.9453}/\left(Z/\bar{y}_c + 2\right)^{1.9871}\right] \tag{A32}$$

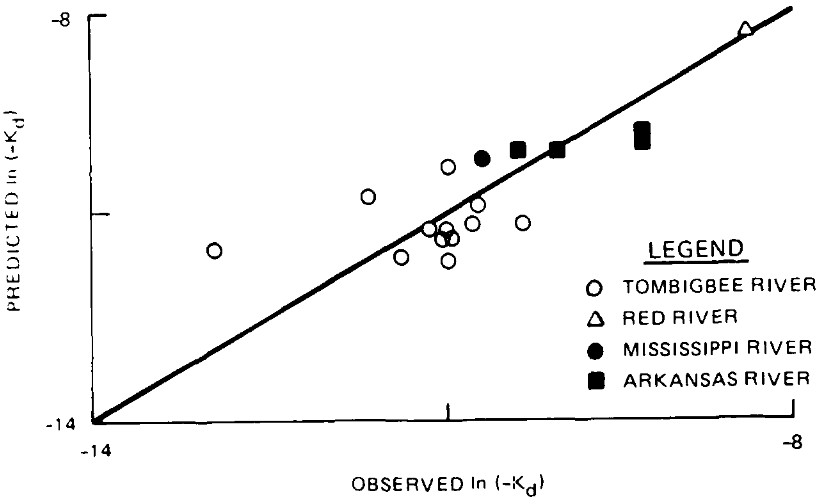
$$r^2 = 0.5535$$

Although the stepwise program did not include $\sin\theta$ in Equation A31, it may be a better predictor variable than $Z/\bar{y}_c$. However, it is difficult to differentiate the effects of $\sin\theta$ and $Z/\bar{y}_c$ using this data set because the site with the maximum value of $-K_d$ (601) also has the minimum values of $\sin\theta$ and $Z/\bar{y}_c$. Furthermore, $\sin\theta$ and $Z/\bar{y}_c$ are collinear, which is why the stepwise program did not include $\sin\theta$ in Equations A30 and A31. Ordinary multiple regression for $\ln(-K_d)$ as a function of $\ln(C_s)$ and $\ln(\sin\theta)$ yielded

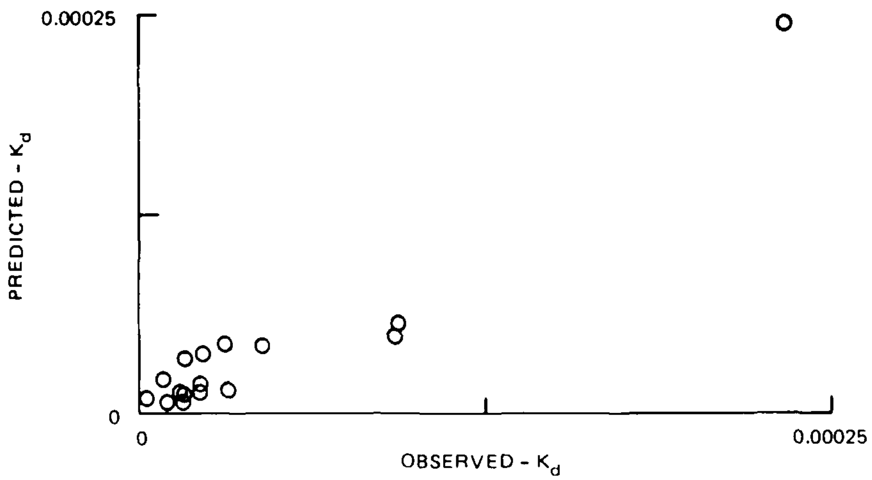
$$K_d = -0.000000203\ C_s^{0.8385}/(\sin\theta)^{1.1992} \tag{A33}$$

$$r^2 = 0.6605$$

This function was judged to be less desirable than Equation A31 because the values of $\ln(\sin\theta)$ are not normally distributed, as shown in Table A21. In addition, the coefficient of determination, r^2, is slightly lower, although

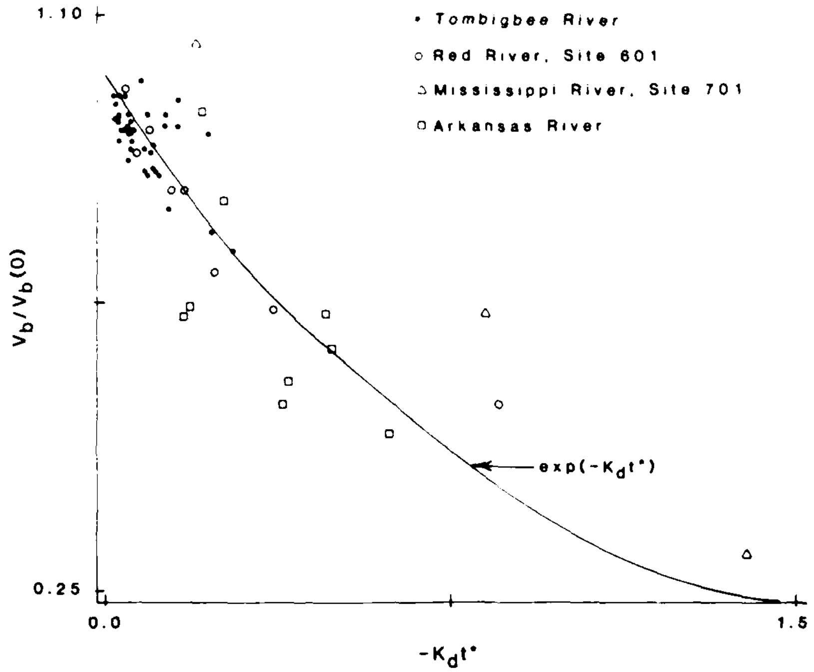


a. Observed values of $\ln(-K_d)$ versus those predicted by Equation A31



b. Observed values of $-K_d$ versus those predicted by Equation A31

Figure A28. Goodness of fit, Equation A31 (Continued)



c. All bend volume decay curves plotted on common axis. Variable $-K_d$ from Equation A31

Figure A28. (Concluded)

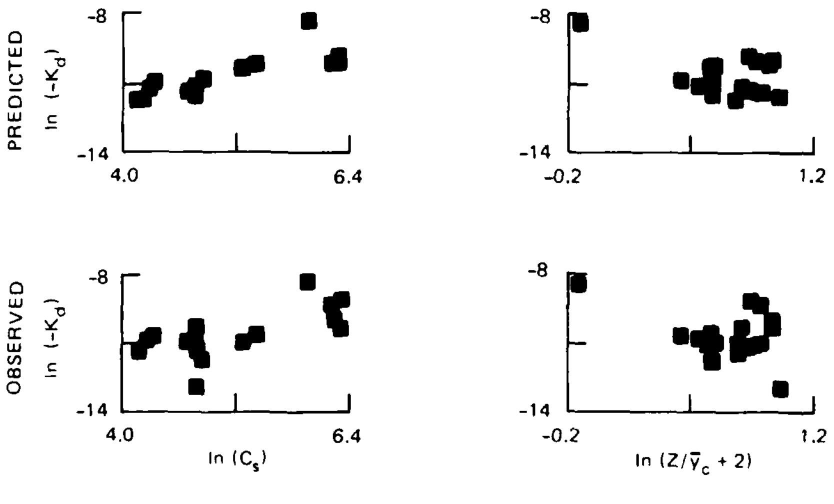


Figure A29. Observed and predicted values of K_d versus independent variables not significantly lower at the 95-percent confidence level. Linear regression for K_d as a function of $C_s/\sin\theta$ yielded

$$K_d = 0.000001\ [-0.116\ (C_s/\sin\theta) + 3.16] \qquad (A34)$$

$$r^2 = 0.9249$$

when all 19 data points were used. Equation A34 is plotted in Figure A30. Although the coefficient of determination, r^2, is quite high, Equation A34 is less attractive than Equation A31 because the variables K_d and $C_s/\sin\theta$ are not normally distributed.

Analysis of residuals of Equation A31

98. The residual errors associated with a regression function are the differences between the observed and predicted values of the dependent variable. Analysis of the residuals of a regression function can reveal whether or not the function (or "model") is appropriate for the data. If the function is appropriate, the residuals will be normally distributed, independent of the sequence of observation, and independent of any variables not included in the regression function. Furthermore, if the functional form of the regression model is appropriate, the residuals will depart from zero in a random rather than a systematic fashion. Furthermore, the variance of the residuals will be fairly constant over the ranges of the independent and predicted dependent

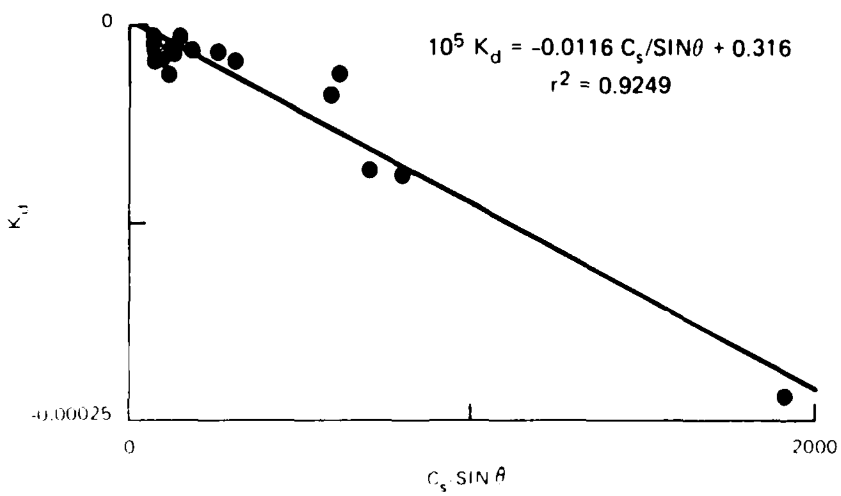


Figure A30. Linear regression plot, K_d versus $C_s/\sin\theta$

variables. Plots of residuals also make it easy to spot extreme or outlying residuals--those four or more standard deviations away from the mean of residuals. Outliers may indicate measurement error or an unusual interaction with a significant independent variable omitted from the regression function.

99. The residuals of Equation A31 were checked for normality by plotting them on probability paper as shown in Figure A31. The Q-Q correlation coefficient, r^2, was 0.9501, which is significant at the 95-percent confidence level. Both Figure A31 and the Q-Q correlation coefficient indicate that the residuals are approximately normally distributed. Residuals were also plotted against each of the independent variables and the predicted $\ln(-K_d)$ values to check goodness of fit of Equation A31. Figure A32 shows plots of residuals expressed as normal deviates. These plots indicate that the variance of the residuals was fairly constant (homoscedastic) and did not reveal any patterns of dependence.

Volume below normal pool elevation

100. A major consideration in management of the cutoff bends on the Tombigbee River is the rate of deposition below normal pool elevation since channel volume below normal pool elevation is equal to the water volume in the bend except during floods. Stepwise regression was used to study the relationship of the decay coefficient to dimensionless variables that describe the site geometry and hydrologic inputs. The ratio of the initial bend volume below normal pool elevation to the initial bend volume below top-bank elevation was added to the set of independent variables. Using data from the 13 Tombigbee River sites, the stepwise regression program yielded

$$K_{d_{pl}} = -0.0000355 + 0.0000731(W_c/r_c) + 0.0000467(\sin \psi_2) \quad \text{(A35)}$$

$$r^2 = 0.5272$$

Observed values are plotted versus those predicted by Equation A35 in Figure A33. The relative importance of each of the two independent variables was explored by plotting the predicted and observed values of $K_{d_{pl}}$ against W_c/r_c and $\sin \psi_2$ as shown in Figure A34. These plots indicate that W_c/r_c tended to dominate for lower values of $K_{d_{pl}}$ and $\sin \psi_2$ for higher values.

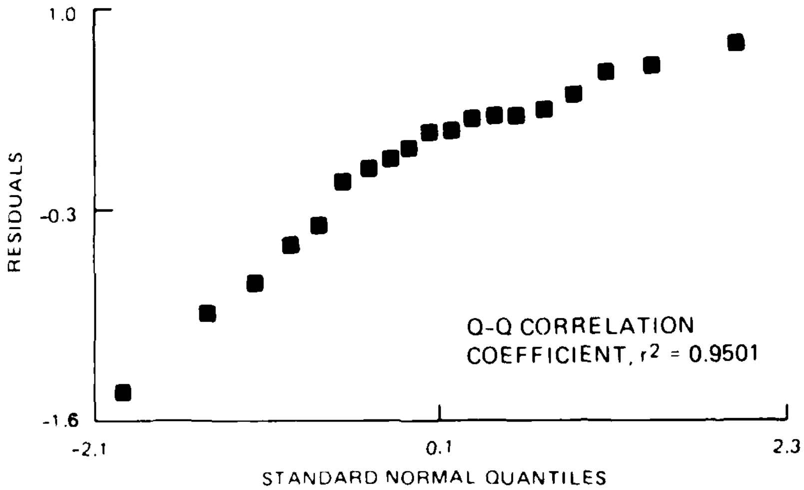


Figure A31. Probability plot of residuals of Equation A31

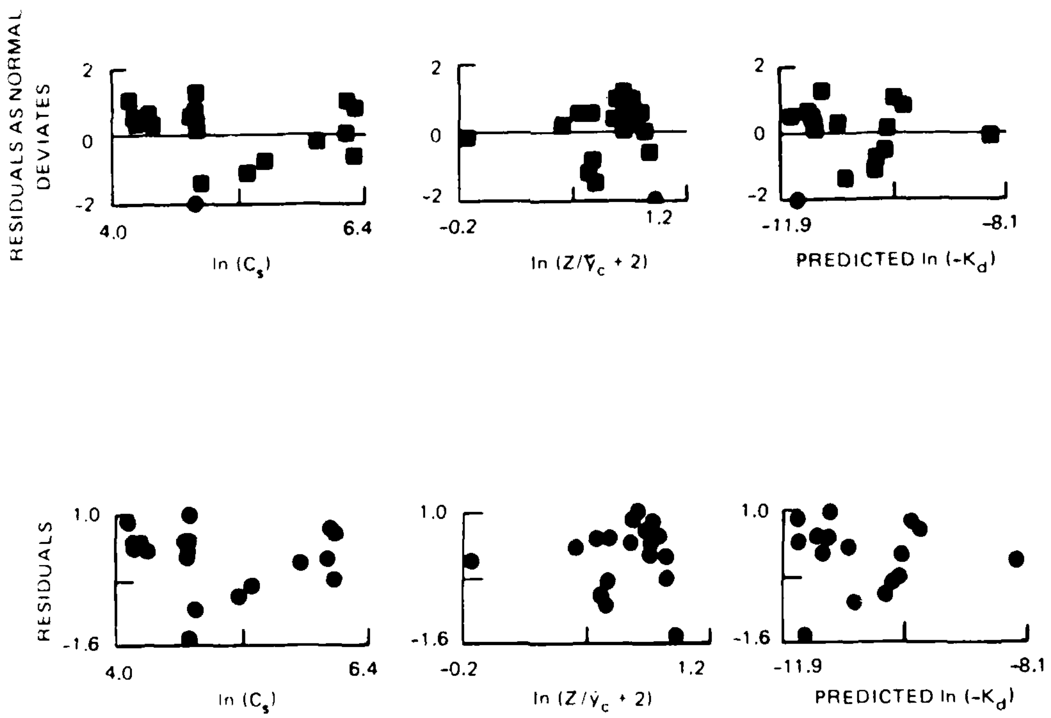


Figure A32. Residuals of Equation A31

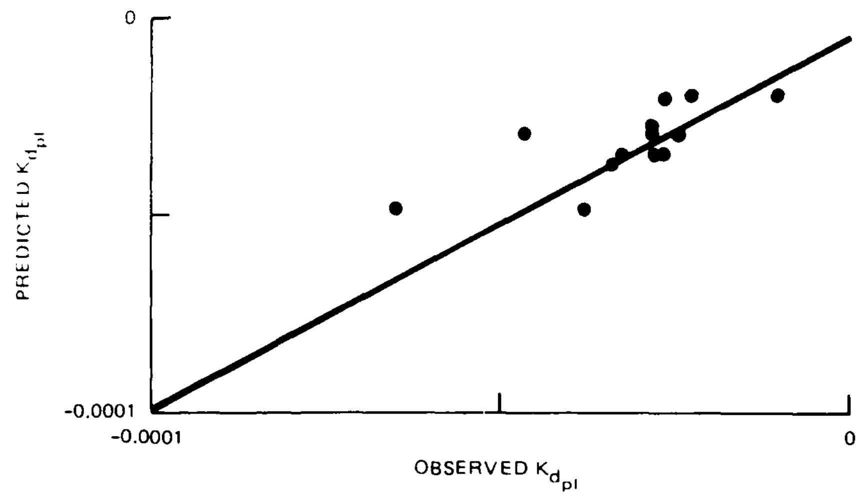


Figure A33. Regression function for $K_{d_{pl}}$ using all Tombigbee River data

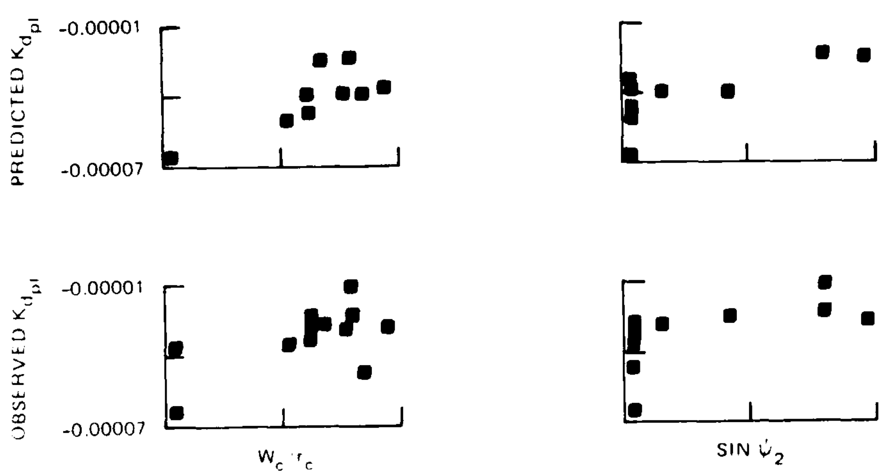


Figure A34. Observed and predicted values of $K_{d_{pl}}$ versus independent variables

Analysis of residuals of Equation A35

101. The appropriateness and goodness-of-fit of Equation A35 were examined by analyzing the residuals. The residuals are plotted on probability paper in Figure A35. Both Figure A35 and the Q-Q correlation coefficient indicate that the residuals are approximately normally distributed. The Q-Q correlation coefficient was 0.9454, which is significant at the 95-percent confidence level. Residuals were also plotted against each of the independent variables and the predicted $K_{d_{pl}}$ values. Figure A36 shows plots of residuals expressed as normal deviates. These plots show that the variance of the residuals was fairly constant and did not reveal any patterns of dependence. Residual analysis for Equation A35 was hindered by the relatively small number of points and the lack of low W_c/r_c values in the data base.

102. When only the eight Columbus Pool observations were used for the regression, the stepwise program selected $\sin \psi_2$ as the independent variable:

$$K_{d_{pl}} = 0.00001\ (-3.409 + 6.862 \sin \psi_2) \qquad \text{(A36)}$$

$$r^2 = 0.5393$$

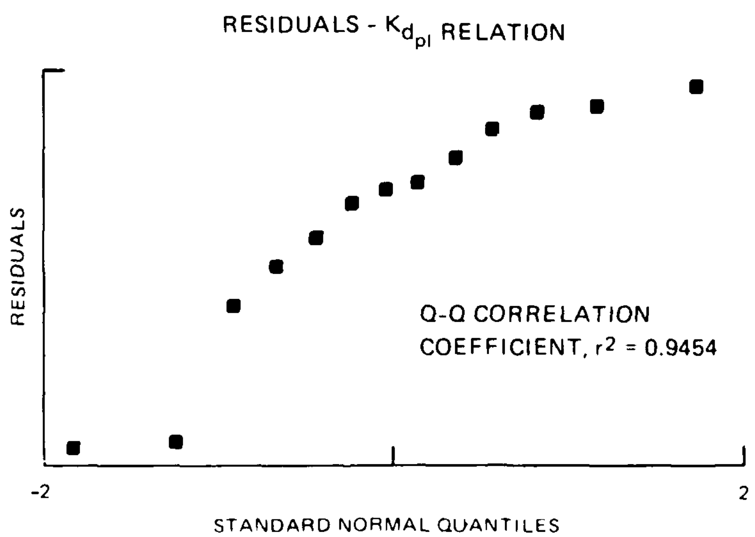


Figure A35. Probability plot of residuals of Equation A35

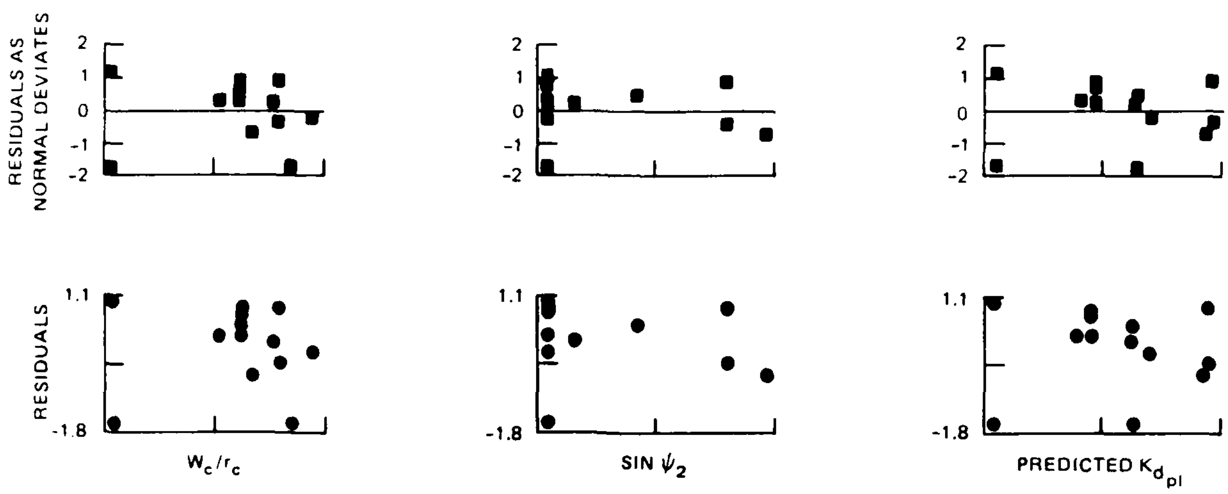


Figure A36. Residuals of Equation A35

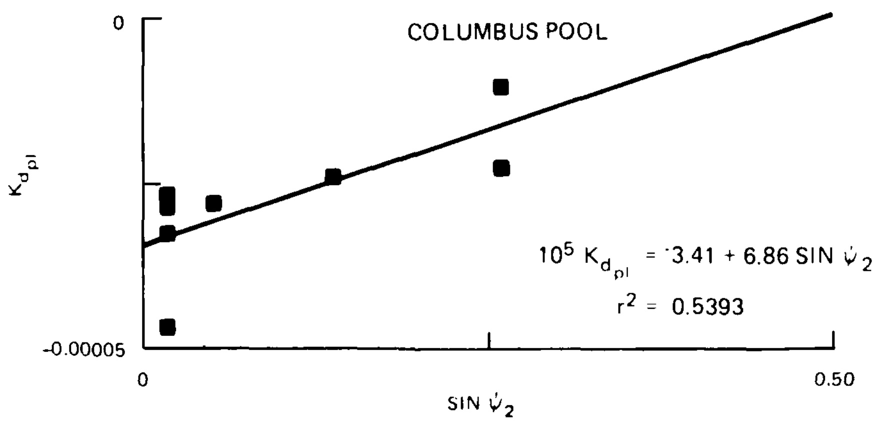


Figure A37. $K_{d_{pl}}$ for Columbus Pool versus $\sin \psi_2$

A linear regression plot for Equation A36 is shown in Figure A37. Equation 36 is useful for management of the 18 cutoff bends in Columbus Pool on the Tombigbee River but should be applied only to situations physically similar to Columbus Pool where the other independent variables are within the ranges observed for that pool. Like all regression equations, it is empirical and cannot be expected to provide reliable predictions for situations different from those used to generate it.

Patterns of deposition

103. The regression functions presented in Table A22 and Equations A27 through A36 relate the channel volume decay coefficient, K_d , for a cutoff bend to independent variables. However, certain management decisions, such as whether or not to construct a block in the upstream entrance of a cutoff bend and the location and elevation of the block, are greatly facilitated by a knowledge of the temporal and longitudinal distribution of deposition along the bend. Accordingly, the measured channel cross-sectional areas from bends with suitably detailed temporal and spatial coverage were used to determine the relationship between dimensionless channel area, surrogate time, and distance:

$$A/A(0) = f(x/L, t^*) \qquad \text{(A37)}$$

where

x/L = distance downstream of the upstream bend entrance

L = total length of the bend length

Since channel volume is simply the integral of area over length, the area at a given section (where x/L is a constant) is a log-decay function of t^* :

$$A/A(0) = e^{K_p t^*} \qquad \text{(A38)}$$

The form of Equation A38 was verified by examining all of the data for sites 601 and 101 through 1984. The effect of x/L on $A/A(0)$ for a given bend was explored by taking logs of both sides of Equation A38, dividing by t^* , and fitting a function of x/L to the resulting K_p values:

$$\ln[A/A(0)] = K_p t^* \qquad \text{(A39)}$$

$$\ln[A/A(0)]/t^* = K_p \tag{A40}$$

$$K_p = f(x/L) \tag{A41}$$

A log-normal distribution function was selected to relate K_p and x/L because of the shape of the curve followed by the plotted data as portrayed in Figure A38 and because of the wide range of shapes that the log-normal distribution function can take. A polynomial regression program was used to determine values of coefficients for the function

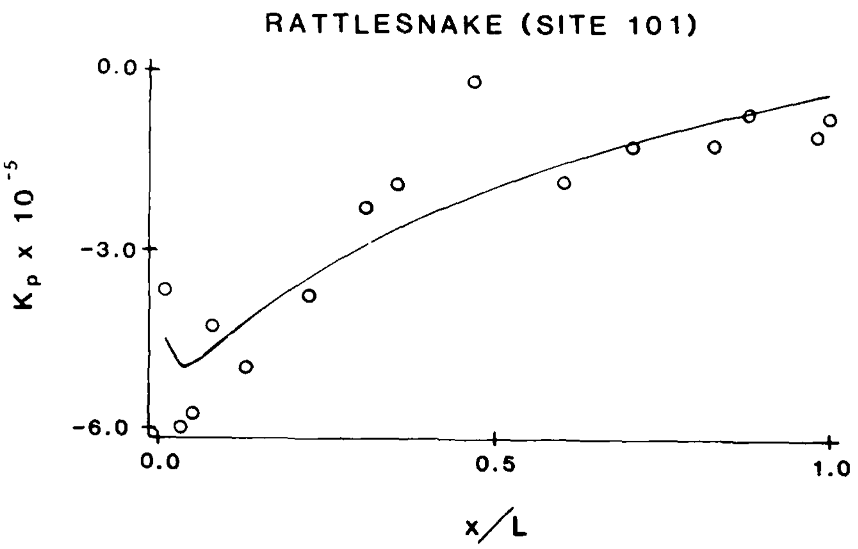
$$K_p = \ln[A/A(0)]/t^* = a[\ln(x/L)]^2 + b[\ln(x/L)] + c \tag{A42}$$

104. Results of the polynomial regression are presented in Table A27. Observed and predicted values of $A/A(0)$ are plotted in Figure A39 against x/L and t^*. Areas were plotted as $1-A/A(0)$ so that the vertical coordinate would be indicative of the magnitude of deposition at a particular time and location.

105. The relationships of the coefficients a, b, and c in Equation A40 to site condition variables were evaluated by computing correlation coefficients and plotting scatter plots with the seven sets of observed values shown in Table A27 and the associated values of the independent variables. A correlation matrix showing a, b, c and some of these independent variables is shown in Table A28. Some of the scatter plots studied are shown in Figure A40. When values from site 601 were removed from the data set, there were no significant correlations between the coefficients a, b, and c and the independent variables.

Measurements from Aerial Photographs

106. Aerial photographs of seven oxbow lakes were selected as described in Part I of this appendix. The seven lakes selected for study included the four Arkansas River sites, site 701 on the Mississippi River, and two additional man-made bendways from the Mississippi. No sites from the TTW were included in this component of the study because of the extremely short period of record there. Maps and site descriptions are given in Part I. Tracings of the photos were measured to determine the changes in lake surface area and



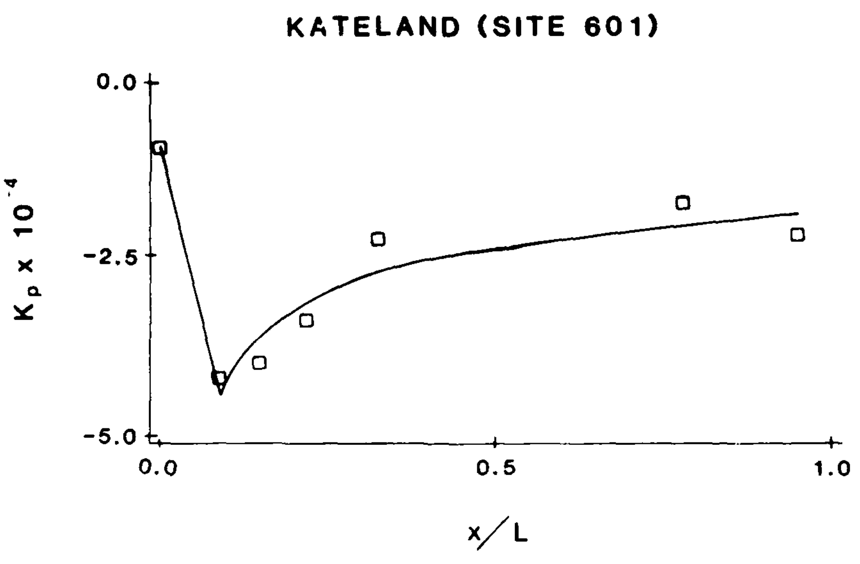


Figure A38. K_p versus x/L for sites 101 and 601

Table A27

Coefficients from Polynomial Regression for Channel Area as a Function of x/L and t*

Site	$a \times 10^6$	$b \times 10^6$	$c \times 10^6$	r^2
101	7.3	47.	4.5	0.770
203	-3.5	2.7	-18.	0.650
311	-3.6	17.	-3.0	0.870
423	2.7	28.	4.2	0.790
429	36.	130.	56.	0.460
601	5.0	230.	-15.	0.280
908	35.	73.	-27.	0.590

perimeter with time. All seven of the lakes studied were man-made cutoff bends in the infilling phase. Five of the seven oxbow lakes were also included in the data base used to study K_d and are listed in Table A19.

107. Analysis of the aerial photography proceeded in two steps. The first step was to prepare maps of each lake from aerial photographs for each photo coverage date. Table A6 shows the dates and scales of the aerial photos used. Maps were traced from the aerial photos on clear mylar. The second step consisted of measuring and tabulating shoreline length and surface area for each coverage of each lake.

Map preparation

108. Maps of each oxbow lake for each photography coverage date were traced on large sheets of clear mylar. Maps were prepared by laying the mylar over the aerial photos and tracing the boundary around the perimeter of the lake formed by large, permanent vegetation (trees). In cases where clearing of trees had obviously influenced this boundary, qualitative judgment based on prior and subsequent surveys was used to estimate the appropriate shoreline location.

109. Nominal photo scales were checked against navigation maps or US Geological Survey topographic survey maps prior to tracing. Scales were checked by comparing distances between three fixed points such as breaks in

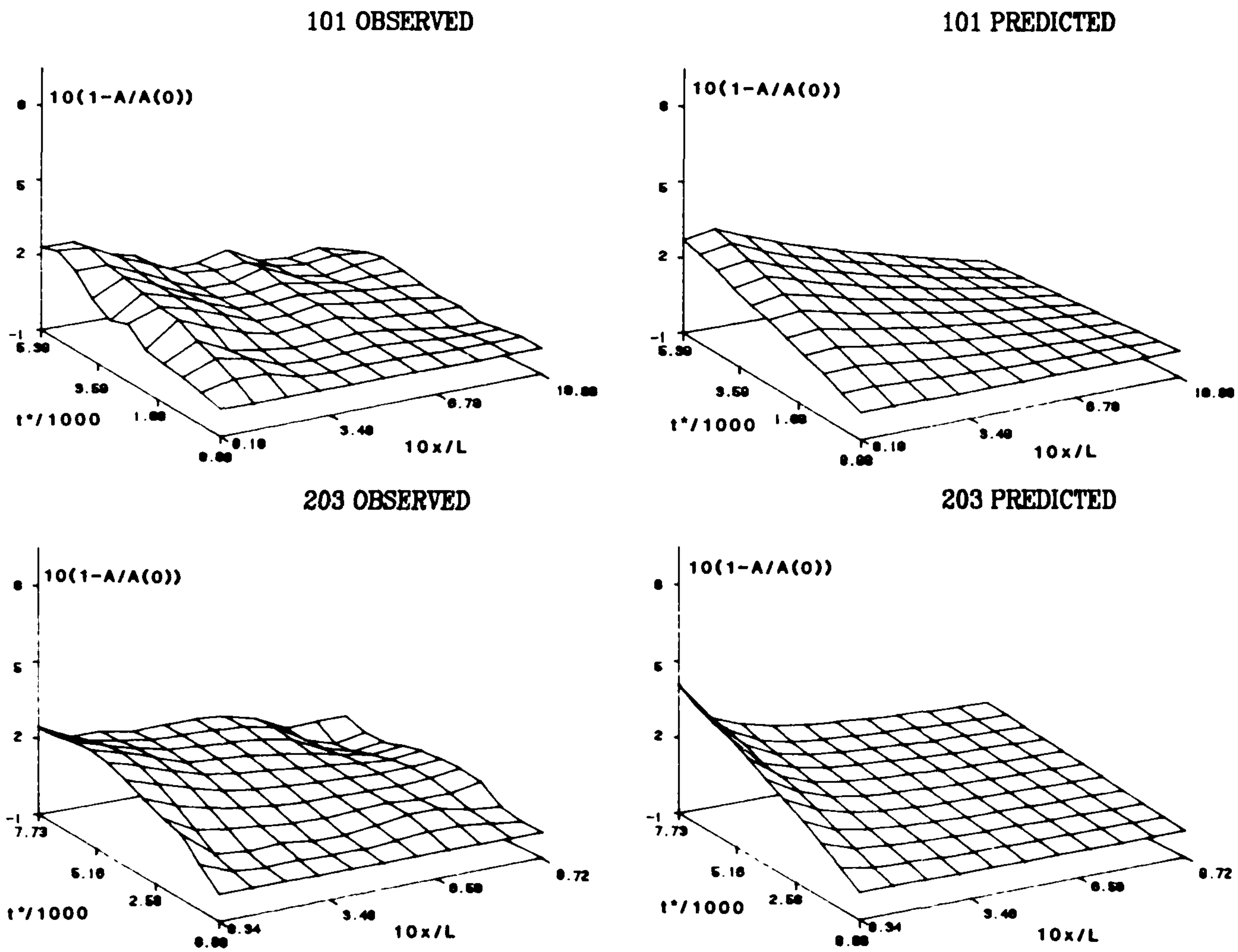


Figure A39. Observed and predicted values of 1-A/A(0) versus x/L and t*
(Sheet 1 of 4)

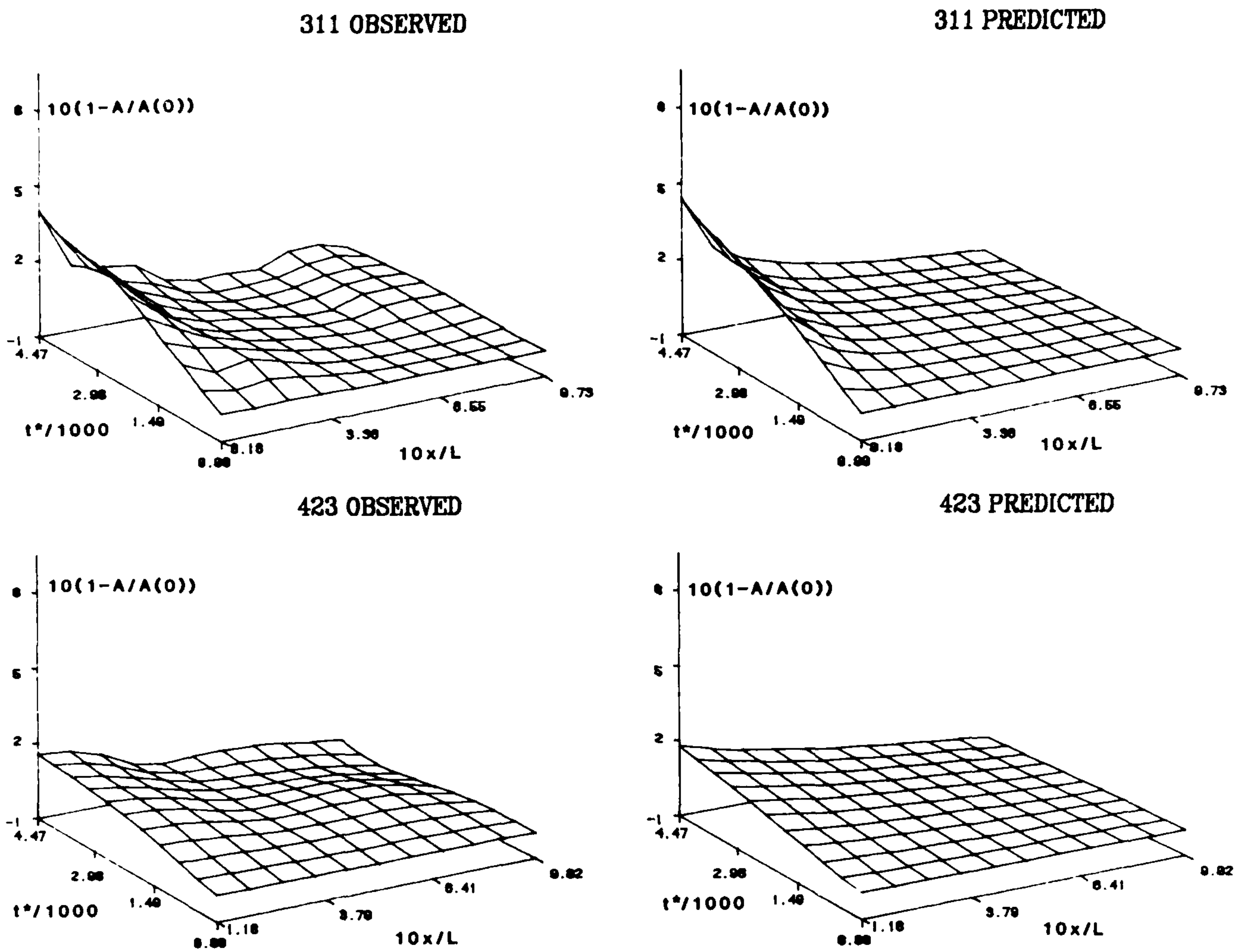


Figure A39. (Sheet 2 of 4)

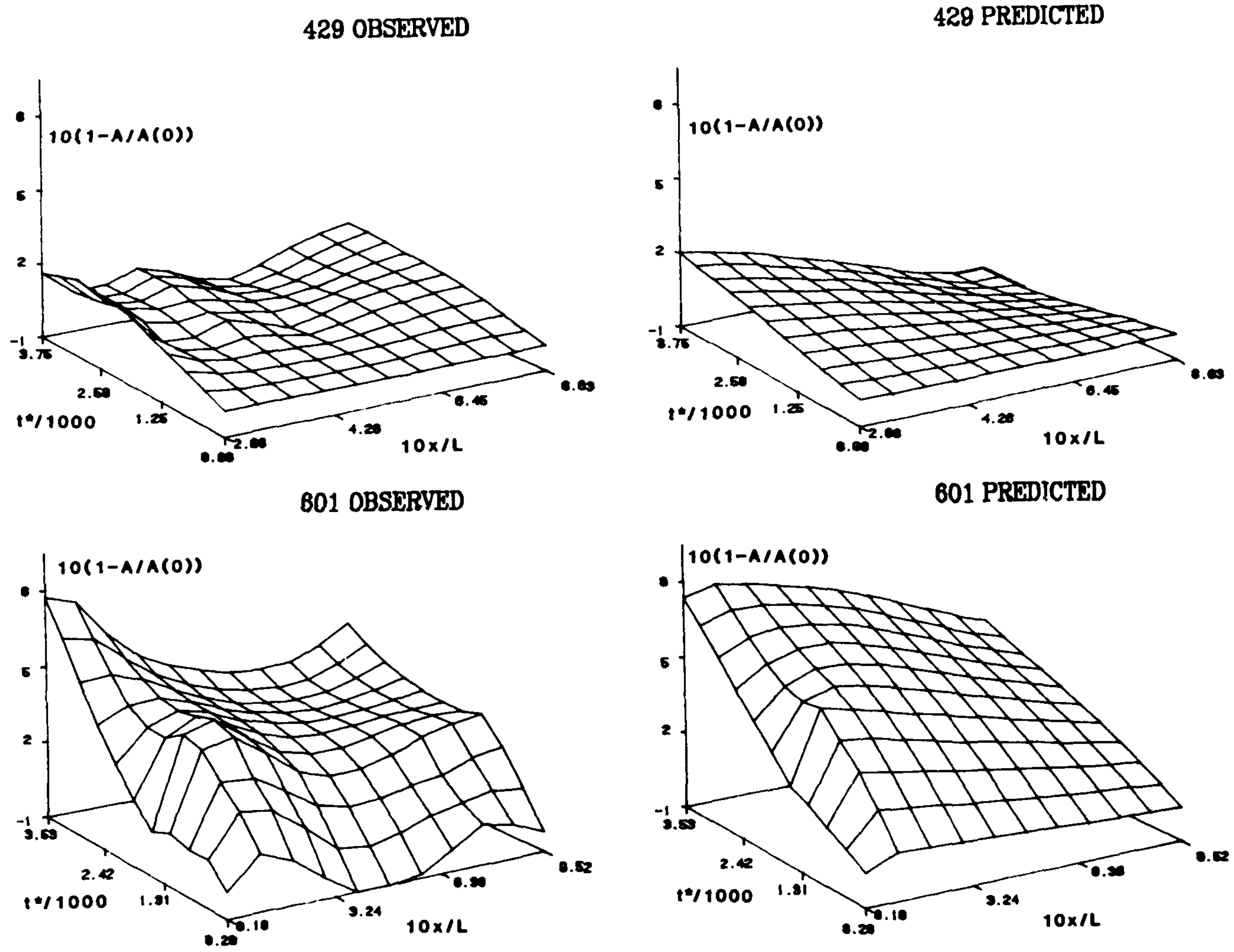


Figure A39. (Sheet 3 of 4)

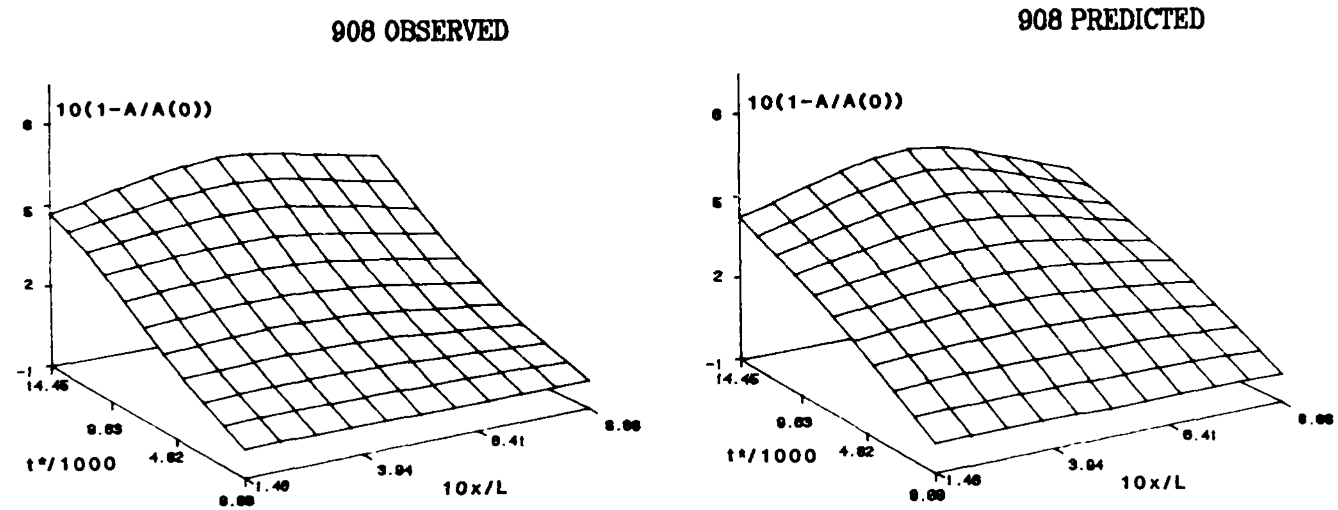


Figure A39. (Sheet 4 of 4)

Table A28

Correlation Matrix, Coefficients a, b, c, and Independent Variables*

	a	b	c	K_g	C_s	sin θ	sin ψ_2	L_r	$\bar{y}_b/L_b$
a	1.000								
b	-0.0310	1.000							
c	0.1339	-0.6185	1.000						
K_g	-0.6407	-0.8350	-0.9237	1.000					
C_s	0.6642	0.4770	-0.5703	-0.4843	1.000				
sin θ	-0.2782	-0.5178	0.8611	0.8600	-0.2578	1.000			
sin ψ_2	-0.2605	-0.3740	0.0506	0.2590	-0.1078	0.0209	1.000		
L_r	-0.5783	-0.4161	0.1339	0.2165	-0.3798	0.2712	-0.2632	1.000	
$\bar{y}_b/L_b$	0.5139	0.6536	-0.7397	-0.7748	0.2251	-0.7960	0.3254	-0.5025	1.000
$Z/\bar{y}_c$	-0.1758	-0.4950	0.7076	0.7456	0.0477	0.6478	0.1091	-0.3359	-0.6175

* Critical value of correlation coefficient at 95-percent confidence level is 0.6764.

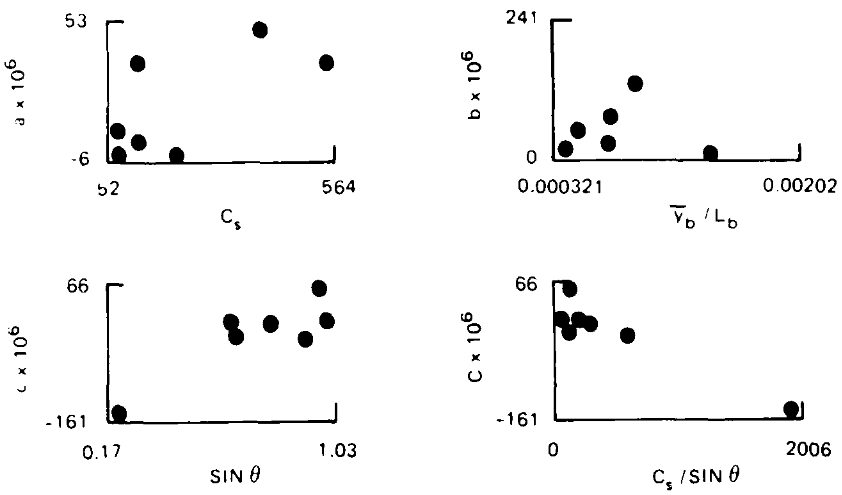


Figure A40. Coefficients a, b, and c versus independent variables

levee alignment, roads, bridges, or railroads with the same three distances measured from the maps. If any of the photos used for a given tracing had scales that were more than 3 percent different from the nominal scale, an average of the photo scales was used to compute area and shoreline length. Only 5 of the 44 tracings required use of scales other than nominal. Records were kept showing the photo number and the distances measured from the photo and the map. None of the photo scales was more than 5 percent different from nominal.

110. In cases where more than one aerial photo was required for a given map, each photo after the first one was registered on the mylar overlay using at least two points located on previously traced frames that overlapped the frame being registered. The prepared maps are in the project files of the Environmental Laboratory at WES.

Measurements of area and perimeter

111. Lake surface area and shoreline length were determined for each coverage of each lake. These measurements were performed using a GTCO digitizer with a resolution of 0.001 in. Before each work session, the calibration of the digitizer was checked by measuring a square of known area. Area and shoreline length measurements were repeated until consecutive

measurements agreed within 1 percent. Results of this procedure are presented in Table A29.

112. Lake surface area, as a fraction of the earliest measured surface area, is plotted for each of the seven sites in Figure A41. Surface areas tended to go through a period of rapid decline and then fluctuate about a value 40 to 60 percent of the initial area. The Arkansas River site located immediately upstream of a navigation dam (site 904) was an exception. Site 904 surface area was reduced to only 6 percent of the initial value in 10 years. However, when Lock and Dam No. 5 was closed just downstream, the surface area increased to about 60 percent of the initial value. The Arkansas River oxbow lakes tended to fill more rapidly than the three Mississippi River lakes studied.

113. Lake shoreline length as a fraction of the earliest measured shoreline length is plotted in Figure A42. Shoreline length declined less rapidly than lake surface area and in many cases remained nearly constant over the period of record.

Table A29

Areas and Perimeters of Oxbow Lakes

Site	Date (YYMM)	Surface Area, ft^2	A/A_i	Perimeter, ft	P/P_i
701	48*	16.5×10^7	1.000	2.72×10^5	1.00
	5910	7.76	0.471	1.88	0.690
	6410	7.63	0.463	1.77	0.650
	6911	7.52	0.457	1.80	0.660
	7510	8.00	0.486	1.91	0.697
	77/78*	8.60	0.522	2.14	0.787
	8203	9.36	0.568	2.03	0.748
709	4911	26.5×10^7	1.000	7.74×10^4	1.000
	5702	12.6	0.473	7.36	0.950
	6611	7.46	0.282	6.01	0.775
	7311	8.24	0.311	6.03	0.778
	7910	9.26	0.349	6.24	0.805
	8401	11.4	0.427	6.57	0.848
716	5004	20.7×10^7	1.000	1.86×10^5	1.000
	5402	20.2	0.752	1.90	1.026
	5710	17.5	0.652	2.01	1.081
	6211	16.4	0.612	2.00	1.079
	6611	15.6	0.581	2.03	1.094
	7311	15.0	0.557	1.98	1.069
	7910	17.4×10^7	0.648	2.05	1.102
904	5812	6.27×10^7	1.000	6.78×10^4	1.000
	6510	0.354	0.0564	6.81	1.004
	6808	0.365	0.0583	6.41	0.945
	6903	3.85	0.6141	8.18	1.206
	7301	3.54	0.5642	6.81	1.004
	7510	3.91	0.6231	8.47	1.250
	8401	4.26	0.6798	8.89	1.310
906	5510	1.33×10^7	1.000	6.07	1.000
	6012	1.04	0.783	4.84	0.797
	6410	0.801	0.603	3.65	0.602
	6610	0.756	0.565	3.54	0.584
	7110	0.845	0.636	4.97	0.775
	7301	0.842	0.634	4.42	0.729
907	6010	2.39×10^7	1.000	4.98×10^4	1.000
	6306	1.71	0.712	4.43	0.890
	6502	0.604	0.252	4.74	0.952
	6610	0.698	0.292	4.37	0.878
	7211	0.981	0.409	5.26	1.050
	7511	1.03	0.432	5.35	1.070
	8112	0.982	0.410	5.38	1.080
908	6011	1.37×10^7	1.000	4.21×10^4	1.000
	6305	1.26	0.921	4.21	1.000
	6809	0.169	0.123	2.99	0.712
	7212	0.135	0.099	3.12	0.742

* Measured from treeline depicted on 1948 hydrographic survey chart.
** Data taken in February 1977 and March 1978.

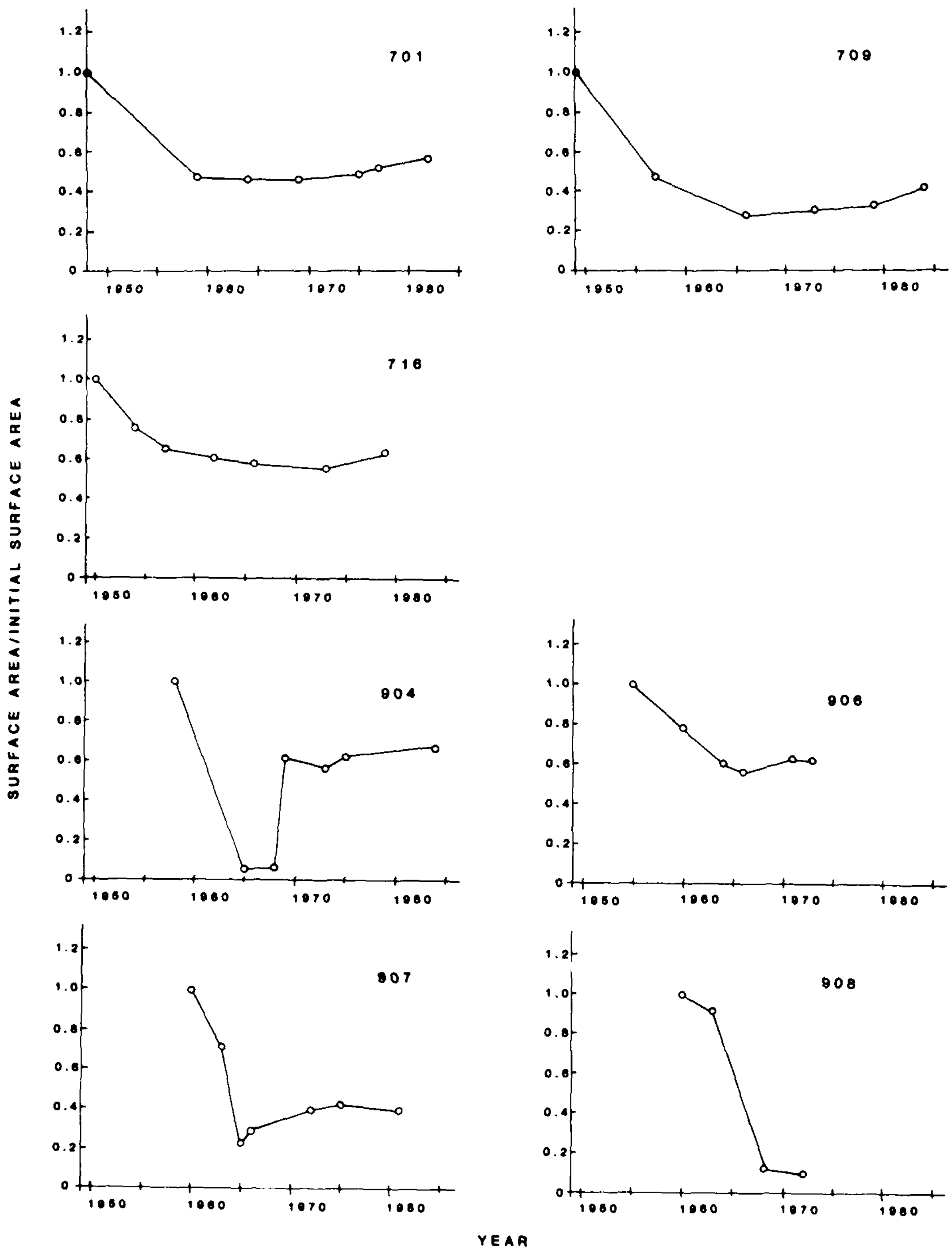


Figure A41. Oxbow lake surface areas

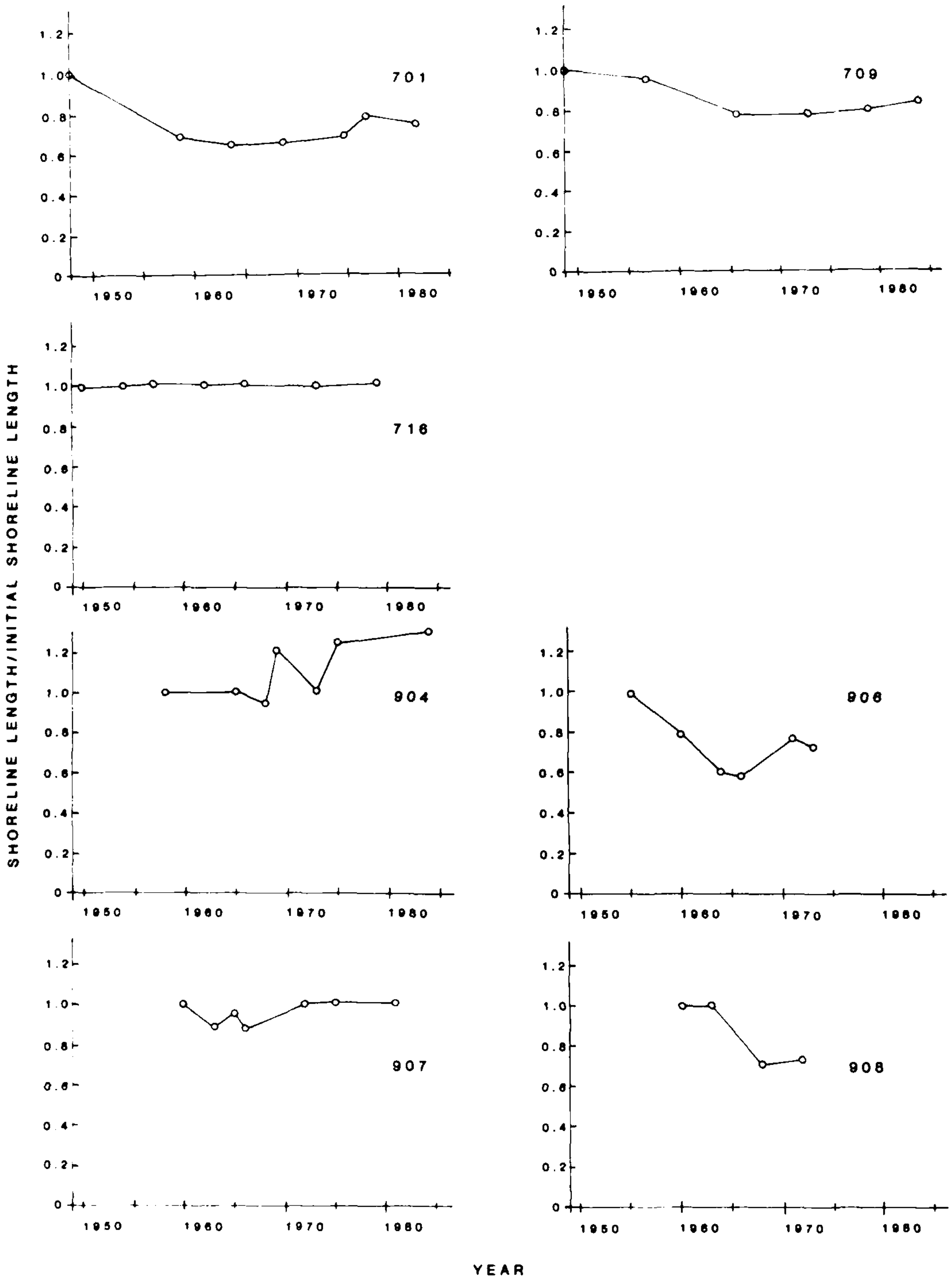


Figure A42. Oxbow lake perimeters

PART III: DISCUSSION OF RESULTS OF ANALYSIS

114. When a cutoff is completed, a divided flow reach is created. Since bed material discharge is a power function of water discharge, and since the sum of power functions is less than the power function of the sum (for powers greater than 1), deposition of bed material will occur in either the old bend or the cut channel. Cut channels are designed, constructed, and maintained to avoid obstruction of flow and to allow free passage of navigation traffic. Accordingly, sediment deposition occurs in the cutoff bends.

115. The rate of sediment deposition varies widely from one bend to another. Individuals faced with decisions regarding allocation of scarce resources for management of cutoff bends need to understand the factors controlling the rapidity and patterns of sediment deposition. Results of this study identify the variables that are most important in controlling physical and thus environmental conditions in cutoff bends along rivers like the Mississippi, Red, Arkansas, and Tombigbee. Furthermore, these results provide a basis for long-term management of cutoff bends on the Tombigbee River.

Bend Volume Decay Constants

116. Values for a dimensionless constant that measures the unit response of a cutoff bend to a unit hydrologic input were calculated for 21 sites. This constant, K_d, is defined by the equation

$$V_b(t)/V_b(0) = e^{-K_d t^*} \tag{A43}$$

where

V_b = bend volume

$t^* = \int_o^t Q\,dt$

The calculated decay constants indicated relatively little variation from site to site despite the considerable variability in all of the major geometric and hydrologic characteristics of the sites studied. The coefficient of variation (the variance divided by the mean) of K_d for the 19 sites used in regression analyses was -1.41. However, the coefficient of variation falls to only -0.902 if sites 601 and 422 are excluded. Except for sites 422 and 601, K_d values clustered in a rather narrow range.

117. The K_d values tend to group about characteristic values for each river. Variation of K_d between rivers appears related to average bed material concentration, C_s, and the rate of riverbank erosion. Bank erosion rates were not included in these analyses, but Lindner (1953) presents results of work by Friedkin (1945) that shows that the path of bed-load movement in a meandering channel is related to the rate of bank erosion. In general, the movement of bed material from caving concave banks onto convex point bars is directly related to the rate of bank erosion. Mouths of old bends, which are usually located on convex banks of the new channel (Ferguson 1940, Petersen 1964), should therefore block more rapidly if banks upstream are rapidly eroding. Thus, the rate of blockage of a cutoff bend and the magnitude of $-K_d$ are directly proportional to the rate of bank erosion. Available information on gross bank erosion rates for the study rivers is presented in Table A1. If the four study rivers are ranked according to their bank erosion rates at the time of observation in units of feet of recession per foot of channel width, the order of ranking is identical to ranking based on average $-K_d$ values: Red, Arkansas, Mississippi, and Tombigbee.

118. The $-K_d$ value for site 601 on the Red River was more than twice as large as $-K_d$ for any other site. The K_d value for site 601 was related to the high value for C_s, low $\sin\theta$, and large negative $Z/\bar{y}_c$. The effects of C_s and $\sin\theta$ have been noted. A negative value for $Z/\bar{y}_c$ indicates that the average bed elevation of the bend mouth is lower than the average bed elevation of the cut mouth, thus inducing more of the sediment-laden lower region of flow to pass into the old bend. Conversely, Lindner (1953) noted that diversions with bottom elevations higher than the main channel would divert little bed load. However, the extremely large negative value for $Z/\bar{y}_c$ for site 720 on the Mississippi probably had the opposite effect on $-K_d$ because the bed of the cut was high enough to force all but the highest flows into the old bend. Since site 720 was a natural chute cutoff, the average

elevation of the cut mouth was considerably higher than both the approach channel and the old bend channel. This would be a highly unusual situation for most man-made cutoffs.

119. The variation in Arkansas River K_d values may be partially explained by the variation in the ratio $C_s/\sin\theta$. The values of $-K_d \times 10^6$ for sites 907, 908, 906, and 904 were 31, 44, 93, and 94, respectively, while $C_s/\sin\theta$ values for the same sites were 630, 600, 710, and 803, respectively. The $-K_d$ values were also influenced by the timing of construction of training works to block the bend entrances. The training works were built to force flow through the cut channels and speed their development. Training works were constructed at site 907 1 to 2 years after cutoff, but were not built at the other three sites until 3 years after cutoff.

120. The $-K_d$ values for the Tombigbee River sites ranged from 2.22×10^{-6} to 3.29×10^{-5}. The two highest values were for sites 427 and 429, which are located in the upper reaches of Columbus Pool. The high value for site 427 (3.12×10^{-5}) is due to the influx of sediment from a nearby surface mine, while the value for site 429 is due, at least in part, to the unmeasured but probably significant amount of deposition in the bend between the initial survey date and completion of the cutoff. This aggradation resulted when the downstream dam (Columbus) was completed and closed 3 years prior to closure of the dam just upstream (Aberdeen). The remaining 12 $-K_d$ values for the Tombigbee River fall between 22.4×10^{-6} and 8.64×10^{-6}, except for site 422, which had a $-K_d$ of only 2.22×10^{-6}. This low value may be partially explained by the high value for $Z/\bar{y}_c$ at site 422, which indicates that the bend entrance was higher than the main channel. In addition, the entrance to site 422 was located on the outer bank of the apex of a bend in the main channel. This unusual entrance location was manifest by high values for $\sin\psi_2$ and W_c/r_c. Values for $\sin\psi_2$ and W_c/r_c for site 417 were identical to those for site 422; but, $-K_d$ for site 417 was 11.6×10^{-6}. The higher value for $-K_d$ at site 417 is probably due to the fact that $Z/\bar{y}_c$ for that site was only 0.083, while $Z/\bar{y}_c$ for 422 was 0.628.

Regression Equations

121. Eighteen prediction equations for the decay constants K_d and $K_{d_{pl}}$ were developed in Part II of this appendix using regression techniques. The goodness of fit and statistical significance of 13 equations selected from this group were assessed by computing test statistics as shown in Table A30. The first three test statistics, r^2, F, and "shrinkage r^2," are indicators of how well the regression equation performs as a whole. The standard error of the estimate is the standard deviation of the residual errors. Residual errors are the differences between observed and predicted values. The beta coefficients and t-statistics measure the importance of each of the independent variables. The runs test and Durbin-Watson statistic indicate whether the residuals are normally distributed and are free of serial correlation.

122. The coefficient of determination, r^2, in Table A30 is the fraction of the variance in the independent variable that is explained by the regression model. The probability of the F-statistic is the fractional probability (1.0 = 100-percent chance) that the regression equation could explain as much of the variance in the dependent variable as it does by chance. This is a test of the statistical significance of the regression equation. The column labeled "shrinkage r^2" contains an estimate of the population coefficient of determination. This statistic is an estimate of the coefficient of determination that would be obtained if the regression equation were validated with another data set randomly sampled from the same population (Herzberg 1969).

123. The beta coefficients and t-probabilities shown in Table A30 are descriptive of the individual independent variables in the regression equations. The beta coefficients are regression coefficients standardized to eliminate the effects of the scales of measurement of the raw data. The relative magnitudes of beta coefficients in a given regression are indicative of the relative importance of the associated independent variables. The probability of the t-statistic is the fractional probability that the population regression coefficient is zero and that there is no relationship between the independent and dependent variables.

124. The last two columns in Table A30 contain statistics that test the residual errors for independence. A major assumption of regression models is

Table A30

Analysis of Regression Equations

References	Data	n	r^2	Probability of F	Shrinkage r^2	Standard Error of Estimate	Dependent Variable	Independent Variables	Coefficient	Beta Coefficient	Probability of t	Tests of Residuals for Independence of Errors: Runs Test	Durbin-Watson
Table A22	Sites 601, 701, 720, 904, 906, 907, 908	7	0.9012	0.00108	--	2.66×10^{-5}	K_d	Constant	-2.87×10^{-4}	--	0.000329	-0.9115	1.8265
								$\sin\theta$	2.84×10^{-4}	--	0.00108	(0.6380)	
Table A22	601, 701, 904, 906, 907, 908	6	0.6682	0.0470	--	5.02×10^{-5}	K_d	Constant	-8.98×10^{-5}	--	0.0120	1.4142	2.6760
								$Z/\bar{y}_c$	9.91×10^{-5}	--	0.0470	(0.8427)	
Table A22	601, 701, 720, 904, 906, 907, 908	7	0.3929	0.1319	--	6.59×10^{-5}	K_d	Constant	1.12×10^{-5}	--	0.8440	-0.3638	2.1223
								$\bar{y}_b/L_b$	-0.0924	--	0.1319	(0.2840)	
Table A22	601, 701, 720, 904, 906, 907, 908	6	0.8161	0.0135	--	3.74×10^{-5}	K_d	Constant	-8.58×10^{-6}	--	0.7384	0.000	2.4026
								W_c/r_c	-5.54×10^{-3}	--	0.0135	(0.0)	
Eq. A27	601, 701, 904, 906, 907, 908	7	0.9452	0.000243	--	1.98×10^{-5}	K_d	Constant	1.79×10^{-5}	--	0.2114	-0.3638	1.7560
								$C_s/\sin\theta$	-1.29×10^{-7}	--	0.000243	(0.2840)	
Eq. A28	Tombigbee R. except for 427	13	0.2130	0.4261	0.0677	6.68×10^{-6}	K_d	Constant	-2.53×10^{5}	--	--	-0.2961	1.5515
								$\bar{y}_b/L_b$	805×10^{5}	0.1121	0.1124	(0.2323)	
Eq. A29	Columbus Pool except for 427	8	0.6932	0.0521	0.2752	5.54×10^{-6}	K_d	Constant	-4.23×10^{5}	--	--	-0.7638	1.9190
								A_r	3.51×10^{5}	-0.1816	0.0336	(0.5550)	
								$Z/\bar{y}_c$	1.51×10^{5}	0.7194	0.1464		
Eq. A30	All data except for sites 720 and 427	19	0.6405	0.0003	0.5175	0.6293	$\ln(K_d)$	Constant	-13.7	--	--	0.3912	1.9760
								$\ln(C_s)$	0.839	-0.00574	0.000437	(0.3044)	
								$\ln(Z/\bar{y}_c + 2)$	-1.80	0.0761	0.00601		
Eq. A31	All data except for sites 720 and 427. C_s doubled for sites 429 and 208a	19	0.6963	<0.0001	0.5924	0.5784	$\ln(K_d)$	Constant	-14.202	--	--	-0.1161	1.9160
								$\ln(C_s)$	0.929	0.0142	0.000108	(0.0924)	
								$\ln(Z/\bar{y}_c + 2)$	-1.86	0.0933	0.00253		
Eq. A32	All data except sites 601, 720 and 427	18	0.5535	0.00240	0.4277	0.5979	$\ln(K_d)$	Constant	-14.202	--	--	-0.1161	1.9012
							$\ln(C_s)$	0.9453		-0.380	-1.952	(0.0924)	
							$\ln(Z/\bar{y} + 2)$		-1.987	0.839	4.312		
Eq. A33	All data except sites 720 and 427	19	0.6605	0.0002	0.5444	0.7516	$\ln(K_d)$	Constant	-15.4	--	--	-0.2243	1.6882
							$\ln(C_s)$	0.839		0.6348	0.000506	(0.1775)	
							$\ln(\sin\theta)$		-1.20	-0.4549	0.00673		
Eq. A35	Tombigbee R. except for 427	13	0.5272	0.0236	0.2534	1.07×10^{-5}	$K_{d_{pl}}$	Constant	-3.55×10^{-5}	--	--	-0.0946	1.8807
								W_c/r_c	7.31×10^{-5}	0.0837	0.0564	(0.0754)	
								$\sin\phi_2$	4.67×10^{-5}	0.0848	0.1105		
Eq. A36	Columbus Pool except for 427	8	0.5393	<0.0001	--	7.39×10^{-6}	$K_{d_{pl}}$	Constant	-3.41×10^{-5}	--	<0.0001	-1.0801	1.6280
								$\sin\phi_2$	6.86×10^{-5}	--	0.0380	(0.7199)	

that the error terms are normally distributed and are free of serial correlation. The plots of residuals presented in Part II of this appendix and the statistics presented in Table A30 indicate that all of the regression equations had residuals that were normally distributed and free of serial correlation.

Mississippi, Red, and Arkansas Rivers

125. Data were obtained for seven cutoff bends, six man-made and one natural, located on rivers other than the Tombigbee. As shown in Table A30 and Figure A25, two geometric variables, $\sin \theta$ and W_c/r_c explained more of the variance of K_d for this data subset than any of the other dependent variables. As expected, $-K_d$ for this subset of the data is inversely proportional to $\sin \theta$, but, counter to expectation, directly proportional to W_c/r_c. The effect of W_c/r_c on $-K_d$ is probably due in part to its collinearity with $\sin \theta$. Most physical situations would require that very low values of $\sin \theta$ be coupled with a tightly curving cut channel (low W_c/r_c). Negative values of W_c/r_c, which occur when the cut channel has concavity opposite that of the old bend, were not found in this subset of the data base. Results of linear regression for K_d in terms of W_c/r_c were changed significantly when data from site 720 were used with the other six observations (Table A22). The W_c/r_c value for site 720 was nine times larger than the next highest value. Also, as was noted above, the K_d value for 720 was dominated by C_s and the atypical $Z/\bar{y}_c$ value.

126. The linear regression equation for K_d in terms of $Z/\bar{y}_c$ derived with data from the six man-made cutoffs was significant at the 95-percent confidence level. This equation indicated that $-K_d$ is inversely proportional to $Z/\bar{y}_c$. This relationship agrees with intuitive reasoning. The higher the bend entrance is relative to the cut entrance, the less sediment diverted into the bend. However, predictions of $-K_d$ based on $Z/\bar{y}_c$ are much less attractive than predictions based on $\sin \theta$ because $Z/\bar{y}_c$ is more likely to change rapidly from its initial value than is $\sin \theta$.

127. The diversion angle for normal flow changes as sediments deposit in the bend entrance. The angles used in analysis were measured based on bank lines. The bar that forms in the bend entrance will change the diversion angle at low and normal stage. However, the diversion angle for bankfull conditions will remain unchanged from initial conditions until blockage is nearly

complete. The regression based on $\bar{y}_b/L_b$ was not significant at the 95-percent confidence level.

128. The first equation in Table A30 is preferred for predicting $-K_d$ for sites that are morphologically and hydrologically similar to the seven non-Tombigbee River sites. However, if $Z/\bar{y}_c \geq -1.0$, results of prediction based on the first equation should be compared with $-K_d$ values predicted using the second equation.

Tombigbee River

129. Stepwise regression for $-K_d$ using the Tombigbee River data gave markedly different results than for the other rivers. Equation A28 is not statistically significant or physically sensible.

130. When only the data from the eight Columbus Pool sites were used in stepwise regression, better results (as indicated by the probability of the F-statistic for Equation A29 in Table A30) were obtained. The coefficient $-K_d$ was found inversely proportional to both A_r and $Z/\bar{y}_c$. As noted, direct proportionality of $-K_d$ with $Z/\bar{y}_c$ is sensible, but one would expect smaller values of A_r to be associated with smaller $-K_d$ values since a smaller bend entrance would tend to exclude inflowing sediments. The beta coefficients and t-statistics shown in Table A30 indicate that $Z/\bar{y}_c$ had much more influence on K_d than A_r. The relationship between K_d and A_r in Equation A29 is probably due to the correlation between the A_r values and the distances from the bend entrances to Columbus Dam. Cut channel cross-sectional areas, A_c, were sized on navigation channel design requirements and were roughly constant throughout the pool. Bend channel areas, A_b, reflected the natural river channel geometry and grew larger downstream. Therefore, A_b/A_c or A_r decreased with distance upstream of the mouth of the Tombigbee River. The sites with the largest $-K_d$ values were located high in the pool at the most upstream locations. A plot of A_r and $-K_d$ versus river mile for the Columbus Pool is shown in Figure A43.

131. Variation in $C_s/\sin\theta$ explains 92.5 and 94.5 percent of the variation in K_d values for both the entire data set (Equation A34) and the subset based on other rivers (Table A22), respectively. However, neither C_s nor $\sin\theta$ is correlated with Tombigbee River K_d values. Perhaps both C_s and K_d for the Tombigbee River sites vary over such narrow ranges, and the estimates of C_s are so rough that the effect of $C_s/\sin\theta$ on K_d is obscured. The lack of correlation between K_d and $\sin\theta$ may also be related to the

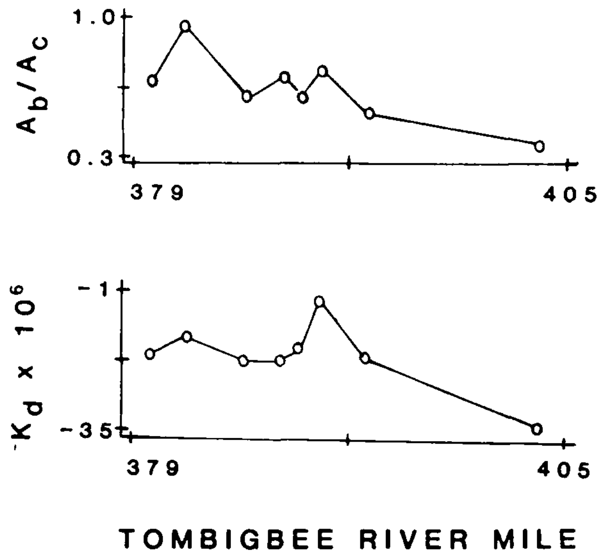


Figure A43. Variation of A_r and K_d with location in navigation pool for cutoff bends in Columbus Pool, Tombigbee River

lower C_s values and higher $\sin\theta$ values for the Tombigbee data. In addition, the initial value of $\sin\theta$ may have a less powerful effect on K_d when cutoffs are constructed to full size, as on the Tombigbee, instead of by allowing a pilot cut to erode. For situations where cutoffs are constructed by the pilot cut method, the division of flow and sediment between the cut and the old bend provides feedback that affects the processes of cut channel enlargement and bend filling.

132. Interestingly, the stepwise regression for the decay coefficient based on bend volume below normal pool elevation, $K_{d_{pl}}$, did not select either $Z/\bar{y}_c$ or A_r, as observed in Equation A35 and Table A30. The two variables describing initial entrance geometry, W_c/r_c and $\sin\psi_2$, were selected when all of the Tombigbee River data were used (Equation A35), but ate that the cut only $\sin\psi_2$ was selected when Columbus Pool values were input (Equation A36). In both cases $-K_{dpl}$ was found to be inversely proportional to $\sin\psi_2$, which agrees with physical reasoning. Large values of $\sin\psi_2$ indicate that the cut channel is poorly aligned with the approach channel, thus forcing a greater fraction of the flow of water toward the bend entrance. It should be noted, however, that ψ_2 varies through a narrow range for both the Columbus Pool data (0 to 15 deg) and all the Tombigbee

River data (0 to 18 deg). Furthermore, 8 of the 14 Tombigbee River ψ_2 values and four of the eight Columbus Pool values are all zero. A wider range of ψ_2 values might have produced more generally applicable results.

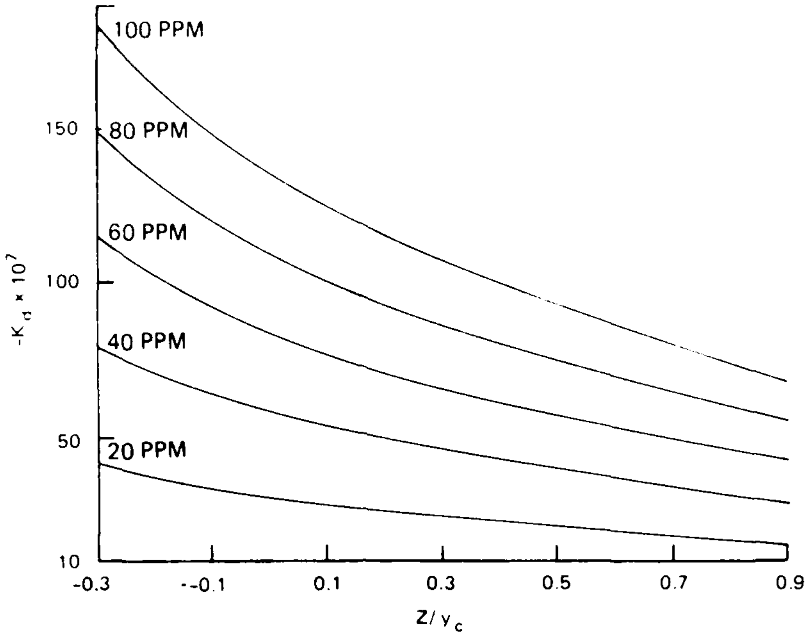
133. The influence of W_c/r_c probably has to do with secondary currents and attendant patterns of sediment movement. Equation A35 indicates that $-K_{d_{pl}}$ is inversely proportional to W_c/r_c. This agrees with intuition since coarse sediments tend to move toward the convex side of a bend. A cut channel with a large positive value of W_c/r_c would have a bend entrance located on the outside of a bend, and thus a smaller $-K_{d_{pl}}$ value. There were no negative W_c/r_c values in the Columbus Pool data, while W_c/r_c values for sites 101 and 208 were negative. The absence of negative W_c/r_c values may account for the absence of W_c/r_c in the Columbus Pool regression equation.

Composite data analysis

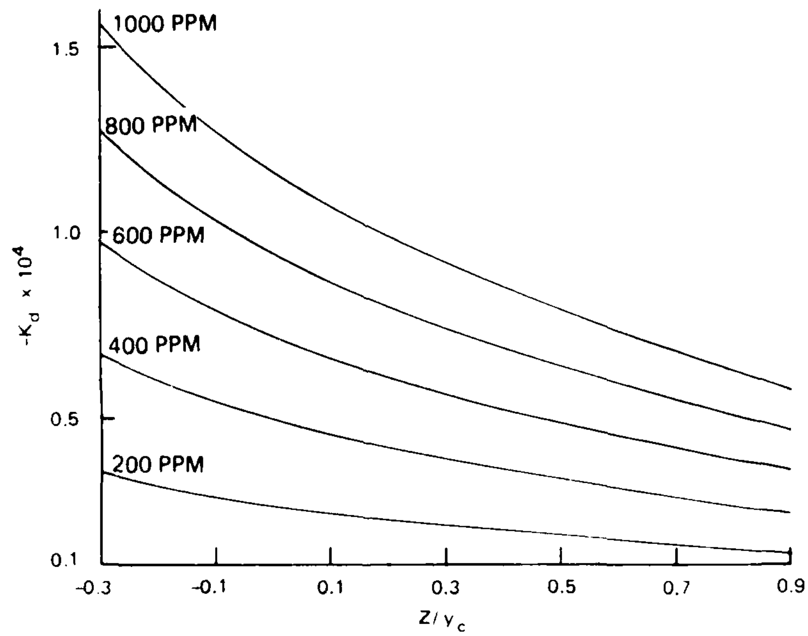
134. When data from all sites were compiled into one data base for regression analysis, the frequency distributions of most of the dimensionless variables were not normal. The variables were therefore log-transformed prior to regression to normalize their distributions, and the resulting regression equations for prediction of K_d were power functions of the selected independent variables rather than linear functions.

135. The stepwise multiple regression program selected C_s and $Z/\bar{y}_c$ from the 12 independent variables for prediction of K_d (Equation A30). Use of modified C_s values for sites 429 and 208a resulted in a similar regression equation (Equation A31) with the same two independent dimensionless variables but with slightly greater statistical significance, as shown in Table A30. When the difference between the correlation coefficients for Equations A30 and A31 was tested using Fisher's Z-transformation (Till 1974), the difference was found to be insignificant at the 95-percent confidence level. Both Equations A30 and A31 indicate that $-K_d$ varies directly with C_s and inversely with $Z/\bar{y}_c$. The sensitivity of $-K_d$ to C_s and $Z/\bar{y}_c$ is illustrated in Figure A44 and Table A31, which are based on Equation A31.

136. Four residuals of Equation A31 were greater than one standard deviation; residuals for sites 208b, 311, 422, and 906 were -1.55, -1.18, -2.56, and 1.15 standard deviations, respectively. The $-K_d$ values were overpredicted for sites 208b, 311, and 422 and underpredicted for site 906. The large residuals for the Tombigbee River sites may be due to poor C_s



a. $-K_d$ FOR C_s BETWEEN 20 AND 100 PPM



b. $-K_d$ FOR C_s BETWEEN 200 AND 1000 PPM

Figure A44. Variable $-K_d$ as a function of C_s and $Z/\bar{y}_c$ from Equation A31

Table A31

$-K_d \times 10$ as a Function of C_s and Z/y_c from Equation A31

C_s ppm	$Z/\bar{y}_c$ -0.3	0	0.3	0.6	0.9	1.2
0	0	0	0	0	0	0
10	22	16	12	10	8	7
20	41	30	23	19	15	13
30	60	44	34	27	22	18
40	78	58	45	35	29	24
50	96	71	55	44	36	30
60	114	84	65	52	42	35
70	132	97	75	60	49	41
80	149	110	85	68	55	46
90	166	123	95	75	61	51
100	183	135	104	83	68	56
200	349	258	199	158	129	108
300	509	376	290	231	188	157
400	666	492	379	302	246	205
500	819	605	466	371	303	252
600	970	717	553	440	359	299
700	1120	827	638	507	414	345
800	1268	937	722	575	469	390
900	1415	1045	806	641	523	435
1000	1560	1153	888	707	577	480

estimates, but the underprediction for site 906 is somewhat difficult to explain. Petersen (1963) noted the rapid rate of deposition at site 906. Deposition was aided by a period of extremely high flows immediately after cutoff construction and rapid development of the cut channel. The influence of high flows should be reflected in the C_s value for site 906. Rapid development of the cut channel may have resulted in local scour just upstream of the bend entrance, thus locally increasing C_s above the value predicted by the power function for the Arkansas River (Equation A16).

Patterns of Deposition

137. Although the bend volume decay constants K_d and $K_{d_{pl}}$ allow prediction of the rate of deposition in a cutoff bend during the blockage phase, they contain little information about the pattern of deposition along the length of a bend. Field inspection of cutoff bends along the Tombigbee River revealed that the bed material deposits in the upstream entrance of cutoff bends had morphology similar to point bars on convex banks. These bars always formed on the upstream side of the bend entrance, while the point at the downstream side of the bend entrance was usually covered with driftwood and was often slightly eroded. The upstream sides of the bars deposited in bend cut entrances tended to be steeper than their downstream sides. Coarser sediments were found on the upstream side. The bars tended to grow from the upstream side of the bend entrance toward the downstream side. Willows and other flood-tolerant vegetation often rapidly invaded the bar as soon as elevations were high enough to support terrestrial vegetation. The growth of a bar could sometimes be traced by noting the parallel bands of young willow trees of various ages. The distance that the bar in the upstream entrance of a cutoff bend extended into the bend was related to the angle of incidence. Gradual diversion angles (low values of $\sin\theta$) produced very long bars, while larger diversion angles produced very short bars.

138. Downstream bend entrances also tended to be deposition locations although the growth of bars there tended to lag those in the upstream entrances. In fact, all of the downstream entrance bars in Tombigbee River bends were underwater at the time of the 1984 and 1985 field inspections. As a result, visual observation and characterization of the morphology of these bars were not possible. Deposition in downstream entrances is probably the result of secondary currents generated by the discontinuous bank line at the old bend entrance.

139. An effort was made to generate prediction functions for channel area based on surrogate time, t^* , and dimensionless distance along the bend, x/L . The functional form of the relationship was

$$A/A(0) = \exp\left\{\left[a\left(\ln\frac{X}{L}\right)^2 + b\ \ln\frac{X}{L} + c\right]t^*\right\} \qquad \text{(A44)}$$

Although the regression functions generated did fit the observed data reasonably well, only weak relationships were found between the independent variables and the regression coefficients a , b , and c . Coefficients a and b control the shape of the three-dimensional surface and longitudinal displacement of the minimum value of $A/A(0)$. The coefficient c controls the magnitude of $A/A(0)$. Accordingly, c was significantly correlated with K_d , K_g , C_s , $\sin\theta$, and $C_s/\sin\theta$. However, no significant correlations were found between a and b and the independent variables. Furthermore, no correlations were found between any of the coefficients and the independent variables if data from site 601 were omitted. The regression functions do indicate that bend filling during the blockage phase is most rapid at or near the upstream entrance where x/L is small and just after cutoff completion, with $A/A(0)$ a log-decay function of t^* .

Error Analysis

140. The coefficients of determination presented in Table A30 are the fraction of variation in observed values of K_d explained by the associated regression equation. Perfect agreement between observed and predicted values would result in a coefficient of determination, r^2 , of 1.00. Values of r^2 less than 1.00 occur because of errors of three types: measurement error, model specification error, and sampling error.

Measurement error

141. Three main classes of variables were measured to produce the bend volume decay constants, K_d : (a) geometries of bends and cut channels, (b) streamflow volumes, and (c) average bed material concentrations. Accuracy and precision of the latter two classes of data are unknown. The Tombigbee River survey data have an accuracy of plus or minus 2.0 ft in the horizontal plane and plus or minus 0.2 ft in the vertical plane. Bend volumes (length * width * depth, LWD) were thus determined within about 4 percent (±2 LD ± 0.2 LW), if the error inherent in using the average-end area method for nonprismatic channels is ignored. The $V_b/V_b(0)$ ratios are therefore accurate within 8 percent. The bend volume decay constant, K_d , is based on the change in the $\log_e V_b/V_b(0)$ per unit change in $t^* = \Sigma Q_w \Delta t/V_b(0)$. Accordingly, K_d values may be measured within about 20 percent if error in $\Sigma Q_w \Delta t$ is negligible.

142. Measurements of angles of incidence and radii of curvature made from plan maps were repeated using different maps (or aerial photos) and a different operator. Measurements were found to vary by less than 10 percent. The value of $Z/\bar{y}_c$, determined from Equation A13, is a linear combination of horizontal and vertical distances. Analysis of the error associated with each term of Equation A13 indicates that $Z/\bar{y}_c$ was determined within 4 percent. A 20-percent error in C_s will produce an error of identical magnitude and direction in $-K_d$ predicted by Equation A29. Predicted K_d values are less sensitive to errors in $Z/\bar{y}_c$. A 20-percent error in $Z/\bar{y}_c$ in the range -0.5 to 0.5 will produce errors of 6 to 11 percent in predicted K_d values.

Model specification error

143. Model specification error is the result of using prediction models that are either incorrect functional forms or do not include all of the important variables. The functional forms of the prediction equations produced by the analysis were intentionally kept simple. The decay coefficient, K_d, measures the unit response of a cutoff bend to a unit hydrologic input. The forms of the regression functions for K_d were selected so that they would display physically sensible relationships between K_d, the initial geometry, and the average sediment input. Natural log transforms were used to normalize the distributions of the dimensionless variables. The result of this process was that the prediction functions for data sets including a wide range of C_s values showed that K_d was equal to a linear (or nearly linear) function of C_s divided by some power of an initial geometry variable. The K_d coefficient reflects the division of sediments between the cut and the bend during the blockage phase.

144. The number of variables in the prediction equations was controlled by the size of the data set. Since useful data were available from only 19 sites, only two or three independent variables could be included in multiple regression functions. The large residuals obtained for some sites (such as 422) may have been the result of the influence of excluded variables.

Sampling error

145. Sampling error refers to error introduced by nonrepresentative sampling. The sites sampled produced a data set of dimensionless variables that covered the ranges of possible values for each variable. However, the data set was deficient in at least two ways: it was too small to adequately represent the effects of all the independent variables, and the bivariate

distributions were skewed. For example, since the data from streams with high sediment concentrations were for bends constructed by excavating pilot channels, there were no low A_r values associated with high C_s values in the data set used to generate Equation A29. However, the data set generated for this study does allow empirical study of the relationships between K_d and the independent variables. Under the conditions prevalent at the sites studied, only a few of the independent variables (i.e., C_s, $Z/\bar{y}_c$, $\sin\theta$, $\sin\psi_2$, and W_c/r_c) were found to have a significant influence on K_d.

Lake Surface Areas and Perimeters

146. Measurements of surface areas and perimeters of cutoff bends in the infilling phase indicated that surface area rapidly declines in the first 5 to 15 years and then mildly fluctuates about a value roughly 40 to 60 percent of the initial value. This mild fluctuation is part of a much slower decline, but the time of observation for the seven lakes studied was not sufficient to reveal a downward trend. Lake perimeter was found to be more nearly constant with time than surface area. The stability of perimeter with time underscores a qualitative impression gained from study of the sequential aerial photography: the lakes tend to fill by narrowing more than shortening. Perimeters of the seven studied lakes decreased an average of only 6 percent while areas declined an average of 50 percent. Since interfaces between different types of habitat are especially valuable from an ecological standpoint, the persistence of lake perimeter indicates that the habitat value of the lakes declines more slowly than the lake area.

147. Evidently, sediment deposition in cutoff bends is radically different during the blockage and infilling phases. Deposition during the blockage phase is primarily bed material in the bend entrances and in the upstream limb of the bendway. Deposition occurs during every flow event large enough to transport bed material over the bar at the upstream bend entrance. In contrast, deposition during the infilling phase is much more sporadic, occurring only during overbank floods. Deposition tends to be characterized by uniform placement of fine material along the length of the bend. The foregoing generalizations are not valid if there are significant local sources of sediment flowing into the cutoff bend.

148. The mild fluctuations of lake surface area observed after the rapid initial decline (Figure A41) are measurement errors. The effects of lake stage fluctuation on area were controlled by using the line of permanent vegetation rather than the water's edge as the lake surface boundary. However, small errors were introduced when lake stages were high enough to cover some of the shoreline vegetation with water. Examination of photography dates in Table A29 reveals that after the initial rapid decline, surface areas tended to be slightly higher for low-flow months (July-November) and slightly lower for high-flow months (January-June).

149. In some cases, most notably the Arkansas River sites, the convex side of the oxbow lake was an old point bar with such a large deposit of sand that invasion by permanent vegetation was slow relative to the rate of morphologic change. The effect of these sandy deposits on vegetation may have introduced error in lake surface area depending on how individual photographs were interpreted.

150. The 25-percent increase in surface area at site 904 between 1968 and 1969 was due to closure of Lock and Dam No. 5 just downstream of the site in December 1968. The other three Arkansas River sites were far enough upstream of dams that they were little affected by dam closure and impoundment.

Comparison of Results Regarding Blockage with Literature

Blockage rates

151. Schega (1951), Clemens (1936), and Simons, Li, and Associates (1982) reported instances where cutoff bends were blocked by natural deposition up to normal flow stages within a few flood seasons after cut off. However, the transition from the blockage phase to the infilling phase is not complete until the bar in the upstream bend entrance is sufficiently high enough to force overbank flood flows. Data used in this study indicated that channel cross-sectional area below top-bank elevation near the upstream entrance of cutoff bends was reduced by 30 to 75 percent within 1 to 9 years after cutoff completion.

152. Table A32 shows values of t^* and estimates of time required for bend blockage ($A/A(0) = 0.95$ and $x/L = 0.1$) that were computed using Equation A38 and the coefficients presented in Table A27. Surrogate time values were converted to ordinary time using average discharges. Table A32

Table A32

Bend Volume Remaining When Entrance Is Blocked

Site	K_d*	a	b	c	r^2**	K_p†	t* for A/A(0) = 0.95	Mean Q, cfs	Initial Volume, ft^3	Time, months for A/A(0) = 0.95	$V_b/V_b(0)$ when A/A(0) = 0.95
101	-2.24E-05	7.30E-06	4.70E-05	4.50E-06	0.770	-6.5E-05	46076	12000	8.94E+08	1324	0.356
203	-2.15E-05	-3.50E-06	2.70E-06	-1.80E-05	0.650	-4.3E-05	70037	10383	3.04E+08	791	0.222
311	-1.70E-05	-3.60E-06	1.70E-05	-3.00E-06	0.870	-6.1E-05	48925	8715	3.03E+08	657	0.435
423	-1.65E-05	2.70E-06	2.80E-05	4.20E-06	0.790	-4.6E-05	65185	3500	9.11E+07	655	0.341
429	-3.29E-05	3.60E-05	1.30E-04	5.60E-05	0.460	-5.2E-05	57097	3500	1.09E+08	683	0.153
601	-2.33E-04	5.00E-05	2.30E-04	-1.50E-04	0.280	-4.1E-04	7227	31500	4.25E+08	38	0.186
908	-4.42E-05	3.50E-05	7.30E-05	-2.70E-05	0.590	-9.5E-06	314602	46000	4.10E+08	1081	0.000

* $V_b/V_b(0) = \exp(K_d t^*)$.

** r^2 for $A/A(0) = \exp(K_p t^*)$.

† $A/A(0) = \exp(K_p t^*)$, and $K_p = a[\ln(x/L)]^2 + b[\ln(x/L)] + c$. For the values of K_p shown, $x/L = 0.1$.

indicates that it would take from 3 to 100 years of average streamflow to completely block the entrances to these bends. Table A32 also shows that during this period of time the total volume of the bend will be reduced by 60 to 100 percent of its initial value. If average discharge during this period exceeds the assumed average values, reductions will be greater.

Effect of diversion angle

153. The literature contains several references that describe the effect of diversion angle on the movement of bed material into a branching channel. These references are presented in summary form by Lindner (1953), Vanoni (1975), and Richards (1982). Although the data from early workers is somewhat scattered, particularly data from lab flumes, these studies demonstrate that the diversion angle does affect the division of bed material between a main channel and a branching channel, but that wash load divides in proportion to the division of water discharge. Furthermore, the fraction of bed material diverted appears to be inversely proportional to $\sin\theta$ for diversion angles between 0 and 90 deg. The effect of diversion angle is more pronounced for coarser sediments and interacts with both the location of the diversion entrance in the main channel planform and the vertical distance between the bottom of the diversion and the main channel.

154. The sites investigated in this study displayed varying responses to the diversion angle. The angle between the upstream bend entrance and the cut entrance (θ) was one of the most influential independent variables controlling the bend volume decay coefficient for rivers other than the Tombigbee. These cutoffs experienced higher values of C_s than the Tombigbee sites and were constructed by allowing small pilot channels to scour rather than being built to full dimensions. Bend volume decay coefficients for Tombigbee River sites were relatively unaffected by variation in θ. However, bend volume decay coefficients for volumes below normal pool elevation were affected by ψ_2, the angle between the main channel upstream of the cutoff and the cut channel. The coefficient $-K_{d_{pl}}$ was inversely proportional to $\sin\psi_2$.

Effect of length ratio

155. Gagliano and Howard (1984) stated that flow persists in natural neck cutoffs longer for lower length ratios. They reasoned that cuts with greater length ratios would develop faster than those with smaller length ratios, and the old bends would thus block faster. Petersen (1963) presented data that

indicated that the time rate of deposition in man-made Arkansas River cutoff bends, per unit of bend length, was directly proportional to length ratio, at least for the first 5 years. However, data analyzed showed no relationship between K_d and L_r . The coefficient K_d was uncorrelated with L_r for both the two major data subsets and the entire data set. Furthermore, L_r was not selected for inclusion by the stepwise multiple regression program. Length ratios mostly likely affect K_d values, but in a complex way as they interact with other variables. For example, the rate of cut development is best measured by the cut channel growth coefficient, K_g , which is determined by the erosivity of the material through which the cut is excavated, the method of cut construction and development, and L_r . Furthermore, the blockage of the bend need not be entirely concurrent with development of the cut channel. Petersen's (1963) deposition rates were based on chronological rather than surrogate time, thus not allowing for different hydrographs at different sites.

Effect of location of bend entrance

156. Lindner (1953) points out that the location of the old bend entrance in relation to the new main channel planform is important because of the effect of secondary currents on movement of bed material, particularly in channels with eroding banks. Cutoff bends with upstream entrances located on concave banks of the main channel, with their axes tangent to the river center line, should block more slowly than bends with entrances located on convex banks. The location of the bend entrance is reflected by two of the independent variables, $\sin \psi_2$ and W_c/r_c .

157. Bends with entrances located on concave banks have positive values of W_c/r_c . The W_c/r_c values in this study varied over a rather narrow range (-0.1830 to 0.1050) because the cut channels were mostly straight. The coefficient $-K_{d_{pl}}$ was found inversely proportional to W_c/r_c , which is consistent with the above physical reasoning.

158. Variable $\sin \psi_2$ measures the deflection between the cut channel and the approaching flow. Small values of ψ_2 occur when the cut channel is well aligned with the approach flow. The value of $-K_{d_{pl}}$ was found to be inversely proportional to $\sin \psi_2$. As flow divides at the upstream junction between the bend and cut, the faster moving upper layers, which have lower sediment concentrations, tend to move into the channel that makes the smallest

angle with the approach flow because they have greater momentum. Accordingly, diversion of sediments into a cutoff bend entrance will be inversely proportional to $\sin \psi_2$. The smallest observed values of both K_d and $K_{d_{pl}}$ were for sites 422 and 417, respectively. Sites 422 and 417 had large values of $\sin \psi_2$ and moderately large positive values of W_c/r_c relative to the other sites.

Proximity to dams

159. The Mobile District (1984) found that bends located high in navigation pools (close to the upstream structure) blocked faster than those located further downstream in the lower portions of the pool. However, neither the dimensionless bend volume decay constants, $K_{d_{pl}}$ and K_d , nor their dimensional counterparts, k_d and $k_{d_{pl}}$ $[k_d = K_d \times V_b(0)]$, were correlated with longitudinal distance below the upstream dam. This contradiction may arise because observations by the Mobile District (1984) were based on blockage at normal stage. Since K_d and k_d are based on total channel volume below top-bank elevation, it is not surprising that they were unrelated to the distance above or below dams. Since the sediment deposits in lower pool bends are below the normal water surface, and those in upper pool bends are well above normal water surface, a casual inspection on the ground or in the air leads to the conclusion that sedimentation rates are higher in upper pool levels. The lack of influence of proximity to dams may be due to the facts that major changes in bend volume along the Tombigbee River have been associated with floods (Mobile District 1984) and the hydraulic influence of the dams is reduced during floods.

160. Another reason for the discrepancy between the findings of this study and the earlier observations has to do with the changes in flow regimes associated with closure of dams and excavation of the navigation channel. The Mobile District's (1984) conclusions were heavily influenced by observations of deposition in cutoff bends located in the upper reaches of Gainesville and Columbus Pools, observations that were made during periods when these sites were prone to aggrade. At each of these sites, aggradation tendencies resulted when a dam downstream of the site had been closed, but the dam upstream had not. In addition, the waterway channel was not dredged until after the dams were closed; therefore, the frequency of overbank flooding and

the magnitude of flows through the cutoff bends were greater during the predredging period.

161. McHenry et al. (1984) found that sedimentation rates in upper Mississippi River backwater areas were lower in the upper portions of navigation pools than in areas just above dams because of "less direct flow." However, the morphology of the upper Mississippi navigation pools is markedly different than the Tennessee-Tombigbee Waterway: the upper Mississippi is a braided channel, while the Tombigbee is meandering. Furthermore, the navigation channel on the Upper Mississippi River was developed by deepening only a part of the natural cross section and by building dams. The navigation channel for the river section of the Tennessee-Tombigbee Waterway is much wider and deeper than the Tombigbee River, particularly in the upper reaches. The waterway channel effectively replaced the natural channel in reaches where the two follow the same course. Nevertheless, infilling-stage sedimentation rates in the Tombigbee cutoff bends may be less for upper pool bends than for lower pool bends because of reduced flood stages in the upper reaches of the pools (Burkett 1986).

Comparison of Results Regarding Infilling with Literature

Effect of length ratio

162. Petersen (1963, 1964) and Gagliano and Howard (1984) found that blockage rates for man-made and natural neck cutoff bends were directly related to length ratios. Wolff (1978) found that the longevity of Missouri River oxbow lakes was directly proportional to the length ratio due to the greater depths and less permeable bottom sediments found in bends with high length ratios. The three Mississippi River oxbow lakes that were sequentially mapped showed a positive relationship between lake longevity and length ratio. Sites 716, 701, and 709 had length ratios of 9.9, 3.3, and 2.1, respectively, and their surface area decay curves terminated in fluctuations about 60, 50, and 34 percent of the initially measured area, respectively. However, this observation should be tempered since sites 701 and 709 were cut off in 1933, while site 716 was not cut off until 1942.

163. Arkansas River sites displayed a similar trend to those on the Mississippi River. Sites 906, 907, and 908 had length ratios of 8.4, 2.4, and

1.8, respectively; their surface area decay curves terminated in fluctuations about 61, 36, and 11 percent of the initially measured area, respectively.

Effect of floods

164. The curves of lake surface area and perimeter versus time appear relatively insensitive to major flood events. For example, curves for the three Mississippi River sites show no observable response to the major floods of 1973, 1975, 1979, and 1983. In contrast, anecdotal evidence regarding oxbow lakes on the Missouri (Jauron 1974) and measurements of deposition in middle Mississippi River lakes showed sharp response to major floods. However, Gagliano and Howard (1984) cited geological and archaeological evidence that the infilling phase lasts about 1,000 years for lower Mississippi River oxbow lakes. If the initial sharp declines in area shown on the plots of Figure A41 are the latter part of the blockage phase, it seems reasonable that little change in surface area would be noticeable over a 10- to 25-year period. Similar information for the duration of the infilling phase for the Arkansas River was not available.

Floodplain width and valley slope

165. Mississippi River oxbow lake surface area reduction rates were evidently unaffected by valley slope or floodplain width. Although site 709 experienced the greatest reduction in surface area, the floodplain width at this site, measured perpendicular to the direction of flow, was only about half as great as for sites 701 and 716. Low-water reference plane slopes for sites 701, 709, and 716 were 0.24, 0.45, and 0.52 ft/mile, respectively. Since site 709 experienced the greatest reduction in surface area and site 716 the least, these data fail to indicate any influence of slope on the persistence of oxbow lakes.

166. Gagliano and Howard (1984) stated that the absolute size of oxbow lakes was an important factor in their longevity. They reasoned that water and sediment from the main channel have to follow longer flow paths through connecting channels to reach distal portions of larger lakes, thus increasing the resistance of the lakes to infilling. No relationship was found between the size of the seven lakes studied herein and the fraction of initial area remaining in the infilling phase.

Management Strategy Formulation for Cutoff Bends

167. The expression "management of cutoff bends" as used herein refers to all types of activities undertaken to steward and conserve the ecological, recreational, and aesthetic resources that may be present in a stream reach containing one or more cutoff bends. A management strategy should include design of the cut channel, design of any types of blockage or entrance modification structure used for the old bend, scheduling of construction activities, and regulation of the uses of the bend and adjacent land areas. Management strategy should be formulated for all cutoff bends in a river reach in an integrated fashion.

168. Persons involved in management strategy formulation for cutoff bends should consider employing an approach similar to the decision pathway shown in Table A33. Factors leading to degradation of environmental conditions in

Table A33

Decision Pathway for Bendway Management Strategy Selection

Step	Decision
1	Determine major factors contributing to bendway environmental change or degradation.
2	Determine and describe desired environmental conditions ("target conditions") within the managed bendway.
3	Select a management strategy that addresses major decay factors and produces targeted conditions. If no such strategy exists or can be devised, return to Step 2.
4	Perform economic analysis. If selected strategy is not economically feasible, return to Step 2.
5	Design and implement management.
6	Monitor resultant bendway conditions and modify management strategy as appropriate.

cutoff bends include sediment deposition by normal flows and/or by overbank floods, poor water quality of inflows, aquatic plant infestation, shoreline erosion, and declining water surface area and shoreline length due to falling water table. Techniques and approaches for cutoff bend management found in the literature are tabulated in Table 3 of the main text. The focus of this study is on techniques that address bend resource loss due to sediment deposition.

169. Desired conditions for the managed bend ("target conditions") should be carefully identified early on (Step 2, Table A33). Target conditions may be expressed as ranges of depth, velocity, bed material grain size, and chemical and physical water quality variables. Communication among interested parties and agencies regarding conditions is important to prevent generation of unrealistic expectations. Target conditions should be selected for all cutoff bends within the managed area at the same time, so that comparisons and trade-offs can be made.

170. In many situations, target conditions are constrained by physical and economic problems. For example, maintaining significant velocity and coarse substrate in a cutoff bend on an alluvial channel is impractical unless the bend is located near a plentiful supply of sediment-free water (just below a dam, for example), such as the one described by Miller, King, and Glover (1983). Typical conditions for old cutoff bends are very low or zero velocity, very fine-grained bed material, and thermal stratification during warm weather with attendant depressed dissolved oxygen concentration below depths of 4 to 6 ft.

171. In general, a distribution of slackwater habitats along the length of a channelized reach is desirable. Generally, larger bends and bends with higher values of L_r (bend length/cut length) should receive management attention in order to preserve the most aquatic habitat for the longest period of time. The bend volume decay coefficient K_d can be computed using Equation A29, read from Table A31, or estimated from Figure A44. The K_d values can be used to compare bends as targets for management, or to estimate the effects of modifying entrance conditions of a given bend. When bend volume decay coefficients for bends that experience equal or nearly equal main channel streamflows are compared, the dimensional form k_d ($k_d = V_b(0) \times K_d$) should be used to remove the effect of initial bend volume.

Construction scheduling

172. The sequence of waterway construction activities can influence bendway sedimentation. Although the TTW bendways are complete, and the following observations are not useful for management of those bendways, this information may prove useful for future projects.

173. One of the most important factors controlling the rate of sediment deposition in a cutoff bend during the blockage phase is the average bed material concentration in the master stream, C_s. Although this quantity is not easily controlled by human action, some precautions can be taken. If the channel alignment project includes construction of dams or grade control structures, all of these structures should be completed and/or closed prior to cutoff construction. If possible, cutoff construction should be delayed until several flood events have occurred to allow initial channel response to the water-retarding structures. Local bank erosion problems can also increase C_s in the vicinity of a cutoff bend entrance. Such problems should be monitored, and if possible, corrected or controlled. If cutoff bends are promptly blocked to top-bank elevation at their upper ends, the control of C_s is less critical.

174. If management plans call for construction of a partial or complete blockage at the upstream end of a cutoff bend, material requirements for the blockage embankment may be reduced by delaying construction until some natural deposition has occurred. The channel cross section where the block is to be located will be partially filled by naturally deposited bed material, and deposits in the upper limb of the bendway will be dredged or excavated to build the blockage. Functions of the form of Equation A44 can be used to forecast the distribution of sediment in the upper limb of the old channel. Although K_d values can be used to estimate the loss of total bend volume that can be expected to occur during the delay period, careful monitoring of the targeted bends is recommended. Surrogate time depends on hydrologic events, and rapid action is in order after the desired natural deposition occurs to prevent further losses of bend habitat.

Entrance conditions

175. Maintenance of a hydraulic connection between the old bend and the main channel at normal stage is often desirable. A hydraulic connection at normal stage would allow aquatic organisms to utilize the old bends more freely and would provide access by boat for recreationists. Furthermore, stage fluctuations in the main channel would result in interchange of water and organisms with the master stream.

176. In most cases the infilling stage may be prolonged by promptly blocking the upstream end of a cutoff bend and maintaining hydraulic connection at the downstream end. However, this may cause access problems for

recreational and commercial users of the old bend if it is rather long. It is not known if limiting connection with the main channel to the downstream end of the old bend has any ecological implications, but it seems doubtful, given the range and mobility of most river fishes.

177. A potential negative effect of blocking the upstream end of a cutoff bend is declining water quality. Oxbow lakes along the Mississippi River have water quality characteristics similar to shallow eutrophic lakes. During warm weather, thermal stratification occurs and anaerobic conditions may develop below depths mixed by wind. Phytoplankton blooms often occur in upper layers and may cause elevated pH and chlorophyll levels. However, these lakes provide highly productive and extremely valuable backwater habitat to the river system (Beckett and Pennington 1986). More harmful water quality effects may occur in blocked bends which receive poor quality inflows due to either point or nonpoint sources of pollution and no longer have sufficiently short mean residence times to flush out the undesirable constituents. Similarly, if a tributary stream or ditch contributes large amounts of sediment to a blocked bend, deposition will occur if the velocity in the bend is no longer sufficient to transport the contributed load. Two of the bends in Columbus Pool on the Tombigbee River have experienced this phenomenon: Hickelson Lake (site 427) receives large quantities of sediment from a surface mine, and Dead River Bend receives sediment from a ditch that is headcutting.

178. Local drainage area of bends considered for management should be carefully inspected for sources of water pollution and sediment. If problems are detected, special studies may be in order and corrective actions (local controls such as water treatment, erosion control, or diversion of inflows) may be taken if feasible.

179. A third issue associated with prompt closure of the upstream entrance arises for cutoffs constructed by the pilot cut method. If the old channel is entirely blocked prior to cut development, flooding and/or overtopping and failure of the block may occur.

180. If the upstream entrance of the old bend cannot be blocked as soon as the cut is completed, design features for the cut channel and bend entrance should be considered that will reduce the fraction of coarse sediment diverted into the old bend. Within the constraints imposed by the overall plan for the main channel, the cut channel should be laid out to minimize the cut radius and thus maximize W_c/r_c. In other words, the cut channel should curve

sharply with concavity in the same direction as the old bend. Locating the new main channel so that the old bend entrance is located on the outer side of a bend is also desirable. The angle between the center lines of the cut channel and the old bend entrances should be near 90 deg, and, if possible, the angle between the approaching channel center line and the cut channel center line should be no less than 30 deg.

181. Modification of the vertical dimensions of the upstream bend/cut junction also will reduce the fraction of sediment diverted into the bend. The junction of the bend and cut should be designed to make the average bend entrance bed elevation as high as possible above the average cut entrance bed elevation. Average bed elevations should be determined by subtracting average depth (area/width) from top-bank elevation. However, the elevation of the bend entrance must be low enough at some point to allow for hydraulic connection at normal stage. In many cases it may be feasible to block the upstream bend entrance across part of its width, leaving only enough of an opening for passage of vessels. In some situations the angle between the cut and bend could be increased to 90 deg when a partial block is constructed.

182. The difference between the average bed elevations of the cut and bend entrances is referred to as Z, which is shown in schematic form in Figure A1. Figure A44 and Table A31 show the effect of $Z/\bar{y}_c$, where $\bar{y}_c$ is the average depth of the cut entrance, on the decay coefficient K_d for various values of average bed material concentration. For an average bed material concentration of 200 ppm, the bend volume decay coefficient K_d may be decreased by 50 percent by increasing $Z/\bar{y}_c$ from 0 to 0.9. However, the pilot cut method of cutoff construction poses a problem. The objective of modifying bend entrance conditions as described is to reduce the fraction of sediments diverted into the old bend. If too small a fraction of the sediments is diverted into the old bend, the pilot channel will aggrade rather than develop. A compromise solution would be to incorporate bend entrance modifications after the pilot cut has developed enough to convey average discharge.

183. If the upstream entrance of a cutoff bend is not to be blocked or allowed to block to top bank, maintenance of the bend entrance will require periodic dredging to remove deposited sediments. Estimated bend volume decay constants from Figure A44 or Table A31 can be used along with forecasted streamflows to estimate the quantities of coarse sediment that must be

removed. The large volume of sediment deposited in cutoff bends along alluvial rivers makes bend management by dredging without blockage construction economically infeasible in most cases. However, a limited amount of dredging is a necessary component of management strategies for cutoff bends and similar backwaters along rivers similar to those studied if plans call for maintenance of connecting channels between the old bend and the new main channel.

Shoreline length and lake depth

184. Cutoff bends should be managed to preserve bends with long, sinuous shorelines and greater depths. Prompt blockage of the upper entrance will reduce the length of the upper limb of the bend totally filled during the blockage phase.

APPENDIX B: DATA TABLES

Table B1

Discharge, Velocity, and Suspended Sediment Data for

Sites 101, 203, 208, and 311

Site	Date (YYMMDD)	Mean Daily Discharge Above Cut cfs	Sediment Discharge Above Cut tons/day	Discharge, cfs Above Cut	In Cut	In Bend
101	820105	76300		47100	26000	21100
101	820106	74500	98934	56200	35800	20400
101	820108	75000	97929	80600	47100	33500
101	820110	61900	20466	50200	29700	20500
101	821203	52200	23984	37800	21800	16000
101	821206	80800	97080	72200	40000	32200
101	821208	86600	95074	78600	44700	33900
101	821210	77500	10901	32300	33100	65400
101	831206	70200				
101	831207	73700				
101	840507	86300	21277	59700	30600	29000
203	820105	53200	77870	48800	26000	22800
203	820107	70100	78345	66400	32600	33800
203	820109	46500	14446	43500	27400	16100
203	821202	35300	20447	34900	12700	21200
203	821205	56500	45865	54100	26100	28000
203	821207	58900	57613	75400	35500	39900
203	821209	60700	32181	68500	30250	38250
203	821211	36700	4337	31500	15900	15600
203	840504		44930	64500	31400	33100
203	840505		37361	70600	36700	33900
203	840506		22206	69700	32200	37500
208	820421	57200	58430	56800	56800	0
208	820422	55700		57100	51400	5700
208	820422	56500	48902	56600		0
208	820423	44300	10379	44700	44100	600
208	821207	58900	36080	57600	46600	11000

(Continued)

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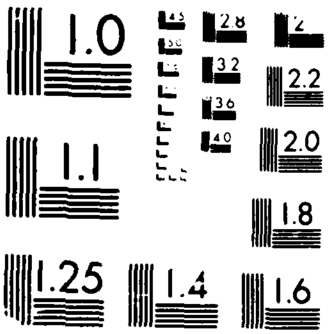
AD-A190 426 MANAGEMENT OF ENVIRONMENTAL RESOURCES OF CUTOFF BENDS 3/3
ALONG THE TENNESSEE (U) ARMY ENGINEER WATERWAYS
EXPERIMENT STATION VICKSBURG MS ENVIR F D SHIELDS
UNCLASSIFIED NOV 87 WES/MP/EL-87-12 F/G 13/2 NL



MICROCOPY RESOLUTION TEST CHART

Table B1 (continued)

Site	Date (YYMMDD)	Mean Daily Discharge Above Cut cfs	Sediment Discharge Above Cut tons/day	Discharge, cfs Above Cut	In Cut	In Bend
208	821208	51200		56400	48100	8300
208	821209	35800	9847	37600	30100	7500
311	820421	57200	63920	58600	47400	11200
311	820422	56500	55760	61100	48300	12800
311	820424	55700	5350	37400	35900	1500
311	821207	58900	43670	58600	50200	8400
311	821208	51200	4980	42900	35900	6990
311	821209	35800	1300	32100	26500	5610
311	831204					
311	840429			54000	44700	9300
311	840430			43100	37200	5900
311	840503			44500	37000	7500
311	840504			54400	45700	8700
311	840505			52200	47700	4500
311	840506			51100	44200	6900

(Continued)

(Sheet 2 of 4)

Table B1 (Continued)

Site	Date (YYMMDD)	Velocity, ft/sec Above Cut	Velocity, ft/sec In Cut	Velocity, ft/sec In Bend	Suspended Sand, ppm Above Cut	Suspended Sand, ppm In Cut	Suspended Sand, ppm In Bend	Suspended Fines,* ppm Above Cut	Suspended Fines,* ppm In Cut	Suspended Fines,* ppm In Bend	Total Suspended Sediment, ppm Above Cut	Total Suspended Sediment, ppm In Cut	Total Suspended Sediment, ppm In Bend
101	820106	3.99	4.16	2.88	61	76	30	591	613	569	652	689	
599													
101	820108	4.77	4.34	3.20	105	85	63	345	337	302	450	422	365
101	820110	2.94	3.19	2.24	6	11	5	145	132	135	151	143	140
101	821203	3.05	2.55	1.52	15	19	14	220	239	215	235	258	229
101	821206	4.74	4.88	2.80	192	137	71	306	290	275	498	427	346
101	821208	5.62	5.21	4.42	207	119	110	241	242	234	448	361	344
101	821210	4.31	4.44	2.95	39	60	103	86	101	103	125	161	206
101	831206										546	565	449
101	831207										416	431	377
101	840507	5.02	4.31								132	113	139
203	820105	3.38	3.97	2.58	37	38	22	554	551	529	591	589	551
203	820107	4.16	4.57	2.01	120	61	30	317	301	196	437	362	226
203	820109	1.99	3.49	1.67	12	9	13	111	115	125	123	124	138
203	821202	2.98	2.33	2.17	16	14	20	201	147	157	217	161	177
203	821205	2.52	3.78	3.09	51	43	69	263	261	290	314	304	359
203	821207	4.00	4.22	3.66	67	88	78	216	214	220	283	302	298
203	821209	3.63	3.51	3.64	79	40	58	95	88	93	174	128	151
203	821211	2.12	2.46	2.30	7	7	10	44	54	61	51	61	71
203	840504	5.12	3.82								258	226	213
203	840505	5.50	4.59								196	175	176
203	840506	5.36	4.45								118	152	255
208	820421	5.20	4.24	0	99	65	14	282	282	239	381	347	253
208	820422		3.75	0		31			112			143	
208	820422	5.92	4.38	0	18	54	13	202	205	175	320	259	188
208	820423	4.20	3.71	0	15	12	8	71	74	73	86	86	81
208	821207				25	32	33	107	211	247	232	343	380
208	821208					26	48		135	142		161	190

(Continued)

* Finer than 0.062 mm.

(Sheet 3 of 4)

Table B1 (Concluded)

		Velocity, ft/sec			Suspended Sand, ppm			Suspended Fines, ppm			Total Suspended Sediment, ppm		
Site	Date (YYMMDD)	Above Cut	In Cut	In Bend	Above Cut	In Cut	In Bend	Above Cut	In Cut	In Bend	Above Cut	In Cut	In Bend
208	821209				7	3	8	90	89	148	97	92	156
311	820421	7.30	6.90	2.08	404	294	48	351	355	334			
311	820422	4.49	6.47	2.00	338	245	55	199	189	192			
311	820424	4.90	4.68	2.00	53	44	11	70	73	91			
311	821207				76	198	298	199	243	185			
311	821208				43	108	21	119	124	133			
311	821209				15	45	21	104	105	139			
311	831204										662	876	
311	840429	4.86	4.75								320	331	257
311	840430	4.50	4.42								244	203	171
311	840503	4.67	4.63								215	213	168
311	840504	5.25	5.09								404	394	355
311	840505	5.23	5.48								324	288	313
311	840506	5.19	5.24								192	198	187

(Sheet 4 of 4)

Table B2

Summary of Hydrographic Survey Data, Tombigbee River

WES	Mobile District	Mile	1977	1978	1979	1980	1981	1982	1983	1984	1985
		Rattlesnake Bend, Demopolis Pool, Pool = 73.00 Bank = 85.40									
101001	RB1	235.9	*	c	*	c	c		c	c	c
101002	RB2	235.7	c	c	c	*	c		*	*	*
101003	RB3	235.5	c	c	c	c	*		c	c	c
101004	RB4	235.2	*	c	*	c	*		c	c	c
101005	RB5	234.7	c	c	c	*	c		*		*
101006	RB6	233.8	*	c		c			c	c	c
101007	RB7	233.0	*	c	c	c	c		c		b,c
101008	RB8	232.5	*	c		c				c	c
101009	RB9	231.4	*	c	*	c	c		c		c
101010	RB10	230.1	*	c		*			*	*	c
101011	RB11	229.1	*	c	*	*	*		*		c
101012	RB12	227.9	*	c		c			*	*	c
101013	RB13	227.4	c	c	c	c	*		c		*
101014	RB14	226.4	*	c		c			c	a	c
101015	RB15	226.2	*	c	*	c	*		c	a	c
		Rattlesnake Cut, Demopolis Pool, Pool = 73.00 Bank = 85.4									
101103	12CD	223.3	*	c	*				c		c
101104	12CC	223.6	*	c		c			c	c	c
101105	12CB	223.9	*	c	*	c	c		c	c	c

(Continued)

Notes:
a = Survey obviously in error, rejected after visual inspection of plotted data.
b = Entry error.
c = Inconsistent range length.
d = Sediment deposition above normal pool elevation for entire range.
e = Bend/cut overlay.
* = Data not edited.
Pool = Normal pool elevation in feet above mean sea level.
Bank = Top-bank elevation in feet above mean sea level.

(Sheet 1 of 8)

Table B2 (Continued)

WES	Mobile District	Mile	1977	1978	1979	1980	1981	1982	1983	1984	1985
Cooks Bend, Gainesville Pool, Pool = 109.00 Bank = 115.00											
203001	CB1	293.5		*	*	*	*		*	a	c
203002	CB2	293.67		*	*	*			*		c
203003	CB3	294.01		*	*	*	*			*	*
203004	CB4	294.3		*	*	*			*	*	*
203005	CB5	294.98		*	*	*	*		*		
203006	CB6	295.3		*	*	*			*		*
203007	CB7	295.68		*		c	c		c	*	*
203008	CB8	295.98		*	*	*			*		*
203009	CB9	296.21		c	*	c	c		c	a	c
203010	CB10	296.53		c	c	c	c		c	a	c
203011	CB11	296.83		*	*	*	*		*	a	*
Cooks Cut, Gainesville Pool, Pool = 109.00 Bank = 116.00											
203104	4AC	276.9				*	*			*	*
203105	4AD	277.2				*	*		*		*
203106	4AE	277.69				*	*		*	*	*
203107	4AF	277.91				*	*		*		*
Big Creek Bend, Gainesville Pool, Pool = 109.00 Bank = 126.00											
208001	BC	331.04	*	c	*	*	*		*	a	*
208002	BCA	330.88	*	c	*	*	c		*		*
208003	BCB	330.7	c	c	c	*	*		*		*
208004	BCC	330.56	*	c	*	*	*		*		*
208005	BCD	330.03	*	c	*	*			*	a	
208006	BCE	328.97	c	c	*	*			*		*
208007	BCF	328.56	*	c	*	*			*	a	*
208008	BCG	328.33	c	c	*	*			*	a	*

(Continued)

(Sheet 2 of 8)

Table B2 (Continued)

WES	Mobile District	Mile	1977	1978	1979	1980	1981	1982	1983	1984	1985
		Big Creek Cut, Gainesville Pool, Pool = 109.00 Bank = 130.00									
208102	15AA	304.5			*	*			*	a	
208103	15AB	304.67			*	*			*		*
208104	15AC	304.87			*	*			*	a	*
208105	15AD	305.08			*	*				a	*
208106	15AE	305.26			*	*			*		c
208107	15AF	305.43	*		*	*			*		*
		Hairston Bend, Aliceville Pool, Pool = 136.00 Bank = 142.8									
311001	1HB	347.2					*	*	*	a	*
311002	2HB	347.4					*	*	*	a	*
311003	3HB	347.7						*	c	a	*
311004	4HB	348.2					*		*	a	*
311005	5HB	348.7					*	*	*	a	*
311006	6HB	349.5					*		b	a	b
311007	7HB	350.3					*	*	*	a	*
311008	8HB	351.0					*		a	a	*
311009	9HB	351.8					*	*	*	a	*
311010	10HB	352.1					*	*	a	a	*
311011	11HB	352.3					*	*	*	a	*
311012	12HB	352.5					*	*	*	a	*
		Hairston Cut, Aliceville Pool, Pool = 136.00 Bank = 146.3									
311102	11A	318.7					*	*			*
311103	12A	319.1					*	*			

(Continued)

(Sheet 3 of 8)

Table B2 (Continued)

WES	Mobile District	Mile	1977	1978	1979	1980	1981	1982	1983	1984	1985
		Columbus Bend, Aliceville Pool, Pool = 136.00 Bank = 155.6									
312001	8B	362.9					c	c	c	*	*
312002	9B	363.5					*	*	*	b	*
312003	10B	364.4					*	*	*	*	*
312004	11B	365.0					*	*	*	*	*
312005	12B	365.6					c	c	c	b,c	*
312006	13B	366.0					*	*	*	*	*
		Columbus Cut, Aliceville Pool, Pool = 136.00 Bank = 158.8*									
312103	23A	362.9									*,*
312104	24A	363.0									*,*
312105	25A	363.6									*,*
312106	26A	364.0									*,*
312107	27A	364.4									c,*
		Stinson Bend, Columbus Pool, Pool = 163.00 Bank 173.6									
416001	8A	378.2					*	e	e	a	e
416002	9A	378.7					*	*	*	a	*
416003	10A	379.4					*	*	*	a	*
416004	11A	379.9					*	*	a	a	*
		Stinson Cut, Columbus Pool, Pool = 163.00 Bank = 174.9									
416101	12A	340.8						*	*	*	c

(Continued)

* Two surveys were taken in 1985: in February and May.

(Sheet 4 of 8)

Table B2 (Continued)

WES	Mobile District	Mile	1977	1978	1979	1980	1981	1982	1983	1984	1985
		Town Creek Bend, Columbus Pool, Pool = 163.00 Bank = 175.2									
417001	14A	380.6					*	*	*	*	*
417002	15A	381.2					*	*	*		*
417003	16A	381.6					*	*	*	*	*
417004	17A	382.0					*	*	*	a	*
417005	19A	382.2					*	e	e		e
		Town Creek Cut, Columbus Pool, Pool = 163.00 Bank = 175.8									
417102	13A	341.7					*	*	*		*
417103	18A	342.2						*	*	*	*
		Buttahatachee Bend, Columbus Pool, Pool = 163.00 Bank = 174.6									
419001	22A	383.3					*	*	*	*	*
419002	23A	383.9					*	*	*		*
419003	24A	384.4					*	*	*	*	*
419004	25A	384.7						*	*		c
419005	26A	385.0						*	*		c
419006	27A	385.3					*	*	*	*	*
419007	28A	385.6						*	*		*
419008	29A	385.9					*	*	*	*	*
		Buttachatachee Cut, Columbus Pool, Pool = 163.00 Bank = 176.7									
419102	21A	343.8					*	*	*		*
419103	30A	344.4						*	*		*
419104	31A	344.8						*	*		*
419105	32A	345.2						*	*	*	*

(Continued)

(Sheet 5 of 8)

Table B2 (Continued)

WES	Mobile District	Mile	1977	1978	1979	1980	1981	1982	1983	1984	1985
		Vinton Bend, Columbus Pool, Pool = 163.00 Bank = 172.00									
420001	34A	386.7						*	*	a	*
420002	35A	387.4					*	*	*	*	*
420003	36A	387.8					*	*	*	*	*
		Vinton Cut, Columbus Pool, Pool = 163.00 Bank = 170.7									
420102	37A	346.3						*	*		*
420103	38A	346.5						e	e		e
		Denmon Bend, Columbus Pool, Pool = 163.00 Bank = 173.3									
421001	39A	388.4					*	*	*	*	*
421002	40A	388.8					*	*	*	*	*
421003	41A	389.2					*	c	c	*	*
		Denmon Cut, Columbus Pool, Pool = 163.00 Bank = 168.8									
421103	42A	347.0							*		b
		Cane Bend, Columbus Pool, Pool = 163.00 Bank = 173.7									
422001	43A	389.4					*	*	*	a	*
422002	44A	389.9					*	*	*	*	*
422003	45A	390.3					*	*	*	*	*

(Continued)

(Sheet 6 of 8)

Table B2 (Continued)

WES	Mobile District	Mile	1977	1978	1979	1980	1981	1982	1983	1984	1985
		Cane Cut, Columbus Pool, Pool = 163.00 Bank = 170.7									
422101	42A	347.0							*		*
422102	46A	347.5						*	*		
		McKinley Bend, Columbus Pool, Pool = 163.00 Bank 175.0									
423001	48A	390.8					*	*	*	*	*
423002	49A	391.2					*	*	*		
423003	50A	391.6					*	*	*	*	c
423004	51A	392.0					*	*	*	a	*
423005	52A	392.4					*	*	*	*	*
423006	53A	392.8					*	*	*		c
423007	54A	393.2					*	*	*	*	*
		McKinley Cut, Columbus Pool, Pool = 163.00 Bank = 175.8									
423102	47A	348.0						*	*		c
423103	55A	348.5						*	*		*
423104	56A	349.8						*	*		*
		Hickleson Lake Bend, Columbus Pool, Pool = 163.00 Bank = 178.5									
427001	61A	397.0					*	*	*	*	*
427002	62A	397.4					*	*	*	*	d
427003	63A	397.8					*	*	*	*	d
427004	64A	398.2					*	*	*	*	
427005	65A	398.7					*	*	*	*	*

(Continued)

(Sheet 7 of 8)

Table B2 (Concluded)

WES	Mobile District	Mile	1977	1978	1979	1980	1981	1982	1983	1984	1985
Hickleson Lake Cut, Columbus Pool, Pool = 163.00 Bank = 178.8											
427103	66A	351.8						*	*		*
427104	67A	352.2						*	*		*
James Creek Bend, Columbus Pool, Pool = 163.00 Bank = 183.1											
429001	70A	400.3					c	c		*	*
429002	71A	400.7					*	*	*		*
429003	72A	401.2					*		*	a	*
429004	73A	401.5					*		*	*	*
429005	74A	402.0					*		*	*	*
429006	75A	402.4					*		c	*	*
429007	76A	402.7					*		*	*	*
429008	77A	403.0								d	d
429009	78A	403.4							d	a	d
James Creek Cut, Columbus Pool, Pool = 163.00 Bank = 184.0											
429102	69A	353.1							*		*
429103	79A	353.7							*	*	*
429104	80A	354.4							*		*
429105	81A	354.9							*		c
429106	82A	355.3							*	*	*

(Sheet 8 of 8)

Table B3

Reduced Hydrographic Survey and Hydrologic Data

Site	Date	Bend Volume, cu ft	Cut Volume cu ft	$V_b/V_b(0)$	$V_c(0)/V_c$	$\int_0^t Q_w\,dt$	t*
101	7702	8.939E+08	3.460E+07	1.000	1.000	0	0
101	7806	8.743E+08	3.439E+07	0.978	1.006	7.664E+11	857
101	7908	8.726E+08		0.976	0.993	1.387E+12	1551
101	8006	8.342E+08		0.933	1.029	2.155E+12	2410
101	8108	8.271E+08		0.925	0.998	2.401E+12	2686
101	8306	8.074E+08	3.415E+07	0.903	1.013	3.803E+12	4255
101	8409	7.994E+08	3.463E+07	0.894	0.999	4.467E+12	4997
101	8507	8.083E+08	3.530E+07	0.904	0.980	4.815E+12	5387
203	7908	3.041E+08	0.000E+00	1.000	0.000	0	0
203	8008	2.935E+08	4.555E+07	0.965	1.000	4.727E+11	1554
203	8108	2.830E+08	4.630E+07	0.931	0.984	6.316E+11	2077
203	8306	2.634E+08	4.794E+07	0.866	0.950	1.612E+12	5301
203	8409	2.654E+08		0.873		2.103E+12	6914
203	8509	2.628E+08	4.825E+07	0.864	0.944	2.352E+12	7736
208	7908	1.366E+08	6.977E+07	1.000	1.000	0	0
208	8008	1.287E+08	6.900E+07	0.942	1.011	4.681E+11	3427
208	8107	1.269E+08		0.929		6.008E+11	4398
208	8108	1.308E+08		1.000		0	0
208	8306	1.222E+08	6.924E+07	0.934	1.000	7.694E+11	5882
208	8509	1.207E+08	6.903E+07	0.923	1.003	1.369E+12	10467
311	8107	3.034E+08	1.952E+07	1.000	1.000	0	0
311	8210	2.977E+08	2.078E+07	0.981	0.939	2.324E+11	766
311	8308	2.877E+08		0.948		7.916E+11	2609
311	8505	2.831E+08	2.306E+07	0.933	0.846	1.357E+12	4473
416	8210	1.128E+08	1.120E+08	1.000	1.000	0	0
416	8308	1.050E+08	9.730E+07	0.930	1.151	4.498E+11	2830
416	8409		1.051E+08		1.066	7.372E+11	4639

(Continued)

(Sheet 1 of 4)

Table B3 (Continued)

Site	Date	Bend Volume, cu ft	Cut Volume cu ft	$V_b/V_b(0)$	$V_c(0)/V_c$	$\int_0^t Q_w \, dt$	t*
416	8507	1.046E+08	1.041E+08	0.927	1.076	8.820E+11	5550
417	8210	1.015E+08	5.367E+07	1.000	1.000	0	0
417	8308	9.637E+07	5.486E+07	0.950	0.978	4.521E+11	3163
417	8507	9.521E+07	5.815E+07	0.938	0.923	8.845E+11	6188
419	8211	1.139E+08	7.659E+07	1.000	1.000	0	0
419	8308	1.080E+08	7.565E+07	0.948	1.012	4.498E+11	1935
419	8411	1.111E+08		0.976		7.511E+11	3232
419	8507	1.049E+08	7.918E+07	0.921	0.967	8.820E+11	3795
420	8212	4.367E+07	8.140E+06	1.000	1.000	0	0
420	8309	3.933E+07	9.336E+06	0.901	0.872	4.041E+11	4534
420	8410	3.775E+07		0.865		6.909E+11	7753
420	8506	3.799E+07	9.372E+06	0.870	0.869	8.309E+11	9324
421	8212	2.765E+07		1.000		0	0
421	8309	2.241E+07	2.604E+07	0.811	1.000	4.064E+11	10438
421	8410	2.163E+07		0.782		6.909E+11	17744
421	8506	2.087E+07	2.663E+07	0.755	0.978	8.309E+11	21340
422	8212	2.846E+07	2.227E+07	1.000	1.000	0	0
422	8309	2.627E+07	2.219E+07	1.000	1.004	4.041E+11	7538
422	8410	2.504E+07		0.953		6.909E+11	12889
422	8506	2.557E+07	2.237E+07	0.973	0.996	8.309E+11	1550
423	8212	9.109E+07	1.290E+08	1.000	1.000	0	0
423	8310	8.617E+07	1.332E+08	0.946	0.968	4.067E+11	2188
423	8410	8.658E+07		0.950		6.909E+11	3717
423	8506	8.474E+07	1.422E+08	0.930	0.907	8.309E+11	4470
427	8212	3.429E+07	2.022E+07	1.000	1.000	0	0
427	8310	2.751E+07	2.573E+07	0.802	0.786	4.067E+11	5811
427	8410	2.501E+07		0.729		6.909E+11	9873

(Continued)

(Sheet 2 of 4)

Table B3 (Continued)

Site	Date	Bend Volume, cu ft	Cut Volume cu ft	$V_b/V_b(0)$	$V_c(0)/V_c$	$\int_0^t Q_w\,dt$	t*
427	8506	2.452E+07	2.748E+07	0.715	0.736	8.309E+11	11874
429	8212	1.086E+08		1.000		0.000E+00	0
429	8310	9.915E+07	1.679E+08	0.913	1.000	4.067E+11	1835
429	8410	9.631E+07	1.724E+08	0.887	0.974	6.909E+11	3118
429	8507	9.897E+07	1.757E+08	0.912	0.956	8.309E+11	3750
601	721107	4.253E+08		1.000		0	0
601	721120	4.208E+08	6.213E+07	0.989	1.000	7.194E+10	169
601	721205	3.822E+08		0.898		1.183E+11	278
601	721221	3.951E+08	7.125E+07	0.929	0.872	1.635E+11	384
601	730115	3.585E+08	8.436E+07	0.843	0.736	2.453E+11	577
601	730129	3.579E+08	9.348E+07	0.841	0.665	2.908E+11	684
601	730226	3.065E+08	9.355E+07	0.721	0.664	4.138E+11	973
601	730329	2.819E+08		0.663		6.338E+11	1490
601	731110	2.233E+08		0.525		1.487E+12	3495
701	3303	1.438E+10	1.188E+08	1.000	1.000	0	0
701	3801	1.520E+10	9.300E+08	1.057	0.128	7.716E+13	5364
701	5101	9.488E+09	2.845E+09	0.660	0.042	3.235E+14	22487
701	6404	4.380E+09	2.785E+09	0.304	0.043	5.472E+14	38037
720	6402	3.286E+09	3.647E+09	1.000	1.000	0	0
720	7407	2.204E+09	5.272E+09	0.671	0.692	1.770E+14	53856
720	8402	1.401E+09	5.621E+09	0.426	0.649	3.461E+14	105323
904	5704	1.372E+09		1.000		0.000E+00	0
904	5908	9.165E+08		0.668		4.411E+12	3216
904	6302	7.669E+08		0.559		9.768E+12	7121
906	5007	9.174E+08	8.072E+07	1.000	1.000	0	0
906	5206	5.975E+08	1.342E+08	0.651	0.601	3.171E+12	3456
906	5804	4.842E+08	1.563E+08	0.528	0.697	7.258E+12	7912

(Continued)

(Sheet 3 of 4)

Table B3 (Concluded)

Site	Date	Bend Volume, cu ft	Cut Volume cu ft	$V_b/V_b(0)$	$V_c(0)/V_c$	$\int_0^t Q_w\,dt$	t*
907	5503	5.008E+08		1.000		0	0
907	5802	4.795E+08		0.957		2.405E+12	4803
907	6007	3.305E+08		0.660		5.514E+12	11010
908	5405	4.098E+08		1.000		0	0
908	5711	3.384E+08		0.826		2.446E+12	5967
908	5911	2.506E+08		0.611		4.721E+12	11518
908	6011	1.981E+08		0.483		5.923E+12	14452

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