Downstream Effects of Dams on Alluvial Rivers

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By GARNETT P. WILLIAMS *and* M. GORDON WOLMAN

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SYMBOLS AND DEFINITIONS LIST

c_i	Coefficient in empirical equations, with $i = 1$ to 4.
d_i	Dominant size of bed material.
r	Correlation coefficient.
t	Time.
$t_{\max}$	Time (years) needed to reach maximum degradation.
t_p	Time needed for degradation to reach a designated proportion of maximum degradation.
C_i	Empirical coefficient in hyperbolic equation of channel change with time, with $i = 1$ or 2.
D	Bed degradation.
$D_{\max}$	Maximum eventual bed degradation.
Q_m	Average daily discharge (arithmetic average of the annual mean daily flows for a post-dam period of years).
Q_p	Arithmetic average of the annual 1-day highest averaged flows for the pre-dam period of record.
W	Channel (bankfull) width.
W_t	Channel width at t years after dam closure.
W_1	Channel width at time of dam closure.
W_2	Channel width as of latest resurvey after dam closure.

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ABSTRACT

This study describes changes in mean channel-bed elevation, channel width, bed-material sizes, vegetation, water discharges, and sediment loads downstream from 21 dams constructed on alluvial rivers. Most of the studied channels are in the semiarid western United States. Flood peaks generally were decreased by the dams, but in other respects the post-dam water-discharge characteristics varied from river to river. Sediment concentrations and suspended loads were decreased markedly for hundreds of kilometers downstream from dams; post-dam annual sediment loads on some rivers did not equal pre-dam loads anywhere downstream from a dam. Bed degradation varied from negligible to about 7.5 meters in the 287 cross sections studied. In general, most degradation occurred during the first decade or two after dam closure. Bed material initially coarsened as degradation proceeded, but this pattern may change during later years. Channel width can increase, decrease, or remain constant in the reach downstream from a dam. Despite major variation, changes [illegible] cross section in streambed elevation and in channel width with [illegible] often can be described by simple hyperbolic equations. Equation coefficients need to be determined empirically. Riparian vegetation commonly increased in the reach downstream from the dams, probably because of the decrease in peak flows.

INTRODUCTION

Many alluvial channels are considered to be systems in equilibrium. This concept implies that the channel size, cross-sectional shape, and slope are adjusted to the quantities of sediment and water transported so that the streambed neither aggrades nor degrades. Similarly, the channel cross-sectional shape remains approximately constant. In this concept, both short-time changes (scour and fill) and long-term geologic or evolutionary changes (associated with climatic changes involving hundreds or thousands of years) are excluded. Neither the time scale nor magnitude of the changes involved in these concepts is precise. Nevertheless, the notion of adjustment and equilibrium implies that alluvial channels could be altered by significant manmade modifications, such as dams, in the regimen of water and sediment delivered.

This study deals with channel changes that have t[illegible] place downstream from 21 dams on alluvial rivers. Documentation of these changes can be useful in evaluating and (or) mitigating the expected effects of dams.

SCOPE OF STUDY

The primary emphasis of this study is on changes in bed elevation and width of river channels after alteration of the flow regimen by closure of dams. Information availability dictated the degree of study. Evidence of changes in bed material and in vegetation is presented where the data permit. Measured water discharges and sediment loads also are discussed because of their effect on all these features.

This study documents changes as they have occurred, particularly changes that have progressed for several decades. We have not been able to develop equations of sediment transport and erosion that might encompass the transient processes described, nor to produce a method of predicting the specific changes likely if a dam is built on a particular river. However, the data presented here should be useful for testing theoretical or empirical approaches. Brief discussion is devoted to the kinds of assumptions and constraints imposed on predictive models. Environmental impacts have received increasing attention during the past decade (see, for example, Turner 1971; Fraser, 1972; Gill, 1973; Sundborg, 1977; American Society of Civil Engineers, 1978; and Ward and Stanford, 1979) but will not be discussed separately here.

STUDY SITES AND SELECTION CRITERIA

The preferred selection criteria for a damsite and downstream reach were:

1. An alluvial bed at the time the dam was built. Generally, this meant bed material in the silt-to-gravel range, as these sizes are more susceptible to erosion.
2. Monumented channel cross sections at various sites downstream from the dam, with repeat surveys (one of which was done at about the time of dam construction).
3. No significant dredging, channelization, or similar operations in the study reach.
4. No significant backwater effects from downstream dams.

Data that met the above criteria were available for 21 dams (fig. 1). Most of these are in the Plains States and semiarid West. Many other dams, too numerous to include in figure 1, also will be mentioned throughout this paper.

Although resurveyed cross sections were the preferred source of data for channel changes, gage height versus discharge relations at U.S. Geological Survey streamflow-gaging stations also were used to estimate bed-level changes, if the gaging station had: (1) An erodible bed in the reach of the gage; (2) a location within about 10 km (kilometers) downstream from the dam; (3) gaging records beginning at the time of the dam closure (and preferably much earlier); and (4) a channel width that has not changed appreciably in the gaging-station reach, during the time period examined. Reaches downstream from 14 dams were found with a gaging station meeting these requirements. Eleven of these reaches have resurveyed cross sections and were among the 21 sites shown in figure 1.

Most of the analysis was based on information from sites that met the criteria noted above. However, where specific information was available on bed material, special channel characteristics, sediment loads, or vegetation, this information was used to illustrate specific changes and to enlarge upon the findings.

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METHODS OF ANALYSIS AND DATA SOURCES

WATER DISCHARGE

Water-discharge data were available for all 21 sites from U.S. Geological Survey gaging-station records. These data were used to determine what effect the dam had on the magnitude and frequency distribution of downstream flows. Comparison of pre-dam and post-dam flow records of the nearest long-term gaging station downstream from the dam indicated the overall effect of the dam on downstream flow. However, any influence of the dam needs to be separated from other factors, such as regional climatic changes and upstream operations of man. Pre-dam and post-dam flow records were examined for the nearest gaging station both upstream and downstream from the dam. The "control" station upstream from the dam reflects to a significant degree the flows that would have occurred downstream from the dam if no dam had been built. A control station is most useful located as close as possible to the dam, as long as it is not within the backwater of the dam.

The flow record used for a damsite was the longest period common to both the downstream gaging station and the upstream control station. This common period sometimes was abbreviated to avoid the effects of a subsequently-built dam on the flow at one of the stations.

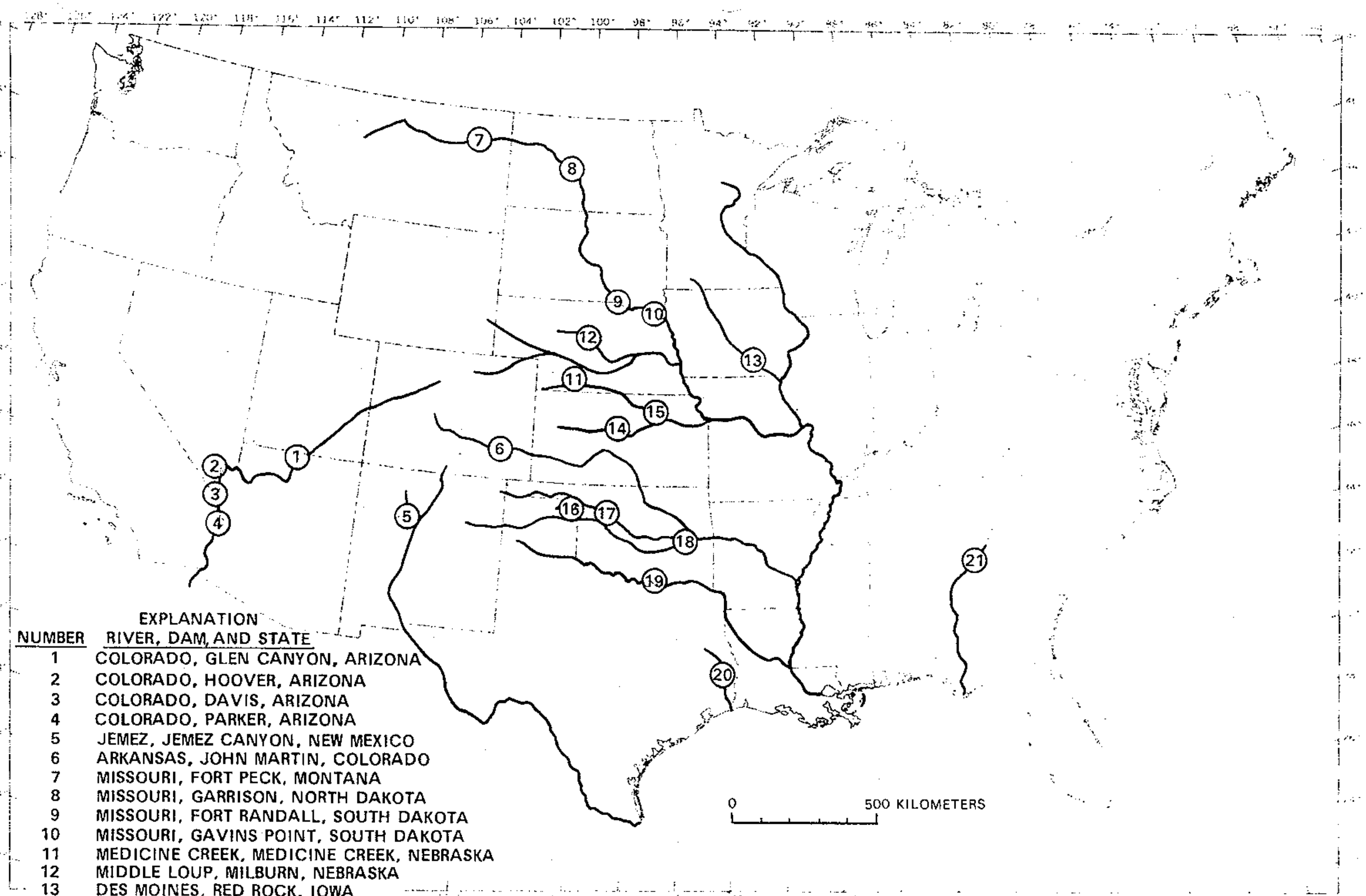
The flow characteristics examined in this paper include average daily flow (commonly called mean annual flow), average annual flood peak, and certain flow-duration features. The average daily discharge for a given year is computed by taking the average discharge during each day, adding these for 365 consecutive days, and dividing the total by 365. We averaged these annual figures for a number of years to get a representative average daily discharge for that period. Similarly, the instantaneous annual peak discharges were averaged for the period of interest. Flow-duration values used here are the discharges equaled or exceeded 5, 50, and 95 percent of the time, where the duration curve is based on flow records for the appropriate period. These statistics represent only an approximate summary of flow characteristics and will not reveal changes in annual, seasonal, or daily mean flows. Daily variations, for example, can be large downstream from dams operated for power production.

SEDIMENT LOAD

Information about measured suspended-sediment loads before and after construction of dams is available for a few river reaches from U.S. Geological Survey and U.S. Army Corps of Engineers reports (some unpublished). Such data have been used in specific cases to show dam-related changes in suspended load.

BED AND BANK MATERIALS

Data on bed and bank materials were available for selected sites from research investigations or from pre- and post-engineering surveys for reservoir and dam



EXPLANATION

NUMBER	RIVER, DAM, AND STATE
1	COLORADO, GLEN CANYON, ARIZONA
2	COLORADO, HOOVER, ARIZONA
3	COLORADO, DAVIS, ARIZONA
4	COLORADO, PARKER, ARIZONA
5	JEMEZ, JEMEZ CANYON, NEW MEXICO
6	ARKANSAS, JOHN MARTIN, COLORADO
7	MISSOURI, FORT PECK, MONTANA
8	MISSOURI, GARRISON, NORTH DAKOTA
9	MISSOURI, FORT RANDALL, SOUTH DAKOTA
10	MISSOURI, GAVINS POINT, SOUTH DAKOTA
11	MEDICINE CREEK, MEDICINE CREEK, NEBRASKA
12	MIDDLE LOUP, MILBURN, NEBRASKA
13	DES MOINES, RED ROCK, IOWA
14	SMOKY HILL, KANOPOLIS, KANSAS
15	REPUBLICAN, MILFORD, KANSAS
16	WOLF CREEK, FORT SUPPLY, OKLAHOMA
17	NORTH CANADIAN, CANTON, OKLAHOMA
18	CANADIAN, EUFAULA, OKLAHOMA
19	RED, DENISON, OKLAHOMA-TEXAS
20	NECHES, TOWN BLUFF, TEXAS
21	CHATTAHOOCHEE, BUFORD, GEORGIA

FIGURE 1.—Location of major study sites.

planning and design. These data have been supplemented by samples collected by the authors. In addition, the authors made pebble counts (Wolman, 1954) of coarse particles on the beds of several rivers downstream from dams. The results of these measurements are used to illustrate some aspects of channel- and bed-material change.

MEAN BED ELEVATION

Mean bed elevation was determined from: (1) Measured cross sections; (2) published graphs of bed elevation at successive times after dam closure (Colorado River only); and (3) gage height-discharge relations at gaging stations.

MEASURED CROSS SECTIONS

The preferred method for determining mean bed elevation was based on plots of 248 resurveyed cross sections provided by the U.S. Army Corps of Engineers and U.S. Bureau of Reclamation. These 248 cross sections had been measured a total of 1,202 times. All measured cross sections were referenced to elevation above sea level (National Geodetic Vertical Datum of 1929). For each of the 1,202 cross-section surveys, we took from 15 to 30 elevation readings at equally-spaced intervals across the entire bed width, then averaged these readings for mean bed elevation.

Bars and unvegetated islands, indicated in field notes, aerial photographs, and published topographic maps, were included as part of the channel-bed data. In a few cases, the edge of a bar was high enough relative to the adjacent streambed that problems arose in defining the edge of the streambed or channel. The surveyors had the same difficulty.

The four chief sources of error or variability in determining mean bed elevation from plotted cross sections are: (1) Locations of placement of the stadia rod; (2) natural changes in the bed configuration with time; (3) recognition of the bed as opposed to the bank on the plotted cross section; and (4) operator error in choosing and averaging many bed elevations to get a mean value. Error due to location of the stadia rod can be assumed to be minor. Bed configurations do change with time, quite apart from scour and fill, because of passage of bedforms and redistribution of sediment. River surveys normally are conducted during low flow (wading conditions). Resurveys associated with the passage of a flood on the Colorado River near Lees Ferry, Arizona, showed about 2 m (meters) of change in mean bed level (Leopold and others, 1964, p. 228); low-flow resurveys of the present study undoubtedly involve changes considerably less than this. Exact error from changes in bed configuration with time is unknown. Recognition of the streambed and banks on plotted cross sections was facilitated by the original notes of surveyors. Operator error was considered by comparing two operator's determination of the average of many elevations across the bed; differences of 0. to 0.4 m appeared, which is not a geomorphically significant error.

Because mean bed elevations naturally fluctuate with time at any alluvial cross section, fluctuations of less than about 0.1 or 0.2 m were considered insignificant in this study. Significance of a measured absolute change in bed elevation depends not only on measuring precision but also on the scatter in elevations, the rate of change of elevation with time, and the period of record. For example, for the magnitudes of changes occurring at one cross section downstream from Fort Peck Dam on the Missouri River, Wolman (1967, p. 90) estimated that about 10 years of record would be needed to reliably show a degradation rate of 0.08 m/yr (meter per year), and 30 years would be needed to show a degradation rate of about 0.01 m/yr. These values will vary from site to site.

PUBLISHED GRAPHS OF BED-ELEVATION CHANGES

For an additional 39 resurveyed cross sections, downstream from Hoover, Davis, and Parker Dams on the Colorado River, U.S. Bureau of Reclamation reports for various years provide graphs of mean bed elevation versus time. We read bed elevations for selected times directly from the plotted curves, for all sections downstream from these dams. The authors of those reports derived the curves from measured cross sections by: (1) Planimetering the cross-sectional area below an arbitrarily chosen low bank-to-bank horizontal baseline, the elevation of which is constant with time for each site; (2) dividing this area by the baseline width (which stayed virtually constant with time), and (3) subtracting the mean depth thus obtained from the elevation of the baseline. In almost every case, no islands were present at the cross sections. The 39 cross sections in this category had been measured a total of 615 times. The total number of resurveyed cross sections for the study thus was 287, and these had been measured a total of 1,817 times. On the average, then, each cross section in the study was measured about 6 times, at intervals ranging from about 1 to many years.

GAGE HEIGHT-DISCHARGE RECORDS (RATING TABLES)

Within the criteria listed earlier, the gage height corresponding to an arbitrarily chosen discharge is approximately proportional to the bed level. Lowering of such a gage height with time would indicate lowering of the streambed. For the reference discharge, a low flow is better than a high one, because the low-flow part of the gage height-discharge relation is more sensitive to changes in bed level and is better defined than the high-now part of the relation. (The elevation corresponding to zero discharge probably would be best, but it is not defined for many gaging stations.) Where possible, we used the discharge exceeded 95 percent of the time as the reference discharge. Where this discharge was not defined on a significant number of rating tables, the lowest discharge common to most of the tables was used.

Although this method can show general trends in bed elevation, it is not as accurate as measured cross sections. Water-surface elevations can be affected by changes in channel shape, channel roughness, and downstream features, even where width has remained approximately constant.

Where the rating-table method was used, a control station upstream from the dam, if available, also was examined. Control stations usually were located more than 10 km upstream from the dam in an attempt to avoid any effects of the reservoir.

CHANNEL WIDTH

Channel (banktop) width was measured directly from plotted cross sections. The survey notes in some cases were used to help define the banks. Defining the banks usually was not difficult.

Regulation of discharge by several dams reduced the channel-forming flows to such an extent that the post-dam channel became narrower. The new banks, as well as the original banks, then appeared on a plotted cross section. In such instances, we measured the width between the newer banks, even though occasional flow releases could overtop those banks.

TIME ORIGIN OF CHANNEL CHANGES

As a preliminary step to constructing a dam across a channel, major or minor rearrangement of the stream and its channel usually is made. Thus, the normal movement of sediment and water are interfered with from the early stages of construction. Such interference can cause channel changes downstream. The extent of these changes will vary from one dam to another, according to the nature and rate of progress on the project. Several years usually are needed to complete construction and officially close a dam. Furthermore, storage in the reservoir generally begins before the dam is closed officially. The date of dam closure, therefore, may represent a rather belated time from which to date channel changes. A more logical date might be the date construction began. However, channel cross sections generally were not established at such an early stage. The available original cross-sectional measurements were made at times ranging from several years prior to the beginning of construction to a year or two after the dam was closed. The year of dam closure is used as the reference date in this study because it is the only date commonly available to all sites. A cross-sectional measurement made no later than about 1 year after dam closure usually was accepted as representative of the channel at the time of dam closure.

VEGETATION

Analysis of vegetation changes in this study is limited to a gross quantitative approach, with little attention to individual plant types. Differences in vegetation cover for a number of study sites were determined in one or more of three ways: (1) Onsite mapping; (2) successive aerial photographs; and (3) successive ground photographs. Onsite, the simple method used consisted of comparing exposed areas of channel bars and islands clearly discernible on earlier aerial photographs with existing stands of vegetation in the same reaches. Mapping was confined to the channel itself and did not include the entire valley bottom.

VARIABILITY OF NATURAL CHANNELS

To evaluate the effect of manmade alterations on natural environment, the natural variability of an environment needs to be considered. A few observations of the characteristics and changes in alluvial rivers virtually unaffected by manmade structures are reviewed briefly here to provide a reference for subsequent analyses of apparent changes associated with dams.

Two kinds of variability are involved in any analysis of channel changes. First, at any time a channel's width, depth, and slope vary in space. For example, although the mean width of the Missouri River downstream from Garrison Dam in North Dakota in 1957 was 415 m for a reach 87 km long, the standard deviation of 24 measurements was approximately 122 m or 29 percent. The actual width ranged from a minimum of 255 m to a maximum of 845 m. This variability also shows that, in comparing present and past widths of the channels, a change needs to be demonstrable statistically and, thus, outside of the range of natural variability in any one set of measurements.

The second, more complex type of variability occurs with time at a given river cross section. Some selected, representative data from the literature on naturally-occurring changes in channel width and bed elevation are summarized in tables 1–3. These changes can be large. For example, within several weeks the Yellow River of China at any one spot may widen by as much as hundreds of meters (Chien, 1961). Another of the world's largest and most sediment-laden rivers, the Brahmaputra in India, also has extreme changes in width with time (Coleman, 1969). The rates of change range from a few meters to hundreds of meters per

TABLE 1.—*Selected examples of rates of change of channel width in alluvial reaches*

[+, increase; –, decrease; USA, United States of America]

River, location	Approximate width of initial channel (meters)	Flood changes: Time	Flood changes: Change in width (meters)	Flood changes: Change in width (percent)	Long-term changes: Years of observation	Long-term changes: Rate of change (meters per year)	Long-term changes: Rate of change (percent per year)	Reference
Brahmaputra River, Bangladesh	6,700	--	--	--	8	+70	+1.0	Coleman, 1969, p. 161.
Brahmaputra River, Bangladesh	11,800	--	--	--	8	-65	-.55	Coleman, 1969, p. 161.
Brahmaputra River, Bangladesh	12,200	--	--	--	11	0	0	Coleman, 1969, p. 161.
Brahmaputra River, Bangladesh	12,600	--	--	--	8	+118	+.93	Coleman, 1969, p. 161.
Brahmaputra River, Bangladesh	11,000	--	--	--	8	+98	+.89	Coleman, 1969, p. 161.
Brahmaputra River, Bangladesh	6,700	--	--	--	8	+15	+.22	Coleman, 1969, p. 161.
Brahmaputra River, Bangladesh	3,100	--	--	--	8	-42	-1.4	Coleman, 1969, p. 161.
Brahmaputra River, Bangladesh	7,400	--	--	--	133	+36	+.49	Latif, 1969, p. 1689.
Katjuri River, India	--	--	--	--	100	+16	--	Inglis, 1949, p. 67.
Gila River, USA	588	--	--	--	21	-21	-3.5	Burkham, 1972, p. 5.
Gila River, USA	98	--	--	--	9	+12.5	+12.8	Burkham, 1972, p. 5.
Gila River, USA	225	--	--	--	1	-64	-28	Burkham, 1972, p. 5.
Gila River, USA	88	--	--	--	1	+85	+97	Burkham, 1972, p. 5.
Gila River, USA	174	--	--	--	1	-73	-42	Burkham, 1972, p. 5.
Rio Salado, USA	4.0	--	--	--	36	+4.3	+108	Bryan, 1927, p. 18.
Rio Salado, USA	14.9	--	--	--	36	+4.2	+28	Bryan, 1927, p. 18.
Cimarron River, USA	18	--	--	--	25	+16.4	+91	Schumm and Lichty, 1963, p. 73-74.
Cimarron River, USA	427	--	--	--	15	-15.3	-3.6	Schumm and Lichty, 1963, p. 73-74.
Cimarron River, USA	198	--	--	--	6	0	0	Schumm and Lichty, 1963, p. 73-74.
Cimarron River, USA	20	--	--	--	25	+34.6	+173	Schumm and Lichty, 1963, p. 73-74.
Cimarron River, USA	884	--	--	--	15	-42.7	-4.8	Schumm and Lichty, 1963, p. 73-74.
Red River, USA (average of 20 sites)	1,200	--	--	--	16	-25	-2	Schumm and Lichty, 1963, p. 86.
Red River, USA (average of 20 sites)	1,070	--	--	--	4	+33	+3	Schumm and Lichty, 1963, p. 86.
Patuxent River, USA	--	26 hours	+6.2	--	--	--	--	Gupta and Fox, 1974, p. 503.
Patuxent River, USA	--	About 2 days	0	0	--	--	--	Gupta and Fox, 1974, p. 503.
Trinity River, USA (many sites)	105	--	0 to +45	0 to +43	--	--	--	Ritter, 1968, p. 17-52.

TABLE 2.—*Illustrative examples of long-term aggradation and flood deposition in alluvial reaches unaffected by manmade works*

[USA, United States of America; USSR, Union of Soviet Socialist Republics]

River, location	Flood deposition: Time	Flood deposition: Depth (meters)	Long-term aggradation: Years of observation	Long-term aggradation: Rate (meters per year)	Reference
Colorado River, USA	--	--	31	0.03	Cory, 1913, p. 1212.
Yellow River, China	--	--	--	.03	Todd and Eliassen, 1940, p. 446.
Alexandra-North Saskatchewan River, Canada	--	--	358-2,400	.0007-.003	Smith, 1972, p. 182.
Kodori River, USSR	--	--	32	.03	Mandych and Chalov, 1970, p. 35.
Last Day Gully, USA	--	--	11	.006	Emmett, 1974, p. 58.
Arroyo de Los Frijoles, USA	--	--	6	.01	Leopold and others, 1966, p. 219.
Nile River, Egypt	--	--	1,900-2,800	.00096-.0016	Lyons, 1906, p. 315.
Mu Kwa River, Formosa	--	--	3	4	Lane, 1955, p. 745-747.
Brahmaputra River, Bangladesh	6 months	0.6-8	--	--	Coleman, 1969, p. 178.
Rio Guacalate, Guatemala	2 hours	1	--	--	Foley and others, 1978, p. 114.
James River tributaries, USA	Several hours	0-1.5	--	--	Williams and Guy, 1973, p. 42.
Van Duzen River, USA	About 3 days	.3-3	--	--	Kelsey, 1977, p. 284-301.
Little Larrabee Creek, USA	About 3 days	2.4	--	--	Kelsey, 1977, p. 284-301.
Trinity River tributaries, USA	--	0-3.4	--	--	Ritter, 1968, p. 53-54.
Waiho River, New Zealand	--	3-24	--	--	Gage, 1970, p. 621.
Centre Creek, New Zealand	8 months	.44-.55	--	--	O'Loughlin, 1969, p. 697.

year; however, most of the changes are less than 1 percent of the channel width per year. The channel width of the Cimarron River in Kansas fluctuated significantly from 1874 to 1954 (Schumm and Lichty, 1963). Wolman and Gerson (1978) suggested that floods affect river width more significantly in arid climates than in humid climates, but the magnitudes are not well-defined. A few instances are noted in table 1 for rivers comparable to those included in the present study.

Natural bed aggradation measured during many

TABLE 3.—*Illustrative examples of long-term degradation and flood erosion in alluvial reaches unaffected by manmade works*

[USA, United States of America; USSR, Union of Soviet Socialist Republics]

River, location	Flood erosion: Time	Flood erosion: Depth (meters)	Long-term degradation: Years of observation	Long-term degradation: Rate (meters per year)	Reference
Castaic Creek, USA	--	--	1/100	0.01	Lustig, 1965, p. 8.
Red Creek tributary, USA	--	--	about 815	.004	LaMarche, 1966, p. 83.
Beatton River, Canada 2/	--	--	250	.011	Hickin and Nanson, 1975, p. 490.
Lena River, USSR 2/	--	--	20	.0005	Borsuk and Chalov, 1973, p. 461.
Klarälven River, Sweden	--	--	about 7,000	.007	de Geer, 1910, p. 161.
Trinity River and tributaries, USA	--	0-0.5	--	--	Ritter, 1968, p. 54.
Wills Cove, USA	Several hours	1/0-3	--	--	Williams and Guy, 1973, p. 35.
Yellow River, China	About 12 hours	5-9	--	--	Todd and Eliassen, 1940, p. 376.
Pickens Creek, USA	1/About 1 hour	0-6	--	--	Troxell and Peterson, 1937, p. 93.
Centre Creek, New Zealand	8 months	.2-.5	--	--	O'Loughlin, 1969, p. 697.
Klarälven River, Sweden	About 1 month	4.7	--	--	de Geer, 1910, p. 174.

1/Estimated.

2/Classification uncertain.

years can be very small (table 2). Examples are 0.0007 to 0.0034 m/yr, or 1 m every 290 to 1,430 years (Alexandra–North Saskatchewan River, Canada) and about 0.001 m/yr, or 1 m every 1,000 years, for the Nile River near Aswan in Egypt. Values of about 0.03 m/yr (1 m about every 30 years) have been given for the Colorado River in the United States, the Yellow River in China, and the Kodori River in the Soviet Union. The most rapid reported rate is about 4 m/yr for the Mu Kwa River in Formosa, where sediment from landslides during 3 years raised the streambed about 12 m.

In contrast to long-term average rates, bed aggradation during floods can be enormous. Some observed maximum depths of fill for a single flood are about 8 m on the Brahmaputra River and 24 m in the Waiho River in New Zealand (table 2). Depths of 1 to 3 m are common for the cases reported in the literature.

Reported measurements of long-term natural degradation (table 3) range from about 0.0005 to 0.011 m/yr. For example, Borsuk and Chalov (1973) gave an averaged bed lowering of 0.0005 m/yr during 20 years for the Lena River, Soviet Union. LaMarche (1966) used vegetation to estimate an average of 0.004 m/yr during 815 years for a small channel in Utah. The longest period examined seems to be 7,000 years by de Geer (1910), who counted varved clays and estimated an average bed degradation of 0.007 m/yr for the River Klarälven, Sweden. Hickin and Nanson (1975) reported an average degradation rate of 0.011 m/yr for the Beatton River, Canada, for 250 years.

During floods, streambeds in southern California in a matter of hours have eroded as much as 6 m (Troxell and Peterson, 1937), and the Yellow River in China has degraded by as much as 9 m (Todd and Eliassen, 1940) (table 3). In some cases, the bed refills during the waning stages of the flood; in others, the bed refills during a number of years, and along some reaches the channel seems to be changed permanently.

Some data used in this study of channels downstream from dams may not demonstrate a cause and effect relation; instead, they may show a sequential or natural change. Cause and effect in certain cases needs to be inferred from the timing of the changes and from their nature and persistence; such proof can be demonstrated only occasionally. Commonly, the precise magnitude of the changes and the separation of manmade causes from those changes associated with climate and other natural phenomena may be difficult, as discussed below.

DOWNSTREAM EFFECTS OF DAMS

WATER DISCHARGES

A number of papers in recent years (for example, Lauterbach and Leder, 1969; Moore, 1969; Huggins and Griek, 1974; DeCoursey, 1975; Petts and Lewin, 1979; and Schoof and others, 1980) have discussed the effects of dams on downstream flows. Because of the various purposes for which dams are built, there are large variations from one dam to another in the magnitude and duration of flow releases. At some dams (for example, Sanford Dam on the Canadian River, Texas, and Conchas Dam on the Canadian River in New Mexico), all or almost all the water is withheld from the downstream reach. Only drainage through the dam, tributary inflow, springs, ground water, and other downstream sources provide water downstream from the dam. At other dams, water is released only a few times per year. Discharge at hydropower dams may be stopped or curtailed for part of a day, and then a relatively large flow released during another part of the day (Fort Peck Dam on the Missouri River, Montana). At diversion dams, such as Milburn Dam on the Middle Loup River in Nebraska, large quantities of water may be diverted during the irrigation season, but all flows (and some sediment) may be passed directly through during the rest of the year. Even at dams built solely for irrigation, water may be released in a variety of patterns. At one extreme, virtually no water is ever released, and all irrigation diversions are made directly from the reservoir (Sanford Dam, Canadian River, Texas). Near the other extreme, practically no water is released during the winter storage period, but relatively large flows are released steadily during the irrigation season, with irrigation diversions made from various points downstream (Caballo Dam on the Rio Grande, New Mexico). Each dam, because of its purposes and the arrival of floods from upstream, has a unique history of daily, seasonal, and annual flow releases. Whatever the pattern of controlled releases, they are almost certain to be distributed differently from the natural flows.

The uniqueness of release policy at each dam precludes simple generalizations about the discharge distributions, except that flood peaks will be decreased (table 4). For the 29 dams of table 4, average annual peak discharges were decreased to 3 to 91 percent of their pre-dam values (averaging 39 percent). The flow exceeded only 5 percent of the time was reduced in many (but not all) cases. High flows may be important, especially in controlling channel size and vegetation.

Average daily discharge in a reach may increase, remain the same, or decrease after a dam has been built (table 4). Low flows (equaled or exceeded 95 percent of the time) also were diminished in some instances and increased in others. Judging from the records at the control stations (table 4), some, and possibly all, of the changes in average daily flow (but not necessarily in other flow statistics) at a number stations in our sample would have occurred in the absence of regulation. Changes in climate, ground-water withdrawals, flow diversions, vegetation, or combinations of these factors could have been the causes.

SEDIMENT LOADS

In addition to changing the flow regimen, dams are effective sediment traps. The curtailment of sediment supply, as with the change in water discharge, could have an important effect on the downstream channel. With some dams, such as those built mainly for hydropower generation, the sediment may be trapped as an incidental consequence of the dam's overall structure and operation. On other dams, sediment control may be a specific intent or purpose in building the dam. For example, Cochiti, Abiquiu, Jemez Canyon, and Galisteo Dams have been built on the Rio Grande and its major tributaries in an effort to reduce or eliminate aggradation on the Rio Grande.

A dam's role in trapping sediment can be shown by periodic reservoir surveys, by sediment-transport measurements, or by both. Sediment-transport measurements generally are given either as sediment concentrations (weight of sediment per unit volume of water-sediment mixture) or as annual sediment loads, in tons per year.

Hoover Dam on the Colorado River is a good example. Suspended loads in the Colorado River have been measured upstream and downstream from Hoover Dam. The upstream station is near Grand Canyon, Arizona, 430 km from the dam; the downstream station is near Topock, 180 km downstream from the dam. Two characteristics of the suspended load under natural conditions— the large quantities and the very large annual variations—are shown in figure 2. Before closure of Hoover Dam in 1936, annual loads at the two stations were similar. After closure, sediment inflow, represented by the data for the Grand Canyon station, continued to be large and variable. Downstream from the dam, at Topock, however, both the load and the annual variations were markedly decreased.

Data for several other dams also indicate a significant decrease in sediment load. For Glen Canyon Dam on the Colorado River (U.S. Bureau of Reclamation, 1976) the average annual pre- and post-dam suspended-sediment loads, as measured 150 km downstream at Grand Canyon, are as follows: Pre-dam (1926–62), 126 million megagrams; post-dam (1963–72), 17 million megagrams. This is a reduction of about 87 percent. On the Missouri River at Bismarck, North Dakota, 121 km downstream from Garrison Dam, sediment loads during 1949–52 averaged 48.6 million megagrams per year. The dam closed in 1953. During 1955, the sediment was 9.8 million megagrams, and during 1959, it was only 5.3 million megagrams. At Yankton, South Dakota, 7 km downstream from Gavins Point Dam, which began storing water in 1955, the Missouri River's pre-dam annual sediment load was about 121 million megagrams. The load then diminished to 8.1 million megagrams during 1955 and was only 1.5 million megagrams during 1960.

Data for the above examples may not reflect accurately the actual trap efficiency, because the measuring stations are a considerable distance downstream from the dam. The entrance of major tributaries, the erosion of sediment from the bed and banks immediately downstream from the dam, and various other factors (Howard and Dolan, 1981) can affect the apparent trends. Measurements made at or just downstream from the dam are much more suitable for an indication of trap efficiency. Such measurements show that the trap efficiency of large reservoirs commonly is greater than 99 percent. For example, during the first 19 years after closure of Canton Dam on the North Canadian River in Oklahoma, a total of 20.5 million megagrams of sediment arrived in the reservoir, and only 0.11 million megagrams went past the outlet works of the dam (U.S. Army Corps of Engineers, 1972, p. 6–8). The dam, therefore, trapped about 99.5 percent of the total sediment load. The trap efficiency of Denison Dam on the Red River, Oklahoma-Texas, during the first 12 years after closure was 99.2 percent (U.S. Army Corps of Engineers, 1960, p. 11).

These examples illustrate the efficiency of dams that do not sluice appreciable volumes of sediment through the dam. Many diversion dams and some sediment-storage dams, however, are built and operated to permit sediment to be flushed out of the reservoir. For example, Milburn Dam on the Middle Loup River and other irrigation-type diversion dams such are those on the Rio Grande and Imperial Dam on the Colorado River are designed for flushing sediment either continuously or periodically through the dam to the downstream channel. Less commonly, a reservoir is emptied approximately once per year, such as at John Martin Dam on the Arkansas River in Colorado. The entire reservoir water storage at John Martin Dam typically has been released each spring during the irrigation season. The escaping water carves a channel in the stored sediment and transports sediment out with it. From 1943 to 1972, the annual trap efficiencies at this dam varied randomly between 0 and 99 percent (U.S. Army Corps of Engineers, 1973). At John Martin Dam and at similar dams, annual trap efficiency (sediment storage) can vary with: (1) Volume of water stored during the winter and released (mainly a function of rainfall); (2) volume of sediment entering the reservoir since the previous year's release; (3) rate at which the reservoir release in made; (4) bottom topography of the pool (deep versus relatively shallow); (5) type and location of outlet gates; and (6) sizes of sediment particles (coarse versus very fine) entering the reservoir.

After dam closure, the downstream sediment loads at a particular site do not appear to recover from their greatly decreased values. Data on pre- and post-dam annual suspended loads were available for five stations downstream from Gavins Point Dam on the Missouri River (U.S Army Corps of Engineers, unpublished data, various years). This dam does not sluice appreciable quantities of sediment. Further, several major reservoirs were built on the Missouri River upstream from Gavins Point Dam at about the same time that Gavins Point Dam was constructed. The post-dam annual loads for a given station downstream from Gavins Point Dam were relatively small and showed no significant change with time, for the 1 to 3 decades after dam closure for which data are available. Instead, the loads only fluctuate within the same relatively narrow range from year to year (as for the Colorado River downstream from Hoover Dam, mentioned above). Similarly, data from various sources show that sediment concentrations for a given discharge at four sites downstream from Canton Dam also have not changed significantly with time for as long as 3 decades (the period of record) after dam closure.

What river distance downstream from a dam is required for a river to recover to its normal pre-dam or upstream-from-the-dam sediment loads or concentrations? Sediment in the channel bed and banks and in tributary inflows are major factors in determining the length of channel needed. This distance for the North Canadian River downstream from Canton Dam is illustrated in figure 3. Upstream from the dam, at Seiling, Oklahoma, a given discharge transported about the same volume of sediment before and after the 1948 dam closure. Reduction in concentration 5 km downstream from the dam is dramatic. A significant post-dam decrease still is quite noticeable 140 km downstream from the dam. Even at Oklahoma City, 182 km downstream from the dam, sediment concentration for a given discharge is not as much as it was prior to dam construction. Finally at Wetumka, 499 km downstream from the dam, with a drainage area some 4,640 km^2 (square kilometers) larger than that at the dam, sediment concentrations have recovered and may even be greater at high flows. Thus, the river required more than 182 km, and possibly as much as about 500 km, of channel distance for bed and bank erosion, coupled with tributary inflows, to provide sediment concentrations equivalent to those transported in the same reach at a given water discharge prior to closure of Canton Dam.

Curves similar to those in figure 3 for the Red River downstream from Denison Dam (U.S. Army Corps of Engineers, 1960, plates 64 and 65) indicate the same order of magnitude of channel distance (or possibly even a longer required reach) for recovery of pre-dam sediment concentrations. At Arthur City, Texas, 150 km downstream from the dam, post-dam sediment concentrations for the 17 years after dam closure were only about 20 to 55 percent of the pre-dam concentrations for the same water discharge. At Index, Arkansas, 387

TABLE 4.—*Water-discharge data*

[km, kilometers; m³/s, cubic

Dam number (fig. 1)	River, dam, State	Year of dam closure	Downstream gaging station and control station[1/]	River distance of station from dam[2/] (km)	Period used (water years)	
					Pre-dam	Post-dam
1.	Colorado, Glen Canyon, Arizona	1963	Colorado River at Lees Ferry, Arizona	26	1922-62	1963-78
			C: No suitable station			
2.	Colorado, Hoover, Arizona	1965	Colorado River near Topock, Arizona	180	1923-34	1935-49
			C: Colorado River near Grand Canyon, Arizona	430	1923-34	1935-49
3.	Colorado, Davis, Arizona	1950	Colorado River near Topock, Arizona	72	1935-49[3/]	1950-78
			C: Colorado River below Hoover Dam, Arizona	108	1935-49[3/]	1950-78[3/]
4.	Colorado, Parker, Arizona	1938	Colorado River below Parker Dam, Arizona-California	0-6.4	1936-37[3/]	1938-78
			C: Colorado River near Topock, Arizona	63	1936-37[3/]	1938-78[3/]
5.	Jemez, Jemez Canyon, New Mexico	1953	Jemez River below Jemez Canyon Dam, New Mexico	1.3	1937;1944-52	1953-78
			C: Jemez River near Jemez. New Mexico	43	1937-41;1950[5/]	1953-78
6.	Arkansas, John Martin, Colorado	1942	Arkansas River at Lamar, Colorado	34	1914-41	1942-55, 1960-73
			C: Arkansas River at LaJunta, Colorado	70	1914-41	1942-55, 1960-73
7.	Missouri, Fort Peck, Montana	1937	Missouri River near Wolf Point, Montana	100	1929-36	1937-78
			C: No suitable station			
8.	Missouri, Garrison, North Dakota	1953	Missouri River at Bismarck, North Dakota	120	1929-52[3/]	1953-78
			C: No suitable station			
9.	Missouri, Fort Randall, South Dakota	1952	Missouri River at Fort Randall, South Dakota	0-11	1948-51[3/]	1952-78
			C: No suitable station			
10.	Missouri, Gavins Point, South Dakota	1955	Missouri River at Yankton, South Dakota	8	1948-54[3/]	1955-78
			C: Missouri River at Fort Randall, South Dakota	110	1948-54[3/]	1955-78[3/]
11.	Medicine Creek, Medicine Creek, Nebraska	1949	Medicine Creek at Cambridge, Nebraska	10-15	1938-48	-
			Medicine Creek below H. Strunk Lake, Nebraska	0.8	-	1951-78
			C: No suitable station			
12.	Middle Loup, Milburn, Nebraska	1955	Middle Loup River at Walworth, Nebraska	19	1946-54	1955-60
			C: Middle Loup River at Dunning, Nebraska	31	1946-54	1955-60
13.	Des Moines, Red Rock, Iowa	1969	Des Moines River near Tracy, Iowa	19	1941-68	1969-76
			C: Des Moines River below Raccoon River at Des Moines, Iowa	94	1941-68	1969-76
14.	Smoky Hill, Kanopolis, Kansas	1948	Smoky Hill River near Langley, Kansas	1.3	1941-47	1948-77
			C: Smoky Hill River at Ellsworth, Kansas	48	1941-47	1948-77[3/]
15.	Republican, Milford, Kansas	1967	Republican River below Milford Dam, Kansas	2.7	1964-66	1967-77
			C: Republican River at Clay Center, Kansas	49	1964-66	1967-77
16.	Wolf Creek, Fort Supply, Oklahoma	1942	Wolf Creek near Fort Supply, Oklahoma	2.6	1938-41	1942-78
			C: No suitable station			
17.	North Canadian, Canton, Oklahoma	1948	North Canadian River at Canton, Oklahoma	.8	1939-47[3/]	1948-78
			C: North Canadian River at Woodward, Oklahoma	106	1939-47[3/]	1948-78

jor pre-dam and post-dam periods

meters per second; C, control station]

Average daily discharge (m^3/s)		Average annual peak discharge (m^3/s)		Flow equaled or exceeded "x" percent of the time, (m^3/s)					
				x = 5 percent		x = 50 percent		x = 95 percent	
Pre-dam	Post-dam	Pre-dam	Post-dam	Pre-dam	Post-dam	Pre-dam	Post-dam	Pre-dam	Post-dam
480	320	2,200	800	1,800	560	230	310	100	31
520	400	2,200	640	1,800	700	270	400	120	145
520	500	2,300	2,300	1,800	1,800	270	250	105	120
400	340	640	550	700	560	400	340	145	140
410	360	650[4/]	615[4/]	700	590	400	370	155	140
230	340	850	640	300	630	250	360	125	140
230	380	400	600	300	620	250	370	135	155
1.5	1.5	160	39	8.5	6.2	0.4	0.5	0.006	0.0
2.0	1.9	50	52	7.0	6.7	.9	.8	.5	.4
7.3	4.8	560	190	29	16.0	.2	.6	.05	.07
7.4	6.6	500	340	20	20	2.3	1.6	.3	.4
200	280	770	690	500	630	140	240	70	40
600	660	3,900[3/]	1,100	1,600	1,100	450	650	140	250
880	680	6,300[3/]	1,500	2,000	1,400	820	680	195	155
930	740	5,200[3/]	1,200	2,100	1,400	820	760	250	220
860	670	5,100[3/]	1,400	1,900	1,300	760	680	220	145
2.7	-	530	-	4.6	-	1.6	-	0.8	-
-	1.9	-	13.5	-	8.2	-	1.0	-	.02
23	22	58	53	31	30	22	22	16.5	16.5
11.0	11.5	18	20	13.5	14.5	11.0	11.5	9.1	9.3
140	200	1,200	800	530	560	62	115	7.6	13.0
105	155	950	900	390	560	46	82	4.5	10.0
8.7	9.9	320	135	35	54	2.4	2.3	.5	.5
7.6	8.9	330	320	27	37	1.8	2.1	.4	.4
23	24	290	150	69	90	13.5	10.5	4.5	1.2
19.5	23	300	450	60	79	11.5	10.5	4.2	3.4
2.5	1.7	240	35	8.5	6.0	.5	.1	.006	.009
7.7	4.7	280	44	29	26	1.8	.2	.0006	.03
7.2	5.0	400	155	26	19.5	1.2	1.1	.0006	.0

TABLE 4.—*Water-discharge data for pre*

Dam number (fig. 1)	River, dam, State	Year of dam closure	Downstream gaging station and control station[1/]	River distance of station from dam[2/] (km)	Period used (water years)	
					Pre-dam	Post-dam
18.	Canadian, Eufaula, Oklahoma	1963	Canadian River near Whitefield, Oklahoma	13	1939-62[3/]	1963-78
			C: Canadian River at Calvin, Oklahoma	108	1939-62[3/]	1963-78[3/]
19.	Red, Denison, Texas-Oklahoma	1943	Red River at Denison Dam near Denison, Texas	0.5-4.0	1937-42	1943-78
			C: Red River near Gainesville, Texas	106	1937-42	1943-78[3/]
20.	Neches, Town Bluff, Texas	1951	Neches River at Evadale, Texas	93	1922-50	1951-64
			C: Neches River near Rockland, Texas	63	1922-50	1951-64
21.	Chattahoochee, Buford, Georgia	1956	Chattahoochee River near Buford, Georgia	4.0	1942-55	1956-71
			C: Chestatee River near Dahlonega, Georgia	73	1942-55	1956-71
--	Rio Grande, Caballo, New Mexico	1938	Rio Grande below Caballo Dam, New Mexico	1.3		1939-77
			C: Not needed			
--	Marias, Tiber, Montana	1955	Marias River near Chester, Montana	3-8	1946-47	1956-78
			C: Marias River near Shelby, Montana	65	1946-47	1956-78
--	Canadian, Sanford, Texas	1964	Canadian River near Canadian, Texas	120	1939-63[3/]	1964-78[8/]
			C: Canadian River near Amarillo, Texas	47	1939-63[3/]	1964-78[3/]
--	Canadian, Conchas, New Mexico	1938	Canadian River below Conchas Dam, New Mexico	4.5-5.6	1937-38	1943-72
			C: Canadian River near Sanchez, New Mexico	50	1937-38	1943-72
--	Canadian, Ute, New Mexico	1963	Canadian River at Logan, New Mexico	3.2	1943-62	1963-72
			C: Canadian River below Conchas Dam, New Mexico	112	1943-62	1963-72
--	Republican, Trenton, Nebraska	1953	Republican River at Trenton, Nebraska	1.5	1948-52[3/]	1953-78
			C: Republican River at Benkelman, Nebraska	50	1948-52	1953-78
--	Republican, Harlan County, Nebraska	1952	Republican River near Hardy, Nebraska	115	1948-51[3/]	1952-77
			C: Republican River near Orleans, Nebraska	37	1948-51[3/]	1952-77[3/]
--	Washita, Foss, Oklahoma	1961	Washita River near Clinton, Oklahoma	43	1938-60	1961-78
			C: Washita River near Cheyenne, Oklahoma	112	1938-60	1961-78

1/ A long-term gaging station upstream from the dam.

2/ Main station is downstream from dam and control station is upstream from dam on same river.

3/ Flows affected by one or more upstream dams.

4/ Highest mean daily flow used, rather than instantaneous peak.

5/ Only years available.

6/ Only data for water years 1961-78 available.

7/ Only data for water years 1921 and 1946 used (only data available).

8/ All post-dam flow is from seepage at dam and from springs and tributaries downstream from dam; no releases are made from the dam.

9/ Water years 1936-39 (before dam closure) used.

km downstream from the dam, a given water discharge after dam construction transported about 50 percent of the volume of sediment it did before the dam. On the Red River, too, then, the deficit persists for hundreds of kilometers. The actual length of reach required for complete recovery on the Red River cannot be determined from the above data.

Five stations downstream from Gavins Point Dam

dam and post-dam periods—Continued

Average daily discharge (m^3/s)		Average annual peak discharge (m^3/s)		Flow equaled or exceeded "x" percent of the time, (m^3/s)					
				x = 5 percent		x = 50 percent		x = 95 percent	
Pre-dam	Post-dam	Pre-dam	Post-dam	Pre-dam	Post-dam	Pre-dam	Post-dam	Pre-dam	Post-dam
175	120	3,600	740	760	480	48	54	3.1	1.6
56	29	2,300	1,300	270	120	9.6	6.8	.3	.1
185	120	3,000	950	720	400	56	74	7.1	3.2
120	70	2,400	1,400	540	280	26	19.0	3.1	4.2
200	130	1,100	800	700	500	93	54	8.8	5.9
77	48	550	360	290	195	31	17.5	1.2	.7
60	54	660	270	140	150	46	40	19.0	12.0
10.0	10.5	220	260	23	24	7.6	8.2	2.8	3.4
-	24	-	77	-	63[6/]	-	16.0[6/]	-	.03[6/]
25	26	115[7/]	90	79	74	11.6	18.0	4.2	2.8
25	27	115[7/]	560	76	105	11.5	11.5	4.2	4.0
16.0	2.6	1,100	370	66	7.6	.9	.7	.01	.003
12.0	5.4	1,100	640	48	24	.7	.6	.08	.05
12.0	.8	1,000[9/]	100	35	1.1	.5	.1	.02	.009
6.5	4.3	640[9/]	420	22	16.0	.6	1.0	.05	.02
3.5[4/]	1.2	550	66	14.0	8.6	.2	.07	.006	.02
1.1[4/]	.3	145	32	1.7	.2	.2	.1	.01	.05
6.0	1.8	290	24	16.0	7.1	4.0	0.08	.001	.02
3.4	2.4	105	60	7.7	4.9	2.8	2.3	.3	.03
32	11.0	530	185	135	42	14.5	4.8	4.0	1.6
16.5	8.0	380	125	52	23	9.3	5.4	2.0	.5
4.1	1.6	290	69	15.5	5.4	.7	.7	.01	.1
1.2	.4	290	66	4.0	1.4	.2	.1	.0003	.0

provide an example of the degree of downstream recovery of suspended-sediment loads. Three dams—Fort Randall (1952), Garrison (1953), and Gavins Point (1955)—were closed on the Missouri River within 3 years during the 1950's. Inspection of the yearly sediment data downstream from Gavins Point Dam shows that annual loads consistently decreased during this period (water years 1953–56), as expected. These years were excluded here in computing pre- and post-dam average loads. For the five downstream stations, the available water years of pre- and post-dam data, respectively, were: Yankton—1940–52, 1957–69; Omaha—1940–52, 1957–73; St. Joseph, Kansas City, and Hermann—1949–52, 1957–76. These stations are 8 (Yankton), 314 (Omaha), 584 (St. Joseph), 716 (Kansas City), and 1,147 (Hermann) km downstream from Gavins Point Dam. From the annual suspended-sediment loads, an average annual load was computed for the pre-dam period and again for the post-dam period. The ratio of these average loads as a function of distance downstream from the dam is shown in figure 4. At Yankton, just 8 km downstream from the dam, the average post-dam annual load was less than 1 percent of that for the pre-dam period. Even 1,147 km

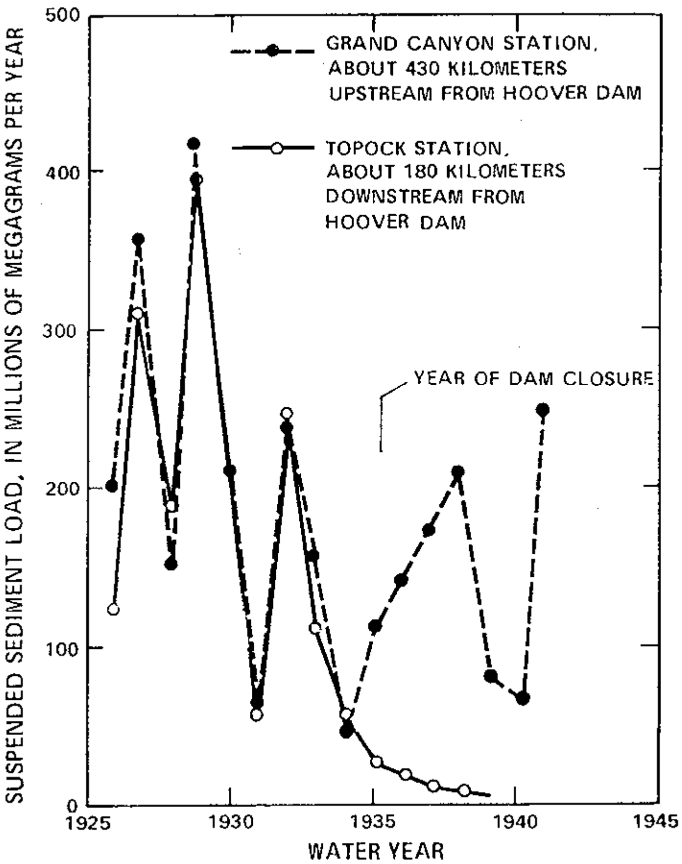


FIGURE 2.—Variation in annual suspended-sediment loads before and after closure of Hoover Dam, Colorado River, Arizona, at a station upstream from the dam (Grand Canyon) and downstream from the dam (Topock).

downstream from the dam, the post-dam average annual load was only 30 percent of the pre-dam load. Data from the Mississippi River at St. Louis, downstream from the confluence of the Missouri and Mississippi Rivers, and about 1,300 km downstream from Gavins Point Dam, show that the mean annual suspended load decreased from about 320 million megagrams during 1949–52 to 109 million megagrams during 1957–80, after closure of the dams on the Missouri River. Changes elsewhere in the Mississippi River basin also may have contributed to the decrease in sediment load in the Mississippi. However, along the nearly 1,300 km of the Missouri River downstream from Gavins Point Dam, post-dam average suspended loads have not approached the much larger pre-dam average values.

Hammad's (1972, p. 601) data for the Nile River downstream from Aswan High Dam show that, even 965 km downstream from the dam, annual sediment loads 2 years after dam closure were only about 20 percent of pre-dam values. The above examples indicate that, in some major rivers, sediment concentrations and annual sediment loads may not achieve pre-dam values for hundreds or thousands of kilometers downstream, if at all. The cases documented here are large dams and reservoirs from specific geographic regions. As noted earlier, a variety of conditions will control the response on different rivers.

MEAN BED ELEVATION

The results of the bed-elevation analyses based on resurveyed cross sections are listed in table 13 at the end of this report. The data for changes in mean bed elevation determined from gaging-station rating tables are listed in table 14 also at the end of this report. From the latter rating tables, changes in mean bed elevation with time were plotted for each gage site (figs. 36–49 at the end of this report). (Such graphic relations proceed in "stairsteps" because a constant bed elevation is assumed for the period during which a given rating table is in effect. The change to a new rating table brings what appears in figures 36–49 as a sudden switch to a new constant bed level. The actual change in bed level with time probably follows a smoother curve.) Similar plots of change in bed level with time were made for all resurveyed cross sections from the voluminous data in table 13, and representative examples are shown below.

GENERAL NATURE OF CHANGES IN BED ELEVATION

For all 21 channels (fig. 1) having resurveyed cross sections, a lowering of the mean bed level—here called degradation—occurred immediately downstream from the dam (figs. 5 and 6), unless constrained by very coarse material or bedrock. Such bed degradation downstream from dams is a well-known phenomenon on alluvial streams (Lane, 1934; Gottschalk, 1964, p. 17–5). Analytical studies of open-channel bed degradation include those by Lane (1948), Mostafa (1957), Tinney (1962), Breusers (1967), Komura and Simons (1967), Aksoy (1970, 1971), Hales and others (1970), Komura (1971), Rzhanitzin and others (1971), de Vries (1973), Hwang (1975), and Strand (1977). Special flume studies of bed degradation have been conducted by Schoklitsch (1950), Harrison (1950), Newton (1951), Ahmad (1953), Willis (1965), Garde and Hasan (1967), Ashida and Michiue (1971), and others.

In some reaches, degradation can occur simply by the removal of bars in the absence of replenishment of sediment from upstream. This was observed on the Red River in the region about 10 to 15 km downstream from Denison Dam. Koch and others (1977) reported a similar removal of bars in the reach downstream from Yellowtail Dam on the Bighorn River, Montana.

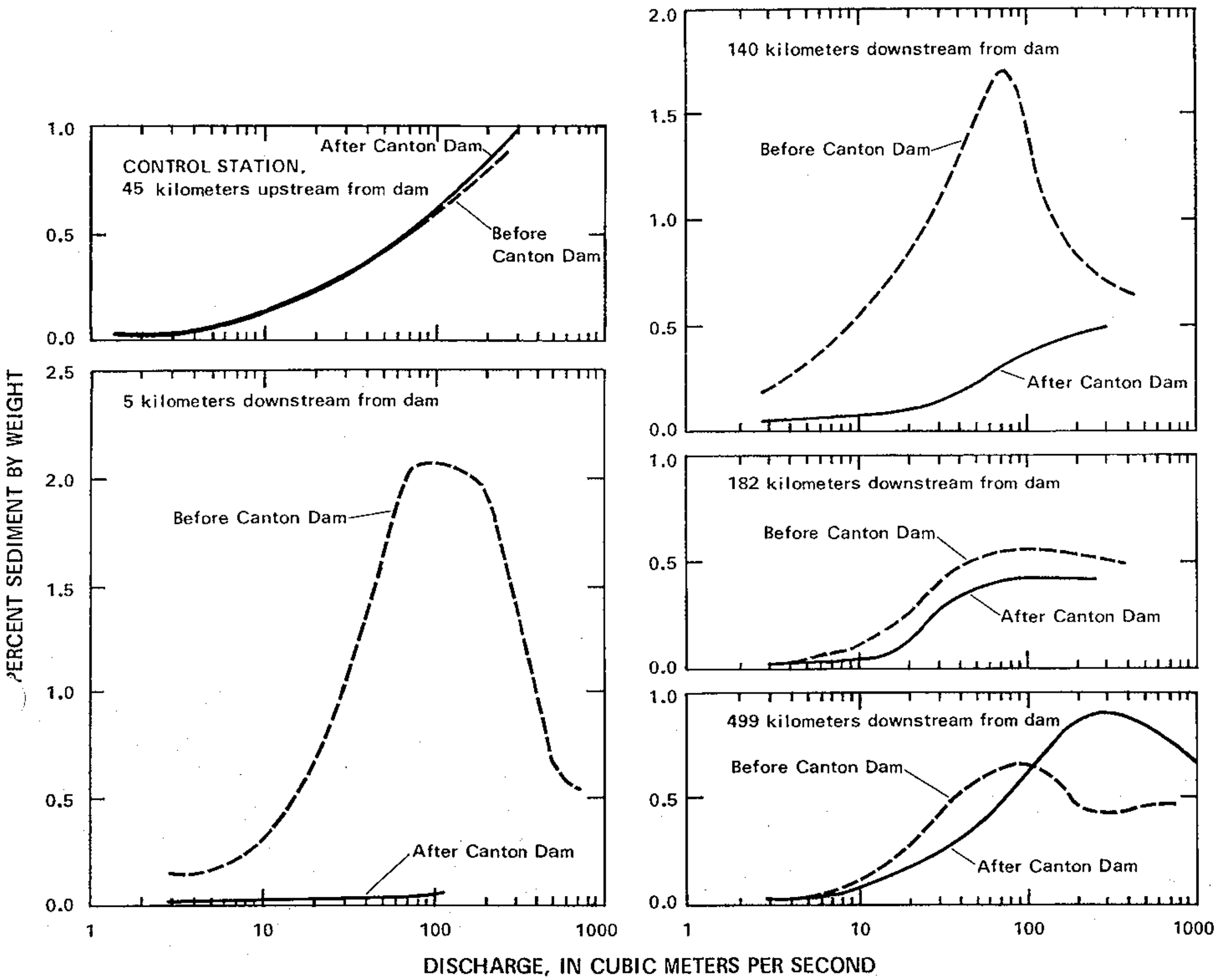


FIGURE 3.—Suspended-sediment loads (concentrations) transported by various discharges at successive downstream stations before and after closure of Canton Dam, North Canadian River, Oklahoma. Control-station curve based on unpublished U.S. Geological Survey data; other curves redrawn from U.S. Army Corps of Engineers, 1958.

On four rivers—Jemez River, Arkansas River, Wolf Creek, and the North Canadian River—post-dam flow releases were so much less than pre-dam discharges that the channel became considerably narrower. In such instances, lowering of the mean bed elevation can result not only from bed erosion but also because the post-dam narrowed river occupies only the lowest part of the original channel.

Should a dam release little or no water, the bed downstream might not degrade. In fact, local aggradation sometimes occurs, because the controlled flows are not strong enough to remove deposits left by tributary flash-floods; by main-channel, sediment-removal works associated with canals; or by wind. Examples are found on the Rio Grande in New Mexico (Lawson, 1925; Lagasse, 1980) and on the Peace River in Canada (Bray and Kellerhals, 1979). Downstream from Elephant Butte Dam on the Rio Grande the controlled releases are depleted systematically by irrigation intakes. In a reach beginning about 265 km downstream from the dam this decrease in flow strength, together with the deposits delivered by tributaries, brought the river bed in many places to an elevation higher than the adjoining farm area (Lawson, 1925).

DEGREE OF CHANGE ATTRIBUTABLE TO DAMS

The magnitude of the measured changes (as much as 7 m, as described below) greatly exceeds the expectable errors in measurement and analysis. Furthermore, occurring as they do during periods ranging from a few

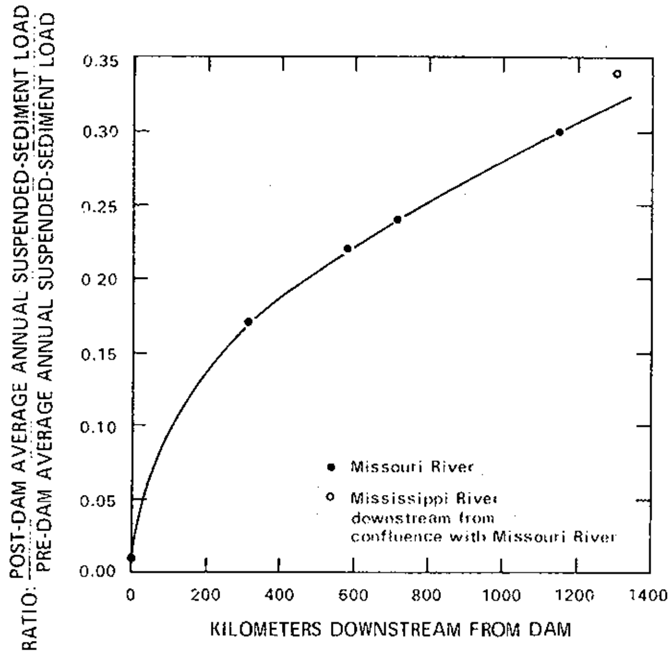


FIGURE 4.—Post-dam/pre-dam ratio of annual suspended-sediment loads versus distance downstream from Gavins Point Dam, Missouri River, South Dakota.

years to 2 or 3 decades, the changes greatly exceed those that would be expected as part of a temporal fluctuation around a mean bed level and those generally observed to occur naturally (table 3). Several considerations support the view that the measured changes in alluvial channels downstream from the dams studied here are due to the dam and reservoir upstream:

1. As the longitudinal profiles discussed below show, degradation generally was greatest at or near the dams and usually decreased somewhat progressively downstream, though with local exceptions.
2. From the rating tables for the 14 streamflow-gaging stations downstream from dams (table 14 and figs. 36–49), the relation of water-surface elevation to discharge for a reference low flow indicates that the channels generally were relatively stable prior to dam construction and began degrading just after the dams were built. This timing is illustrated by the bed changes, as assumed from the stage-discharge relation, for the Smoky Hill River near Langley, Kansas, about 1.3 km downstream from Kanopolis Dam (fig. 7).
3. Whereas the river bed downstream from the dam tended to erode, the elevation of the bed at eight

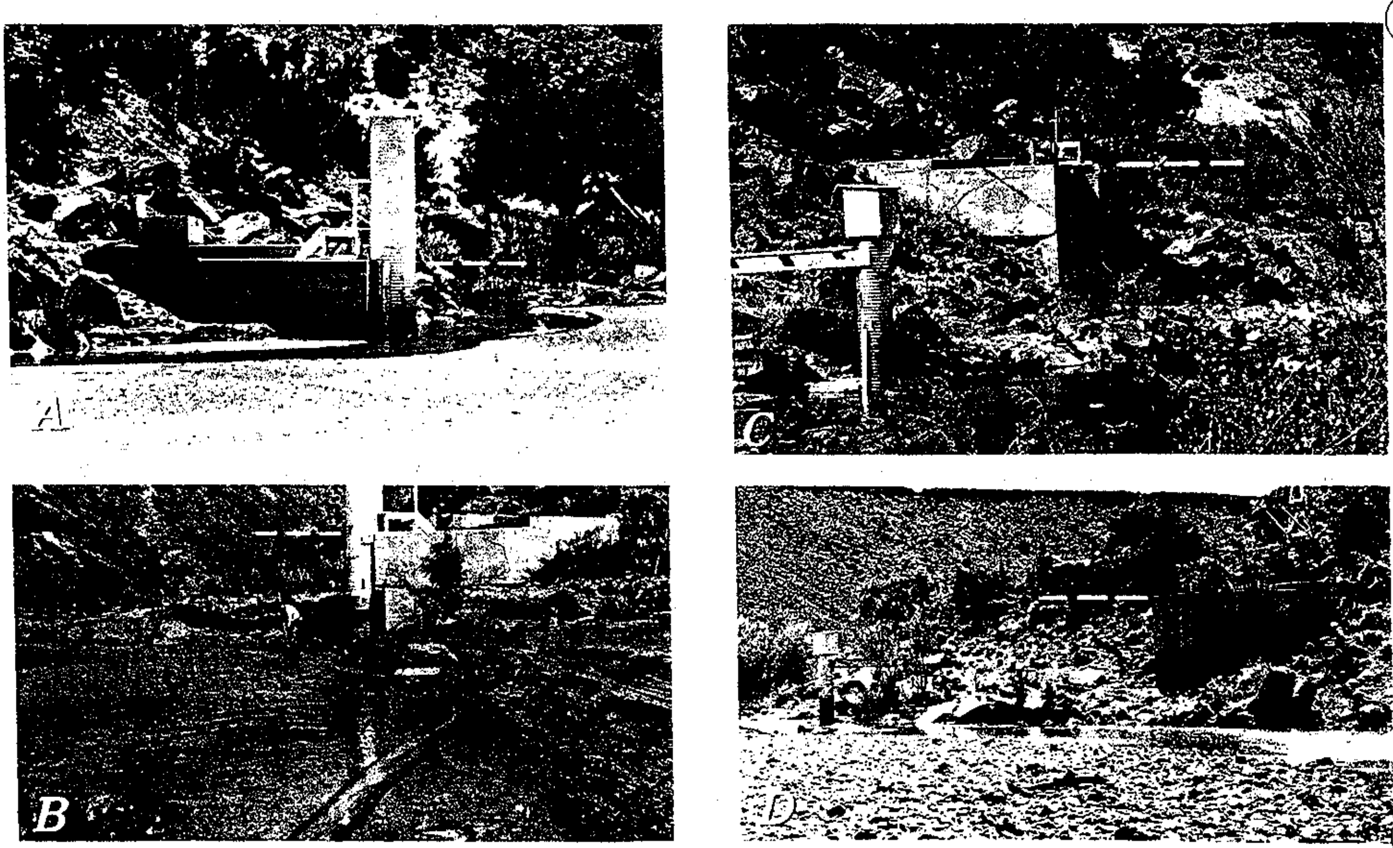


FIGURE 5.—Time progression of bed degradation and channel armoring at the streamflow-gaging station downstream from Jemez Canyon Dam, Jemez River, New Mexico. *A*, 1952; *B*, 1957; *C* and *D*, 1980. Dam was closed in 1953. Station is 1.3 kilometers downstream from the dam. White dashed line is at a constant elevation for reference.

FIGURE 6.—Degradation represented by successively lower water-intake pipes for streamflow-gaging station 2.6 kilometers downstream from Fort Supply Dam, Wolf Creek, Oklahoma. Dam was closed in 1942; photograph was taken in 1951.

control stations upstream from dams for which data were available did not change significantly during the years after dam closure (fig. 7; table 14).

For the channels having resurveyed cross sections, and for those with gaging-station records, extrapolation of the post-dam degradation rates back into the pre-dam years would place the pre-dam streambeds at unrealistically high elevations.

Thus, the timing, magnitude, and spatial distribution of the measured changes in the alluvial channels studied here indicate that the dams and upstream reservoirs are responsible for the measured degradation.

DEGRADED REACH DOWNSTREAM FROM A DAM

Given the capacity of flow releases to entrain sediment from channel bed and banks, erosion of the bed and banks should continue downstream from a dam until some factor or a combination of factors results in establishment of a new stable channel. These factors may include: (1) Local controls of bed elevation (emergence of bedrock; development of armor by winnowing of fines); (2) downstream base-level controls (ocean, lake, or larger river; manmade structure such as a dam; barrier of deposited sediment); (3) decrease in flow competence (flattening of slope by progressive degradation; expansion of channel width, resulting in decreased depth, redistributed flow velocities, or both); (4) infusion of enough sediment to restore the balance tween arriving and departing sediment (upstream osion; sluicing from the upstream dam; inflow from tributaries); and (5) growth of vegetation. Several of these changes or processes are considered or illustrated separately here; any number of them may occur together along any given reach of river.

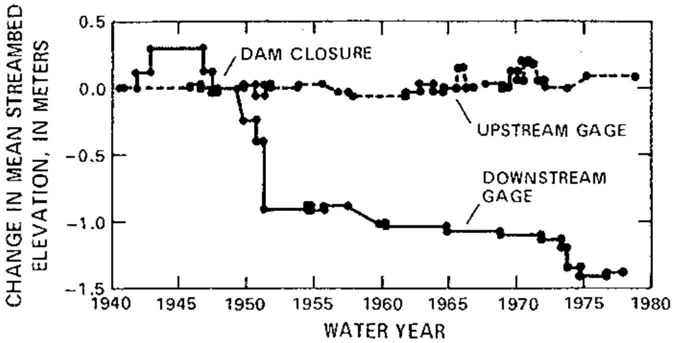


FIGURE 7.—Changes in mean bed elevation with time at streamflow-gaging stations 48 kilometers upstream and 1.3 kilometers downstream from Kanopolis Dam, Smoky Hill River, Kansas. Bed elevations assumed proportional to the gage height that corresponds to a constant low discharge of 0.42 cubic meter per second at the upstream gage and 0.51 cubic meter per second at the downstream gage.

GENERAL FUNCTION OF DEGRADATION WITH TIME AT A SITE

Except for cross sections underlain only by sand beds of unlimited depth, the degradation rate at a section would be expected to decrease with time as the bed becomes armored, or until the channel slope in that reach becomes too flat for the bed material to be moved. Eventually, an equilibrium bed elevation should be reached, as postulated in many analytical studies cited earlier. A number of the sections for which data are given in table 13 show this trend. At many other cross sections, however, the rate of degradation with time varies considerably (table 13). For instance, one or more temporary periods of aggradation may be included within a long-term trend of degradation. Or, after some initial degradation, the bed level may become constant rather abruptly with time at a certain depth, probably an indication that bedrock was reached or that armor had developed. Other sites have an S-shaped curve, where initial degradation rates were slow, then increased with time for some years, and then reversed this trend to decrease in later years. (A possible cause of such a curve might be minimal releases the first few years after dam closure to fill the reservoir, and greater releases thereafter.) Some of these irregular degradation-time trends are shown in figure 8. Besides variations in flow releases with time, departures from a regular degradation curve could be due to differences in bed material with depth, to changes in cross-sectional shape, and to development and death or eradication of vegetation.

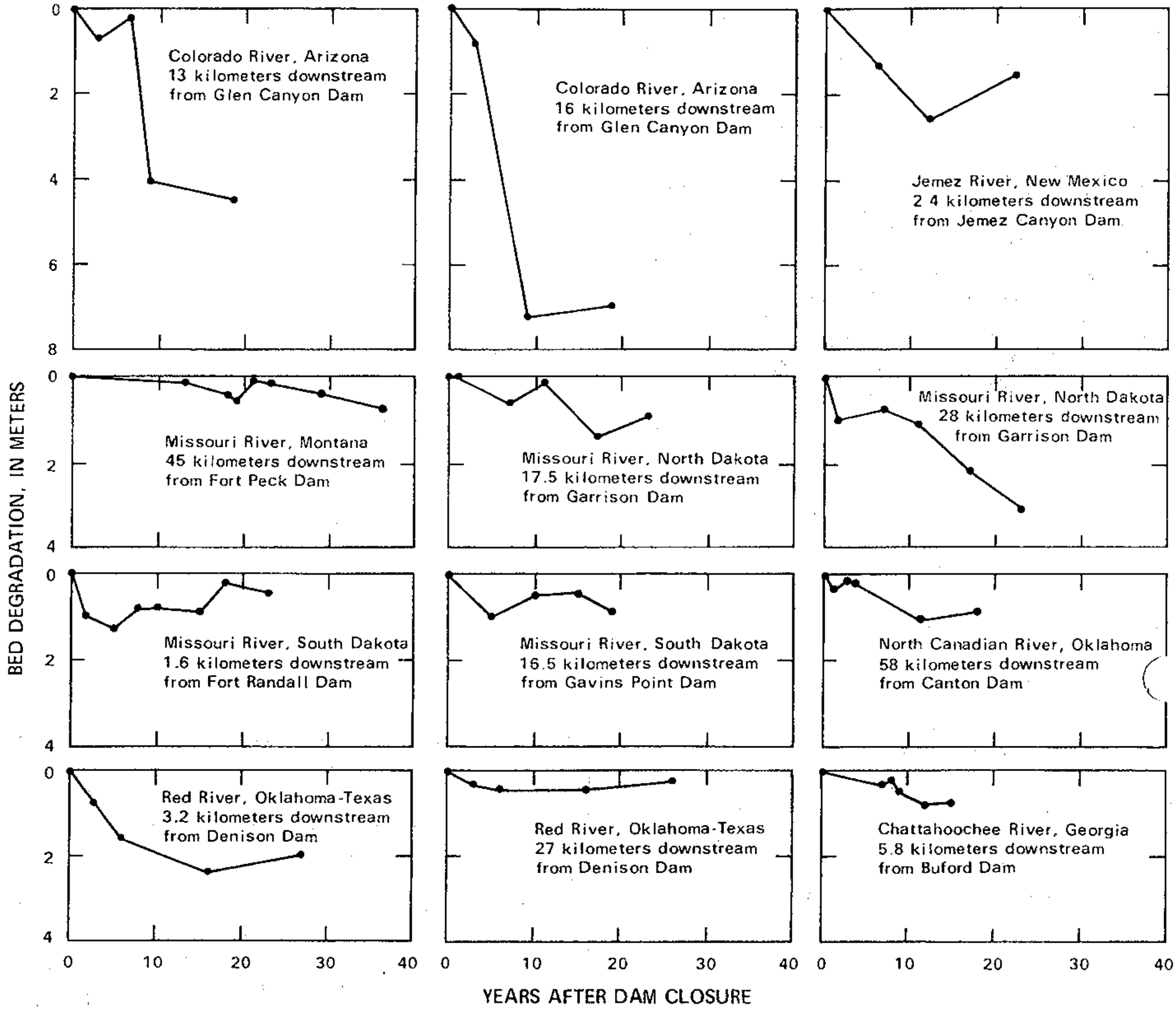


FIGURE 8.—Examples of irregular rates of bed degradation with time. Data from table 13.

To search for a possible general function of bed degradation with time at a site, all 287 resurveyed cross sections were used except for those:

1. That did not show a general trend of bed lowering (84 sections, mostly in the zone of varied bed changes downstream from the degraded zone);
2. Of the remaining 203 sites that lacked enough data points to justify fitting a curve, our arbitrary requirement being at least three resurveys after the onset of degradation, not counting the original survey (49 sites); and
3. Survivors of the above two requirements that showed marked aberrations in general degradation, such as abrupt cessation of bed erosion or even substantial aggradation after inital erosion (40 sites, exemplified in figure 8).

One hundred fourteen cross sections were left, after the above exclusions, for use in the degradation-time analysis. Plots of bed lowering with time (representative examples given below) for the 114 cross sections generally show that the rate of degradation is fastest immediately after erosion begins and gradually slows with time, becoming asymptotic toward some new stable bed elevation. Some of the plots have large scatter, scarcity of points, or an irregular trend; any of several types of functions could be fitted to such data with a large standard error. Empirically analyzing the trends for the more regular, better-defined curves, either of two functions appeared to fit most cases: (1) Logarithmic, with degradation D (arithmetic scale) as a function of the logarithm of time, t; or (2) hyperbolic, with $1/D$ as a function of $1/t$, both on arithmetic scales.

Least-squares regressions were calculated applying each of these functions to each of the 114 cross sections. For the prediction of D (not $1/D$) at the observed times, the square of the correlation coefficient (r^2) is as follows: for the logarithmic function, a range of 0.16 to 1.00 with an average of 0.82; for the hyperbolic function, a range of 0.10 to 1.00 with an average of 0.81. The average of 0.82 corresponds to an r-value of about 0.91, and the average of 0.81 corresponds to an r-value of about 0.90; they indicate a reasonably good fit.

The logarithmic relation had a greater r^2 for 55 of the 114 cross sections; the hyperbolic relation had a greater r^2 for 50 sections; and, at the 9 remaining cross sections, r^2 was the same for both equations. In most cases, there was little difference in the two correlation coefficients for a given cross section. However, at a few cross sections the hyperbolic equation predicted values of D that diverged greatly from the measured values; whereas, no such grossly disparate predictions resulted from the logarithmic relation.

Analytical considerations indicate that the bed erosion should decrease with time. The degradation-time plots indicate that this decrease or cessation of degradation tends to occur within decades or a few centuries. For the data of this study, the hyperbolic equation generally predicts this approximate time much more closely than the logarithmic equation, the latter in some instances predicting billions of years for degradation to cease.

The relative advantages of using each type of equation seem to be:

Logarithmic Equation:
1. Slightly—but probably not too significantly—greater correlation coefficient.
2. Reasonable predictions for a few cross sections at which the hyperbolic equation gives a very poor fit.

Hyperbolic Equation:
1. Better calculated-versus-measured agreement of the time within which approximate eventual maximum degradation occurs, and of the magnitude of this maximum limiting degradation.
2. The practical benefit of providing a reasonable value of maximum degradation for planning purposes.
3. Better consistency in the sign of the first coefficient (intercept) of the regression equation. (With degradation considered positive, only 3 of the 114 cross sections have a negative coefficient using the hyperbolic equation, as opposed to 24 such cross sections for the logarithmic equation. Reasons for such negative coefficients are mentioned below.)

On the basis of the previous discussion, the hyperbolic equation seems more suitable as a model for bed degradation with time at the many sites analyzed here. This equation has the form:

$$D=\frac{t}{c_1+c_2t} \qquad (1)$$

where

D is degradation, in meters, at t years after the start of bed erosion; and

c_1 and c_2 are constants for a given cross section or graph.

Such a hyperbola is asymptotic to a line parallel to the x axis (time). Its equation (eq. 1) plots as a straight line on arithmetic scales when written in the form:

$$(1/D) = c_2+c_1\ (1/t) \qquad (1a)$$

where

c_2 is the intercept; and

c_1 is the slope of the best-fit straight line.

For convenience, degradation is considered to be in a positive direction. Degradation can be considered negative simply by making the signs of c_1 and c_2 negative. Regression coefficents for each cross section are given in table 5.

The reciprocal of c_2 is the asymptote on a plot of D versus t; that is, $1/c_2$ is the eventual limit of degradation. The reciprocal of c_1 on the same plot is the slope or tangent just after degradation has first begun; that is, $1/c_1$ is the initial degradation rate, in meters per year. Therefore, both c_1 and c_2 have an important practical significance.

To fit a curve of this type, the time origin (t=0 years) needs to be taken as the year at which degradation began. Degradation at sites close to the dam can be taken as beginning at the time of dam closure. However, for some downstream sites, there is a response time or lag time between the date of dam closure and the start of degradation. In some instances the year in which degradation began was not determined accurately and had to be estimated from the plots of degradation versus time.

Twelve typical curves, using the hyperbolic function as the general model, are shown in figure 9. The data to which the least-squares regressions were applied are listed in table 13. These particular examples were chosen to reflect the range of r^2 values of the 114 applicable cross sections.

TABLE 5.—*Values associated with fitted degradation curves*[1]

Distance of cross section downstream from dam (kilometers)	Response time[2] (years)	Correlation coefficient[3] r^2	Intercept c_2	Slope of best-fit straight line c_1	Maximum expected degradation D_{max} (meters)	Estimated time to achieve 0.95 D_{max} (years)	Estimated time to achieve 0.5 D_{max} (years)
Colorado River, Arizona, Glen Canyon Dam							
2.6	0	0.88	0.30	2.03	3.3	130	7
4.3	0	.77	.24	.75	4.2	60	3
6.4	0	.93	.52	1.78	1.9	65	3
10.5	2.0	.99	.33	2.54	3.0	150	8
19.5	2.0	1.00	.29	1.93	3.5	130	7
Colorado River, Arizona, Hoover Dam							
2.3	.5	.69	.52	.57	1.9	20	1.1
3.2	0	.87	.19	.17	5.3	17	.9
4.5	0	.81	.37	.13	2.7	7	.4
6.1	0	.56	.41	.18	2.4	8	.4
7.1	0	.84	.27	.26	3.7	18	1.0
8.0	0	.77	.23	.14	4.4	12	.6
9.7	0	.94	.18	.56	5.6	60	3
11.0	0	.94	.48	.59	2.1	24	1.2
12.5	0	.73	.18	.23	5.6	24	1.3
13.5	0	.54	.32	.16	3.1	10	.5
15.5	0	.93	.18	.26	5.6	28	1.4
16.5	.5	.79	.31	.20	3.2	12	.6
18.0	.5	.92	.37	.25	2.7	12	.7
19.5	.5	.74	.25	.23	4.0	18	.9
21	.5	.84	.36	.34	2.8	18	.9
28	1.5	.98	.20	1.38	5.0	130	7
36	1.0	.91	.22	1.97	4.6	170	9
42	.5	.84	.34	1.62	2.9	90	5
51	2.0	.88	-.05	3.40	--	--	--
57	1.3	.91	.10	2.30	10.0	440	22
63	2.0	.80	.18	1.31	5.6	140	7
70	1.0	.94	.18	1.05	5.6	110	6
77	2.6	.93	.28	1.93	3.6	130	7
87	3.5	.96	.35	1.90	2.9	100	5
94	3.0	.84	.20	1.71	5.0	160	9
104	3.0	.94	.23	1.65	4.4	140	7
110	3.2	.96	.08	2.29	12.5	540	28
117	4	.98	.031	2.00	32	1,200	65
Colorado River, Arizona, Davis Dam							
1.1	0	0.97	0.15	0.69	6.7	85	5
8.8	.5	.95	.32	2.46	3.1	150	8
Colorado River, Arizona, Parker Dam							
27	0	.97	.26	1.29	3.9	95	5
39	2.0	.95	.19	1.05	5.3	100	6
46	1.0	.93	.17	1.29	5.9	140	8
66	1.0	.77	.20	1.31	5.0	120	7
80	1.75	.66	.45	1.11	2.2	45	2.5
95	1.0	.63	.43	2.30	2.3	100	5
Arkansas River, Colorado, John Martin Dam							
12.0	6	1.00	.57	13.29	1.8	440	24
15.5	6	1.00	.66	10.02	1.5	290	15
22	3.0	.77	.73	5.55	1.4	140	8
26	7	.91	.94	6.10	1.1	120	6
Missouri River, Montana, Fort Peck Dam							
9.2	0	.10	1.28	1.97	.78	30	1.5
13.0	0	.64	.74	11.45	1.4	290	15
16.5	0	.48	.58	6.33	1.7	210	11
23	9	.83	.49	6.18	2.0	240	13
Missouri River, North Dakota, Garrison Dam							
2.7	0	.99	.13	4.86	7.7	710	38
6.4	0	1.00	.17	2.06	5.9	230	12
8.0	0	.90	.33	1.22	3.0	70	4
10.5	0	.71	.46	.89	2.2	36	1.9
12.0	2.0	.87	.39	3.09	2.6	150	8
15.0	2.0	.92	.60	4.99	1.7	160	8
24	0	.96	.51	.74	2.0	28	1.5
32	0	.28	1.82	.77	.55	8	.4
36	0	.82	.66	2.21	1.5	65	3
38	0	.37	1.65	3.49	.61	40	2
51	1.0	.37	.73	2.09	1.4	55	3
Missouri River, South Dakota, Fort Randall Dam							
3.1	0	0.77	0.74	4.25	1.4	110	6
4.2	1.0	.90	.70	3.23	1.4	90	5
5.1	2.5	.77	1.26	3.61	.8	55	2.9
6.6	1.0	.84	.40	4.59	2.5	220	11
7.7	1.0	.81	.52	3.46	1.9	130	7
11.0	0	.33	.52	.48	1.9	18	.9
12.5	2.0	.50	.96	1.52	1.0	30	1.6
29	0	.33	1.67	1.25	.60	14	.8
Missouri River, South Dakota, Gavins Point Dam							
2.3	0	.86	.33	2.37	3.0	140	7
3.4	0	.99	.25	3.78	4.0	290	15
4.3	4	.98	.28	3.71	3.6	250	13
5.3	0	.99	.026	8.86	38	6,500	340
6.8	0	.87	.44	10.59	2.3	460	24
7.9	0	.96	.30	7.84	3.3	500	26
8.4	0	.13	.88	1.04	1.1	22	1.1
8.5	3.5	.98	.18	5.76	5.6	610	32
9.5	0	.94	.23	10.35	4.4	860	4.5
11.0	0	.75	.82	6.68	1.2	160	8
12.5	0	.45	.92	6.72	1.1	140	7
36	0	.48	.60	5.03	1.7	160	8
44	0	1.00	1.51	12.53	.66	160	8
Middle Loup River, Nebraska, Milburn Dam							
.2	0	.59	.48	.24	2.1	10	.5
1.6	6.3	.97	.64	2.76	1.6	80	4
5.6	6.3	.98	.78	2.00	1.3	48	2.6
Smoky Hill River, Kansas, Kanopolis Dam							
.8	0	.92	.61	1.68	1.6	50	2.8
2.9	2	.97	.66	4.35	1.5	130	7
Wolf Creek, Oklahoma, Fort Supply Dam							
0.3	2?	1.00	0.25	1.21	4.0	90	5
1.0	2?	.48	.46	.29	2.2	12	.6
1.3	2?	.94	.33	1.92	3.0	110	6
1.6	6?	.95	.31	3.70	3.2	230	12
2.9	2?	.96	.42	4.10	2.4	190	10
3.9	2?	.70	.51	1.68	2.0	65	3
4.7	2?	1.00	.29	9.67	3.5	630	34
6.6	2?	.96	.16	13.44	6.3	1,600	85
North Canadian River, Oklahoma, Canton Dam							
1.8	0	.93	.35	.83	2.9	46	2.4
3.1	0	.79	.63	1.00	1.6	30	1.6
5.0	0	.40	.93	.80	1.1	16	.9
5.6	0	.54	.51	2.15	2.0	80	4
7.4	0	.90	.33	2.43	3.0	140	7
12.0	0	.63	.25	6.01	4.0	460	24
14.5	1.0	.85	1.05	3.08	.95	55	3
35	0	.59	2.26	2.77	.44	24	1.2
125	0	.99	1.34	1.99	.75	28	1.5
Red River, Oklahoma-Texas, Denison Dam							
.6	0	.87	.64	.52	1.6	15	.8
2.1	0	.97	.36	1.15	2.8	60	3
7.2	3	.97	.82	.92	1.2	22	1.1
8.4	0	.84	.59	.87	1.7	28	1.5
11.5	0	.98	.45	1.15	2.2	48	2.6
15.0	0	.90	.31	1.20	3.2	75	4
109	4	.79	1.52	2.63	.66	32	1.7
Chattahoochee River, Georgia, Buford Dam							
.5	0	.31	.88	1.12	1.14	24	1.3
1.9	0	.99	.10	4.32	10.0	820	44
2.9	0	.95	-.02	7.96	--	--	--
4.0	0	.88	-.11	11.49	--	--	--

[1] $(1/D) = c_2 + c_1\ (1/t)$, where D = measured degradation, in meters, at t years after start of degradation.

[2] Years between dam closure and start of degradation.

[3] Listed r^2 is for estimation of D rather than for 1/D.

A small r^2 (presumably indicative of a minimum correlation between variables for the type of function being used) can result not only from large scatter about the

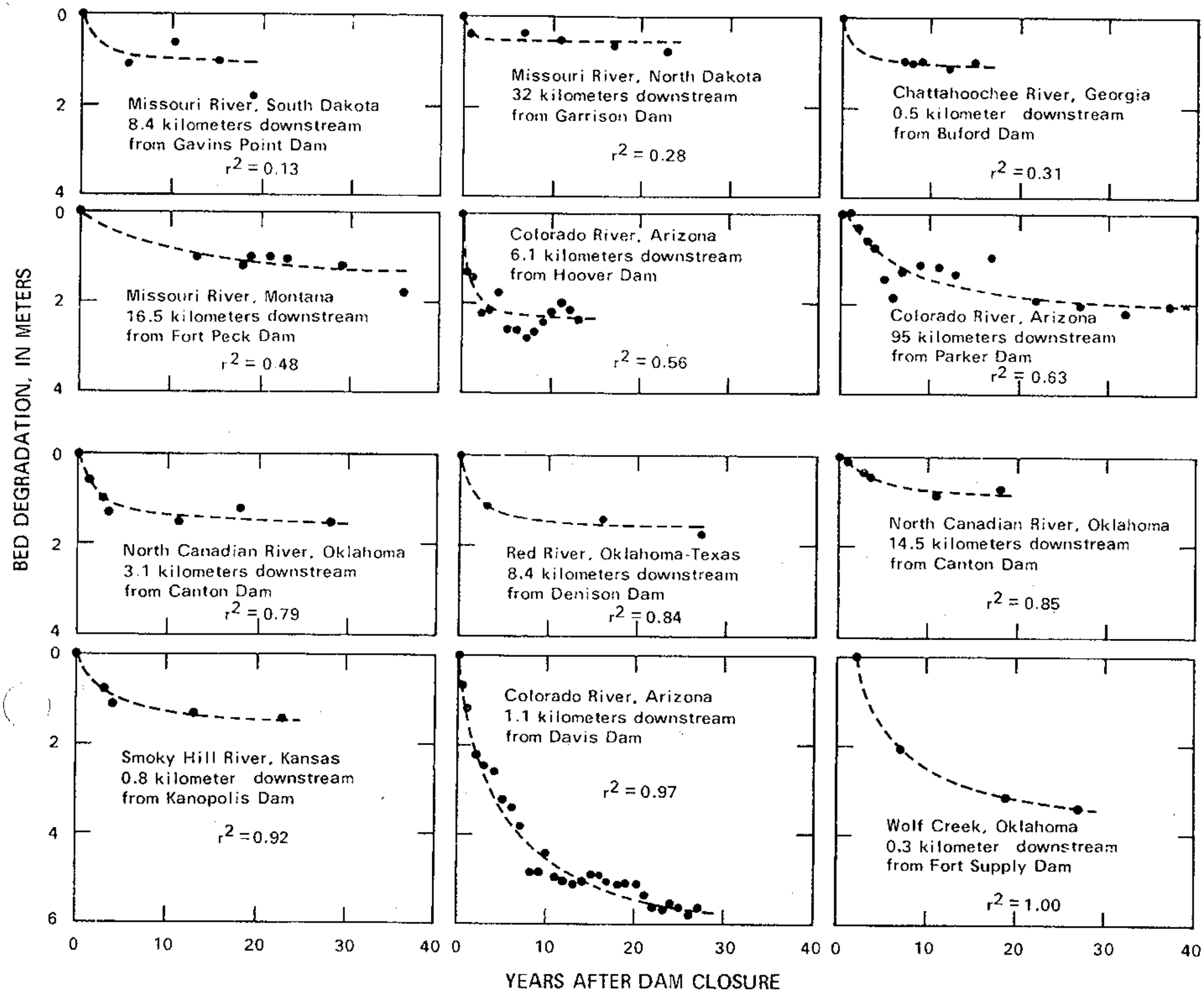


FIGURE 9.—Representative regression curves (dashed lines) of bed degradation with time at selected sites. Data from table 13.

line, but from other factors, such as: (1) Small depths of degradation (flat slope of best-fit straight line); (2) small number of data points (especially during the first few years after bed erosion begins); (3) errors in estimating any response time; and (4) irregularities in the trend of the curve, such as a rather abrupt cessation of degradation or an S-shaped curve. These features also contribute to a negative value of the coefficient c_2 (intercept). A negative c_2 precludes estimation of the maximum limit of degradation and associated values.

The type equation used here could predict degradation with time at a cross section if the coefficients c_1 and c_2 could be predicted. These certainly are functions at least of bed material and water discharge. A third factor might be distance downstream from the dam. At present (1982), the coefficients cannot be determined in advance. Therefore, prior to dam closure any estimates of bed erosion need to be based on some type of degradation analysis using measured bed-material sizes and expected water discharges (Strand, 1977; Priest and Shindala, 1969a). This approach requires: (1) Adequate sampling of the bed material with depth, distance across the section, and distance along the channel; and (2) accurate predictions of future flow releases. On the other hand, with a few years of measurements after the start of degradation, the model described above might be used with due caution. (References cited earlier include models of degradation based on transport equations, particle-size measurements, and the assumption of winnowing.)

MAXIMUM DEGRADATION AND ASSOCIATED TIME

At a given cross section within the degraded reach, the maximum observed depth of bed erosion (table 6) was negligible on some channels but was as much as 7.5 m on others (Colorado River 12 km downstream from Hoover Dam, Arizona). (Maximum values for a cross section do not necessarily apply to an entire reach, as local features can affect the extent of degradation at any one site.) Had Davis Dam not been built downstream, more degradation than 7.5 m probably would have occurred at the Colorado river section just mentioned. The data (table 13) show that the bed at this site was still degrading at a rapid rate 13 years after dam closure, when measurements were discontinued due to backwater from Davis Dam.

The maximum possible degradation in some cases can be limited or restricted by a fixed base level. For example, bedrock is encountered in places on the Smoky Hill River downstream from Kanopolis Dam (Kansas) and on the Republican River downstream from Harlan County Dam (Nebraska). On the Rio Grande and along reaches of the Colorado River, fans of very coarse debris are controlling. In contrast, certain wide, shallow cross sections in some reaches on the Missouri River downstream from Fort Randall Dam (South Dakota) may no longer degrade because flow velocities are too slow.

If one assumes that the bed does not contain a subsurface layer of erosion-resistant material and that the same discharges will continue, it is interesting to extrapolate the empirical hyperbolic equation for each of the 114 applicable cross sections discussed above into the future. With due regard both for the uncertainties of the assumptions and for the risks of extrapolation, we have nevertheless done this (table 5) to estimate: (1) Maximum eventual degradation D_{max}; (2) years needed to achieve 95 percent of the eventual maximum degradation (the function goes to infinity at maximum degradation); and (3) years needed for the bed to erode to 50 percent of its eventual maximum degradation. All estimates were computed from the regression coefficients c_1 and c_2 and rounded off appropriately.

D_{max} values ($1/c_2$) were estimated for all 114 cross sections. Three of these D_{max} values obviously were unreasonable and were not considered further. A frequency distribution of D_{max} for the remaining 111 sections is shown in figure 10. The distribution is virtually the same if the 21 cross sections that narrowed considerably are excluded. Ordinarily degradation needs to be viewed in relation to the size of the channel rather than in absolute values. Thus, D_{max} needs to be adjusted by a scaling factor, such as the channel width. Because widths were not available for 35 cross sections on the Colorado River (about 33 percent of the total), the frequency distribution was drawn without applying any scaling factor. The 111 cross sections used to compile figure 10*A* are downstream from the following dams (number of cross sections in parentheses): Glen Canyon (5), Hoover (27), Davis (2), Parker (6), John Martin (4), Fort Peck (4), Garrison (11), Fort Randall (8), Gavins Point (13), Milburn (3), Kanopolis (2), Fort Supply (8), Canton (9), Denison (7), and Buford (2). A variety of rivers and channel conditions is reflected in figure 10*A*.

According to the data in figure 10A, the modal or average maximum expectable degradation for the cross sections represented on the graph is about 2 m. The range is from about 0.4 to 38 m; about 98 percent of the values are less than 10 m. Accuracy of these predictions is related to the fit from the data themselves, the number and duration of measurements, the assumed nature of the subsurface sediment, and the validity of the many other assumptions.

If the coefficients in equation 1 are known, then the time needed for the bed to degrade to any proportion of the maximum eventual degradation depth can be estimated quickly by the following method. The actual depth value need not be known. Let p = the decimal proportion of the maximum degradation depth, for example, 0.95 if the depth of interest is 0.95 D_{max}. The time t_p needed to reach any designated proportion of D_{max} is

$$t_p = c_p \, c_1 / c_2$$

where $c_p = (\frac{1}{1-p}) - 1$. For example, the Colorado River 2.6 km downstream from Glen Canyon Dam, at which

TABLE 6.—*Maximum degradation downstream from various dams*

[Data from table 13, except last two entries which are from unpublished sources]

River, dam, State	Years since closure	Maximum lowering of bed elevation (meters)
Colorado, Glen Canyon, Arizona	9	7.3
Colorado, Hoover, Arizona	13	7.5
Colorado, Davis, Arizona	26	5.8
Colorado, Parker, Arizona	27	4.6
Jemez, Jemez Canyon, New Mexico	12	2.8
Arkansas, John Martin, Colorado	30	.9
Missouri, Fort Peck, Montana	36	1.8
Missouri, Garrison, North Dakota	23	1.7
Missouri, Fort Randall, South Dakota	23	2.6
Missouri, Gavins Point, South Dakota	19	2.5
Medicine Creek, Medicine Creek, Nebraska	3	.6
Middle Loup, Milburn, Nebraska	16	2.4
Des Moines, Red Rock, Iowa	9	1.9
Smoky Hill, Kanopolis, Kansas	23	1.5
Republican, Milford, Kansas	7	.9
Wolf Creek, Fort Supply, Oklahoma	27	3.4
North Canadian, Canton, Oklahoma	28	3.0
Canadian, Eufaula, Oklahoma	6	5.1
Red, Denison, Oklahoma-Texas	16	3.0
Neches, Town Bluff, Texas	14	.9
Chattahoochee, Buford, Georgia	15	2.6
South Canadian, Conchas, New Mexico	7	3.0
Salt Fork, Arkansas, Great Salt Plains, Oklahoma	9	.6

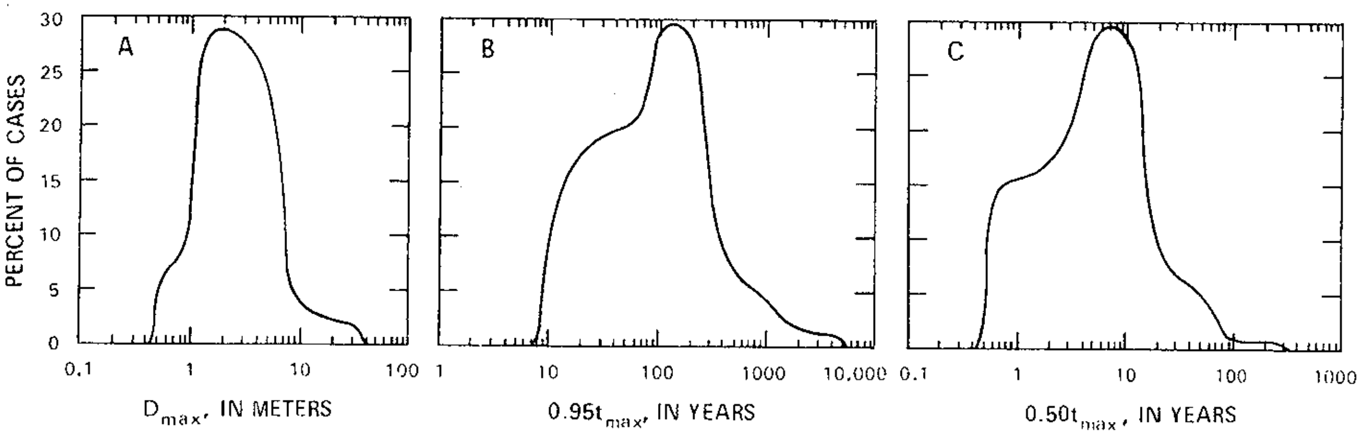


FIGURE 10.—Frequency distributions based on 111 measured cross sections on various rivers: *A*, maximum expected degradation depth; *B*, years needed to deepen to 95 percent of maximum depth; and *C*, years needed to deepen to 50 percent of maximum depth.

$c_1=2.03$ and $c_2=0.30$ (table 5), would be predicted to reach 0.95 D_{max} in $19\times2.03/0.30=129$ years (or about 130 years) after the start of degradation.

This shortcut method is preferable to equation 1 for estimating times needed to reach a given depth because rounding of D in equation 1 causes variations in the computed times, compared to the times calculated from the coefficients alone. Variations are insignificant for the steeper part of the degradation-time curve (early years, shallow depths) but can be as much as 60 percent where the curve flattens in later years.

The number of years predicted for the bed to achieve 95 percent of its eventual total degradation (0.95 t_{max}) for the 111 cross sections ranges from 7 to 6,500 years (fig. 10*B*). About 91 percent of the values are between 7 and 500 years. The modal time is about 140 years. Data for many of the cross sections (table 13) indicate that these individual estimates of 0.95 t_{max} are of the right order of magnitude. Each such computation, however, is based on the assumption that the remaining subsurface material does not differ substantially from the original channel bed sediment and that the same flow pattern will continue.

The adjustment period at a site, or predicted time required to reach the new stable depth (0.95 D_{max}), does not seem to have any consistent relation to distance downstream from the dam, for the few reaches where this aspect could be assessed. Any relation probably is obscured by the irregular differences in degradation from one cross section to another along a river.

Most of the 111 cross sections eroded one-half of their predicted eventual maximum depths within the first few years after the start of degradation. The range of these predicted times (0.5 t_{max}) is from 0.4 to 340 years (fig. 10*C*); modal value is about 7 years. All distributions in figure 10 are skewed, with a preponderance of smaller values within the respective range.

Initial degradation rates (the reciprocal of the coefficient c_1) range from virtually negligible to as much as 7.7 m/yr. Even downstream from the same dam, different sites show different initial degradation rates. No direct relation between initial degradation rate and predicted eventual maximum depth of degradation could be established.

STANDARDIZED DEGRADATION-TIME PLOT

The degradation-versus-time plots (fig. 9) can be standardized and made dimensionless by converting the D axis to $D/0.95\ D_{max}$ and the t axis to $t/0.95\ t_{max}$. (The extrapolated 95-percent value is taken as a reasonable approximation of the eventual maximum values, as the latter are unusable because t_{max} becomes infinite.) By substituting the type function (eq. 1a) for each of D and 0.95 D_{max} in the ratio $D/0.95\ D_{max}$, the coefficients c_1 and c_2 are eliminated, and $D/0.95\ D_{max}$ is proportional to $t/0.95\ t_{max}$. This means that if the standardized, dimensionless plot is used, the site-specific coefficients c_1 and c_2 become irrelevant, and all the various D-versus-t curves collapse onto one general curve. The straight-line form of the equation for this generalized curve, in which the reciprocals of the two variables are used as in equation 1a, is

$$\frac{0.95\ D_{max}}{D}=0.95+0.05\frac{(0.95\ t_{max})}{t}. \qquad (2)$$

This general curve is shown in figure 11, with the data for the 12 representative cross sections of figure 9. (Axes in fig. 11 correspond to the form of eq. 1 rather than eq. 2 for easier comparison to the plots of fig. 9.) The scatter is greatest for sites having low correlations with the model curve on the unstandardized plots (fig. 9) and improves as the fit on the unstandardized plots improves.

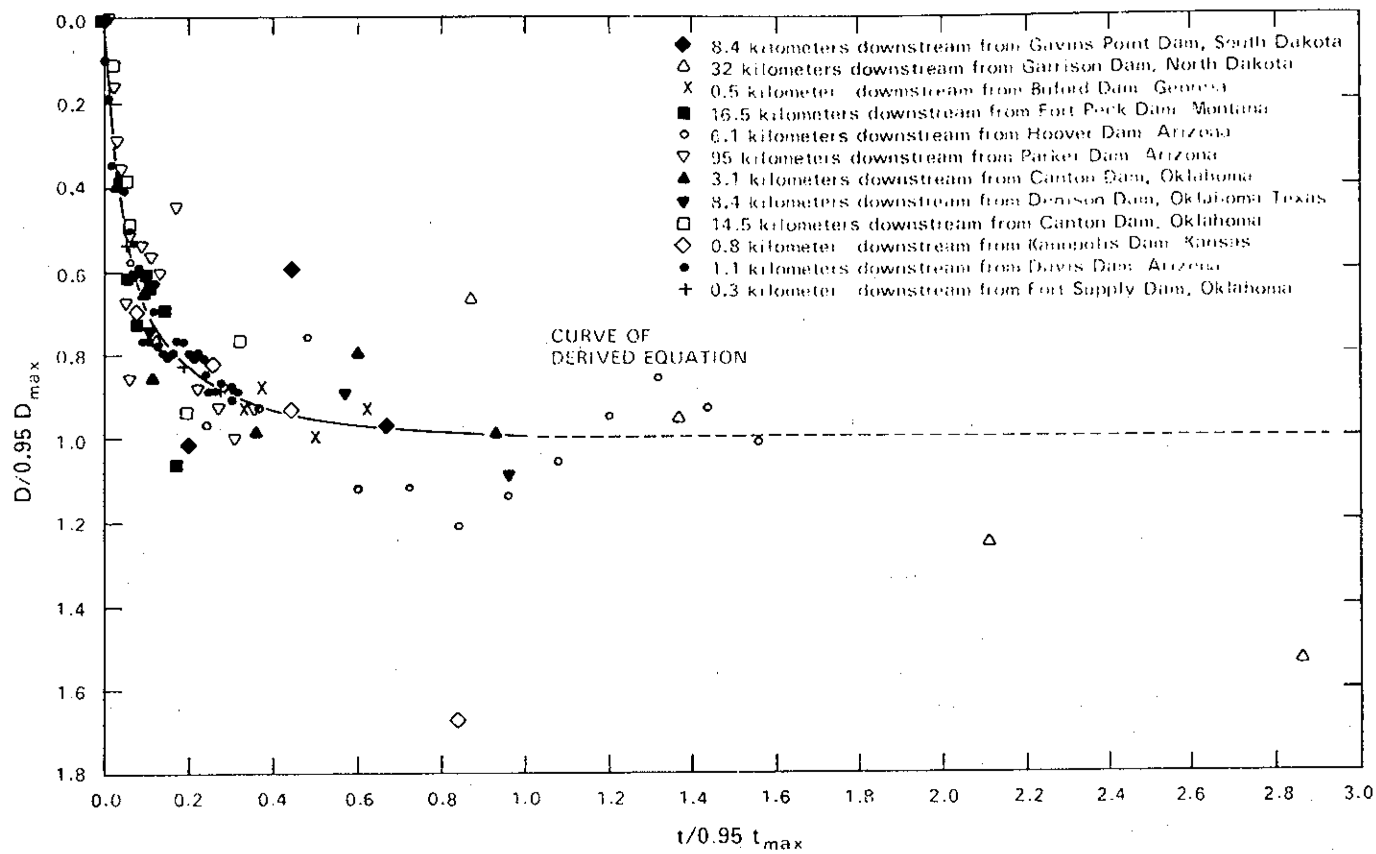


FIGURE 11.—Standardized degradation-time dimensionless plot of degradation curves in figure 9.

The general curve (fig. 11) represents the bed degradation relative to maximum estimated degradation for the standardized period, for any eroding cross section that has the ideal degradation function of equation 1. According to equation 2, such degrading sections achieve 50 percent of their maximum eventual degradation after only the first 5 percent of their adjustment period. Similarly, they achieve 75 percent of their eventual total degradation after just 13 percent of the adjustment period. Thus, the vast majority of bed degradation occurs within the first 10 to 15 percent of the adjustment period, as the shape of the general curve shows. In other words, if normal releases are made when the dam is closed, the first years after dam closure tend to be the period of greatest bed degradation, and later years become relatively unimportant. Some river engineers previously have reported this in connection with specific dams (U.S. Army Corps of Engineers, 1960, p. 13).

In the preceding paragraphs, we have described an empirical relation between degradation and time in a search for some potentially useful generalization. However, it is important to remind readers that the degradation at individual cross sections is variable, and that 40 sites with aberrant data and 84 sites that showed no regular trend (samples shown in fig. 8) were eliminated from the analysis. Assumptions about flow releases, particularly in the absence of high-flow releases, may well produce significant errors in estimating rates or depths of degradation, or rates of change of channel form. Nevertheless, for the class of channels included in this sample (predominantly sand, but including some coarser material, and with irregular depths to bedrock controls), the results may provide some boundaries on expected depths, rates, and times of degradation.

LENGTH OF DEGRADED REACH

The reach, downstream from each dam, in which all cross sections (except those of obvious bedrock control) showed significant degradation, was defined as the degraded zone. The length of this reach was taken as the distance from the dam to the farthest inclusive degrading cross section.

The length of degraded reach downstream from most dams increased with time, as expected (table 7). This downstream progression with time has long been recognized from onsite observations (Stanley, 1951, p. 944; Makkaveev, 1970, p. 109) and in theoretical studies

TABLE 7.—*Data on the degraded reach downstream from dams*

[Dams not listed because of lack of data are Davis, Parker, Medicine Creek, Milburn, and Milford Dams]

Years after dam closure	Location of front of degraded reach downstream from dam (kilometers)	Rate of advance (kilometers per year)	Distance from dam to site of maximum degradation (kilometers)	Location of first measured section downstream from dam (kilometers)
	Colorado River, Arizona, Glen Canyon Dam			
3	25	8	4	1
7	--	--	4	--
9	[1]>25	--	16	--
19	[1]>25	--	16	--
	Colorado River, Arizona, Hoover Dam			
.5	21	42	8	2
1	28	14	3	--
2	50	22	3	--
3	85	35	3	--
5	[1]>120	--	3	--
7	[1]>120	--	15	--
12	[1]>120	--	13	--
	Jemez River, New Mexico, Jemez Canyon Dam			
6	[1]>2.1	--	.6	.6
12	[1]>2.1	--	1.1	--
22	[1]>2.1	--	1.0	--
	Arkansas River, Colorado, John Martin Dam			
9	26	3	22	4
24	26	0	4	--
30	26	0	22	--
	Missouri River, Montana, Fort Peck Dam			
13	[1]>75	--	17	9
18	[1]>75	--	17	--
23	[1]>75	--	23	--
36	[1]>75	--	17	--
	Missouri River, North Dakota, Garrison Dam			
1	12	12	28	3
7	19	1.2	6	--
11	18	-.25	6	--
17	21	.5	6	--
23	21	0	6	--
	Missouri River, South Dakota, Fort Randall Dam			
2	5	2.5	11	1.6
5	13	2.3	1.6	--
8	14	.3	11	--
15	14	0	11	--
23	15	.1	11	--
	Missouri River, South Dakota, Gavins Point Dam			
5	15	3	2	1.5
10	14	-.2	4	--
15	23	1.8	2	--
19	23	0	2	--
	Des Moines River, Iowa, Red Rock Dam			
9	20	2.2	12	2.3
	Smoky Hill River, Kansas, Kanopolis Dam			
3	5	1.7	.8	.8
4	4	-1.0	.8	--
13	14	1.1	.8	--
23	--	--	.8	--
	Wolf Creek, Oklahoma, Fort Supply Dam			
7	[1]>7	--	.3	.3
19	[1]>7	--	.3	--
27	[1]>7	--	.3	--

(Mostafa, 1957; Albertson and Liu, 1957; Hales and others, 1970). Such lengthening occurred downstream from 9 of the 11 dams for which this feature could be determined (table 7). Lengths as of the latest resurvey ranged from 4 km on the Neches River downstream from Town Bluff Dam, Texas, to more than 120 km on the Colorado River downstream from Hoover Dam, California-Arizona. In most of these cases, there is no indication that the reach had stopped lengthening by the time of the most recent survey. This means that the zone of degradation can continue increasing in length for at least 30 years or more after dam closure, although it could stop sooner. The migration rate and the final length of the degradation zone should vary with flow releases, bed-material sizes, and topography. Consequently, growth rate and eventual length are likely to vary from one dam to another.

TABLE 7.—*Data on the degraded reach downstream from dams*—Continued

Years after dam closure	Location of front of degraded reach downstream from dam (kilometers)	Rate of advance (kilometers per year)	Distance from dam to site of maximum degradation (kilometers)	Location of first measured section downstream from dam (kilometers)
	North Canadian River, Oklahoma, Canton Dam			
1	7	--	<1.8	1.8
2.8	7	--	<1.8	--
3.4	7	--	<1.8	--
11	7	--	<1.8	--
18	7	--	<1.8	--
	Canadian River, Oklahoma, Eufaula Dam			
6	16	2.7	.8	.8
14	29	1.6	.8	--
	Red River, Oklahoma, Denison Dam			
3	7	2.3	15	.6
6	[1]>27	--	15	--
16	[1]>27	--	1	--
27	[1]>27	--	15	--
	Neches River, Texas, Town Bluff Dam			
9	--	--	--	.2
14	4	--	.2	--
	Chattahoochee River, Georgia, Buford Dam			
7	7	1	2	.5
9	9	1	2	--
12	--	--	2	--
15	10	.2	2	--

[1] Distance of farthest cross section that was established at time of dam closure.

Migration of the front of the degraded zone means that at a downstream site a response time or lag time occurs before the bed reacts to the dam, if it is going to react. For some dams, this response time (and hence the migration rate of the edge of the degraded zone) could not be determined, because: (1) Cross sections were not established far enough downstream; (2) downstream measurements were not started until too many years after dam closure; or (3) a downstream base level interrupted or controlled the normal degradation process. A probable example of the latter is Wolf Creek downstream from Fort Supply Dam, Oklahoma. This stream joins the North Canadian River 6 km downstream from the dam. Successive profiles showed a hinge or base-level control at or near the confluence with the larger river. Similarly, the zero degradation point downstream from Town Bluff Dam on the Neches River, Texas, is sea level (Gulf of Mexico). Bedrock outcrops appear along the Republican River downstream from Harlan County Dam, and there are cobble riffles that act as controls on the Red River downstream from Denison Dam.

Within a year or two after dam closure, the length of the degraded reach can range from little or nothing to as much as 50 km. After 2 or 3 decades, the length downstream from some dams remained as short as a few kilometers (and theoretically could be much less), but downstream from Hoover Dam it was more than 120 km (table 7).

Hales and others (1970) proposed a method for predicting the temporary length of the degraded zone, based on 15 years or less of data for the Missouri River downstream from Garrison, Fort Randall, and Gavins Point Dams. This channel length in their treatment is a function of an average peak discharge, the time during which the degradation has been occurring, the dominant size of the bed material, and the area of the channel cross section. We have not tested their relation, mainly because of uncertainties in their definition of the peak discharge, uncertainties in the location of the cross section at which the area and particle sizes are to be measured, and their definition or way of determining the dominant grain size. Similarly, because of the few instances in which the degraded reach had stopped lengthening, a test of the method that Priest and Shindala (1969b) proposed for predicting that ultimate distance was not possible.

Migration rates of the leading edge ranged from very little to as much as 42 km/yr (kilometers per year) immediately after dam closure (table 7). Slower rates for subsequent periods ranged from virtually negligible to about 29 km/yr. Most of the travel rates range from about 0 to 2 km/yr. According to Makkaveev (1970, p. 109), his countryman Fedorov determined migration rates of several kilometers per year on large lowland rivers, and several tens of kilometers per year on mountain rivers in the Soviet Union.

The rate of advance of the downstream edge of the degraded zone depends on the flow releases and bed materials; these vary widely from one stream to another. According to the data in table 7, the rate on any river is not constant; the front occasionally may appear to retreat for isolated periods, even though the long-term trend is downstream. Migration rates appear to be fastest during the years immediately after dam closure. The relatively slow rates of subsequent years might be expected in some cases due to a flattening of gradient (discussed below); however, variable flow releases also will affect the rate with time. Whether the rates eventually become constant or continue to get slower with time cannot be determined from available data.

ZONE OF VARIABLE BED CHANGES

Cross sections downstream from the degraded zone may aggrade, degrade, or stay at the same level (table 13). There is some uncertainty as to whether bed-elevation changes in this downstream zone are due to the dam. Cross sections were not established prior to dam construction; therefore, the investigator does not have the benefit of this control. Marked trends, such as sudden and deep degradation typical of many cross sections near the dam and of the time when changes began, are not readily apparent on many measured sections. Most bed changes shown by the gaging-station data for control stations (table 14 and figs. 36–49) do not show trends. For these reasons, there is little basis for believing that the dam caused any observed changes in bed elevation beyond the degraded zone. Availability of ground and aerial photographs eliminates much of this uncertainty in regard to channel width and density of vegetation, but does not help to define bed elevations. We, therefore, have not evaluated observed fluctuations in bed level in the reach beyond the degraded zone.

It is possible that degradation results in aggradation at some point downstream. Borland and Miller (1960, p. 70) noted that after closure of Hoover Dam in 1935 and Davis Dam about 1950 on the Colorado River, degradation downstream from the dams increased the aggradation in a reach farther downstream at Needles, California. Similarly, while only small changes in the overall longitudinal profile of the Rio Grande occurred after closure of Elephant Butte Dam and reservoir, J. F. Friedkin (International Boundary Commission, written commun., 1959) noted degradation of 1 to 2 m just downstream from the dam and deposition of about 1.5 m at El Paso, Texas, about 225 km downstream. These data are suggestive but are too limited to support a generalization regarding downstream aggradation associated with upstream degradation. Our study provides no additional data.

A related intriguing possibility is that enlargements in channel width (discussed in detail below) could result in downstream aggradation. On the Missouri River downstream from Garrison, Fort Randall, and Gavins Point Dams, and on the Red River downstream from Denison Dam, significant increases in channel width at some cross sections are associated with bed aggradation near the approximate downstream edge of the degraded reach.

LONGITUDINAL-PROFILE CHANGES

To analyze changes in bed elevation with distance downstream (longitudinal profiles), we required at least four cross sections downstream from the dam and enough post-dam resurveys, bed degradation, inclusive time, and total downstream distance to reveal trends and features. Of the 21 dams (fig. 1), these requirements eliminated Davis, Jemez Canyon, John Martin, Medicine Creek, Milburn, Milford, and Red Rock Dams, leaving 14 dams for this particular analysis.

Degradation models based on flume studies generally show maximum bed erosion at or near the dam, relative to the total reach undergoing bed changes (Ahmad, 1953; Mostafa, 1957; Aksoy, 1970; Hwang, 1975). In a general way, our data support that finding. The cross section of greatest degradation at a given time was the closest section to the dam in five cases (Gavins Point, Kanopolis, Fort Supply, Canton, and Eufaula Dams). Downstream from seven other dams, the greatest degradation was some distance, generally 2 to 16 km, downstream from the dam, but still generally nearer the upstream than downstream end of the degrading reach. (Variations in the downstream location of maximum bed erosion were mentioned by Wolman, 1967). For the two remaining dams, the location of maximum degradation was indeterminate.

Due to the spacing of the cross sections and the natural variations of bed and bank erodibility with distance downstream, the data do not reveal how close to the dam the maximum degradation will occur when bed material is homogeneous with depth and distance. Results of Ahmad's (1953) flume study indicate that the greatest degradation takes place closer to the upstream than to the downstream end of the degraded zone, but not right at the dam. Data in table 13 at least show more degradation closer to the upstream than downstream end of the degraded zone. Whether maximum degradation occurs immediately downstream from the dam needs to be determined by new measurements.

Flume studies also indicate progressively less degradation with distance downstream, at a given time. For our data, this occurs in some reaches, but others do not seem to have a well-defined trend of degradation with distance. Instead, downstream from some dams, varying depths of bed erosion seem to be distributed almost randomly. For example, the data for the Colorado River downstream from Hoover Dam (table 13) show considerable variability in degradation depths with distance downstream. Within the general degraded zone, some cross sections had only minor bed erosion, while others degraded many meters by the same year. Because flows were the same for all sections and channel width did not vary significantly, such degradation differences probably are due to differences in bed erodibility (Stanley, 1951, p. 945).

Variations with time also occur. If degradation is a maximum at or near the dam, then the channel's downstream longitudinal profile should flatten with time as degradation proceeds. This process has been observed in the laboratory, along with the expected decline in the rate of degradation. At a given cross section, the sediment-transport rate decreases progressively with time as the bed slope (and hence stream competence) decreases. Transport eventually should cease if the slope becomes sufficiently flat (Tinney, 1962).

Where no bed controls exist, Ahmad's (1953) flume studies show that the point of maximum degradation migrates downstream with time. For most of our cross sections, maximum degradation either stayed at the same cross section with time (six dams) or varied from one cross section to another while showing a general preference for one site (seven dams), with one dam indeterminate. In several of the seven instances where the location varied with time, the first resurvey after dam closure showed maximum erosion at the cross section nearest the dam, but for later resurveys, the greatest bed degradation occurred at some fixed downstream cross section. In general, then, the site of greatest bed erosion tends to remain constant with time for the dams of this study, in which there is probably great variability of bed materials at or close to the surface.

In nature, the bed profile downstream from a dam is affected by differences in bed material with both depth and distance, the presence of local controls, the history of flow releases, tributary contributions of water and sediment, and other factors. The profile downstream from a dam varies irregularly with time, and a uniform flattening of slope is not common. In most cases, the rate and depth of degradation are greater closer to the dam, but, in other respects, each dam is unique in regard to profile adjustment. Four examples are shown in figure 12.

The Smoky Hill River downstream from Kanopolis Dam perhaps most closely approaches laboratory results and theoretical expectation, at least for the first 10 km or so downstream from the dam. Beginning at or immediately downstream from the dam, degradation decreases progressively downstream (fig. 12).

The profile of the Colorado River downstream from Parker Dam is remarkably different in that only to a very slight extent is the expected flattening of the slope evident (fig. 12). Instead, degradation seems to be almost uniform throughout a reach at least 60 to 70 km long.

In contrast, the channel profile downstream from Fort Randall Dam on the Missouri River, though generally tending to flatten with time, has widely varying degrees of bed-level change with time from one cross section to another (fig. 12). Degradation, no change, and aggradation all have happened at different downstream locations.

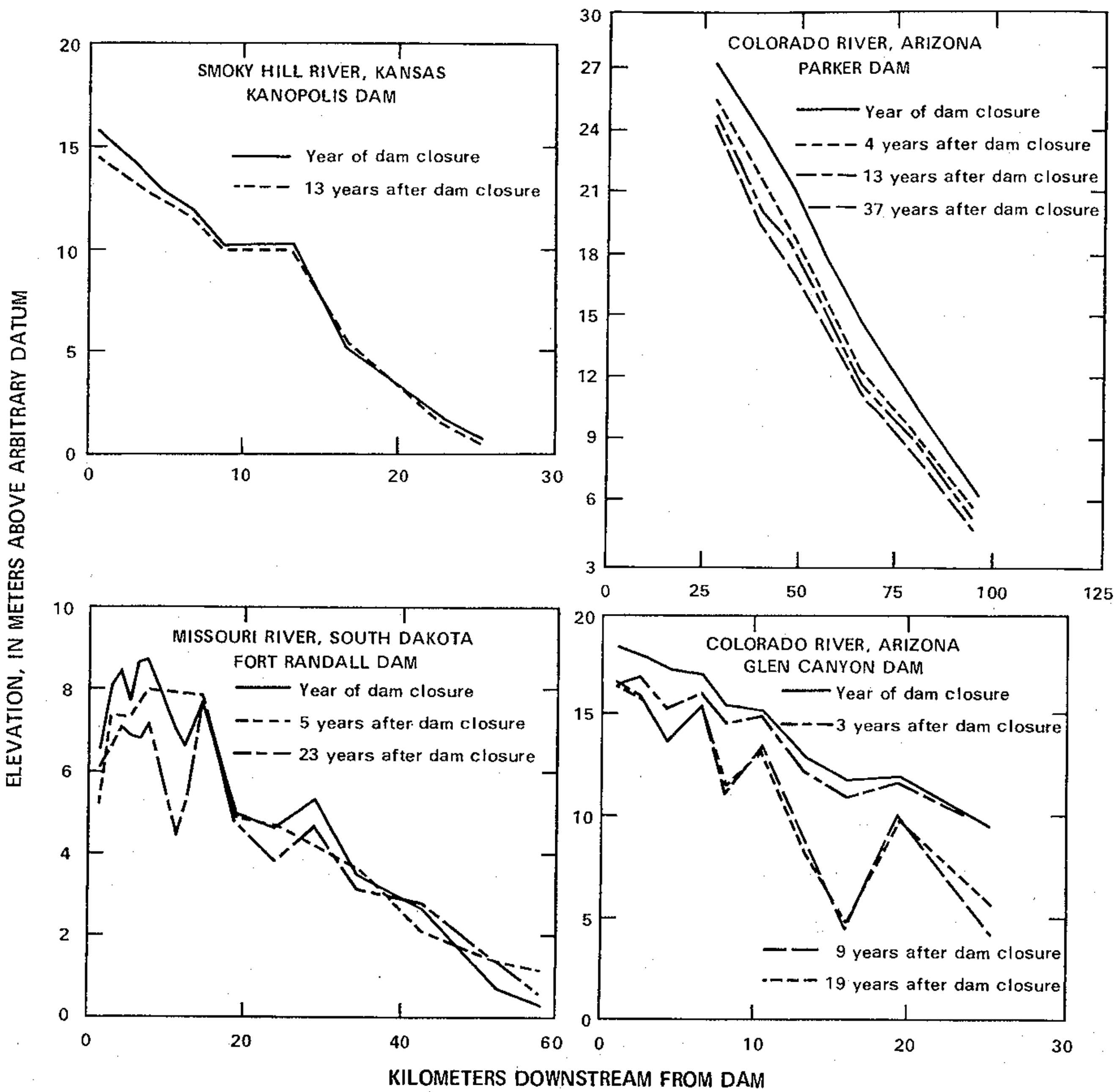


FIGURE 12.—Longitudinal-profile changes downstream from four dams.

Finally, the Colorado River channel throughout about a 25 km-long reach downstream from Glen Canyon Dam has undergone both a decrease and increase in slope with time (fig. 12). By 3 years after dam closure, the expected trend in degradation and flattening of slope had developed. However, degradation then ceased near the dam and, despite local irregularities such as cobble riffles, increased in the downstream direction. By 9 years after dam closure, this process had produced an average slope steeper than the slope at the time of dam closure. No change in the profile occurred during the following 10 years. Coldwell (1948) shows other examples of variability in the development of post-dam longitudinal profiles.

The profile along the Green River downstream from Flaming Gorge Dam, Utah, is changing due to the development of rapids (Graf, 1980). The reduced (post-dam) high flows are no longer able to move the coarse material. Some bed degradation near the rapids might accentuate the profile changes.

Detailed records from the Rio Grande (J. F. Friedkin, written commun., 1959) provide one of the best illustrations of the variability of degradation and aggradation and their effect on the longitudinal profile. The reach for this example extends from Elephant Butte Dam, New Mexico, to and including a cross section downstream from El Paso, Texas; however, the upper reaches of the Rio Grande have similar problems (Lagasse, 1980). This complex case demonstrates both the effects of man (diversion dams) and the effects of sediment contributions from tributaries. From 1917 to 1932, immediately downstream from Elephant Butte Dam, the streambed degraded to a depth of about 1.8 m. Similarly, downstream from each of a number of diversion dams that control the channel elevation but provide little storage, degradation during 1917–32 ranged from 0.3 to 2.0 m. Due to this degradation and the downstream controls, the slope flattened downstream from each diversion structure. For example, in a reach 17 km long downstream from Percha Dam (46 km downstream from Elephant Butte Dam), from 1917 to 1932, the slope decreased from 0.00080 to 0.00065. Maximum depth of scour downstream from Percha Dam was about 2.0 m. In addition to the effects of these diversion dams, a number of steep arroyos, with intermittent large flows and large quantities of coarse material, periodically deliver that sediment to the Rio Grande. Because Elephant Butte Dam virtually eliminated downstream floods along the Rio Grande, the main channel can no longer transport the coarse material brought in by the arroyos. These sediment accumulations along some reaches block the channel and divert it completely. Along other reaches, such as those controlled by bank-protection works and jetties, such sediment accumulations provide a control by raising the elevation of the main stream at the confluence. This, in turn, induces deposition in the main channel for short distances upstream. The gradient of the Rio Grande is about 0.00028 to 0.00076, so deposition of coarse material can significantly flatten the local gradient.

A river's longitudinal profile and slope also can be affected by changes in river length or sinuosity. An increase in sinuosity (or in river length) has been noted in connection with local aggradation and vice versa (Hathaway, 1948; Ahmad, 1951; Frederiksen, Kamine and Associates, Inc., 1979).

BED MATERIAL AND DEGRADATION

THEORETICAL EXPECTATIONS

Few if any natural channels are underlain by perfectly uniform sediments. Because magnitude and frequency of high flows are significantly decreased by dams, and because released flows may not be able to transport sizes previously moved by higher flows, successive flows can winnow finer materials from the bed. Progressive winnowing concentrates the coarser fraction. As degradation proceeds, the average particle size on the bed increases, possibly eventually resulting in a surface covering or armor of coarse particles alone. This idealized theory has long been accepted in engineering planning.

Onsite and laboratory studies (Pemberton, 1976; Harrison, 1950; Little and Mayer, 1972) have demonstrated the importance of armoring in limiting degradation. In a general way, the number or extent of coarser particles should govern partly the depth of degradation in the cross section. Livesey (1965) has shown that as little as 10 percent coarse material in a standard sieved sample may be sufficient to provide the bed armor. (This underlines the importance of adequately sampling the surface and subsurface material for predictive purposes, before the dam is built. Representative sampling is difficult.) Livesey's observations show further that a postdam armored bed need not be covered entirely by coarse material, and that the percentage covered is about 50 percent. The estimated gravel cover for the bed of the Red River downstream from Denison Dam, as obtained by pebble counts throughout long reaches of the river, indicates that 30 to 50 percent cover limits or controls degradation.

Armor is a veneer underlain by normal or unwinnowed material. To date, onsite studies have not provided any proven examples of unravelling or unrolling of the veneer and reexposure of the subsurface sands. Assuming releases of large discharges from a dam, one would expect some unravelling of the surface. The extent should depend on the magnitude and duration of such excessive flows. Presumably restabilization and rearmoring of the bed should follow.

The progressive changes in particle size in the vertical should have their counterparts along the longitudinal profile, as degradation moves progressively downstream with time. Thus, armoring of the bed should appear first close to the dam, then disappear somewhere downstream.

VARIATIONS IN BED-MATERIAL SIZES WITH TIME AT A CROSS SECTION

An unpublished U.S. Army Corps of Engineers report gives median grain size (d_{50}) at different years for two sites downstream from Gavins Point Dam on the Missouri River. Various U.S. Bureau of Reclamation reports, for example U.S. Bureau of Reclamation (1948), show size-frequency curves for the bed material at different locations downstream from Hoover, Davis, and Parker Dams on the Colorado River. The variation of d_{50} with time for these Missouri River and Colorado River sites is shown in figure 13.

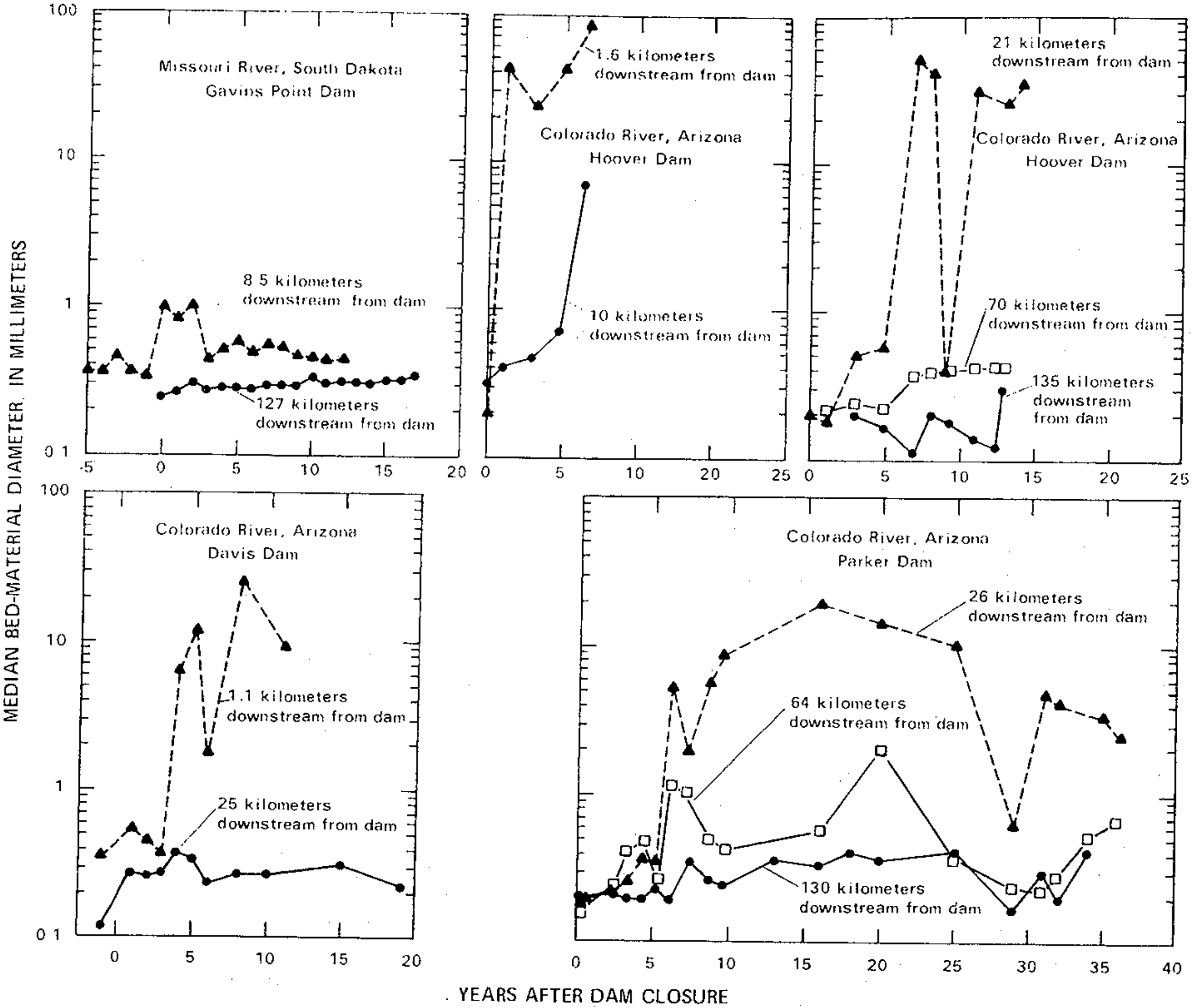


FIGURE 13.—Variation in bed-material size with time at a site, after dam closure.

Initially, d_{50} increased with time following dam closure, at least at cross sections near the dam. The magnitude of this increase can be more than a factor of 100 (and theoretically much more) in the value of d_{50}, depending on the sizes and number of coarse particles in the reach. Within about 1 to 10 years after the start of the coarsening, the particle sizes seemed to stabilize. From the graphs in figure 13, stabilization occurred relatively abruptly rather than gradually, but such an impression may be due to the sampling intervals. In a few instances, the data suggest a subsequent reversal of the trend, that is, a decrease of d_{50} with time following the initial increase. Possible explanations, all speculative, are the arrival of finer material from upstream or from tributary inflow, the uncovering of finer material at some depth below the original surface, lateral movement of the channel, and sampling inaccuracies. Such a decrease in d_{50} may or may not reach a new stable value, judging from figure 13. Thus the changes in median size of bed material at these sites, while initially tending to coarsen as expected, did not follow an ideal or common pattern thereafter, but varied in several ways during later periods.

Near the downstream end of the degraded zone, an increase of d_{50} with time may or may not occur. Where it does occur, it may lag behind the time of dam closure. Coarsening at these downstream sites seems to be less than that occurring near the dam. Whether this relatively limited coarsening is partly a function of distance from the dam, in addition to the distribution of particle sizes in the subsurface material and other factors, cannot be determined from the available data.

Particle-size distributions given in U.S. Bureau of Reclamation publications for Colorado River reaches show that sorting as well as median size of streambed material downstream from dams varies with time. Some finer material is present in all samples, but later samples tend to have larger sizes (hence a wider range of sizes) than the earlier ones, as well as a greater percentage of coarse particles. Sorting, therefore, decreases with time. The presence of fine material in all samples may mean that such small grains really are on the bed surface, or it may result from the sampling technique, that is, the sample could include both surface and subsurface material.

VARIATIONS IN BED-MATERIAL SIZES WITH DISTANCE DOWNSTREAM

Some streams, such as the North Canadian River, have nearly constant sediment sizes for long distances downstream. Others, such as the Republican River downstream from Harlan County Dam in Nebraska and the Salt Fork of the Arkansas River downstream from Great Salt Plains Dam in Oklahoma, show great downstream variability in bed-material sizes. Such variability in these last two examples results in part from the sediment contributed by cliffs that abut the channel in places. Thus local geology can mask changes that might occur from dam construction.

Where bedrock controls are absent and the bed of the river has a mixture of grain sizes, the postulated succession of particle size with distance occurs. Kira (1972, fig. 11) showed a gradual decrease in the mean diameter of bed-surface particles with distance downstream from Huchu Dam on the Aya River, Japan, as of 5 years after dam closure. Downstream from Kanopolis Dam on the Smoky Hill River and Denison Dam on the Red River, pebble counts of the sediment on gravel bars exposed at low water were obtained in 1960 throughout long reaches. Sieve analyses also were available for the bed material of the Colorado River downstream from Hoover Dam from U.S. Bureau of Reclamation sources. For these three rivers, the upper part of each of the three plots in figure 14 shows relatively coarse particles nearest the dam and a gradual grain-size decrease in the downstream direction. Bed-sediment analyses (discussed below) made when Hoover Dam was closed show that the bed material at that time was much finer than it was 6½ years later (the year of the data plotted in fig. 14). The post-dam decrease of particle size with distance downstream, therefore, is reasonably attributable to the dam. Downstream from Kanopolis and Denison Dams, bed-material sizes were not measured at the time of dam closure. Therefore, one cannot say with certainty whether the post-dam trend resulted from the dam or whether it occurred naturally. However, the similarity of the two grain-size versus distance curves to one another and to that for the Hoover Dam data, along with qualitative agreement with theoretical expectations, indicate that the decrease in grain size probably is due to the dams.

The lower plot for each dam in figure 14 shows variation in bed elevation with distance downstream, using the data of table 13 for the same year as the sediment-size data. The relative changes in grain size, degradation, and distance downstream then can be compared. If one assumes that the sizes of pre-dam channel sediment downstream from these three dams did not vary significantly with distance within the reach examined, then the relation between bed-material changes, degradation, and distance downstream agrees with the theoretical model described above.

Reading the associated values of grain size and degradation at successive distances from the smoothed curves in figure 14, the curves in figure 15 were drawn to show the increase in bed-material grain size with degradation for each study reach. This shows more graphically the increase in bed-material sizes relative to the depth of bed degradation. The curves in figures 14 and 15 might have been different in position on the graph if the data had been measured at some other time after dam closure; however, the trend would not be affected.

U.S. Bureau of Reclamation data permit an evaluation of how the grain size–distance relation varies with time for the Colorado River downstream from Hoover Dam (fig. 16). During the first year or so after dam closure, the reach that underwent changes (coarsening) in bed-sediment sizes was somewhat less than 10 km long. After 3 years, coarsening was quite noticeable at 20 km but not at 70 km downstream from the dam; and by about 6 or 7 years after closure, coarsening was apparent 70 km, but not at 135 km, downstream from the dam. Coarsening did not seem to progress to the site 135 km downstream from the dam until about 13 years after closure.

CHANNEL WIDTH

GENERAL NATURE OF WIDTH CHANGES

Channel widths downstream from the dams of this study narrowed, widened, or remained constant, depending on the site, in the years following dam closure (table 13). In general, the post-dam changes in channel width at a cross section as documented by measured cross sections, photographs, and maps, can be divided into five categories.

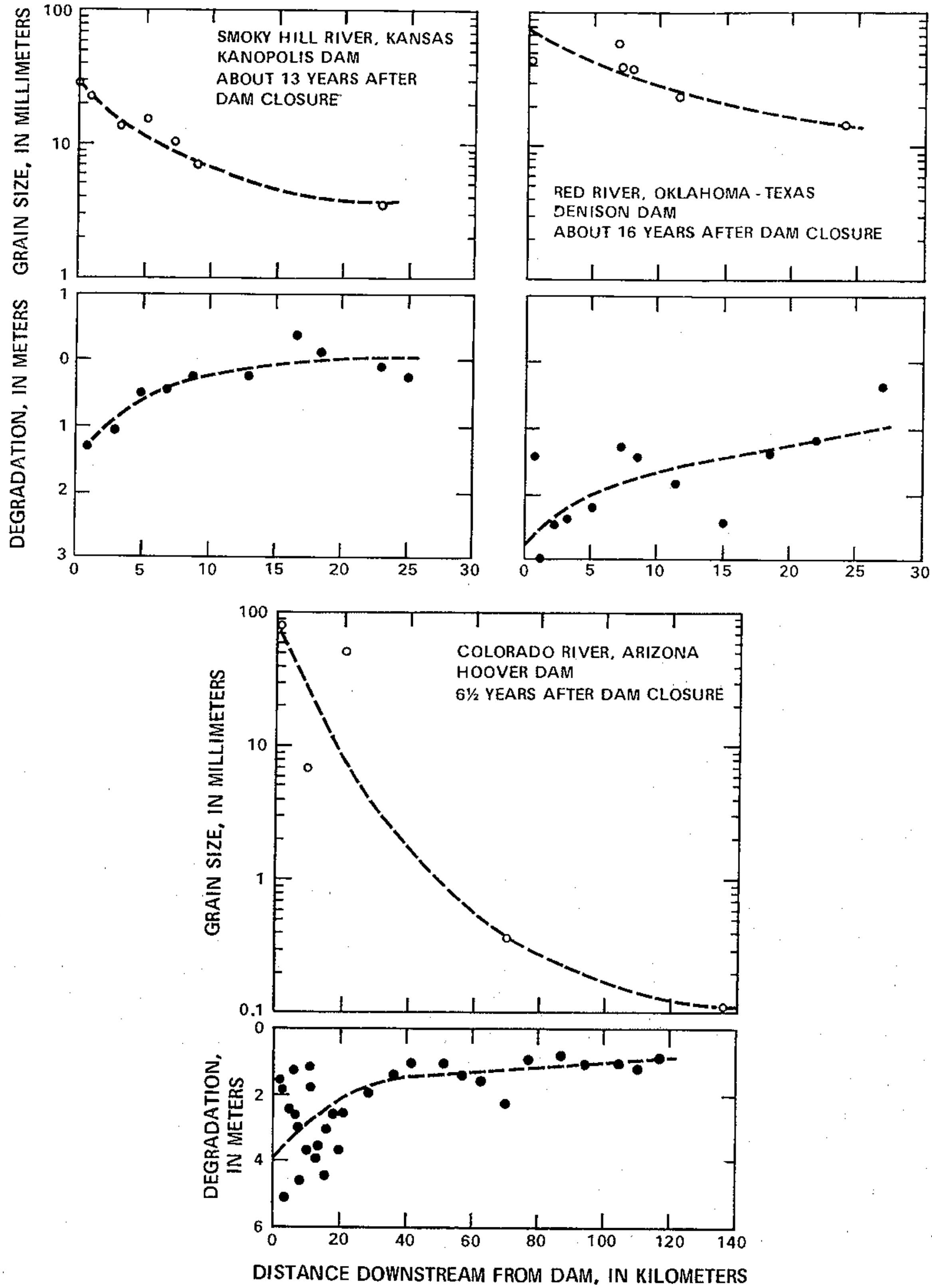


FIGURE 14.—Variation in bed-material diameter and bed degradation with distance downstream, at a given time after dam closure. Smoky Hill and Red River data are median diameter from pebble counts on gravel bars; Colorado River size data are d_{50} for entire sample of sieved bed material. Degradation data are from table 13.

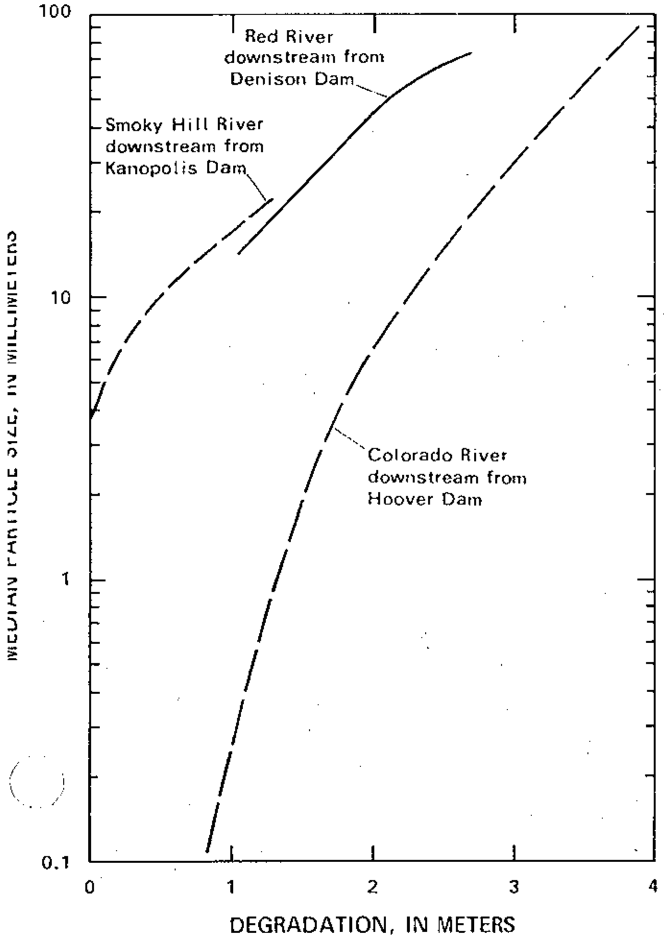


FIGURE 15.—Increase in bed-material size with bed degradation downstream from three dams (as estimated from the smoothed curves in figure 14).

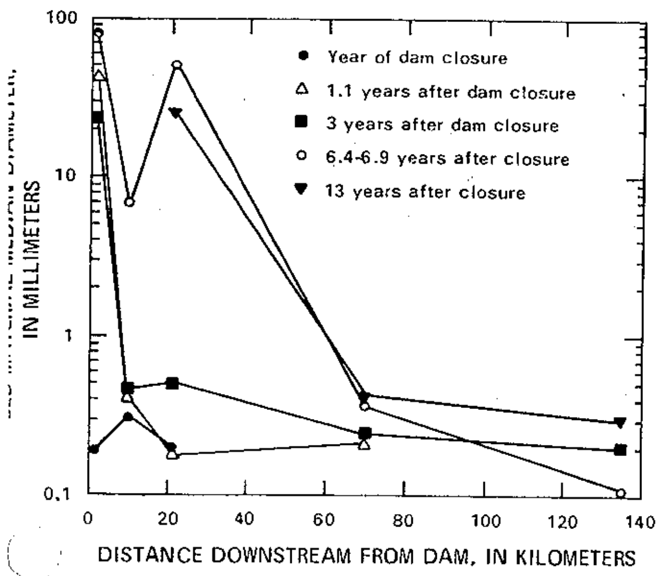


FIGURE 16.—Variation in median bed-material diameter with distance along the Colorado River downstream from Hoover Dam, at successive times after dam closure.

The first category is a statistically constant width, in which the width at successive times is within about ±4 percent (an arbitrary figure) of the width at the time of dam closure. In table 13, 231 cross sections downstream from 17 dams have meaningful width data. The width has remained virtually constant at 51 of these sections (about 22 percent of the total). (Such percentages are affected by the number of measuring sections downstream from the various dams and do not necessarily reflect relative frequency of the five categories of width change.)

Channel width in canyons, such as occur along some reaches downstream from Colorado River dams, obviously is constrained. Such sections were excluded from the total of 231 considered here. However, Howard and Dolan (1981) report that fine-grained terrace materials in depositional reaches on the Colorado River downstream from Glen Canyon Dam are being reworked by flow releases, resulting in slight channel widening.

A second category of channels widened, where widening arbitrarily is defined here as the most recently measured width being at least 5 percent greater than the width at the time of dam closure. About 46 percent (105 cross sections) are in this category. Although sometimes the channel has become about twice as wide during the post-dam period, most increases as of the latest resurvey were less than about 50 percent. Pronounced widening occurred at some cross sections downstream from Fort Peck, Gavins Point, Medicine Creek, Town Bluff, and Fort Randall Dams, but widths at other sites downstream from these dams did not change significantly. Also, changes in width were not consistent with distance downstream. Minor increases in width (less than about 15 percent) happened at a number of cross sections downstream from Milburn, Milford, Kanopolis, Red Rock, and Buford Dams. However, the magnitude varied considerably with distance along the river.

Category three consists of channels that have become narrower. Using the arbitrary 5 percent criterion, 59 cross sections (about 26 percent) are in this group. About one-half of these are located downstream from Jemez Canyon, John Martin, Fort Supply, and Canton Dams (figs. 17–20). These channels are now only about 17 to 50 percent of their pre-dam widths.

The fourth category includes channels that widened initially after dam closure, but later reversed this trend, and were most recently narrower than at the time of dam closure. Twelve cross sections (about 5 percent) are in this group. The North Canadian River downstream from Canton Dam, Oklahoma, has several such sections.

The fifth category, including only 4 of the 231 cross

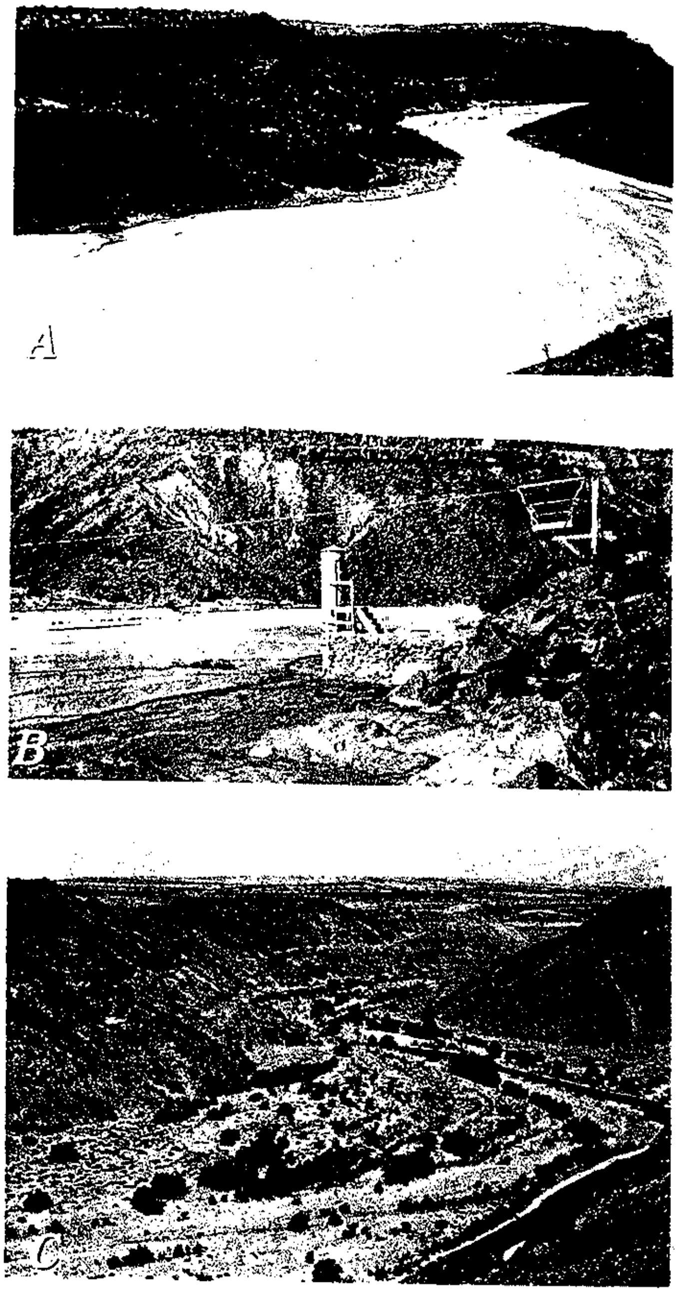


FIGURE 17.—Jemez River downstream from Jemez Dam, New Mexico. *A*, April 1936; *B*, spring 1951; *C*, June 1980. Dam was closed in 1953.

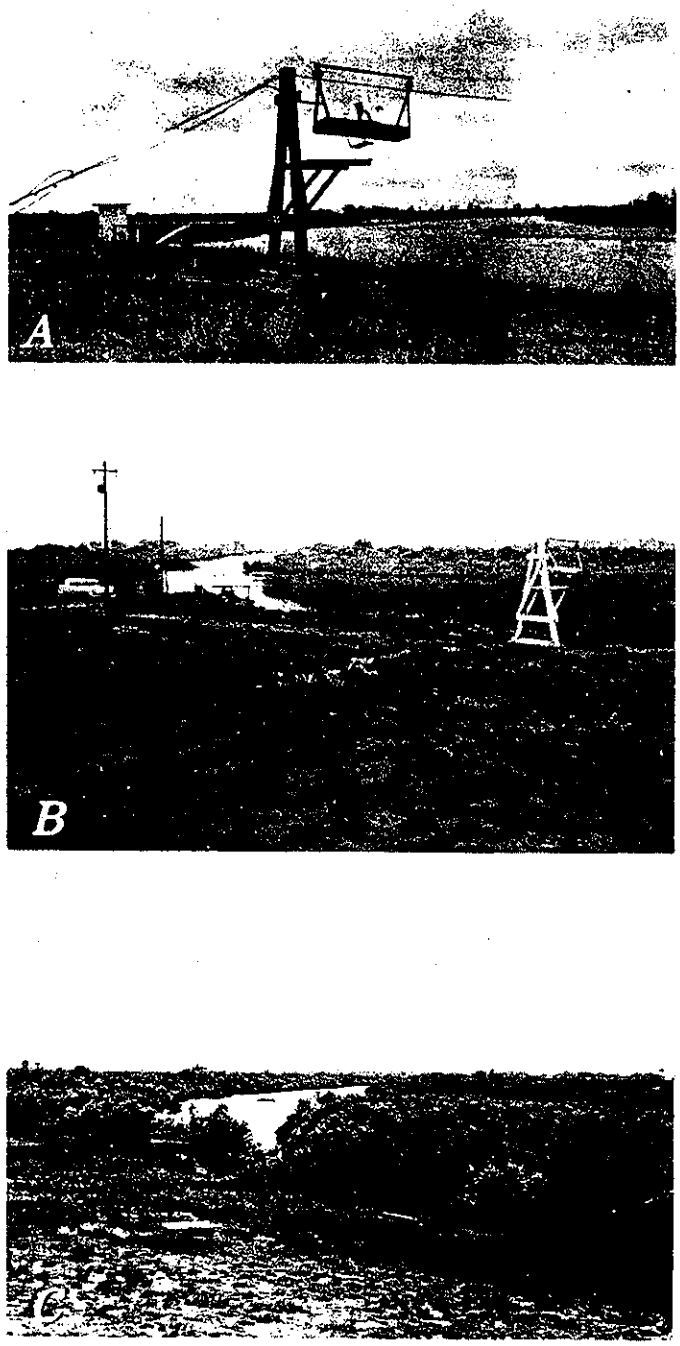


FIGURE 18.—Old streamflow-gaging site on Arkansas River 3 kilometers downstream from John Martin Dam, Colorado. *A*, March 1946; *B*, September 1959; *C*, July 1980. Dam was closed in 1943.

sections, shows an initial channel narrowing followed by widening. The channel as of the latest resurvey was wider than at dam closure.

Changes in width seem to have occurred at least from the time of dam closure; such changes tend to accompany changes in bed elevation. However, as with bed degradation, there can be a considerable lag time before effects become noticeable at some of the downstream sections. Examples occur along the Red River downstream from Denison Dam.

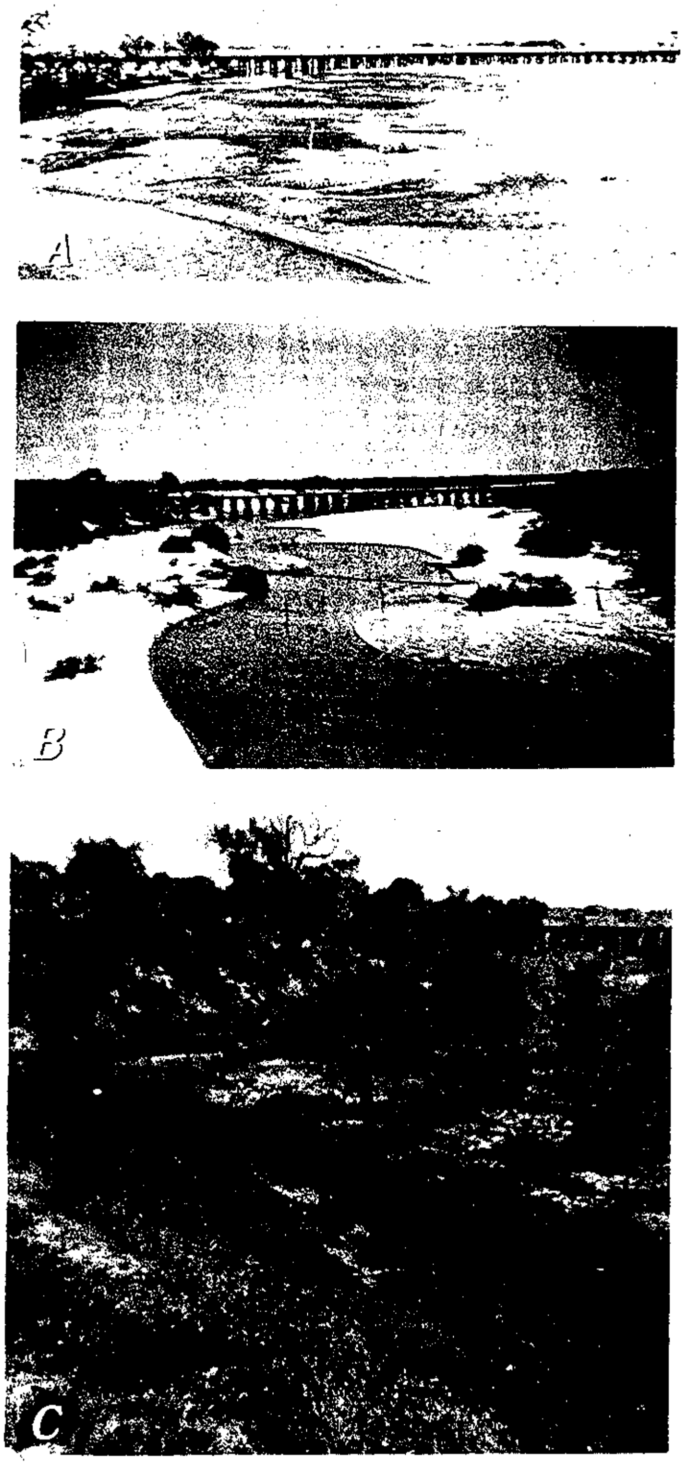


FIGURE 19.—Wolf Creek about 2.6 kilometers downstream from Fort Supply Dam, Oklahoma. *A*, April 1940; *B*, September 1958; *C*, August 1972. Dam was closed in 1942.

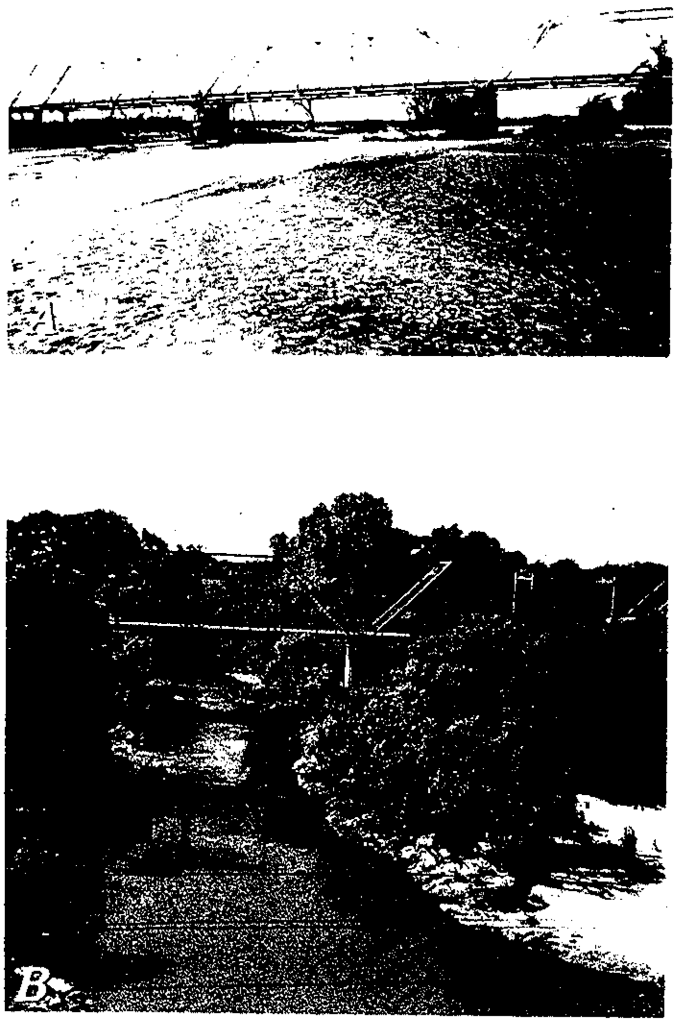


FIGURE 20.—North Canadian River about 0.8 kilometer downstream from Canton Dam, Oklahoma. *A*, about 1938; *B*, July 1980. Dam was closed in 1948. Both scenes are looking downstream at the highway bridge.

DISTANCE AFFECTED

For those rivers having significant increases or decreases in width, the changes extend at least to the farthest measured cross section. (In most instances this was well beyond the zone of bed degradation.) Thus, the extent of a reach over which width has changed cannot be determined due to lack of data; however, it can be many tens of kilometers.

No downstreamward trend in the magnitude of change in width is discernible for most reaches. This is true whether one considers the degraded zone alone or the entire reach for which data are available. For example, width changes do not seem to be greater near the dam. Rather, changes in most cases appear to vary randomly with distance or to remain about constant.

FACTORS AFFECTING CHANGES IN CHANNEL WIDTH

ALLUVIAL-BANK MATERIALS

Data on bank materials were not available for most of the cross sections and reaches described here. However, some analyses and onsite observations illustrate the variety of bank-material factors that affect channel widening.

At different locations along the Missouri River downstream from Garrison Dam, two distinctive types of channel bank occur. In one location (fig. 21) about 10 km downstream from the dam, the entire bank is composed of almost uniform sand (median diameter 0.17 mm (millimeter), standard deviation 0.027 mm). Erosion of these sugar sands, as they are called, appears to be a function of the shear of the flow against the surface of the bank. The rate of erosion is likely to be proportionate to the discharge and time the bank is subjected to the flow. Moderate fluctuations in flow, without major high flows, result in erosion of the sand deposit at the base of the bank, forming a narrow beach. With minor changes in water stage, this beach provides some protection against further erosion of the bank. The river bank in figure 21 eroded at a rate of about 3.6 m/yr between 1946 and 1957. (This approximate rate is mentioned only in a general sense and is not meant to show any effect of Garrison Dam, which was closed in 1953.)

FIGURE 21.—Sandy bank of Missouri River about 10 kilometers downstream from Garrison Dam, North Dakota.

FIGURE 22.—Stratified sand and silt bank, Missouri River downstream from Garrison Dam, North Dakota.

In contrast to the uniform sands in the bank in figure 21, the banks at other cross sections consist of layers of sand interbedded with finer-grained strata (fig. 22). The sand, about 1 m thick, is overlain by stratified silts (median diameter 0.009 mm, 99 percent finer than 0.074 mm) about 5 m thick. Low water on the outside of the bend impinges directly upon the sand, which is eroded readily by the continuing flow, even at low stages. The bank collapses by undercutting, with large blocks dropping vertically into the flow. Such silt-clay blocks retard bank erosion for a time, but eventually disintegrate and then are transported by the continuing flow. The bank in figure 22 eroded at a rate of 73.2 m/yr during 1946–57. Similar banks composed entirely of sand erode even more rapidly. This is a very rapid rate of erosion, but even at other cross sections downstream from Garrison and other Missouri River dams, the erosion rates generally exceed 20 or 30 m/yr (table 13; Rahn, 1977).

All manner of permutations and combinations of bank materials and stratigraphy occurs on the Plains rivers, which dominate the sample of rivers studied here. On the Missouri River in the 100 km reach downstream from Garrison Dam, the percentage of silt (particles less than 0.074 mm) in the banks ranges from 3 to 100 percent. The bank commonly has thin strata containing large percentages of silt and some clay; however, on the average, silt and smaller sizes constitute no more than 33 percent. In this reach, the average of samples of bed material contained less than 2 to 10 percent silt size or finer. In contrast, a representative sample of bank material from 1 m above low water on the Smoky Hill River downstream from Kanopolis Dam had 75 percent of the particles finer than 0.074 mm.

Samples from the bed and banks of the Salt Fork of the Arkansas River illustrate both the stratigraphy of the flood plain or channel banks and the contrasting character of bed and bank materials. As the data in table 8 show, 54 percent of the bed material is larger than 0.5 mm (coarse sand). With increasing distance above the bed, the proportion of silt-clay in the channel perimeter increases; that is, the percentage of coarse and medium sand decreases. Only in the upper 0.5 m of the flood plain is the percentage of silt and clay appreciable, a fact clearly evident in the stratigraphy of the bank as seen at the site. For the 2 m-high bank as a whole, 75 percent of the vertical section is composed of sand coarser than 0.125 mm. The remaining 25 percent is very fine sand or smaller. Considering the entire bank as a whole, the percentage of silt and clay (weighted according to the proportion of the vertical section described by the sample) is about 12 percent.

For the few rivers where bank materials were examined in detail, no general and simple correlation ᷊ld be made between erosion rates and the percen- ᷊e of sands or silt and clay in the banks, except for isolated examples along the Missouri River and for straight reaches several kilometers downstream from Kanopolis Dam on the Smoky Hill River, where erosion of the silty banks appeared minimal. (Bank erosion on the Smoky Hill River, however, was significant at bends or where the thalweg of the channel meandered.) Although cohesive banks retard erosion, tests of stability criteria based on a weighted silt-clay content in bed and banks, using the method proposed by Schumm (1960, fig. 10, p. 23), indicate that measured channel sections known to be either aggrading, widening, stable, or unstable are not distinguishable on the basis of the width-depth ratio and weighted mean percentage of silt and clay. The difficulty appears to be that weighting of the particle size of the sediments by the channel width significantly distorts a controlling relationship between actual differences in bed and bank sediments. Generally, a cohesive bank will limit both channel width and the tendency to bank erosion or lateral migration; however, many other factors occurring simultaneously appear to dominate in the control of bank erosion.

BEDROCK-BANK CONTROLS AND DOWNSTREAM EFFECTS

Several cross sections on the Missouri River downstream from Garrison Dam indicate that channel shifting and bank erosion may increase downstream from cross sections at which bank erosion is controlled or retarded. Bedrock on one or both sides of the valley constricts the valley and channel in places. Lateral erosion at such constrictions usually is minimal, but in the expanding valley width downstream from such controls, erosion of one or both banks is relatively much greater. Further work is needed to determine whether the lateral erosion downstream from the constricted sections is greater than it would be without the constrictions.

WATER FLOW

In a detailed analysis, Chien (1961, p. 751) showed that the shifting of a river's course varies directly with the rate of rise and fall of flood flows, bed shear stress, relative width of water surface at peak floods and at bankfull stage, width-depth ratio at bankfull stage, and varies inversely with particle size. Chien also noted (1961, p. 744) that channel shifting is related to the

TABLE 8.—*Particle-size distributions of bed and bank material, Salt Fork, Arkansas River, downstream from Great Salt Plains Dam, Oklahoma*

[Total height of flood plain above water surface is 1.83 meters]

River bank and bed features (Distance below flood plain, in meters)	Percent finer than indicated size (millimeters)											
	0.002	0.004	0.008	0.016	0.031	0.062	0.125	0.25	0.50	1.0	2.0	4.0
Top surface of clay band in silt	42	50	59	69	79	87	93	99	100	--	--	--
0.30-0.43	9	9	11	16	24	44	68	90	99	100	--	--
0.49-0.67	--	--	--	--	--	4	36	96	100	--	--	--
1.47-1.22	--	--	--	--	--	1	6	77	100	--	--	--
1.49-1.77	--	--	--	--	--	0	4	25	84	98	99	100
Channel bed[1/]	--	--	--	--	--	--	0	10	46	88	99	100
r at water level	--	--	--	--	--	--	0	7	81	98	100	--

[1/] Sand sample beneath shallow water in braided channel.

downstream spacing of control points. These relationships probably are not precise correlatives of bank erosion, but channel shifting is related closely to bank erosion. It has not been possible to obtain sufficiently complete data with which to verify equations provided by Chien. However, many observed phenomena in the alluvial channels described here qualitatively support his conclusions.

Observations on the Missouri River downstream from Fort Peck Dam in Montana indicate that bank erosion increases markedly with discharges equal to or greater than about 500 m^3/s (cubic meters per second). This is equivalent to flows that occurred equal to or less than about 12 percent of the time prior to closure of the dam (U.S. Army Corps of Engineers, 1952, p. 37). The increase in erosion accompanying increases in flow, particularly at or near the bankfull stage, also is documented elsewhere (Chien, 1961, p. 741; Leopold and others, 1964, p. 88).

Net erosion in terms of enlargements in cross-sectional area (width and depth increases) can occur even with decreases in certain flow statistics. A decrease in mean daily discharges and in peak discharges during the years immediately after dam closure on the Red River downstream from Denison Dam nevertheless was accompanied by about a 25 percent increase in the average bankfull cross-sectional area of the downstream channel. Reductions in those same flows in the North Platte River downstream from Guernsey Dam in Wyoming were accompanied by a doubling of the average cross-sectional area throughout a 5 km-long reach downstream from the dam. Thus in these cases the mean daily flow and the annual peaks do not reflect adequately the erosive flows.

Along other channels, decreases in flows have been accompanied by decreases in cross-sectional area and in width. Flow reductions due largely to various dams probably have caused the observed decrease in width of the Platte River in much of Nebraska to as little as 10 to 20 percent of its 1865 width (Williams, 1978). Where the decrease in flow has been significant, as in the lower Rio Grande, J. F. Friedkin (International Boundary Commission, written commun., 1959) has shown that the channel almost may disappear as vegetation, windblown sand, and sediment deposited by low flows clog the channel. Comparable changes on the Canadian River downstream from Sanford Dam, Texas, are described later in this report.

Sandstone Creek near Cheyenne, Oklahoma, provides one of the better-documented examples of cross-section decreases and channel narrowing due to dams, in this instance, a combination of dams (Bergman and Sullivan, 1963). Sandstone Creek has a drainage area of 277 km^2. Land-treatment measures were begun during the 1940's; by 1952, 24 floodwater-retarding structures and 17 gully plugs had been built in the watershed. Further construction continued during the 1950's and 1960's. During the 1950's the hydrologic regimen of the stream was altered significantly (table 9). From 1951 to 1959, mean daily flow tended to increase as the number of days of zero flow decreased from almost two-thirds of the year to zero. In addition, a significant increase in the number of peak flows occurred during 1953–56, suggesting a brief period of increased rainfall. In 1954, the channel cross section still retained the box-like form characteristic of an arroyo (fig. 23). By 1961, however, a much narrower channel (about one-third the former width), stabilized by vegetation (grass, shrubs, and some trees) had formed within the original cross section. A new flood plain had been created, virtually as an inset fill. The effect of the new channel cross section and vegetation is illustrated by the decreases in cross-sectional area and flow at successive stages (fig. 23).

The metamorphosis of Sandstone Creek seems to follow a pattern typical of a number of other dammed streams (see Frickel, 1972, p. 29; Gregory and Park, 1974; Petts, 1977). Once the larger flows are eliminated, the flows occupy a somewhat narrower channel. Vegetation commonly tends to become established on the lesser-used part of the old streambed. This plant growth probably traps sediment during any inunda-

TABLE 9.—*Flow data for Sandstone Creek near Cheyenne, Oklahoma, 1951–59*

[m^3/s = cubic meters per second]

Water year	Mean daily flow (m^3/s)	Days of zero flow	Number of peaks greater than 14 m^3/s
1952	0.028	222	0
1953	.020	184	2
1954	.36	114	5
1955	.14	39	7
1956	.075	87	3
1957	.25	62	2?
1958	.11	7	1
1959	.45	0	1

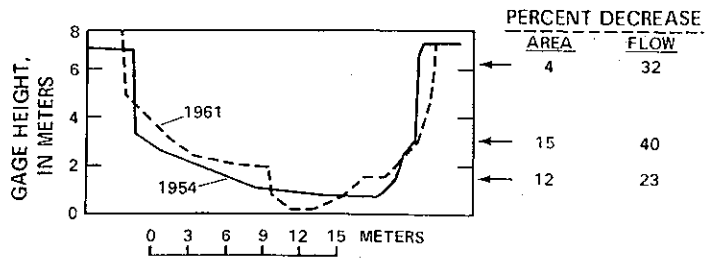


FIGURE 23.—Changes in channel cross section of Sandstone Creek, Oklahoma, at the streamflow-gaging station, 1954–61, caused by many upstream flood-detention dams (modified from Bergman and Sullivan, 1963).

tions. The vegetated zone thereby aggrades (fig. 23) and becomes a new flood plain. The old flood plain becomes inactive (a terrace), rarely or never flooded. In this manner, the stream channelizes itself, commonly in more stable banks from the binding properties of the vegetation.

Although it is intuitively obvious that the magnitude and frequency of flows must affect bank erosion, a precise characterization of such flows for purposes of a general equation has not yet been obtained. Some preliminary efforts to develop a general equation are described later in this discussion.

WIDTH-DEPTH RATIO

Analysis of a number of cross sections indicated that wide, shallow channels tend to increase in width at a somewhat greater rate than relatively narrow, deep sections. A large initial width-to-depth ratio indicates that bank material in such sections may be more erodible, and that these sections are likely to predominate in braided reaches. Because such a process cannot continue forever, channels may narrow by taking a new course or by developing several distributary sections.

TIME TRENDS OF CHANNEL WIDENING AT A SITE

A dimensionless relative change in width can be defined as W_t/W_1, where W_1 is the bankfull channel width at the time of dam closure at the cross section of interest and W_t is the bankfull channel width t years later at the same section. A plot of this ratio with time was made for each cross section downstream from the 17 dams for which data (table 13) were available. On these plots, nearly 50 percent of the 105 cross sections that became wider have either too many aberrations, no noticeable pattern, or insufficient data to warrant an attempt to fit a line to the points (see fig. 24*A* for some typical examples of such cross sections).

The trend of relative increase in width with time for the remaining 54 cross sections can be described by a simple hyperbolic equation of the same type used for bed degradation. As applied to relative channel-width changes, this equation has the straight-line form

$$(W_1/W_t) = c_3 + c_4\,(1/t) \qquad (3)$$

where

c_3 is the intercept; and

c_4 is the slope of the fitted straight line on a plot of W_1/W_t versus $1/t$.

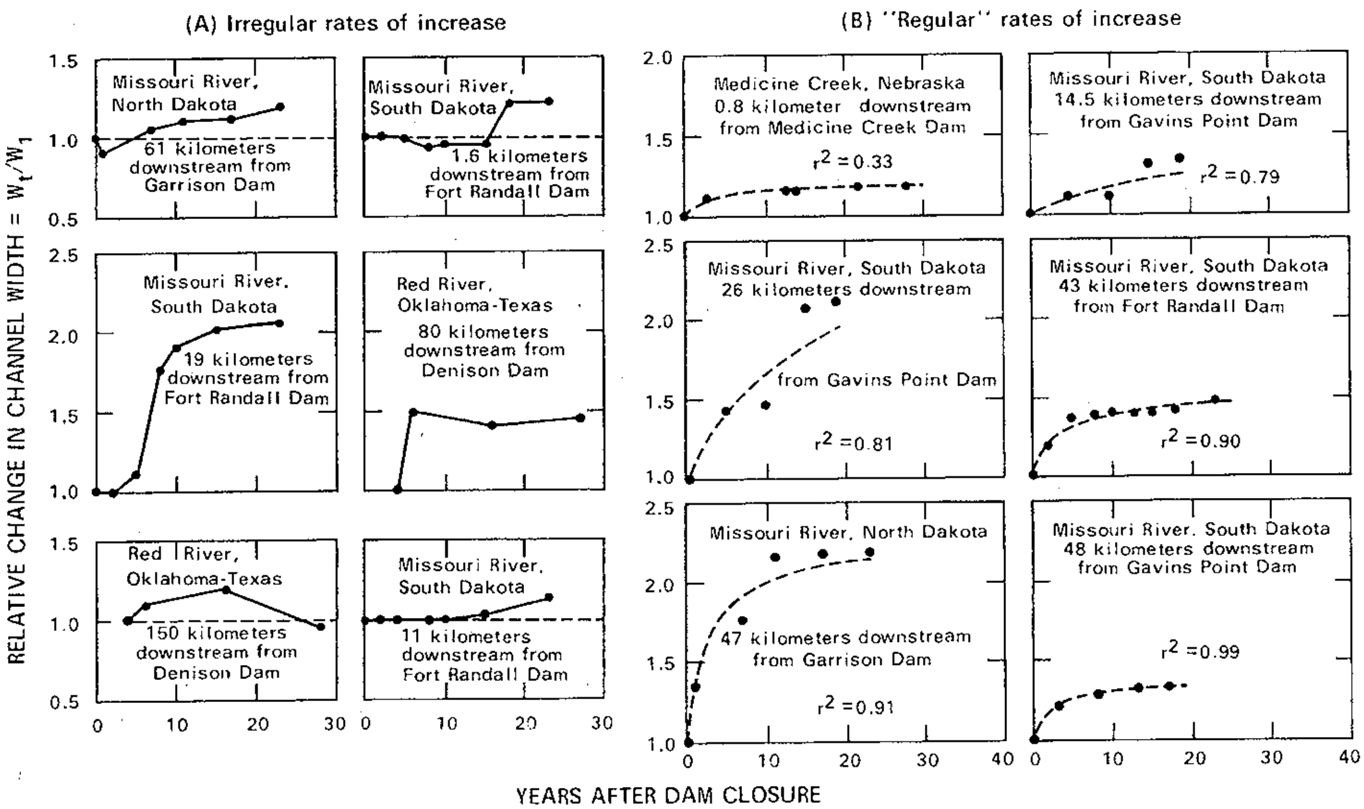


FIGURE 24.—Examples of relative increase of channel width with time: *A*, irregular rates; *B*, regular rates with fitted regression curves (dashed lines). Data from table 13.

The coefficients are positive where width has increased, as in the present discussion, and negative where width has decreased. The reciprocal of c_4 is the initial rate of change, in relative-change (W_t/W_1) units per year. The reciprocal of c_3 ordinarily would be the asymptote or eventual new value of W_t/W_1. However, with the present application, the value of W_t/W_1 at $t = 0$ is 1.0 rather than 0. To adjust the data to an origin of 0, 1.0 first needs to be subtracted from each W_t/W_1 before performing the regression. Consequently, the asymptote or final predicted W_t/W_1 is $(1/c_3) + 1.0$. Similarly, the value of W_t/W_1 at any time, t, is

$$(W_t/W_1) = \frac{1}{(c_3 + \frac{c_4}{t})} + 1.0$$

Values associated with these channel-width regression curves, such as coefficients c_3 and c_4, estimated final equilibrium values of W_t/W_1, time needed to complete the estimated total change (here given as 95 percent of the estimated change), time needed to attain 50 percent of the estimated total change, and the square of the correlation coefficient (r^2) are given in table 10.

As discussed in connection with bed degradation, several features that do not directly affect the goodness of fit influence the value of r^2. For example, the value of r^2 is somewhat sensitive to the location of the origin; that is, to the specification of the response time where such a lag period occurs. Hence, measurements in the first few years after (and before) dam closure are very important in defining the curve.

The asymptote of the curve, or extrapolated eventual value of W_t/W_1, needs to be treated with caution. Where the basic data fit the curve, the extrapolated final value is valid. However, in several instances, the data show enough departures from a smooth curve that illogical values of the asymptote obtain. These few cases are noted in table 10.

Based on the coefficients and the observed fit of the curve to the data points, the equations for 10 of the 54 sections are questionable. The remaining 44 cross sections, listed by dam and number of sections, were downstream from Fort Peck (3), Garrison (11), Fort Randall (3), Gavins Point (20), Medicine Creek (1), Kanopolis (3), and Denison Dams (3).

The regression features for these widening cross sections show a wide range in initial rate of increase of channel width, predicted (or observed) final relative increase, and time required for the new width to develop. Some representative trends are shown in figure 24*B*. The initial rate of increase (reciprocal of the coefficient c_4) for the 44 cross sections ranges from 0.0032 to 4.0 relative-change units per year.

The predicted final values of W_t/W_1 (called $(W_t/W_1)_{max}$ in table 10) as extrapolated from the regression curves (again keeping in mind the risks of extrapolation) range from very slight (1.05) to about 2.8. (The latter number would indicate that the final width would be 2.8 times the width at the time of dam closure.) The frequency distribution of these 44 values (fig. 25*A*) shows most of them closer to the smaller end of the range, with the mode at about 1.12.

The estimated time needed for completion of 95 percent of the eventual change in width (see bed-degradation section for computation details) ranges from about 2 to nearly 1,900 years (table 10). The modal value of the 44 estimates is about 35 years (fig. 25*B*). Assuming no radical changes in the flow regime, most sections are predicted to need from about 1 decade to 600 years to complete their widening. Within this range, the longer durations (as much as hundreds of years) of course are mathematical results. We have no evidence that channel widening continues for such durations, and there is considerable evidence of discontinuity and change.

As with bed degradation, much of the estimated widening occurs relatively quickly. One-half the total estimated overall increase in channel width can occur in as little as 1 or 2 months (table 10). For the 44 cross sections, the maximum estimate of the time needed for a section to complete 50 percent of its widening was 100 years. The distribution within this range (fig. 25*C*) has its mode at about 1½ to 2 years. At most cross sections, 50 percent of the total eventual increase in width probably occurs within 2 or 3 decades after dam closure, according to these data.

The above estimates of magnitudes of eventual widening and of adjustment time also apply to many cross sections for which the data were not fitted by a regression curve, judging from plots of W_t/W_1 versus time (fig. 24).

Curves of relative increase in width with time (fig. 24*B*) can all be combined onto one general, dimensionless curve (fig. 26) similar to the one for bed degradation. The ordinate in this case is the ratio of observed relative change in width (W_t/W_1) at a given time to the extrapolated maximum expectable relative change, the latter being approximated by 0.95 $(W_t/W_1)_{max}$. The abscissa on the plot is the proportion of total adjustment time that has elapsed, $t/0.95\ t_{max}$. Here the denominator ($0.95\ t_{max}$) is 19 c_4/c_3 (as explained earlier). The dimensionless equation, referred to as the derived equation in figure 26, is identical to equation 2, for degradation, with the new dependent variable inserted.

To the extent that the data fit the standardized curve, the same tendencies that described bed degradation with time also apply to the rate of channel widening. One-half the total change occurs during the first

TABLE 10.—*Values associated with hyperbolic curves fitted to changes in channel width with time, at a cross section*[1]

[km, kilometer; yr, year; r^2, square of correlation coefficient; c_3, coefficient (intercept) of fitted straight line on plot of W_t/W_1 versus $1/t$; c_4, coefficient (slope) of fitted straight line on plot of W_t/W_1 versus $1/t$; W_t, channel width at t years after dam closure; W_1, channel width at time of dam closure]

Distance of cross section downstream from dam (km)	Response time (yr)	r^2 [2]	c_3 [3]	c_4	$(W_t/W_1)_{max}$ [4] [5]	Time to reach $0.95(W_t/W_1)_{max}$ [5] (yr)	Time to reach $0.5(W_t/W_1)_{max}$ [5] (yr)
			Jemez River, New Mexico, Jemez Canyon Dam				
1.0	0	0.37	-1.041	-2.66	0.039	49	2.6
1.3	0	.79	-.943	-2.32	--	--	--
1.6	0	.77	-.565	-8.51	--	--	--
1.8	0	.83	-.941	-5.87	--	--	--
2.4	0	.52	.010	-19.2	--	--	--
3.1	0	.64	-1.279	-1.77	.22	26	1.4
			Arkansas River, Colorado, John Martin Dam				
15.5	0?	.99	-.926	-10.74	--	--	--
22	0?	.99	-.902	-11.35	--	--	--
33	0?	.79	-1.15	-13.83	.13	230	12
36	0?	.91	-1.62	-12.78	.38	150	8
			Missouri River, Montana, Fort Peck Dam				
9.2	0	.79	4.89	26.36	1.20	100	5
16.5	0	.62	1.51	31.39	1.66	395	21
75	0	.90	3.12	308.8	1.32	1,880	100
			Missouri River, North Dakota, Garrison Dam				
12.0	0	0.65	11.48	5.62	1.09	9	0.5
15.0	0	.81	2.16	10.51	1.46	90	5
17.5	0	.48	.901	.306	2.11	6	.3
21	0	.61	19.4	31.64	1.05	30	1.6
32	0	.94	9.01	3.52	1.11	7	.4
38	0	.36	4.24	2.16	1.24	10	.5
44	0	.98	.764	10.33	(2.31)	(260)	(14)
47	0	.91	.780	2.09	2.28	50	3
54	0	.57	1.05	.350	1.95	6	.3
58	0	.83	5.67	8.73	1.18	29	1.5
78	0	.68	4.95	6.36	1.20	24	1.3
87	0	.56	2.46	.249	1.41	2	.1
			Missouri River, South Dakota, Fort Randall Dam				
7.7	0	.84	5.62	42.1	1.18	140	7
43	0	.90	1.88	7.01	1.53	70	4
58	0	.59	16.2	42.2	1.06	50	3
			Missouri River, South Dakota, Gavins Point Dam				
4.3	0	.58	4.19	3.04	1.24	14	.7
5.3	0	1.00	11.5	196.1	1.09	320	17
6.8	0	.27	5.03	3.03	1.20	11	.6
11.0	0	.95	4.37	9.71	1.23	42	2
12.5	0	.95	2.18	17.00	1.46	150	8
14.5	0	0.79	1.79	41.0	1.56	440	23
16.5	5	.94	2.24	4.50	1.45	38	2
22	0	.97	8.77	210.5	1.11	460	24
26	0	.81	.552	9.71	2.81	330	18
27	0	.84	3.17	7.59	1.32	45	2
28	0	1.00	2.03	13.6	1.49	130	7
30	0	1.00	3.81	1.80	1.26	9	.5
32	0	.95	3.54	14.0	1.28	75	4
34	0	.90	1.88	63.6	1.53	640	34
48	0?	.99	2.69	6.28	1.37	44	2
52	0?	.98	.990	23.0	(2.01)	(440)	(23)
61	5?	1.00	9.80	22.9	1.10	44	2
64	4.5?	.95	2.90	23.5	1.35	150	8
69	3?	.39	15.5	21.6	1.06	26	1.4
72	4?	.97	2.37	47.6	(1.42)	(380)	(20)
82	5?	1.00	4.68	144.3	1.21	590	31
85	4?	.95	1.75	5.91	1.57	65	3
93	4?	.86	.290	4.95	(4.45)	(320)	(17)
			Medicine Creek, Nebraska, Medicine Creek Dam				
.8	0	.33	4.78	13.5	1.21	54	3
13.0	0	.35	.937	52.4	(2.07)	(1,060)	(55)

TABLE 10.—*Values associated with hyperbolic curves fitted to changes in channel width with time, at a cross section*[1]—Continued

Distance of cross section downstream from dam (km)	Response time (yr)	r^2 [2]	c_3 [3]	c_4	$\left(\frac{W_t}{W_1}\right)_{max}$ [4] [5]	Time to reach $0.95\,(W_t/W_1)_{max}$ [5] (yr)	Time to reach $0.5\,(W_t/W_1)_{max}$ [5] (yr)
			Smoky Hill River, Kansas, Kanopolis Dam				
6.8	0	0.64	1.89	-338.9	--	--	--
8.7	0	.80	.866	45.1	(2.15)	(990)	(50)
13.0	0	1.00	6.75	4.42	1.15	12	.7
25	0	1.00	6.03	79.9	1.17	250	13
73	0	.75	5.49	7.26	1.18	25	1.3
			Wolf Creek, Oklahoma, Fort Supply Dam				
2.9	0?	.98	-1.22	-1.47	.18	23	1.2
3.9	0?	.34	-1.24	-1.28	.19	20	1.0
4.7	0?	.90	-.912	-8.35	(0)	--	--
6.6	0?	.99	-.901	-5.47	(0)	--	--
			North Canadian River, Oklahoma, Canton Dam				
1.8	4	.81	-1.13	-4.82	.12	80	4
5.6	2.5	.71	-1.93	-2.80	.48	28	1.5
14.5	1.0	.99	-1.01	-7.48	(.01)	(140)	(7)
114	2.8	.75	-3.00	-1.37	.67	9	.5
125	2.8	.72	-3.64	-2.80	.73	15	.8
134	0	.30	-5.99	-1.33	.83	4	.2
			Red River, Oklahoma-Texas, Denison Dam				
.6	0	.63	1.74	34.0	(1.57)	(370)	(20)
18.5	0	1.00	8.33	125.1	1.12	285	15
27	0	.83	2.28	11.1	1.44	90	5
34	0?	0.82	0.416	39.0	(3.40)	(1,780)	(95)
48	0?	.97	.725	3.42	(2.38)	(90)	(5)
90	0?	.60	4.52	40.5	1.22	170	9
132	0?	.93	1.52	63.5	(1.66)	(790)	(42)

[1] $(W_1/W_t) = c_3 + c_4\,(1/t)$.

[2] Listed r^2 is for W_t/W_1, not the reciprocal.

[3] All values of W_t/W_1 were adjusted to an origin of 0 by subtracting 1.0 prior to the regression.

[4] The predicted final values of W_t/W_1 (called $W_t/W_{1\,max}$ in table) are computed as $(1/c_3) + 1.0$.

[5] Values in parentheses seem unreasonable. Leaders mean that a value cannot or was not listed due to curve-fitting difficulties.

5 percent of the adjustment period. Three-fourths of the total increase takes place within the first 13 percent of the adjustment period. Channel changes are most pronounced in the early years after the onset of widening.

TIME TRENDS OF CHANNEL NARROWING AT A SITE

Fifty-nine cross sections became narrower, and 39 of these have a sufficiently irregular trend of relative width with time that no smooth curve can be fitted to the points; some representative examples of such cases are shown in figure 27*A*. At some cross sections, the new width already was established by the time of the first resurvey and changed little thereafter. Other sites show fluctuations in width with time.

At the remaining 20 of the 59 narrowed cross sections, the data of table 13 again indicate the hyperbolic curve of the type used earlier in this report (eq. 3). The regression statistics (table 10) indicate that only 11 of these cross sections are suitable for estimating final channel widths and adjustment periods. The 11 cross sections are downstream from Jemez Canyon, John Martin, Fort Supply, and Canton Dams. Six typical regression curves are shown in figure 27*B*.

Initial rates of narrowing ranged from 0.05 to 0.78 relative-change units per year. The extrapolated final values of W_t/W_1 (table 10) ranged from 0.83 to 0.04 for the 11 curve-fitted cases that could be assessed reliably.

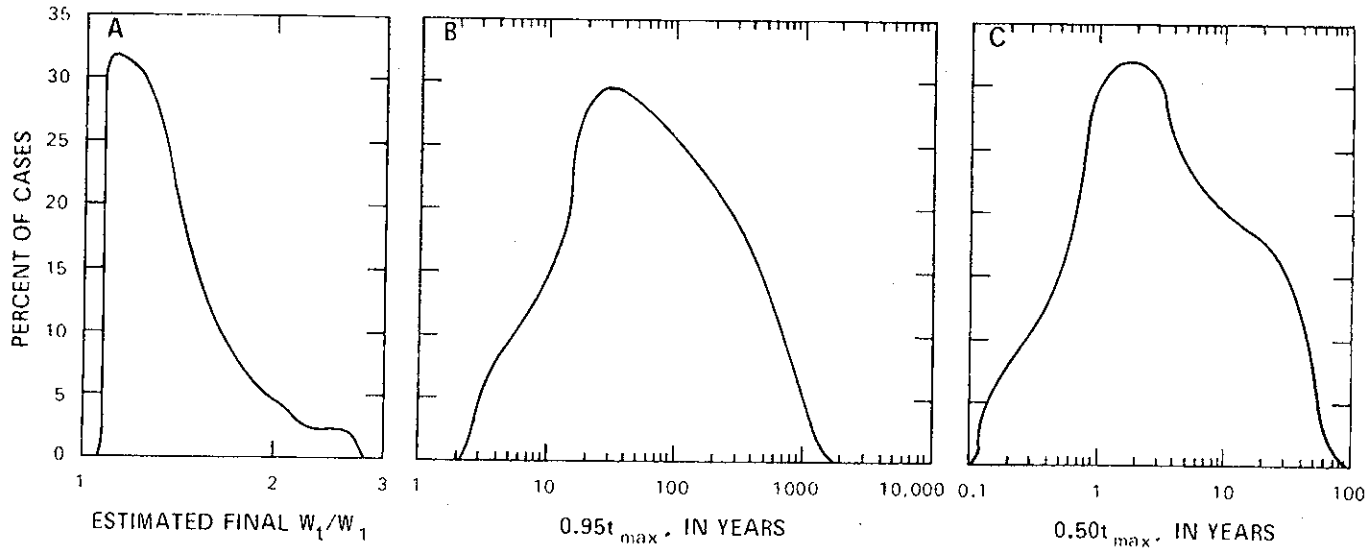


FIGURE 25.—Frequency distributions of estimated eventual increases in channel width, based on 44 measured cross sections on various rivers: *A*, final values of W_t/W_1; *B*, years needed to widen to 95 percent of final W_t/W_1; *C*, years needed to widen to 50 percent of final W_t/W_1.

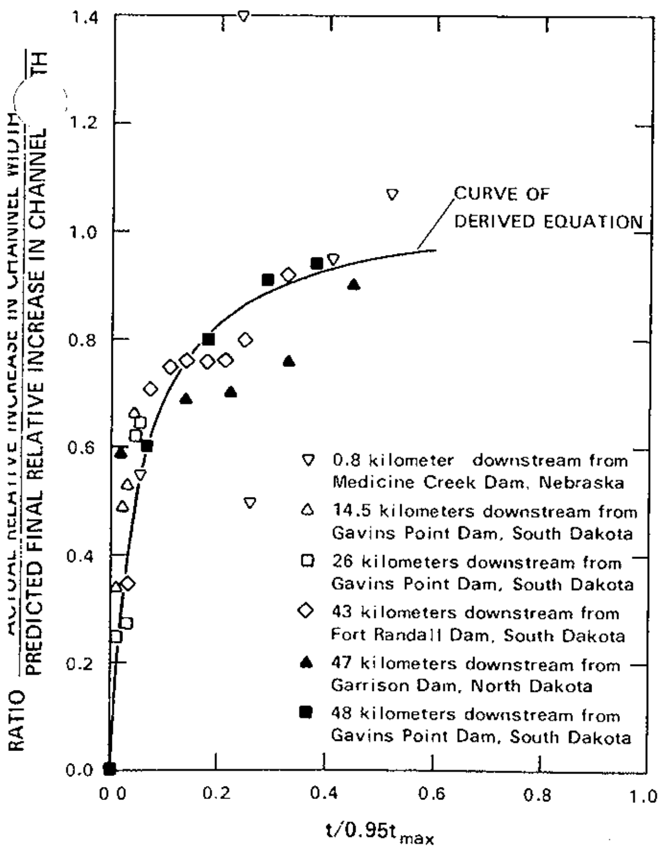


FIGURE 26.—Dimensionless plot of relative increase in channel width with time, for the 6 representative cross sections of figure 24*B*. Data from table 13.

At sections not describable by a hyperbolic curve downstream from these same four dams, the new width generally was only about 25 to 50 percent of the initial width, except for a few of the cross sections downstream from Canton Dam.) Theoretically, the relative decrease in width for a channel can range from almost 1.00 to 0, depending on flow regulation.

The estimated time needed for the channel to reach its new, narrow width varies from 4 to 230 years for the 11 cross sections (table 10). Most estimates from the fitted curves are about a few decades or less. One-half the total adjustment can occur virtually immediately or within as much as about a decade. Less than 1 or 2 years is typical for the available data.

The dimensionless standardized curve of the type applied above to bed degradation and channel widening is shown in figure 28. The derived equation is that of equation 2 with the appropriate dependent variable (proportional relative decrease in width).

PREDICTION OF POST-DAM CHANNEL-WIDTH CHANGES

Channel width depends primarily on water discharges and the boundary sediment. A multitude of regime- and hydraulic-geometry equations relate width to discharge. Unfortunately, most of those that are not site-specific require a resistance coefficient, a characteristic or dominant discharge, or both. Bed-material sizes change with time during the armoring process downstream from many dams (fig. 13), so even in the rare case where the size distribution had been measured adequately, it would be hard to build this changing particle-size variable into a resistance coefficient to predict eventual channel width. Similarly, identification of the most diagnostic or dominant discharge to use in an equation for

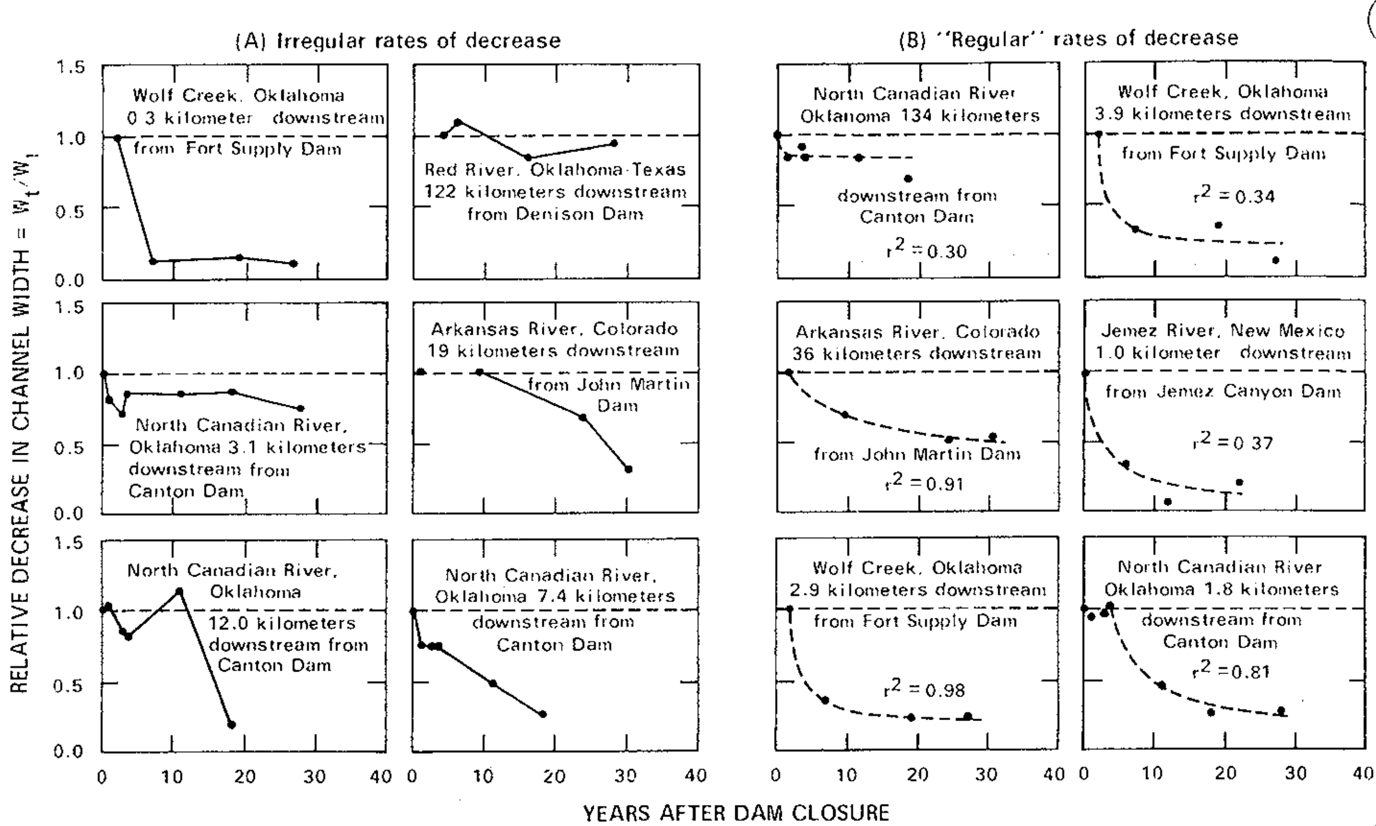


FIGURE 27.—Examples of relative decrease in channel width with time: *A*, irregular rates; *B*, regular rates with fitted regression curves (dashed lines). Data from table 13.

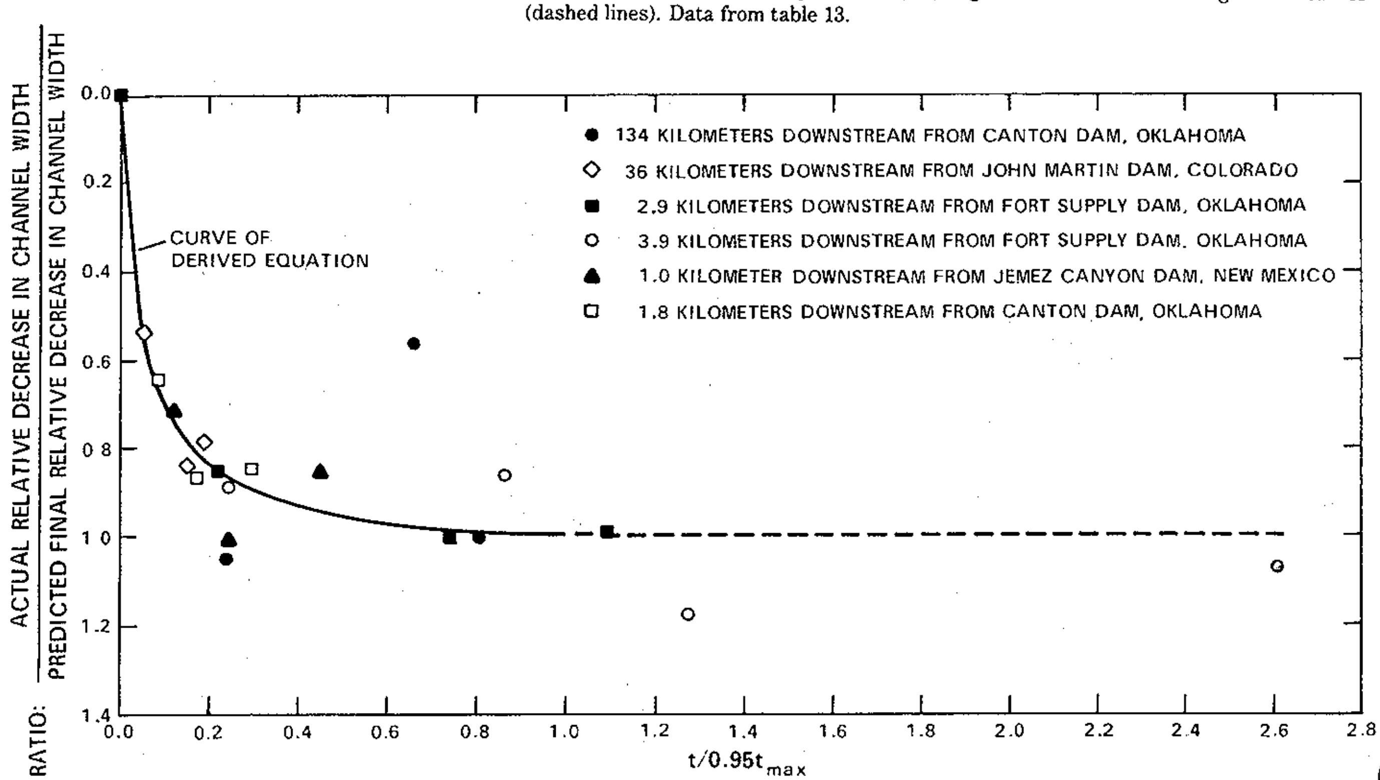


FIGURE 28.—Dimensionless plot of relative decrease in channel width with time, for the 6 cross sections of figure 27*B*. One point (for the section 134 kilometers downstream from Canton Dam) plots off the graph. Data from table 13.

channel form remains an unsolved problem. An empirical effort was made (no acceptable theory being available) to determine those measures of discharge best related to width and to changes in width. Due to lack of data on bank cohesiveness, the search involved only water discharge.

We used stepforward multiple regressions to test possible correlations between channel width and magnitudes, frequencies, and characteristics of discharge, namely: (1) Mean daily discharge; (2) average annual instantaneous peak flow; (3) single highest and lowest instantaneous annual peak flow; (4) highest average daily flow for consecutive periods of 1, 3, 7, 15, 30, 60, 90, 120, and 183 days for each year; (5) flow equaled or exceeded 1, 5, 10, 25, and 50 percent of the time; and (6) variability of flows within periods ranging from 1 to many years. Many different possible expressions for flow variability (item 6) involving the ratio of a high flow to a standardized flow were tested. Variations within a day, however, could not be considered, and such variations could be important on channels where flows are regulated by dams for hydroelectric power. Seasonal sequences were not explored. All of the above lischarges, including ratios thereof, were examined for b re- and post-dam periods, separately. The many h arge statistics, plus the log of each, amounted to 15 independent variables.

For each river, the average width for all cross secions as a group was taken as the representative chanel width for the particular year. These reaches in genral have little significant tributary inflow throughout heir lengths. Average width was calculated for the ear of dam closure (first surveys of cross sections), ielding W_1, and for the year of the latest resurvey, W_2. The relative change in width is then W_2/W_1. Nine oss sections had special local topographic features and ere not included in the calculation of the average ange in width for the entire reach downstream from dam. These nine sections are downstream from a total 6 dams and probably do not affect significantly the gression results described here.

Along some reaches, sparseness of cross sections is drawback of this sampling approach to generalizing e change in width of a reach. Locations of cross secns is another possible disadvantage, in regard to: (1) sition around or near meander bends versus straight aches, and (2) spacing with river distance wnstream. Usually, the sections are close together mediately downstream from the dam and become ther apart with distance downstream.

ly, the length of river reach within which the nge applies needs to be standardized for the entire oup of rivers. The first standardized length of reach considered was 47 channel widths (from the most recent resurvey), this being the longest distance common to the 15 reaches for which enough data were available. Second, we tried defining the standard reach as the zone of bed degradation, again from the most recent resurvey. A third reach used—the entire distance covered by the measured cross sections—was not standardized for the group. Best correlations came from this last approach, probably because the greater number of cross sections provided a better representation.

A general estimate of W_2 downstream from the 15 dams is given by

$$W_2 = 13 + 0.5\,Q_m + 0.1\,Q_p \qquad (4)$$

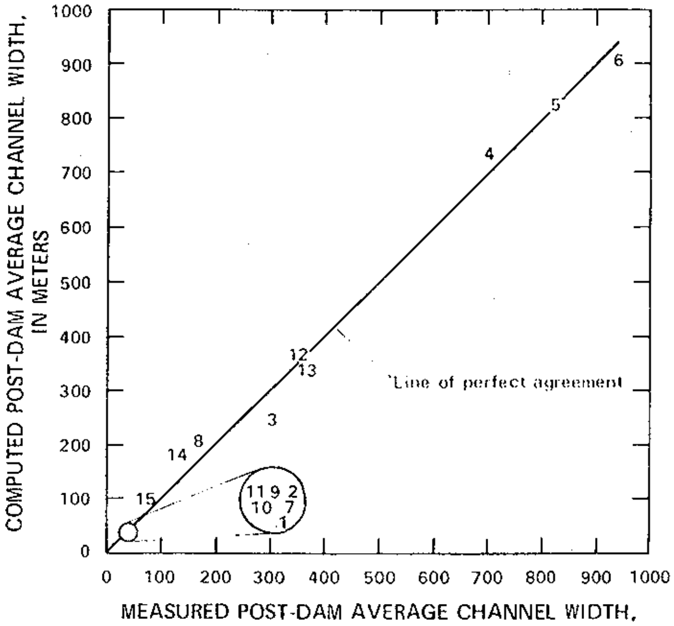
where

- W_2 is the average bankfull width at the time of the latest resurvey, in meters;
- Q_m is the arithmetic average of the annual mean daily flows during the post-dam period from dam closure to the latest resurvey, in cubic meters per second; and
- Q_p is the arithmetic average of annual 1-day highest average flows for the pre-dam period of record, in cubic meters per second.

Thus, both pre- and post-dam flows are represented, though by different flow statistics. As with many empirical expressions, the relation is not correct dimensionally. The r^2 for the regression equation is 0.99, and the average absolute error in the predicted W_2 is ± 19 percent. Computed versus observed values of W_2 are compared in figure 29.

The ranges of values used in determining equation 4 are $30 \leq W_2 \leq 939$ m, $22 \leq Qp \leq 5{,}000$ m^3/s; and $1.6 \leq Qm \leq 830$ m^3/s (table 11). Average daily discharges differ slightly from those of table 4 because only flow data up through the latest channel resurvey were used for equation 4. Also, filling of the reservoirs for Fort Peck, Garrison, Fort Randall and Gavins Point Dams was not completed until about 1964, so mean daily discharges were computed beginning with 1965 for these dams. The period of reservoir filling for the other dams was assumed to be negligible. This empirical equation applies only to the ranges of data included in the analysis. For example, the equation may not be valid for dams which release little or no flow. We have no explanation for why the post-dam mean daily flow and pre-dam average annual 1-day high flow turned out to be the significant variables.

Two sites with the required flow data were found to test equation 4. The tests are only approximate because the measurement or estimate of post-dam width is not made for a long reach of the river. The Canadian River at 3 km downstream from Ute Dam (closed in 1963) is shown in figure 30. Three measurements of



EXPLANATION

NUMBER	DAM AND STATE
1	Jemez Canyon, New Mexico
2	John Martin, Colorado
3	Fort Peck, Montana
4	Garrison, North Dakota
5	Fort Randall, South Dakota
6	Gavins Point, South Dakota
7	Medicine Creek, Nebraska
8	Red River, Iowa
9	Kanopolis, Kansas
10	Fort Supply, Oklahoma
11	Canton, Oklahoma
12	Eufaula, Oklahoma
13	Denison, Oklahoma-Texas
14	Town Bluff, Texas
15	Buford, Georgia

FIGURE 29.—Computed (by the equation $W_2 = 13+0.5Q_m+0.1\ Q_p$) versus measured values of post-dam average channel widths.

channel width were made in 1981 at different sections along a nearly uniform 0.3-km reach (fig. 30). This reach is typical in regard to present channel width, according to the local U.S. Geological Survey engineers. The measured widths ranged from 43 to 46 m, averaging 44 m. According to equation 4, the width should be 55 m (Q_m = 1.2 m^3/s, Q_p = 410 m^3/s). This estimate is therefore slightly (25 percent) too large.

The second test area is the Republican River downstream from Trenton Dam, Nebraska (fig. 31). The flow records provide Q_m = 1.8 m^3/s and Q_p = 112 m^3/s, for which equation 4 yields a width of 25 m. Judging from figure 31, the present width is an estimated 30 percent less than 25 m.

None of the 115 variables correlated particularly well with the relative change in channel width (W_2/W_1), although some approximate correlations will be mentioned below. With respect to W_2/W_1, the 15 damsites can be divided into two distinct groups. The first includes the 11 dams downstream from which the channel either has undergone a slight widening, on the average, or has not changed appreciably. All hydropower dams, and some others, are in this group. The channels in the second group (downstream from Jemez Canyon, John Martin, Fort Supply, and Canton Dams) have narrowed considerably (as described earlier). The distinctive feature of the post-dam flow regime for the latter group seems to be that these channels convey little or no flow during a large part of the year. In contrast, the channels in which the width has remained constant or has enlarged are rarely dry and generally convey substantial (though not overbank) flows. Osterkamp and Hedman (1981) studied regulated Kansas streams on which the flow releases, though sustained, were not large and erosive. The channels tended to be narrower downstream from the dams than upstream. A general knowledge of a proposed dam's release policy, therefore, might indicate whether significant channel widening or narrowing is likely to occur. Further study needs to be given to this possibility.

Some of the narrowed channels may have conveyed little water during much of the year even during the pre-dam era; however, periodic floods then probably kept the channels wider. With the virtual elimination, or marked curtailment, of such high flows (table 4), low-flow periods appear to have assumed much greater importance. Such prevailing low flows form their own new (narrower) channel. Those high post-dam flows that are released may not be sufficient to maintain the former channel, especially since such flows generally are lower than pre-dam high flows (table 4). Vegetation has a better chance to become established on the lesser-used part of the streambed, and the course of events described above in connection with Sandstone Creek (table 9; fig. 23) can occur. Northrop (1965) reported similar processes on the Republican River in Nebraska, although flows there have been greater.

W_2/W_1 did show an approximate correlation with flow durations of low flows and also of certain high flows, namely: (1) The percent of time which a low flow equal to about 0.06 Q_m was equaled or exceeded; (2) the percent of time a high flow equal to 8 Q_m was equaled or exceeded; and (3) the percent of time a high flow equal to 0.1 times an estimated bankfull discharge was equaled or exceeded. In all three cases, correlation was improved by adding the average bankfull width-depth ratio as of the year of dam closure as a second independent variable. From these tests, it seems quite possible that flow durations help determine relative channel changes (W_2/W_1); however, the general cause-and-effect relation remains unsolved. Part of the difficulty lies in the fact that the mechanisms are erosional in some

TABLE 11.—*Data used to derive post-dam channel-width equation*

[F, flood control; I, irrigation and water conservation; L, low-flow augmentation; M, municipal and industrial supply; N, navigation; P, hydropower; R, re-regulation of flow; S, sediment control; m, meters; m^3/s, cubic meters per second]

Dam no.[1/]	Dam	Year of closure	Main purpose of dam	Water years included in analysis: Pre-dam	Water years included in analysis: Post-dam	Latest average width W_2 (m)	Relative change in width W_2/W_1	Post-dam average daily discharge Q_m (m^3/s)	Pre-dam average 1-day high flows Q_p (m^3/s)
5.	Jemez Canyon	1953	S,F	1937; 1944-52	1954-75	46	0.22	1.64	22.2
6.	John Martin	1943	I,F	1914-41	1943-72	50	0.31	3.37	283
7.	Fort Peck	1937	N,P,F	1929-36	1965-73	299	1.16	332	746
8.	Garrison	1953	N,P,F	1929-52	1965-76	703	1.08	795	3,420
9.	Fort Randall	1952	N,P,F	1948-51	1965-75	820	1.12	779	4,460
10.	Gavins Point	1955	N,P,F	1948-54	1965-74	939	1.18	830	4,990
11.	Medicine Creek	1949	I	1938-48	1951-78	47	1.18	1.88	170
13.	Red Rock	1969	F,L,I	1941-68	1970-78	167	1.03	170	1,160
14.	Kanopolis	1948	L,F	1941-47	1949-71	40	1.03	10.1	228
16.	Fort Supply	1942	F,M	1938-41	1943-69	31	0.15	1.93	119
17.	Canton	1948	F,M	1939-47	1949-71	30	0.47	5.32	219
18.	Eufaula	1963	P,S,F	1939-62	1965-77	357	0.97	135	2,920
19.	Denison	1943	P,F	1937-42	1944-69	373	1.10	120	2,760
20.	Town Bluff	1951	R,I,M	1922-50	1952-65	126	1.19	119	1,110
21.	Buford	1956	P,F	1942-55	1957-71	73	1.04	56.4	566

[1/] In figure 1 and table 4.

FIGURE 30.—Canadian River about 3 kilometers downstream from Ute Dam, New Mexico. *A*, August 1954; *B*, April 1980. Dam was closed in 1963.

channels (those that have widened) but not in others (those that have narrowed).

ROLE OF A DAM IN EFFECTING A CHANGE IN CHANNEL WIDTH

Through control of water and sediment flow, the change in hydrologic regime associated with reservoir releases could result in an increase, decrease, or no change in downstream channel width. Channel widening conceivably might result from : (1) A decreased sediment load in the flow, enhancing the capacity of the flow to entrain sediment from the bed and banks; (2) a decrease in the volume of sediment brought to, and deposited on or near, the banks, due to the reduced sediment transport and decreased high flows (net removal of material); (3) diurnal flow fluctuations (power or other controlled releases) causing consistent bank wetting and promoting greater bank erodibility; (4) bed degradation, where it occurs, resulting in flows impinging at a lower level on the banks, undermining vegetation and the higher section of the banks; and (5) rapid changes in flow releases (common with power dams) causing the river position to wander indiscriminately from one side of the channel to the other, encouraging

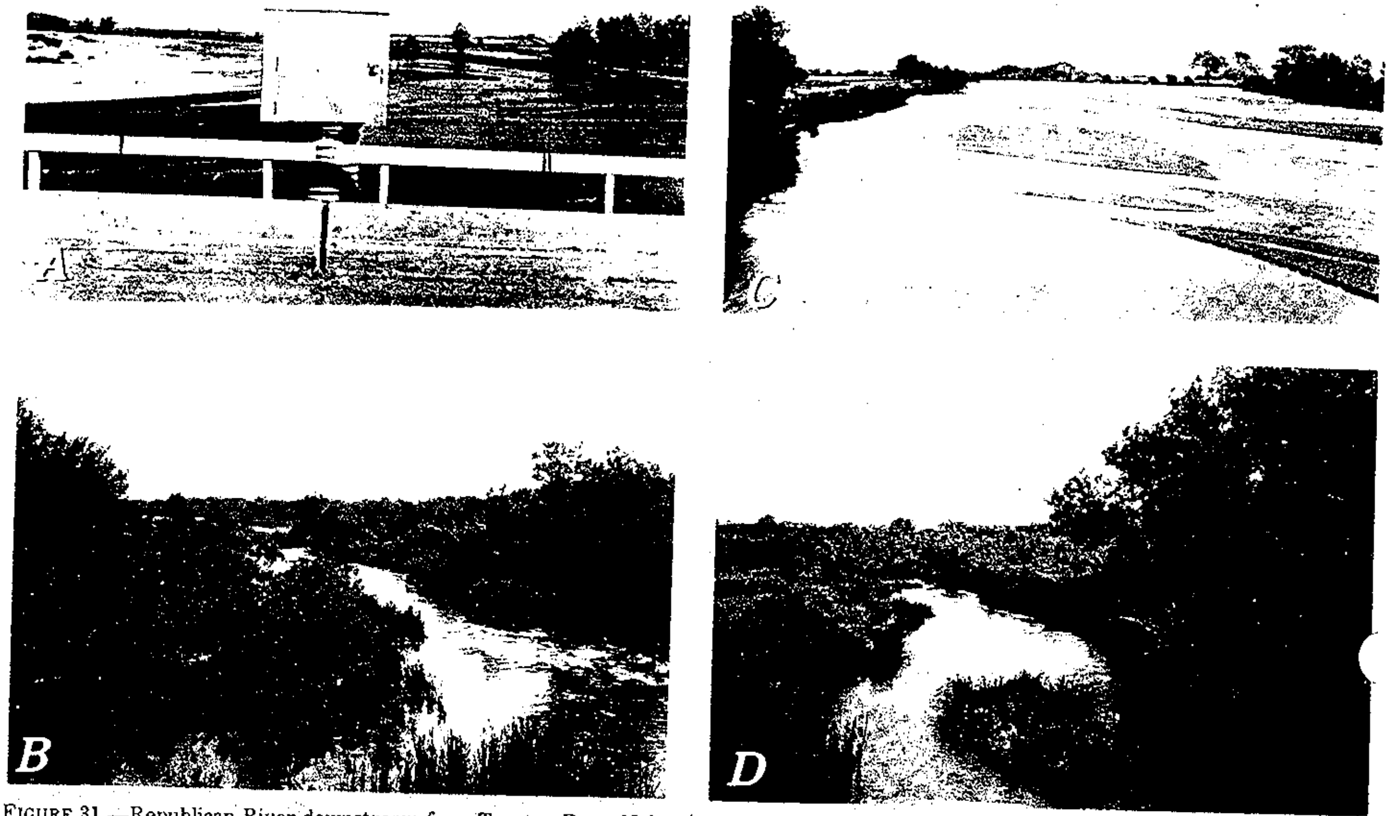


FIGURE 31.—Republican River downstream from Trenton Dam, Nebraska. Dam was closed in 1953. Looking downstream from bridge at Trenton (4 kilometers downstream from the dam), about 1949 (A) and July 1980 (B). Looking downstream from bridge at Culbertson (19 kilometers downstream from dam), July 1932 (C) and July 1980 (D).

periodic erosion of first one bank and then the other without compensatory deposition. Whether the specific increases in width reported in this study are due to the dams cannot be determined because of lack of conclusive data, especially pre-dam cross-section measurements.

The dam's role on the four channels that have become narrower is clearer. Photographs of the Jemez River (fig. 17) show that little if any significant narrowing of the channel occurred from 1936 to 1951, while a very marked reduction in width took place sometime between 1951 and 1980 (dam closure was 1953). Measured cross sections (table 13) indicate a relatively wide channel around the time of dam closure and a striking decrease in width in the years immediately thereafter. No major reduction in water discharge occurred at the control station upstream from the dam during the post-dam period (table 4), and 1978 aerial photographs show that the channel upstream from the reservoir is still relatively wide (about as wide as the pre-dam channel downstream from the dam). This upstream-downstream aerial-photograph comparison of reaches which are geographically near one another rules out any climatic effects or other factors that might be noticeable on other mountain streams in the western United States. Finally, the data of table 13 indicate that the overall bed degradation and channel narrowing on the Jemez River downstream from Jemez Canyon Dam have not been affected significantly by any changes farther downstream, such as on the Rio Grande. The channel narrowing since 1951 downstream from Jemez Canyon Dam, therefore, must be due to the dam.

Wolf Creek downstream from Fort Supply Dam (fig. 19) in 1969 was only about 15 percent as wide as it was when the dam was closed in 1942. Aerial photographs taken in 1973 show a relatively wide channel upstream from the reservoir, compared to the narrow channel downstream from the dam. The similarity of the present upstream reach to the pre-dam channel upstream and downstream from the dam, coupled with the decreases in width shown by onsite measurements (table 13) and photographs (fig. 19) indicate that the radical post-dam decrease in width downstream from the dam very probably is due to the altered flow regime controlled by the dam.

Measured cross sections (table 13) and photographs (fig. 18) of reaches downstream from John Martin Dam on the Arkansas River show a pronounced decrease in width (an average of nearly 70 percent for the W_2/W_1 values) after the 1943 dam closure. Such a radical change has not occurred upstream. Cableway discharge measurements at Las Animas, about 25 km upstream from the dam, show no change in the channel width during 1946–57, the period for which usable data are available. At Nepesta, about 100 km upstream from the dam, a similar analysis of cableway measurements for 1943–65 shows only about a 5 percent decrease in channel width. Two ground photographs of the latter site, taken in 1938 and 1963, also indicate no significant change in width. Aerial photographs taken in 1950 and 1970 seem to show a slight channel narrowing and an increase in vegetation for many tens of kilometers upstream from the reservoir during that period. The vegetation change had been occurring since at least 1936 (Bittinger and Stringham, 1963). Due to man's extensive effect on the hydrology of the Arkansas River, some channel narrowing and vegetation growth probably would have occurred even without the dam. The differences upstream and downstream from the dam are large enough, however, that most of the channel narrowing downstream from the dam probably has resulted from the dam.

Bankfull width at the streamflow-gaging station 4.8 km downstream from the site of Canton Dam was about 60 m in 1938, according to the station description of that year. In 1947, the first cross-section surveys downstream from Canton Dam (closed in 1948) showed channel widths of 65 m 3.1 km downstream from the dam and 47 m 5.0 km downstream from the dam. These figures indicate some, but not a major, decrease in channel width in the reach 5 km downstream from the dam during the 9 years before construction of the dam. According to the 1976 resurvey, the channel by then was 74 percent and 37 percent of its 1947 width at the same two cross sections. No control station at which water discharges and channel changes are unaffected by flow regulation is available for the North Canadian River at Canton Dam. However, the fairly stable predam width compared to the decrease in post-dam width indicates that much of the decrease in channel width is due to Canton Dam.

SEDIMENT VOLUMES REMOVED AND CHANNEL EQUILIBRIUM

Year-to-year estimates of volumes of sediment removed from the entire channel boundary within a finite reach can be determined from end-area measurements of cross sections. Such estimates, made by the Corps of Engineeers and Bureau of Reclamation, show many of the same features as bed degradation. For example, U.S. Bureau of Reclamation (1976) computations of this type for separate reaches on the Colorado River downstream from Davis Dam show that the largest volumes of sediment removal per year take place soon after dam closure. As years go by, the estimated volumes removed tend to approach zero net change. These tendencies agree with observed degradation and channel-width changes with time, described by the hyperbolic curve discussed above. Large differences, however, can be found from one year to the next, and in some years net deposition takes place. Net erosion in one reach can occur during the same year as net deposition in an adjoining reach.

Similar data obtained by the U.S. Army Corps of Engineers for the Red River show how the volume of sediment removed varies with distance downstream. Successive times after dam closure also can be compared. A plot of cumulative volumes of sediment removed from the channel boundary as a function of distance downstream is shown in figure 32. A steep line on the plot indicates a large increase in the volume removed from one cross section to the next, or, in other words, a large volume of erosion has occurred throughout a unit downstream distance during the inclusive period represented by the plotted line. The steepness of the curve is proportional to the erosion rate for the unit reach. A horizontal line indicates that the cumulative volume removed, as of the survey year, no longer changes with distance downstream. In the latter case neither net erosion nor deposition occurs with distance, presumably an indication of a stable channel unaffected by the dam.

Both curves in figure 32 show maximum channel erosion in the reaches closest to the dam, with the volume of erosion (slope of line) decreasing with distance downstream. In 1948, 6 years after closure, the reach of appreciable sediment removal extended downstream about 55 km. By 1958, the steep curve extended to about 90 km; even 160 km downstream, it had not become horizontal. From 1942 to 1948, the first 6 years after dam closure, the average rate of sediment removal from the first 25 km downstream from the dam was about 863,000 m^3/yr. By 1958, this rate had decreased to about 620,000 m^3/yr.

The downstream patterns of degradation and channel widening discussed earlier show that the relative volumes of erosion of bed and banks along a given river are variable. The contribution from the bed appears to be greater closer to the dam; therefore, the longer the eroded reach (or the farther the subreach of interest

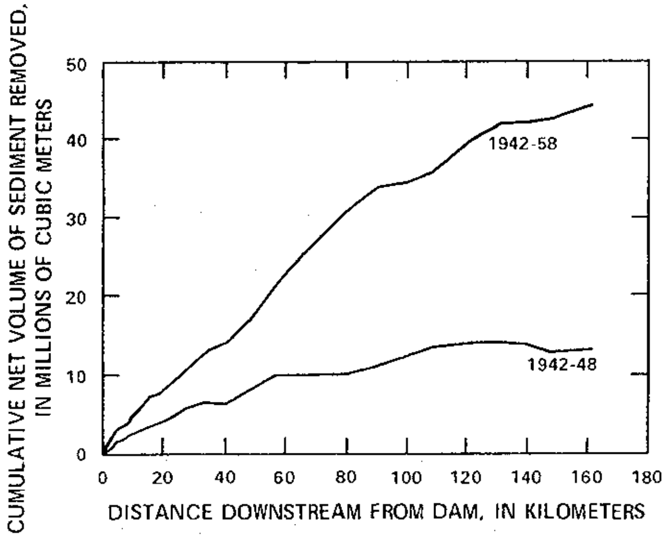


FIGURE 32.—Variation in cumulative net sediment volumes of channel erosion with distance downstream from Denison Dam on the Red River, Oklahoma–Texas.

from the dam), the greater the relative contribution from the banks.

Variations from one river to another also are considerable, as has been shown by Petts (1979) for British rivers. The U.S. Army Corps of Engineers (1952, p. 37) examined measured cross sections and estimated that, of the channel erosion downstream from Fort Peck Dam, about 60 to 70 percent of the sediment removed came from the banks and 30 to 40 percent from the bed. Estimates for the Red and North Canadian Rivers would make this percentage about 80 to 95 percent from the banks. In comparison, in certain reaches downstream from several dams on the Colorado River, the width is constrained, directing most of the erosion to the bed alone.

The persistence of disequilibrium or the reestablishment of equilibrium in the relation of sediment inflow and outflow in reaches downstream from dams probably varies considerably from river to river. Clear water released from the dam may receive a new supply of sediment mainly from the channel bed, the channel banks, or from tributary inflows. Unless tributary inflows supply a relatively large proportion of the sediment, the regulated river has difficulty in regaining its former sediment load from the bed and banks alone.

VEGETATION

OBSERVED CHANGES IN VEGETATION

Vegetation cover in and along channels downstream from the dams of this study either remained about the same or (most commonly) increased, following dam closure. A decrease in vegetation after a dam was built was reported by other investigators in only one case, cited below.

Noticeable, and in some cases very extensive, encroachment of vegetation onto former streambeds is apparent downstream from dams on the Jemez River (fig. 17), Arkansas River (fig. 18), Wolf Creek (fig. 19), North Canadian River (fig. 20), Canadian River (fig. 30), Republican River (fig. 31), and others shown below. Considerable vegetation has grown on the Platte River downstream from Kingsley Dam in Nebraska (Williams, 1978).

A striking increase in vegetation has occurred on the Canadian River downstream from Sanford Dam, Texas (fig. 33), where virtually no releases of any magnitude have been made since dam closure in 1964. Due to the scarcity of major tributaries, the effect still is very pronounced 120 km downstream from the dam and probably much farther. Vegetation cover increased in direct proportion to the reduction in channel width.

Studying the flood plain rather than the channel, Johnson and others (1976) reported a post-dam decrease in overall extent of forest cover and in certain kinds of trees downstream from Garrison Dam on the Missouri River. Green ash (*Fraxinus pennsylvanica*), however, increased.

Vegetation changes in selected reaches downstream from 10 dams were mapped in the present study. Vegetated zones were marked on aerial photographs taken about the time of dam closure. About 7 to 13 years after the date of the aerial photograph, the same areas were visited, and vegetated areas again were mapped on the same aerial photographs. Of the 10 reaches examined, vegetation had covered as much as 90 percent of the channel bottomland in some cases (table 12). Seven of the 10 areas showed an increased growth of more than 50 percent.

The alternative presence of willow (*Salix* sp.) or saltcedar (*tamarisk* sp.) for the sites in table 12 appears to be dictated at least in part by water quality. For example, saltcedar seems to thrive in the saline water of the Salt Fork of the Arkansas River in Oklahoma, while willow covers large areas on the Republican River in Nebraska. Differences are less apparent between the Arkansas, Canadian, and Republican Rivers.

Distribution of vegetation in and along channel areas appears in at least three common patterns. In the first pattern, the increase in vegetation occurs in a strip along each bank. Turner and Karpiscak (1980) beautifully document such increases in riparian vegetation on the Colorado River between Glen Canyon Dam and Lake Mead, Arizona. Of their many sets of photographs, even those that were taken 0 to 13 years prior

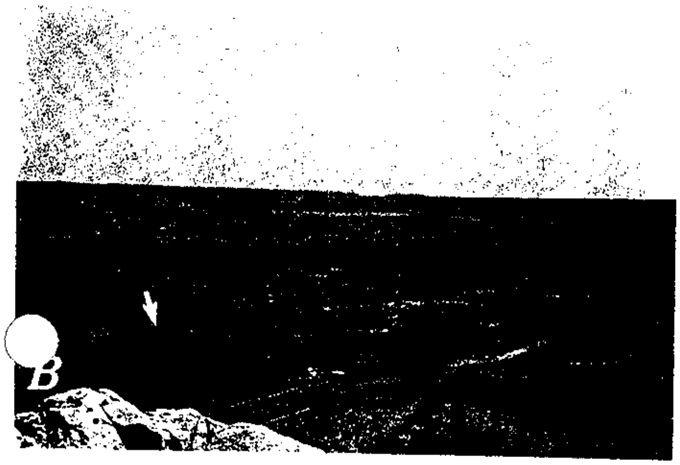


FIGURE 33.—Canadian River downstream from Sanford Dam, Texas. Dam was closed in 1964. Looking downstream from about 400 meters downstream from damsite, October 1960 (A, prior to dam) and April 1980 (B). White arrow points to 1980 channel, about 5 meters wide. Looking upstream from railroad bridge near Canadian, about 120 kilometers downstream from dam, October 1960 (C, before Sanford Dam) and March 1980 (D). (Photograph credits: *A* and *C*, U.S. Bureau of Reclamation; *B*, U.S. Soil Conservation Service; *D*, U.S. Geological Survey.)

to closure of Glen Canyon Dam (1963), compared to recent (1972–76) photographs almost all show a definite increase in vegetation. The authors note (p. 19) that "in the short period of 13 years the zone of post-dam fluvial deposits has been transformed from a barren skirt on both sides of the river to a dynamic double strip of vegetation." The Des Moines River downstream from Red Rock Dam, Iowa, also exemplifies this kind of distribution. Overbank areas that formerly had relatively frequent flooding now have significantly more trees. Most of the trees sprouted naturally, the remaining few having been planted by residents who found the land along the riverside much more habitable after dam closure upstream.

In the second pattern, vegetation encroachment occurs within and adjacent to the former channel, leaving a much narrower single channel to carry the decreased post-dam flows. The succession of changes that a reach undergoes in this transformation is illustrated by the Washita River 1.4 km downstream from Foss Dam, Oklahoma (fig. 34). (Other smaller dams, farther upstream, also have affected this and other streams in this part of Oklahoma, as discussed below.)

The Republican River downstream from Harlan County Dam in Nebraska exemplifies a third characteristic pattern. This is shown on aerial photographs taken in 1949 and in 1956 (fig. 35). The dam was closed in 1952. The discharge on the day of the 1949 photograph was 29 m^3/s, whereas the regulated flow on the day of the 1956 photograph was only 1.8 m^3/s. The vegetation changes are quite evident, nevertheless. In 1949 the channel shown in the photograph had the typical island and bar topography of a braided channel, with exposed expanses of clean white sand. In contrast, in 1956 the channel consisted of thin threads of open water in channels converging and diverging around "dark" islands fixed by vegetation. The vegetation consists of a dense growth of willows that form a virtually impenetrable jungle (see also fig. 31, Republican River downstream from Trenton Dam, Nebraska).

TABLE 12.—*Change in approximate percentages of riparian vegetation downstream from various dams*

River, dam, location	Year of dam closure	Post-dam time period analyzed	Length of reach (kilometers)	Average percent change in area covered by vegetation	Type of vegetation
Arkansas, John Martin, above Lamar, Colorado	1942	1947-60	40	90	Saltcedar
Republican, Trenton, below Trenton, Nebraska	1953	1952-60	6	50-60	Willow
		1960-80	6	85-95[1]	Willow
Republican, Harlan County, near Franklin, Nebraska	1952	1949-56	32	60-80	Willow
		1956-80	32	85-95[1]	Willow
Republican, Harlan County, Superior, Nebraska	1952	1950-56	26	65	Willow
Red, Denison, Denison, Texas	1943	1948-55	35	6	--
Salt Fork, Arkansas, Great Salt Plains, Jet, Oklahoma	1941	1941-54	31	33	Saltcedar
		1960	16	60	Saltcedar
North Canadian, Canton, Oklahoma	1948	1960	16	30-50 (local)	Willow
Wolf Creek, Fort Supply, Fort Supply, Oklahoma	1942	1951-59	5	0	--
		1959-72	5	80-90[1]	Grass, shrub, willow

[1] Estimated for short reach from ground photographs.

POSSIBLE CAUSES OF VEGETATION CHANGES

The roots of a plant are vital to its survival; therefore, the scouring effect of high flows can be devastating to vegetation. (The root depth and strength, the age and size of the plant and its trunk flexibility all affect a plant's ability to withstand the scouring action of floods.) Even when a plant is not uprooted completely by a flood, germination and seedling survival generally depend on species flood tolerance. This in turn is a function of flood magnitude, frequency, and duration (Turner, 1974; Teskey and Hinckley, 1977). A reduction in such flood characteristics, therefore, often enhances vegetation survival and growth.

If one deals only with the flood plain as opposed to the channel and banks, the effect of floods is less clear. Some trees, for example, may grow better under periodic flooding, especially where vigorous scouring is less active or less effective than gentler inundation. Johnson and others (1976) attributed a post-dam decrease in cottonwood (*Populus deltoides* Marsh), box elder (*Acer negundo* L.), and American elm (*Ulmus americana* L.) on the flood plain of the Missouri River downstream from Garrison Dam in part to the reduction of floods that formerly brought more nutrients and produced a higher water table.

An increase in low flows has been thought to increase riparian plant growth. Such augmentation would raise the water table and increase the soil moisture, thus effecting an increase in vegetation. Some of the dams listed in table 12, such as Wolf Creek downstream from Fort Supply Dam, seem to support this thesis, insofar as an increase of both vegetation and low flows has occurred. However, a number of other dammed rivers, such as the Jemez and part of the Republican, have considerably reduced low flows, and yet vegetation also increased downstream from the dams on these rivers (figs. 17, 31, and 35). Thus, while increased low flow can encourage the spread of riparian vegetation along rivers, it does not appear to be a requirement, provided moisture is available.

Ground-water withdrawals downstream from some dams have increased in recent years. Such withdrawals theoretically should lower the water table and decrease soil moisture, tending to inhibit many plant species. The importance of ground-water withdrawals in regard to post-dam vegetation changes could not be determined for the rivers studied here.

Climatic changes could bring new conditions of temperature, humidity, and rainfall. The reaction of vegetation type and density to such changes may not be readily apparent. A period of less annual rainfall, for

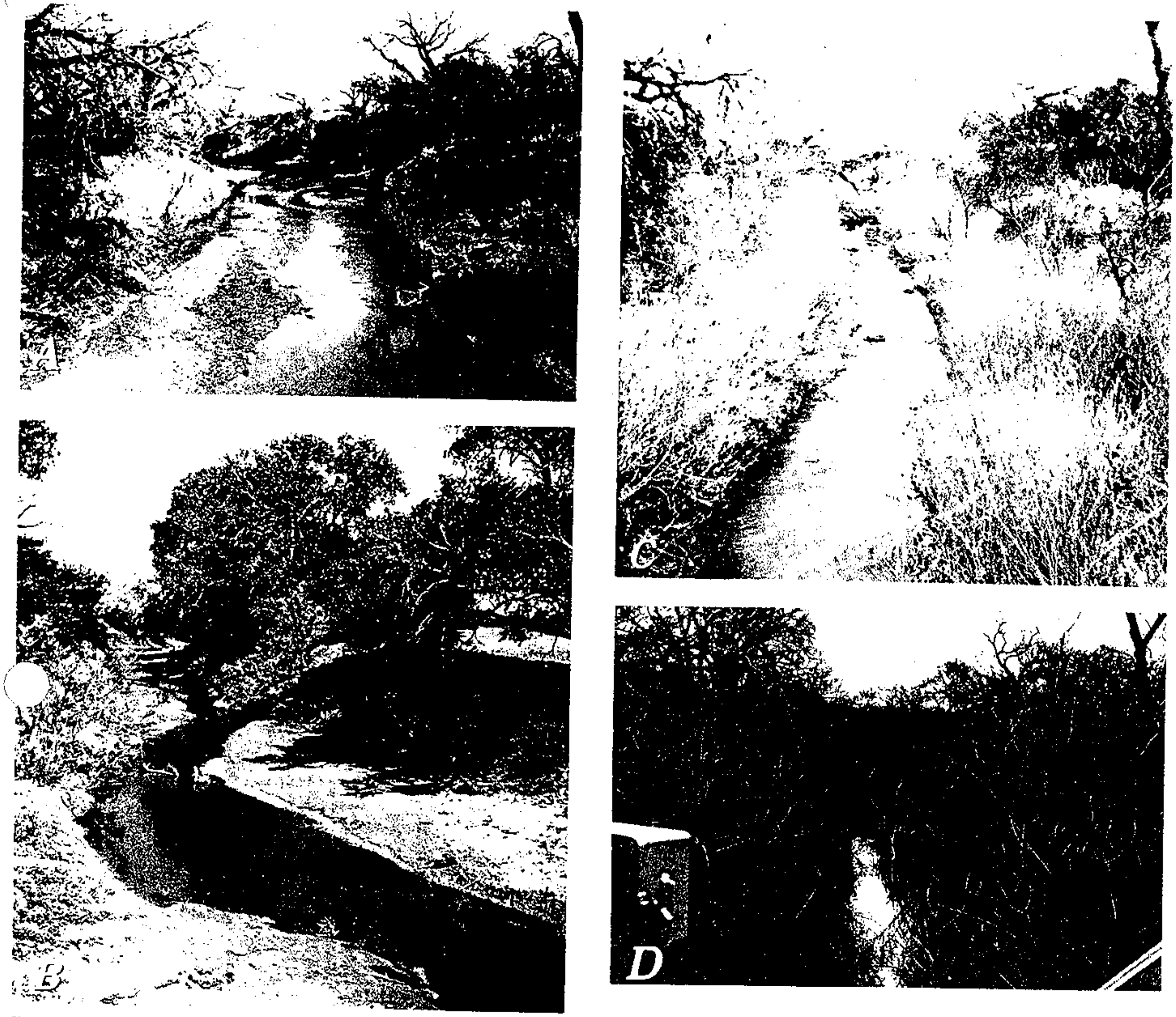


FIGURE 34.—Washita River about 1.4 kilometers downstream from Foss Dam, Oklahoma. *A*, February 1958; *B*, May 1962; *C*, March 1967; *D*, February 1970. Dam was closed in 1961.

example, could mean fewer flood peaks and an attendant establishment of vegetation, or it could mean less moisture in the ground and less vegetative growth. (Flood intensity and spatial distribution, which in turn depend on the intensity and distribution of precipitation, may be as important for plant survival as flood frequency. Total annual rainfall might not show changes in any of these factors.) In any event, changes in plant species might accompany climatic changes.

Channel shape also could be a factor in vegetation changes. Little change can be expected on a narrow, deep channel. In comparison, a wide, shallow channel offers a better opportunity for vegetation to become established.

Rate of channel meandering has not been treated separately in this paper. However, if sinuosity is affected by a dam (as mentioned briefly above), then rate of channel meandering also would change. Gill (1973) explains that the nature of the flood-plain plant community is very closely related to lateral migration of the channel. Johnson and others (1976) attributed a lack of young stands of cottonwood (*Populus* sp.) along the Missouri River downstream from Garrison Dam to a lesser rate of meandering after dam construction.

The U.S. Fish and Wildlife Service studied the seed germination and seedling establishment of willows and cottonwoods along the Platte River in Nebraska,

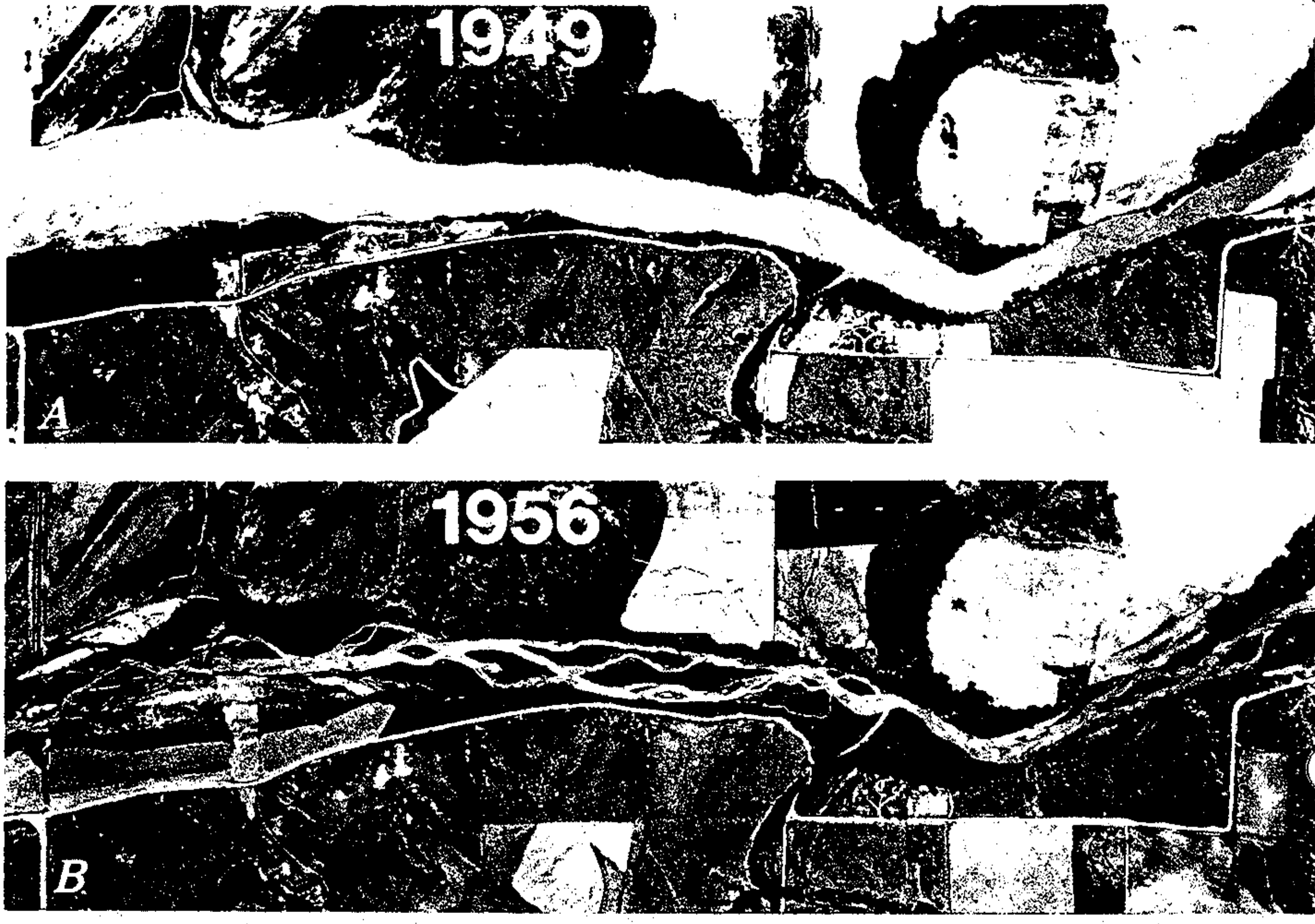


FIGURE 35.—Republican River downstream from Harlan County Dam, Nebraska, before and after dam closure. Reach shown is near Bloomington, Nebraska. Flow was 29 cubic meters per second at time of 1949 photograph and only 1.8 cubic meters per second at time of 1956 photograph, but the increase in vegetation (dark areas) and the change in channel pattern are nonetheless apparent.

downstream from Kingsley Dam (U.S. Fish and Wildlife Service, 1981). Favorable features were a significant soil-moisture content, bed material in the fine sand-to-sand size class, at least 1 to 2 weeks of ground exposure during the time when viable seed is available (mid-May to August), and moderate water depth during flooding. New seedlings survived only on bare sandbars, and not in upland shrub and woodland areas. Many factors, most of which could be affected or controlled by flow regulation, affect plant growth.

SEPARATING FLOW REGULATION FROM OTHER FACTORS AFFECTING VEGETATION CHANGE

A downstream increase in vegetation following dam construction does not necessarily mean the dam caused the change. As noted above, a number of factors, not all of which are dam-related, can affect vegetation. In addition, a particular plant may spread rapidly and even achieve dominance in a given region. Saltcedar growth, for example, is highly suspect as an indicator of the effects of flow regulation. This plant has been spreading at a rapid rate along innumerable valleys in the southwestern United States since its introduction late in the 18th century (Everitt, 1980). Although many of the valleys into which it has spread have been subjected to flow regulation, reaches or sections of many others have not. Larner and others (1974) concluded that, in view of the regional spread of saltcedar in west-central Texas since about the 1920's, the observed accelerated increase in saltcedar downstream from various dams in that area meant that flow regulation by dams contributed to, but was not solely responsible for, the increase in riparian vegetation. On the Arkansas River, infestation by saltcedar is, if anything, more extensive on flood plain and channel bottom upstream from John Martin Dam, including several hundred kilometers beyond the backwater reach, than it is downstream from the dam (Bittinger and Stringham, 1963). Flow regulation at John Martin Dam does not appear to be a sufficient explanation of the spread of saltcedar along this reach of the Arkansas. Similar growth has been observed on the Pecos River both upstream and downstream from Red Bluff Reservoir near the New Mexico–Texas State line (memorandum and photographs of Trigg Twichell, U.S. Geological Survey, December 21, 1961). In low areas along a 25-km reach of the Gila River valley in Arizona, saltcedar has become a dominant species of vegetation from 1944 to 1964. Turner (1974, p. 10) notes that changes in vegetation since 1914 have not coincided with channel changes. Moreover, while natural changes in flow regime have reduced winter flood frequency, and although increased summer low flow would enhance saltcedar growth, a decrease in cottonwoods does not correspond with changes in hydrologic regime (Turner, 1974 p. 13). Turner (1974, p. 18) concludes that, for the reach studied on the Gila River, neither disruption of the channel nor changes in flow regime account for the ascension of saltcedar to dominance over the indigenous vegetation. Rather, saltcedar competed succesfully with native plants and appears to be able to sustain its position indefinitely (Turner, 1974, p. 19).

Climatic variability can complicate any attempt to determine the extent of channel changes and of increased vegetation growth attributable to dams. For example, a number of major dams were built in Oklahoma in the 1950's and 1960's. At the same time, hundreds of smaller flood-detention reservoirs were installed on tributaries. In the Washita River basin, 476 such reservoirs were completed from 1952 to 1972 (Carr and Bergman, 1976). Average annual rainfall in west-central Oklahoma during 1961–71 was about 12 percent less than during 1938–60. This reduced rainfall alone could have resulted in decreased streamflows and in observed changes in channels. In fact, streamflows during 1961–70 were decreased by as much as 60 percent, compared to the earlier period. Both dam construction and less rainfall probably were responsible for this reduction; although, given the very large changes in flow regime associated with the dams, their effect may well have been more significant than the change in rainfall.

Even discounting possible effects of rainfall variability, the extensive simultaneous construction of small flood-detention dams and of dams on major rivers in parts of Oklahoma means that observed channel changes on the bigger rivers in those areas cannot be assumed to be entirely due to just the one dam immediately upstream. Thus, for example, some of the [illegible]tic changes on the Washita River downstream from [illegible]s Dam (fig. 34) might have occurred even without Foss Dam because of the many upstream detention dams.

Because vegetation can increase regardless of changes in post-dam low flows, an increase in vegetation cannot be attributed necessarily to low-flow augmentation from reservoir regulation.

Regulation of high flows (magnitude, frequency, and duration) seems to be the only dam-related factor that is reasonably certain to encourage an increase in vegetation. Even with this feature, evidence on the extent to which the dam is accountable commonly may be absent. Little information exists on the response of riparian vegetation to changes in climate and hydrology unaffected by man. Vegetation changes comparable to those observed downstream from dams have occurred in the past in the absence of dams, though not as abundantly. Examples are on the Gila River (Turner, 1974; Burkham, 1972) and on the Cimarron River (Schumm and Lichty, 1963). Thus, although an increase in riparian vegetation due to flow regulation might logically be expected, the degree of the change ascribable to the dam cannot always be fixed from available data. Regulation of high flows in some cases could be virtually the sole cause of the change, while in other cases, it could be only a contributory part of the cause. In general, however, information from this and other studies indicates that the reduction of high flows by dams, if not controlling, often contributes significantly to the downstream growth of riparian vegetation, especially in cases where the channel has become narrower (figs. 17–20, 30–31, 33–35).

EFFECTS OF VEGETATION GROWTH

Channel vegetation blocks part of the channel, resulting in reduced channel conveyance, faster flow velocities in the channel thalweg or both. Conveyance is decreased both by physical reduction of flow area by the vegetation and by impeding the sediment transport process and inducing bed aggradation. On the Republican River in Nebraska, vegetation decreased the channel capacity by 50 to 60 percent in some reaches (Northrop, 1965). Such reduced conveyance leads to more frequent and longer-lasting overbank flooding. Faster velocities in the channel thalweg have been observed in some California streams, resulting in chutes where riffles used to be (John Hayes, California Fish and Game Commission, oral commun., 1980).

Vegetation also enhances greater bed stability. Not only does vegetation impede the flow, but the roots help bind the sediment. Sediment within vegetated areas can be extremely difficult to erode.

A potential effect of vegetation, though not documented specifically in this study, is greater bank stability, due to the binding and protective effects of the vegetation. Such bank stability would be enhanced by decreases in damaging flood flows.

Another potential major effect of significant new vegetation growth is an increase in water losses by evapotranspiration. No comparative studies of water losses from sand channels before and after vegetation growth have been made. The only work done seems to have dealt with flood plain rather than channel vegetation. Similarly, it is still unclear whether more water is lost from a plain water surface than from one with a plant cover. On flood plains, comparisons of evapotranspiration before and after phreatophyte removal, as well as studies using evapotranspirometers, indicate possibly significant increase in consumptive use of water by phreatophytes compared to volumes for sand and bare soil (Van Hylckama, 1970; Culler and others, 1982; Leppanen, 1981). Several studies (Meyboom, 1964; Bowie and Kam, 1968; Ingebo, 1971) suggest that increased vegetation depletes streamflow, but the variety of conditions under which this occurs is not yet established. The elevation of the water table also has an effect. Evaporation is decreased significantly if the water table is lowered 0.6 m (Hellwig, 1973, p. 106).

CONCLUSIONS

The large data set compiled and examined in this report includes 287 measured cross sections downstream from 21 dams. Each cross section was resurveyed periodically, under the auspices of the U.S. Army Corps of Engineers or the U.S. Bureau of Reclamation, since about the time of dam closure. We have analyzed 1,817 such cross-section surveys (table 13). For each resurvey, we determined the mean bed elevation and measured the bankfull channel width. In addition, gage height-water discharge relations at 14 streamflow-gaging stations (table 14, figs. 36–49) were inspected. Thirdly, numerous supplementary observations and measurements (such as time-sequential photographs, grain-size measurements, and vegetation mapping) downstream from other damsites have been included in the study.

Data published here and in many other reports show that the construction of dams on alluvial channels, by altering the flow and sediment regimen, is likely to result in a number of hydrologic and morphologic changes downstream. For example, average annual peak discharges for the rivers of this study were reduced by from 3 to 91 percent of their pre-dam values by the dams. Mean daily flows and average annual low flows were decreased in some instances and increased in others.

On most of the alluvial rivers surveyed, the channel bed degraded in the reach immediately downstream from the dam. Channel width in some cases showed no appreciable change, but in others, increases of as much as 100 percent or decreases of as much as 90 percent were observed. At many cross sections, the changes in bed elevation and in channel width proceeded irregularly with time. At other cross sections, however, the average rates of degradation and also of changes in channel width can be described by a simple hyperbolic equation of the form:

$$(1/Y)=C_1+C_2(1/t)$$

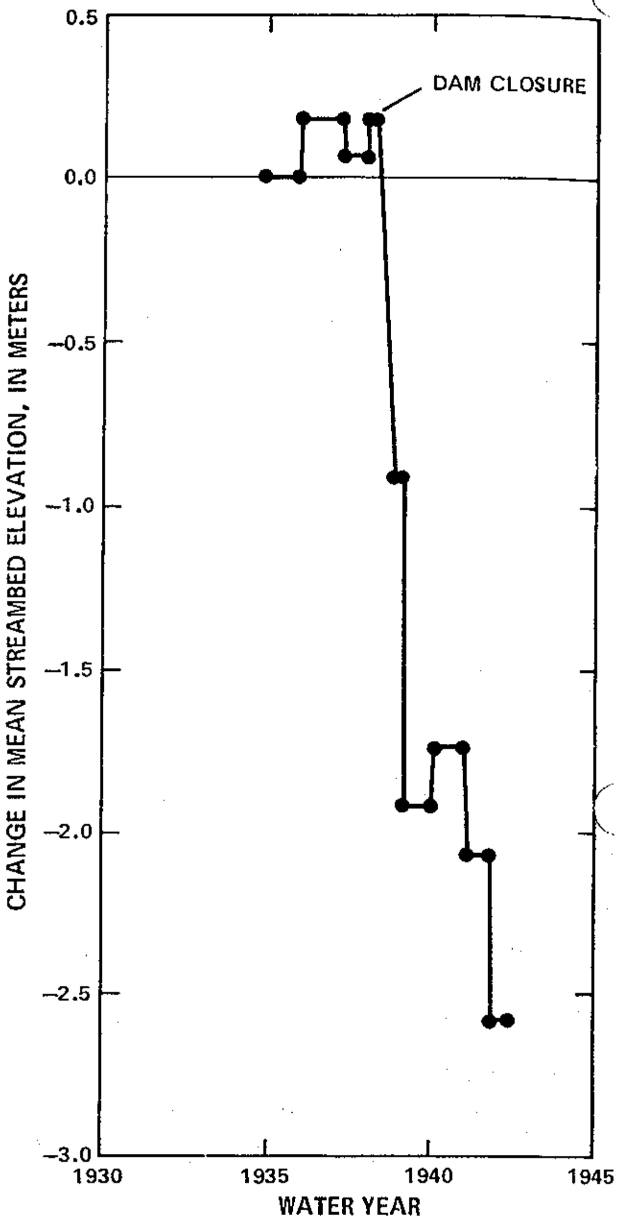


FIGURE 36.—Changes in mean streambed elevation with time at streamflow-gaging station on Colorado River 6.4 kilometers downstream from Parker Dam, Arizona. Plotted points represent elevation corresponding to a discharge of 90.6 cubic meters per second, as determined from rating tables. No upstream control station available.

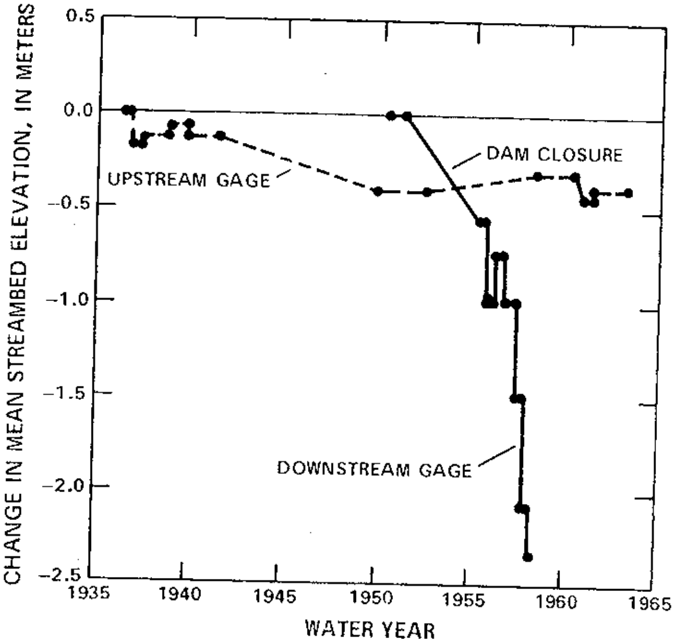
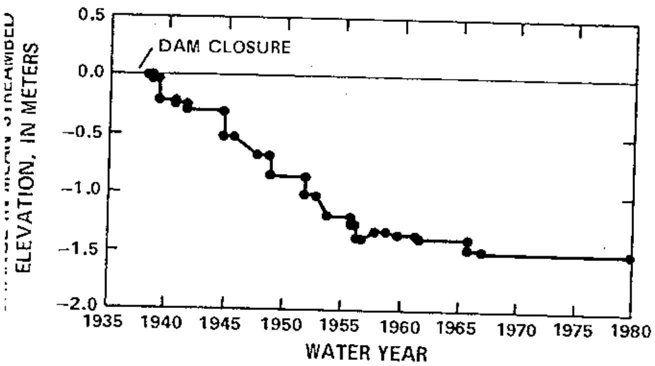


FIGURE 37.—Changes in mean streambed elevation with time at streamflow-gaging station on Jemez River 1.3 kilometers downstream from Jemez Canyon Dam, New Mexico, and at the control station near Jemez 13 kilometers upstream from dam. Plotted points represent elevation corresponding to a discharge of 0.034 meter per second downstream from dam and 0.37 cubic meter per second upstream from dam, as determined from rating tables.



GURE 38.—Changes in mean streambed elevation with time at streamflow-gaging station on Missouri River 13 kilometers downstream from Fort Peck Dam, Montana. Plotted points represent elevation corresponding to a discharge of 85 cubic meters per second as determined from rating tables. No upstream control station available.

here

is either bed degradation in meters or relative change in channel width;

and C_2 are empirical coefficients; and

s e in years after the onset of the particular channel change.

This model equation at present only describes observed channel changes. However, it perhaps could be-

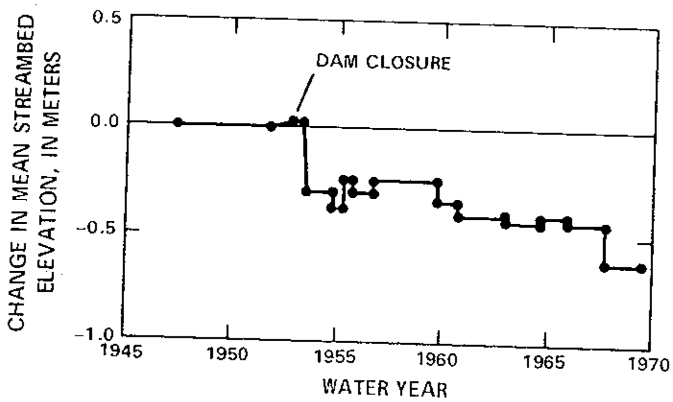


FIGURE 39.—Changes in mean streambed elevation with time at streamflow-gaging station on Missouri River 11 kilometers downstream from Fort Randall Dam, South Dakota. Plotted points represent elevation corresponding to a discharge of 464 cubic meters per second, as determined from rating tables. No upstream control station available.

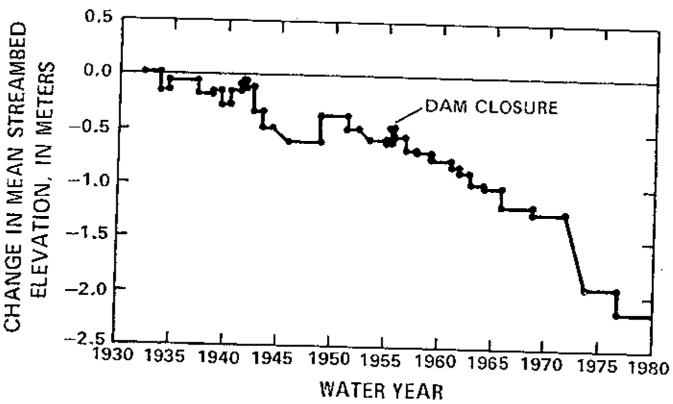


FIGURE 40.—Changes in mean streambed elevation with time at streamflow-gaging station on Missouri River 8 kilometers downstream from Gavins Point Dam, South Dakota. Plotted points represent elevation corresponding to a discharge of 312 cubic meters per second, as determined from rating tables. No upstream control station available.

come usable for pre-construction estimates if a way could be found to predict the two coefficients, at least where subsurface and bank controls are absent. These coefficients probably are functions, at least, of flow releases and boundary materials. Research is needed to find a way of determining the coefficients prior to dam closure.

Without a predictive equation, estimates of expected degradation need to be based on sediment-transport equations. The applicability of sediment-transport equations will depend on the channel-bed material, hydraulic characteristics, and depth to bedrock. The subsurface conditions are assessed best by detailed engineering and geologic surveys, such as excavations and core borings. It is difficult, however, to conduct such surveys

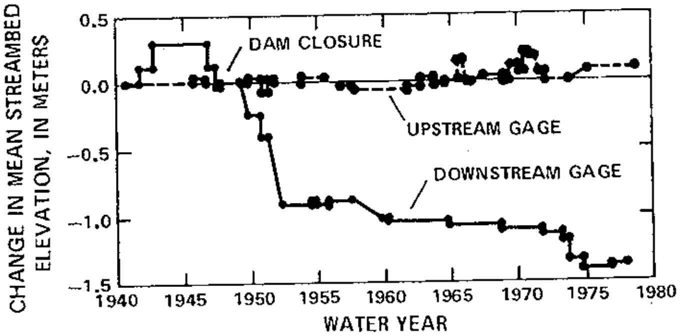


FIGURE 41.—Changes in mean streambed elevation with time at streamflow-gaging station on Smoky Hill River 1.3 kilometers downstream from Kanopolis Dam, Kansas, and at the control station at Ellsworth 48 kilometers upstream from dam. Plotted points represent elevation corresponding to a discharge of 0.51 cubic meter per second downstream from dam and 0.43 cubic meter per second upstream from dam, as determined from rating tables.

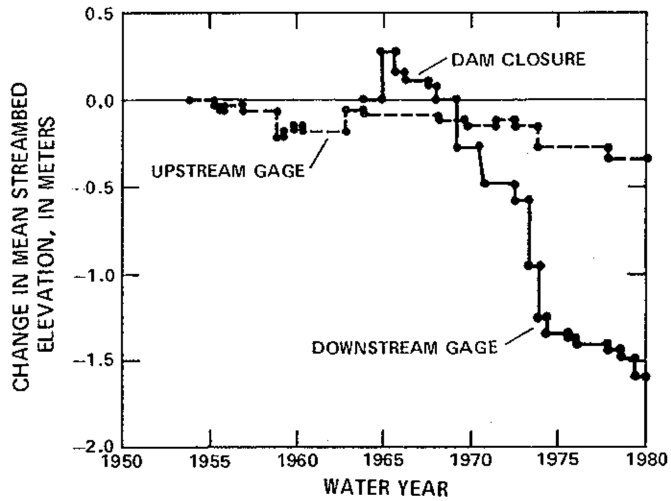


FIGURE 42.—Changes in mean streambed elevation with time at streamflow-gaging station on Republican River 2.7 kilometers downstream from Milford Dam, Kansas, and at control station at Clay Center 49 kilometers upstream from dam. Plotted points represent elevation corresponding to a discharge of 1.2 cubic meters per second downstream from dam and 3.4 cubic meters per second upstream from dam, as determined from rating tables.

accurately. Core borings might fail to disclose coarse sediments at depth, and excavations or more detailed examinations may be required to find any controls. Even excavations may be insufficient if not suitably located.

Extrapolation of a fitted hyperbolic curve to estimate future bed degradation or changes in width at a site probably will give reliable estimates in a number of cases, assuming no major hydraulic changes are introduced. However, bed degradation at some (possibly many) cross sections will not be as deep as the predicted bed degradation because of unassessed subsurface controls (coarse sediment or bedrock). Similarly,

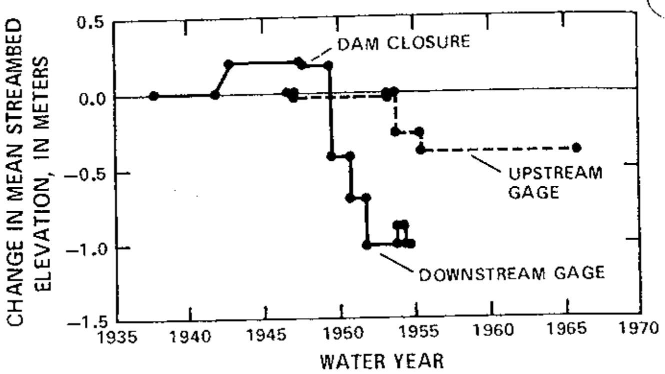


FIGURE 43.—Changes in mean streambed elevation with time at streamflow-gaging station on North Canadian River 4.8 kilometers downstream from Canton Dam, Oklahoma, and at the control station near Seiling 45 kilometers upstream from dam. Plotted points represent elevation corresponding to a discharge of 0.031 cubic meter per second downstream from dam and 0.00057 cubic meter per second upstream from dam, as determined from rating tables.

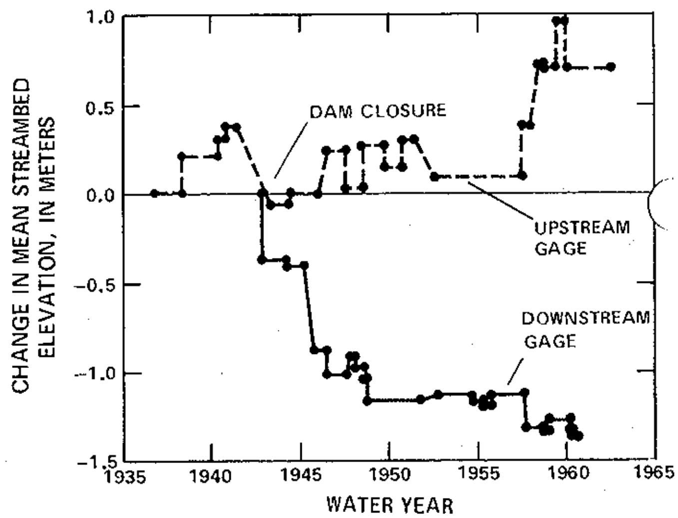


FIGURE 44.—Changes in mean streambed elevation with time at streamflow-gaging station on Red River 4.5 kilometers downstream from Denison Dam, Oklahoma, and at the control station near Gainesville, Texas, 106 kilometers upstream from dam. Plotted points represent elevation corresponding to a discharge of 3.7 cubic meters per second downstream from dam and 4.2 cubic meters per second upstream from dam, as determined from rating tables.

unassessed variations in bank erodibility can affect the predicted width changes.

In the sites studied here, rates of degradation during the initial period following dam closure are about 0.1 to 1.0 m/yr, but ranged from negligible to as much as 7.7 m/yr. (Such rapid rates generally did not last for more than a few months). Rates at many sites became very slow after 5 to 10 years.

The maximum depth of degradation varied considerably from one cross section to another and ranged from less than 1 m to as much as 7.5 m. On rivers having

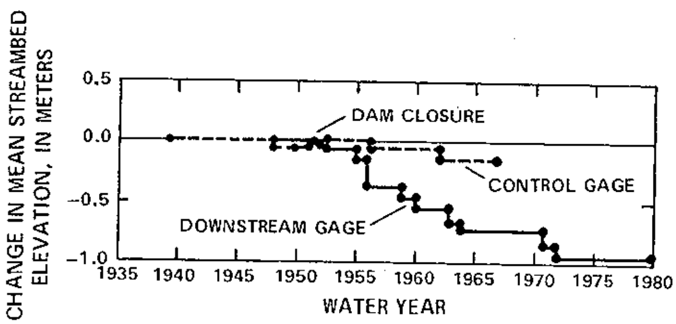


FIGURE 45.—Changes in mean streambed elevation with time at streamflow-gaging station on Neches River 0.5 kilometer downstream from Town Bluff Dam, Texas, and at the control station on Village Creek near Kountze in an adjacent drainage basin. Plotted points represent elevation corresponding to a discharge of 4.2 cubic meters per second downstream from dam and 1.5 cubic meters per second at the control station, as determined from rating tables.

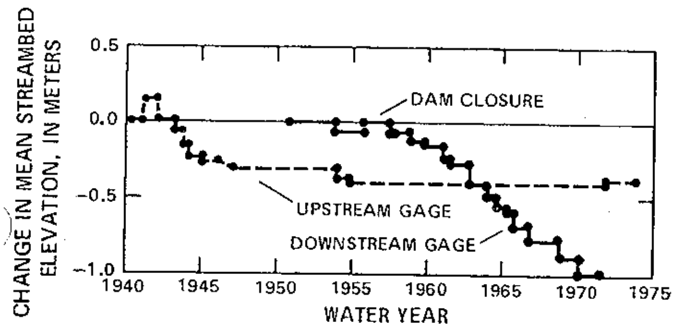


FIGURE 46.—Changes in mean streambed elevation with time at streamflow-gaging station on Chattahoochee River 4 kilometers downstream from Buford Dam, Georgia, and at the control station on the Chestatee River near Dahlonega 73 kilometers upstream from dam. Plotted points represent elevation corresponding to a discharge of 12.2 cubic meters per second downstream from dam and 3.4 cubic meters per second upstream from dam, as determined from rating tables.

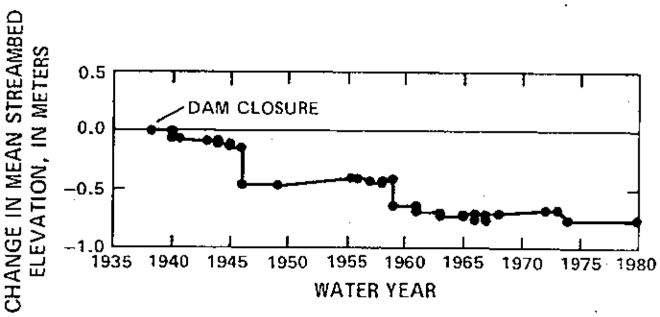


FIGURE 47.—Changes in mean streambed elevation with time at streamflow-gaging station on Rio Grande 1.3 kilometers downstream from Caballo Dam, New Mexico. Plotted points represent elevation corresponding to a discharge of 28.3 cubic meters per second, as determined from rating tables. No control station.

slopes of about 1 to 3 m/km, degradation of as little as 1 m significantly decreases the gradient.

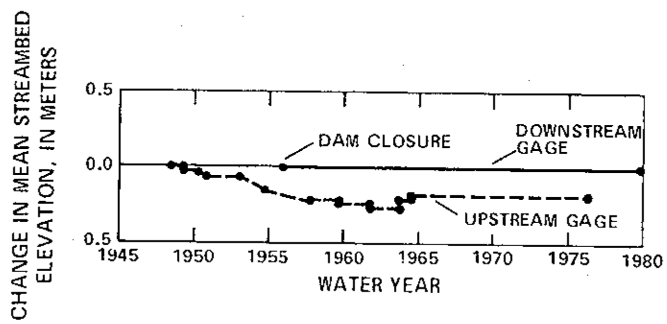


FIGURE 48.—Changes in mean streambed elevation with time at streamflow-gaging station on Marias River 3.2 kilometers downstream from Tiber Dam, Montana, and at the control station near Shelby 65 kilometers upstream from dam. Plotted points represent elevation corresponding to a discharge of 2.8 cubic meters per second downstream from dam and 4.0 cubic meters per second upstream from dam, as determined from rating tables.

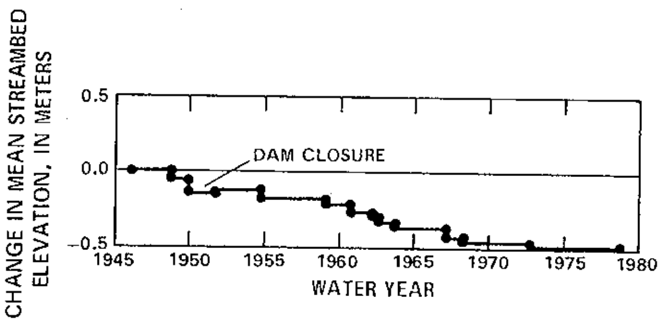


FIGURE 49.—Changes in mean streambed elevation with time at streamflow gaging station on Frenchman Creek 0.3 kilometer downstream from Enders Dam, Nebraska. Plotted points represent elevation corresponding to a discharge of 1.3 cubic meters per second, as determined from rating tables. No control station available.

Some of the rates and volumes of degradation in this study may appear small in the abstract. However, on a channel only 90 m wide and 15 km long, about 2 billion megagrams of sediment would be removed within 10 years from the bed of the channel alone, at the rates described. The consequences of such degradation can include undermining of structures, abandonment of water intakes, reduced channel conveyance due to flatter gradients, and a decreased capacity for the transport of sediment contributed by tributaries.

Commonly, the section of maximum degradation in most cases was close to the dam, and degradation then decreased progressively downstream. However, large and small depths of degradation commonly were distributed somewhat irregularly with distance downstream from the dam. Also, the downstream location of zero degradation ranged from several to about 2,000 channel widths (4 to 125 km). For these reasons a smooth longitudinal profile is rare. In some cases not even the anticipated downstream decline in degradation was observed within the distance covered by the cross sections. Further, although the longitudinal profile downstream from many dams tended to flatten with time as expected, this did not occur in all cases. Changes in channel elevation limited even to 1 or 2 m can significantly affect the longitudinal profile on many rivers.

Many analyses were performed in seeking correlations of variables that would characterize conditions before and after dam closure. No simple correlations could be established between channel size, channel gradient, particle size, or quantities of flow, with the exception of a tentative relation for channel width. This reflects the number of variables and great variability of conditions in the sample.

In several of the rivers studied, bank erosion appears to account for more than 50 percent of the sediment eroded from a given reach. Bank erosion is related to bank composition. Erosion may be particularly severe where the river impinges on a bank of readily erodible sand. Fine-grained cohesive sediments may slow the rate of erosion at specific points. In large rivers flowing on sand beds, such as those found in many areas of the western plains of the United States, the location of controls, discharge, and fluctuations of discharge appear to be principally responsible for varying rates of bank erosion.

Many large dams trap virtually all (about 99 percent) of the incoming sediment. The erosion of sediment immediately downstream from the dam, therefore, is not accompanied by replacement. Thus, although the rate of removal by the post-dam regulated flows may be less than that prevailing prior to regulation within a reach, the process does not result quickly in a new equilibrium. Both lateral erosion and degradation cease when the flow no longer transports the available sediments. Such cessation of net erosion may occur through local controls on boundary erosion, downstream base-level controls, decrease in flow competence (generally associated with armoring), infusion of additional transportable sediment, and through the development of channel vegetation. Armoring (increase in d_{50}) appeared to be approximately proportional to the depth of bed degradation downstream from three dams for which data were available (fig. 15).

Hundreds of kilometers of river distance downstream from a dam may be required before a river regains, by boundary erosion and tributary sediment contributions, the same annual suspended load or sediment concentration that it transported at any given site prior to dam construction. On the North Canadian River downstream from Canton Dam, this distance is about 200 to 500 km. On the Red River downstream from Denison Dam, the distance is about the same or possibly longer. On the Missouri River, 1,300 km downstream from Gavins Point Dam, the post-dam average annual suspended loads are only about 30 percent of the pre-dam loads. The Missouri and some other rivers probably are not long enough for complete recovery.

Evaluation of the effects of dams on downstream channels is made difficult by the absence of adequate observations on the changes of natural channels in different climatic and physiographic regions under unregulated conditions. Natural variability that characterizes such changes (tables 1–3) may mask the response of the channel to flow regulation. To the extent that it is known, the geologic record indicates that small changes in climatic factors can produce significant alterations in channel morphology. This potential effect also complicates the identification of those changes in channel morphology and vegetation that can be ascribed solely to the effect of manmade structures. Some of the channel changes documented here might well have occurred during the period of observation even in the absence of human interference. However, several common trends should be noted, namely: (1) Frequent occurrence of major changes right after dam closure; (2) appearance in many cases of the greatest change just downstream from the dam with progressive decrease or recovery downstream; (3) progressive change toward an apparent new stability at a site, in the years after dam closure; (4) continuous or non-reversible character of the change at many locations; and (5) diversity of climatic and physiographic regions in which the process has been observed. These trends point to the installation of water-regulating dams and reservoirs and to the consequent elimination or significant decrease of sediment into downstream reaches as primary causes of the progressive channel change in a number of instances.

Vegetation generally increased in the reaches downstream from the dams studied here, covering as much as 90 percent of the channel bars and banks along some rivers. In some cases, part of this increased growth might have occurred even without the dam. That is, vegetation in the region may have proliferated as a result of climate changes or for other reasons not fully understood. Decreases of high flows by the dam seem to contribute to an increased downstream growth of riparian vegetation in many cases.

Most of the rivers investigated here are in a semiarid environment where the effective annual precipitation is between 20 and 40 cm. This is precisely the precipitation zone that Langbein and Schumm (1958, p. 1080) suggested is the critical point at which sediment yield may either decrease or increase, depending upon whether vegetation increases or decreases in response to a change in precipitation. The changes of the alluvial ınnels downstream from dams, and, in particular, the ınges in vegetation and channel morphology observed a number of locations, indicate the sensitivity of ·se relationships to small changes within short times, to the effects of unusually large changes at a given ment in time. These effects may be mitigated or re- ·sed in several decades. However, it is still difficult predict what the effect of a persistent but small .nge in runoff, for example, would be on a given ch of channel. Interestingly, environmental-impact .lyses require predictions of just such changes.

Vhere downstream channels are surveyed following n construction, the usual method consists of topo- .phic resurveys of fixed cross sections. These are asured either at predetermined, approximately equal e intervals (usually every 5 or 10 years), or on rare l sporadic occasions as funds permit. Such surveys :ead need to be scheduled at frequent intervals (at st every 1 or 2 years) during the first 5 or 10 years ır dam closure, because most of the channel changes ur during this period. Later surveys can be done :h more infrequently, because much less change es place during a unit time in these later years. The :ter on a plot of channel change versus time reflects, sc extent, the desirable frequency of resurveys. e. .he scatter is large, shorter time intervals (more a) are needed to define a trend, and vice versa.

.lthough successive surveys of cross sections provide ential data for analyzing sediment and channel nges, repetitive aerial photography keyed to specific er stages might well provide more satisfactory data some purposes at less cost. Consideration needs to given to monitoring some major streams by means ıerial photography, perhaps using infrared tech- ıes, where photographs can be taken at specific er stages and seasons to make successive sets of :ography comparable. Such comparability is virtu- non-existent at the present time.

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TABLES 13, 14

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*

[Footnotes on last page of table]

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Colorado River, Arizona, Glen Canyon Dam				
Year of dam closure 1956[1]				
1956	0	1.1	0	[2] (104)
1959	3	1.1	-1.75	(137)
1963	7	1.1	-1.30	(141)
1965	9	1.1	-1.70	(141)(?)
1975	19	1.1	-1.90	(141)
1956	0	2.6	0	(183)
1959	3	2.6	-1.00	(183)
1963	7	2.6	-1.85	(183)
1965	9	2.6	-2.00	(183)
1975	19	2.6	-2.15	(183)
1956	0	4.3	0	(169)
1959	3	4.3	-2.10	(167)
1963	7	4.3	-2.45	(167)
1965	9	4.3	-3.65	(167)
1975	19	4.3	-3.70	(167)
1956	0	6.4	0	(272)
1959	3	6.4	-.90	(272)
1963	7	6.4	-1.20	(272)
1965	9	6.4	-1.50	(272)
1975	19	6.4	-1.60	(272)
1956	0	8.0	0	(140)
1959	3	8.0	-1.05	(143)
1963	7	8.0	-1.70	(146)
1965	9	8.0	-4.35	(146)
1975	19	8.0	-4.10	(146)
1956	0	10.5	0	(252)
1959	3	10.5	-.35	(252)
1963	7	10.5	-1.00	(280)
1965	9	10.5	-1.90	(285)
1975	19	10.5	-2.05	(285)
1956	0	13.0	0	(97.5)
1959	3	13.0	-.75	(99.0)
1963	7	13.0	-.25	(95.5)
1965	9	13.0	-4.05	(99.0)
1975	19	13.0	-4.50	(99.0)
Colorado River, Arizona, Glen Canyon Dam--Continued				
Year of dam closure 1956[1]				
1956	0	16.0	0	(95.5)
1959	3	16.0	-.85	(95.5)
1965	9	16.0	-7.25	(95.5)
1975	19	16.0	-7.00	(95.5)
1956	0	19.5	0	(189)
1959	3	19.5	-.45	(189)
1965	9	19.5	-2.00	(189)
1975	19	19.5	-2.20	(189)
1956	0	25	0	(109)
1959	3	25	0	(107)
1965	9	25	-5.20	(108)
1975	19	25	-3.80	(107)
Colorado River, Arizona, Hoover Dam				
Year of dam closure 1935				
1935	0	1.9	0	[2]
1935	.5	1.9	-1.20	--
1936	1	1.9	-1.30	--
1937	2	1.9	-1.35	--
1938	3	1.9	-.95	--
1939	4	1.9	-1.15	--
1940	5	1.9	-1.65	--
1941	6	1.9	-1.55	--
1942	7	1.9	-1.50	--
1943	8	1.9	-1.45	--
1944	9	1.9	-1.35	--
1945	10	1.9	-1.35	--
1946	11	1.9	-1.20	--
1947	12	1.9	-1.30	--
1948	13	1.9	-1.50	--
1935	0	2.3	0	--
1935	.5	2.3	-.10	--
1936	1	2.3	-.60	--
1937	2	2.3	-1.25	--
1938	3	2.3	-1.25	--
Colorado River, Arizona, Hoover Dam--Continued				
Year of dam closure 1935				
1939	4	2.3	-1.20	--
1940	5	2.3	-1.70	--
1941	6	2.3	-1.90	--
1942	7	2.3	-2.05	--
1943	8	2.3	-2.05	--
1944	9	2.3	-1.65	--
1945	10	2.3	-1.50	--
1946	11	2.3	-1.70	--
1947	12	2.3	-1.65	--
1948	13	2.3	-1.60	--
1935	0	3.2	0	--
1935	.5	3.2	-1.95	--
1936	1	3.2	-2.70	--
1937	2	3.2	-3.60	--
1938	3	3.2	-3.60	--
1939	4	3.2	-3.65	--
1940	5	3.2	-5.25	--
1941	6	3.2	-5.10	--
1942	7	3.2	-5.10	--
1943	8	3.2	-4.90	--
1944	9	3.2	-5.00	--
1945	10	3.2	-4.70	--
1946	11	3.2	-4.70	--
1947	12	3.2	-4.90	--
1948	13	3.2	-5.20	--
1935	0	4.5	0	--
1935	.5	4.5	-1.60	--
1936	1	4.5	-2.15	--
1937	2	4.5	-2.15	--
1938	3	4.5	-2.25	--
1939	4	4.5	-2.25	--
1940	5	4.5	-2.45	--
1941	6	4.5	-2.45	--
1942	7	4.5	-2.55	--
1943	8	4.5	-2.50	--
Colorado River, Arizona, Hoover Dam--Continued				
Year of dam closure 1935				
1944	9	4.5	-2.75	--
1945	10	4.5	-2.80	--
1946	11	4.5	-2.80	--
1947	12	4.5	-2.85	--
1948	13	4.5	-2.75	--
1935	0	5.5	0	--
1935	.5	5.5	-1.10	--
1936	1	5.5	-1.20	--
1937	2	5.5	-1.15	--
1938	3	5.5	-1.20	--
1939	4	5.5	-1.15	--
1940	5	5.5	-1.25	--
1941	6	5.5	-1.25	--
1942	7	5.5	-1.30	--
1943	8	5.5	-1.45	--
1944	9	5.5	-1.25	--
1945	10	5.5	-1.00	--
1946	11	5.5	-.80	--
1947	12	5.5	-.95	--
1948	13	5.5	-1.15	--
1935	0	6.1	0	--
1935	.5	6.1	-1.35	--
1936	1	6.1	-1.45	--
1937	2	6.1	-2.25	--
1938	3	6.1	-2.15	--
1939	4	6.1	-1.75	--
1940	5	6.1	-2.60	--
1941	6	6.1	-2.60	--
1942	7	6.1	-2.80	--
1943	8	6.1	-2.65	--
1944	9	6.1	-2.45	--
1945	10	6.1	-2.20	--
1946	11	6.1	-2.00	--
1947	12	6.1	-2.15	--
1948	13	6.1	-2.35	--

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Year of data collection: Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Colorado River, Arizona, Hoover Dam—Continued				
Year of dam closure 1935				
1935	0	7.1	0	--
1935	.5	7.1	-1.20	--
1936	1	7.1	-2.05	--
1937	2	7.1	-2.70	--
1938	3	7.1	-3.15	--
1939	4	7.1	-3.05	--
1940	5	7.1	-3.00	--
1941	6	7.1	-3.05	--
1942	7	7.1	-3.85	--
1943	8	7.1	-3.20	--
1944	9	7.1	-3.20	--
1945	10	7.1	-3.25	--
1946	11	7.1	-3.15	--
1947	12	7.1	-3.15	--
1948	13	7.1	-3.10	--
1935	0	8.0	0	--
1935	.5	8.0	-2.20	--
1936	1	8.0	-2.30	--
1937	2	8.0	-2.70	--
1938	3	8.0	-2.95	--
1939	4	8.0	-3.35	--
1940	5	8.0	-4.45	--
1941	6	8.0	-4.65	--
1942	7	8.0	-4.70	--
1943	8	8.0	-4.55	--
1944	9	8.0	-4.35	--
1945	10	8.0	-4.35	--
1946	11	8.0	-4.35	--
1947	12	8.0	-4.35	--
1948	13	8.0	-4.35	--
1935	0	9.7	0	--
1935	.5	9.7	-.75	--
1936	1	9.7	-1.60	--
1937	2	9.7	-1.85	--
1938	3	9.7	-2.35	--

Year of data collection: Year	Year of data collection: Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Colorado River, Arizona, Hoover Dam—Continued				
Year of dam closure 1935				
1939	4	9.7	-2.75	--
1940	5	9.7	-3.75	--
1941	6	9.7	-3.70	--
1942	7	9.7	-4.40	--
1943	8	9.7	-4.50	--
1944	9	9.7	-4.55	--
1945	10	9.7	-4.50	--
1946	11	9.7	-4.35	--
1947	12	9.7	-4.35	--
1948	13	9.7	-4.35	--
1935	0	10.5	0	--
1935	.5	10.5	-.50	--
1936	1	10.5	-1.20	--
1937	2	10.5	-1.10	--
1938	3	10.5	-1.05	--
1939	4	10.5	-.95	--
1940	5	10.5	-1.15	--
1941	6	10.5	-1.15	--
1942	7	10.5	-1.15	--
1943	8	10.5	-1.15	--
1944	9	10.5	-1.05	--
1945	10	10.5	-1.05	--
1946	11	10.5	-1.15	--
1947	12	10.5	-1.15	--
1948	13	10.5	-1.15	--
1935	0	11.0	0	--
1935	.5	11.0	-.60	--
1936	1	11.0	-1.00	--
1937	2	11.0	-1.20	--
1938	3	11.0	-1.40	--
1939	4	11.0	-1.35	--
1940	5	11.0	-1.70	--
1941	6	11.0	-1.80	--
1942	7	11.0	-1.85	--
1943	8	11.0	-2.00	--

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Year of data collection: Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Colorado River, Arizona, Hoover Dam—Continued				
Year of dam closure 1935				
1944	9	11.0	-1.90	--
1945	10	11.0	-1.85	--
1946	11	11.0	-1.85	--
1947	12	11.0	-1.90	--
1948	13	11.0	-1.90	--
1935	0	12.5	0	--
1935	.5	12.5	-1.75	--
1936	1	12.5	-2.15	--
1937	2	12.5	-2.55	--
1938	3	12.5	-2.95	--
1939	4	12.5	-2.90	--
1940	5	12.5	-4.35	--
1941	6	12.5	-3.95	--
1942	7	12.5	-5.25	--
1943	8	12.5	-5.70	--
1944	9	12.5	-5.90	--
1945	10	12.5	-6.20	--
1946	11	12.5	-6.35	--
1947	12	12.5	-6.90	--
1948	13	12.5	-7.45	--
1935	0	13.5	0	--
1935	.5	13.5	-1.90	--
1936	1	13.5	-1.70	--
1937	2	13.5	-1.90	--
1938	3	13.5	-1.85	--
1939	4	13.5	-1.70	--
1940	5	13.5	-3.30	--
1941	6	13.5	-3.55	--
1942	7	13.5	-3.45	--
1943	8	13.5	-3.65	--
1944	9	13.5	-3.65	--
1945	10	13.5	-3.70	--
1946	11	13.5	-3.65	--
1947	12	13.5	-3.70	--
1948	13	13.5	-3.70	--

Year of data collection: Year	Year of data collection: Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Colorado River, Arizona, Hoover Dam—Continued				
Year of dam closure 1935				
1935	0	15.5	0	--
1935	.5	15.5	-1.50	--
1936	1	15.5	-2.15	--
1937	2	15.5	-2.50	--
1938	3	15.5	-3.30	--
1939	4	15.5	-4.40	--
1940	5	15.5	-4.35	--
1941	6	15.5	-4.45	--
1942	7	15.5	-5.50	--
1943	8	15.5	-5.10	--
1944	9	15.5	-5.20	--
1945	10	15.5	-5.10	--
1946	11	15.5	-5.15	--
1947	12	15.5	-5.25	--
1948	13	15.5	-5.25	--
1935	0	16.5	0	--
1935	.5	16.5	-.25	--
1936	1	16.5	-1.50	--
1937	2	16.5	-1.90	--
1938	3	16.5	-2.00	--
1939	4	16.5	-2.25	--
1940	5	16.5	-3.05	--
1941	6	16.5	-3.05	--
1942	7	16.5	-3.10	--
1943	8	16.5	-3.15	--
1944	9	16.5	-3.10	--
1945	10	16.5	-3.10	--
1946	11	16.5	-3.10	--
1947	12	16.5	-3.35	--
1948	13	16.5	-3.65	--
1935	0	18.0	0	--
1935	.5	18.0	-.25	--
1936	1	18.0	-1.15	--
1937	2	18.0	-1.85	--
1938	3	18.0	-2.00	--

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Year of data collection: Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Colorado River, Arizona, Hoover Dam--Continued				
Year of dam closure 1935				
1939	4	18.0	-2.15	--
1940	5	18.0	-2.60	--
1941	6	18.0	-2.55	--
1942	7	18.0	-2.45	--
1943	8	18.0	-2.60	--
1944	9	18.0	-2.60	--
1945	10	18.0	-2.50	--
1946	11	18.0	-2.40	--
1947	12	18.0	-2.45	--
1948	13	18.0	-2.55	--
1935	0	19.5	0	--
1935	.5	19.5	-.20	--
1936	1	19.5	-1.65	--
1937	2	19.5	-1.65	--
1938	3	19.5	-1.85	--
1939	4	19.5	-2.55	--
1940	5	19.5	-3.55	--
1941	6	19.5	-3.65	--
1942	7	19.5	-4.15	--
1943	8	19.5	-4.30	--
1944	9	19.5	-4.40	--
1945	10	19.5	-4.50	--
1946	11	19.5	-4.50	--
1947	12	19.5	-4.65	--
1948	13	19.5	-4.80	--
1935	0	21	0	--
1935	.5	21	0	--
1936	1	21	-1.00	--
1937	2	21	-1.50	--
1938	3	21	-1.65	--
1939	4	21	-2.05	--
1940	5	21	-2.40	--
1941	6	21	-2.55	--
1942	7	21	-2.60	--
1943	8	21	-2.60	--
1944	9	21	-2.60	--
1945	10	21	-2.60	--
1946	11	21	-2.65	--
1947	12	21	-2.75	--
1948	13	21	-2.75	--
1935	0	28	--	--
1935	.5	28	[3] 0	--
1936	1	28	-.10	--
1937	2	28	-.35	--
1938	3	28	-.75	--
1939	4	28	-1.00	--
1940	5	28	-1.75	--
1941	6	28	-1.95	--
1942	7	28	-3.10	--
1943	8	28	-3.10	--
1944	9	28	-2.95	--
1945	10	28	-2.95	--
1946	11	28	-3.25	--
1947	12	28	-3.25	--
1948	13	28	-3.35	--
1935	0	36	--	--
1935	.5	36	0	--
1936	1	36	[3] 0	--
1937	2	36	-.45	--
1938	3	36	-.90	--
1939	4	36	-1.20	--
1940	5	36	-1.20	--
1941	6	36	-1.40	--
1942	7	36	-2.15	--
1943	8	36	-2.30	--
1944	9	36	-2.30	--
1945	10	36	-2.40	--
1946	11	36	-2.30	--
1947	12	36	-2.30	--
1948	13	36	-2.30	--
1935	0	42	--	--
1935	.5	42	[3] 0	--
1936	1	42	-.30	--
1937	2	42	-.50	--
1938	3	42	-.75	--
1939	4	42	-1.00	--
1940	5	42	-1.20	--
1941	6	42	-1.05	--
1942	7	42	-2.70	--
1943	8	42	-2.60	--
1944	9	42	-2.60	--
1945	10	42	-2.90	--
1946	11	42	-3.30	--
1947	12	42	-3.40	--
1948	13	42	-3.40	--
1935	0	51	--	--
1935	.5	51	--	--
1936	1.1	51	[3] 0	--
1937	2	51	-.15	--
1938	3	51	-.30	--
1939	4	51	-.60	--
1940	5	51	-.85	--
1941	6	51	-1.05	--
1942	7	51	-2.30	--
1943	8	51	-2.20	--
1944	9	51	-2.75	--
1945	10	51	-2.80	--
1946	11	51	-2.80	--
1947	12	51	-3.00	--
1948	13	51	-3.10	--
1935	0	57	--	--
1935	.5	57	--	--
1936	1.1	57	[3] 0	--
1937	2	57	-.30	--
1938	3	57	-.65	--
1939	4	57	-1.00	--
1940	5	57	-1.50	--
1941	6	57	-1.35	--
1942	7	57	-2.05	--
1943	8	57	-2.95	--
1944	9	57	-2.95	--
1945	10	57	-3.10	--
1946	11	57	-3.55	--
1947	12	57	-3.00	--
1948	13	57	-3.00	--
1935	0	63	--	--
1935	.5	63	--	--
1936	1.1	63	[3] 0	--
1937	2	63	-.10	--
1938	3	63	-.75	--
1939	4	63	-.90	--
1940	5	63	-1.35	--
1941	6	63	-1.50	--
1942	7	63	-3.55	--
1943	8	63	-3.30	--
1944	9	63	-3.15	--
1945	10	63	-3.60	--
1946	11	63	-3.50	--
1947	12	63	-2.80	--
1948	13	63	-4.50	--
1935	0	70	0	--
1935	.5	70	+.05	--
1936	1	70	-.15	--
1937	2	70	-.90	--
1938	3	70	-1.20	--
1939	4	70	-1.45	--
1940	5	70	-1.95	--
1941	6	70	-2.20	--
1942	7	70	-3.15	--
1943	8	70	-3.55	--

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Year of data collection: Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
		Colorado River, Arizona, Hoover Dam--Continued		
		Year of dam closure 1935		
1944	9	70	-3.95	--
1945	10	70	-4.15	--
1946	11	70	-4.35	--
1947	12	70	-4.35	--
1948	13	70	-4.40	--
1935	0	77	--	--
1935	.5	77	--	--
1936	1	77	--	--
1937	2.6	77	[3/] 0	--
1938	3	77	-.20	--
1939	4	77	-.55	--
1940	5	77	-.70	--
1941	6	77	-.90	--
1942	7	77	-1.65	--
1943	8	77	-1.70	--
1944	9	77	-2.45	--
1945	10	77	-2.45	--
1946	11	77	-2.30	--
1947	12	77	-2.45	--
1948	13	77	-2.50	--
1935	0	87	--	--
1935	.5	87	--	--
1936	1	87	--	--
1937	2.6	87	[3/] 0	--
1938	3	87	-.10	--
1939	4	87	-.25	--
1940	5	87	-.50	--
1941	6	87	-.75	--
1942	7	87	-.85	--
1943	8	87	-1.20	--
1944	9	87	-2.05	--
1945	10	87	-2.10	--
1946	11	87	-2.15	--
1947	12	87	-2.20	--
1948	13	87	-2.40	--
		Colorado River, Arizona, Hoover Dam--Continued		
		Year of dam closure 1935		
1935	0	94	--	--
1935	.5	94	--	--
1936	1	94	--	--
1937	2.6	94	[3/] 0	--
1938	3	94	-.25	--
1939	4	94	-.60	--
1940	5	94	-.65	--
1941	6	94	-1.00	--
1942	7	94	-1.70	--
1943	8	94	-2.10	--
1944	9	94	-2.55	--
1945	10	94	-2.75	--
1946	11	94	-2.80	--
1947	12	94	-3.00	--
1948	13	94	-3.10	--
1935	0	104	--	--
1935	.5	104	--	--
1936	1	104	--	--
1937	2	104	--	--
1938	3	104	[3/] 0	--
1939	4	104	-.65	--
1940	5	104	-.55	--
1941	6	104	-1.05	--
1942	7	104	-1.70	--
1943	8	104	-2.05	--
1944	9	104	-2.15	--
1945	10	104	-2.60	--
1946	11	104	-3.10	--
1947	12	104	-3.30	--
1948	13	104	-3.10	--
1935	0	110	--	--
1935	.5	110	--	--
1936	1	110	--	--
1937	2	110	--	--
1938	3.2	110	[3/] 0	--
		Colorado River, Arizona, Hoover Dam--Continued		
		Year of dam closure 1935		
1939	4	110	-0.35	--
1940	5	110	-.60	--
1941	6	110	-1.15	--
1942	7	110	-1.80	--
1943	8	110	-1.85	--
1944	9	110	-2.40	--
1945	10	110	-2.55	--
1946	11	110	-2.65	--
1947	12	110	-2.75	--
1948	13	110	-2.95	--
1935	0	117	--	--
1935	.5	117	--	--
1936	1	117	--	--
1937	2	117	--	--
1938	3.2	117	[3/] 0	--
1939	4	117	0	--
1940	5	117	-.50	--
1941	6	117	-.85	--
1942	7	117	-1.85	--
1943	8	117	-1.85	--
1944	9	117	-2.45	--
1945	10	117	-2.65	--
1946	11	117	-3.05	--
1947	12	117	-3.55	--
1948	13	117	-3.70	
		Colorado River, Arizona, Davis Dam		
		Year of dam closure 1948[4/]		
1948	0	1.1	0	[2/]
1948	.5	1.1	-.65	--
1949	1	1.1	-1.20	--
1950	2	1.1	-2.20	--
1951	3	1.1	-2.45	--
		Colorado River, Arizona, Davis Dam--Continued		
		Year of dam closure 1948[4/]		
1952	4	1.1	-2.60	--
1953	5	1.1	-3.25	--
1954	6	1.1	-3.40	--
1955	7	1.1	-3.80	--
1956	8	1.1	-4.85	--
1957	9	1.1	-4.85	--
1958	10	1.1	-4.40	--
1959	11	1.1	-4.95	--
1960	12	1.1	-5.05	--
1961	13	1.1	-5.10	--
1962	14	1.1	-5.05	--
1963	15	1.1	-4.90	--
1964	16	1.1	-4.90	--
1965	17	1.1	-5.05	--
1966	18	1.1	-5.10	--
1967	19	1.1	-5.05	--
1968	20	1.1	-5.10	--
1969	21	1.1	-5.35	--
1970	22	1.1	-5.65	--
1971	23	1.1	-5.65	--
1972	24	1.1	-5.50	--
1973	25	1.1	-5.60	--
1974	26	1.1	-5.75	--
1975	27	1.1	-5.65	--
1948	0	8.8	0	--
1949	1	8.8	-.20	--
1950	2	8.8	-.45	--
1951	3	8.8	-.50	--
1952	4	8.8	-.65	--
1953	5	8.8	-1.40	--
1954	6	8.8	-1.45	--
1955	7	8.8	-1.45	--
1956	8	8.8	-1.55	--
1957	9	8.8	-1.70	--

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
		Colorado River, Arizona, Davis Dam--Continued		
		Year of dam closure 1948 4/		
1958	10	8.8	-2.00	--
1959	11	8.8	-2.00	--
1960	12	8.8	-2.05	--
1961	13	8.8	-2.05	--
1962	14	8.8	-2.15	--
1963	15	8.8	-2.15	--
1964	16	8.8	-2.40	--
1965	17	8.8	-2.60	--
1966	18	8.8	-2.70	--
1967	19	8.8	-2.75	--
1968	20	8.8	-2.80	--
1969	21	8.8	-2.65	--
1970	22	8.8	-2.40	--
1971	23	8.8	-2.30	--
1972	24	8.8	-2.45	--
1973	25	8.8	-2.60	--
1974	26	8.8	-2.70	--
1975	27	8.8	-2.75	--
		Colorado River, Arizona, Parker Dam		
		Year of dam closure 1938		
1938	0	27	5/0	2/
1939	1	27	-.65	--
1940	2	27	-1.00	--
1941	3	27	-1.50	--
1942	4	27	-1.80	--
1943	5	27	-2.05	--
1944	6	27	-2.30	--
1945	7	27	-2.45	--
1947	9	27	-2.60	--
1949	11	27	-2.55	--
1951	13	27	-2.60	--
1955	17	27	-2.85	--
1960	22	27	-2.95	--
1965	27	27	-3.00	--
1970	32	27	-3.05	--
1975	37	27	-3.15	--
		Colorado River, Arizona, Parker Dam--Continued		
		Year of dam closure 1938		
1938	0	39	0	--
1939	1	39	-.05	--
1940	2	39	-.10	--
1941	3	39	-.75	--
1942	4	39	-1.80	--
1943	5	39	-2.05	--
1944	6	39	-2.60	--
1945	7	39	-2.45	--
1947	9	39	-2.75	--
1949	11	39	-2.80	--
1951	13	39	-3.50	--
1955	17	39	-3.80	--
1960	22	39	-3.85	--
1965	27	39	-3.65	--
1970	32	39	-4.35	--
1975	37	39	-4.35	--
1938	0	46	0	--
1939	1	46	-.15	--
1940	2	46	-.65	--
1941	3	46	-1.30	--
1942	4	46	-2.25	--
1943	5	46	-2.45	--
1944	6	46	-2.60	--
1945	7	46	-2.70	--
1947	9	46	-2.85	--
1949	11	46	-2.85	--
1951	13	46	-2.85	--
1955	17	46	-3.65	--
1960	22	46	-4.20	--
1965	27	46	-4.60	--
1970	32	46	-4.15	--
1975	37	46	-4.25	--
1938	0	66	0	--
1939	1	66	-.30	--
1940	2	66	-.60	--
1941	3	66	-1.35	--
1942	4	66	-2.25	--
		Colorado River, Arizona, Parker Dam--Continued		
		Year of dam closure 1938		
1943	5	66	-2.30	--
1944	6	66	-2.55	--
1945	7	66	-2.90	--
1947	9	66	-2.85	--
1949	11	66	-2.70	--
1951	13	66	-3.00	--
1955	17	66	-2.75	--
1960	22	66	-3.30	--
1965	27	66	-2.70	--
1970	32	66	-3.30	--
1975	37	66	-3.45	--
1938	0	80	0	--
1939	1	80	-.10	--
1940	2	80	-.20	--
1941	3	80	-1.05	--
1942	4	80	-1.40	--
1943	5	80	-1.75	--
1944	6	80	-1.50	--
1945	7	80	-1.50	--
1947	9	80	-1.40	--
1949	11	80	-1.05	--
1951	13	80	-1.60	--
1955	17	80	-1.50	--
1960	22	80	-1.70	--
1965	27	80	-2.05	--
1970	32	80	-2.05	--
1975	37	80	-2.40	--
1938	0	95	0	--
1939	1	95	+.05	--
1940	2	95	-.35	--
1941	3	95	-.65	--
1942	4	95	-.80	--
1943	5	95	-1.50	--
1944	6	95	-1.90	--
1945	7	95	-1.35	--
1947	9	95	-1.20	--
1949	11	95	-1.25	--
		Colorado River, Arizona, Parker Dam--Continued		
		Year of dam closure 1938		
1951	13	95	-1.35	--
1955	17	95	-1.00	--
1960	22	95	-1.95	--
1965	27	95	-2.05	--
1970	32	95	-2.20	--
1975	37	95	-2.05	--
		Jemez River, New Mexico, Jemez Canyon Dam		
		Year of dam closure 1953		
1952	0	1.0	0	142
1959	6	1.0	-2.7	49.0
1965	12	1.0	-2.7	11.5
1975	22	1.0	-1.7	31.0
1952	0	1.3	0	272
1959	6	1.3	-2.4	70.0
1965	12	1.3	-2.7	17.0
1975	22	1.3	-1.5	24.0
1952	0	1.6	0	270
1959	6	1.6	-1.8	138
1965	12	1.6	-2.8	21.5
1975	22	1.6	-2.1	20.0
1952	0	1.8	0	216
1959	6	1.8	-2.2	105
1965	12	1.8	-3.0	48.5
1975	22	1.8	-1.9	49.5
1952	0	2.4	0	190
1959	6	2.4	-1.4	133
1965	12	2.4	-2.7	18.5
1975	22	2.4	-1.6	29.5
1952	0	2.7	0	220
1959	6	2.7	-1.8	39.5
1965	12	2.7	-2.1	42.0
1975	22	2.7	-1.3	59.0

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Jemez River, New Mexico, Jemez Canyon Dam--Continued				
Year of dam closure 1953				
1952	0	3.1	0	214
1959	6	3.1	-1.5	75.5
1965	12	3.1	-1.8	74.5
1975	22	3.1	-1.0	47.0
1952	0	3.4	0	178
1959	6	3.4	-1.1	74.5
1965	12	3.4	-1.3	100
1975	22	3.4	-.6	110
Arkansas River, Colorado, John Martin Dam				
Year of dam closure 1942				
12/43-2/44	1	3.5	[3] 0	146
1951	9	3.5	-.10	142
1966	24	3.5	-1.95	30.5
1972	30	3.5	-.40	27.0
12/43-2/44	1	5.0	[3] 0	128
1951	9	5.0	-.10	131
1966	24	5.0	-1.05	46.5
1972	30	5.0	-.35	44.0
12/43-2/44	1	8.5	[3] 0	76.0
1951	9	8.5	-.30	69.5
1966	24	8.5	-.80	39.5
1972	30	8.5	-.35	34.0
12/43-2/44	1	12.0	[3] 0	100
1951	9	12.0	-.20	95.5
1966	24	12.0	-.80	30.0
1972	30	12.0	-.85	35.0
12/43-2/44	1	15.5	[3] 0	157
1951	9	15.5	-.25	88.0
1966	24	15.5	-.85	40.5
1972	30	15.5	-.90	38.5

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Arkansas River, Colorado, John Martin Dam--Continued				
Year of dam closure 1942				
12/43-2/44	1	19.0	[3] 0	144
1951	9	19.0	-.05	144
1966	24	19.0	-.15	96.5
1972	30	19.0	-.50	43.5
12/43-2/44	1	22	[3] 0	288
1951	9	22	-.60	165
1966	24	22	-1.15	74.0
1972	30	22	-.95	72.5
12/43-2/44	1	26	[3] 0	230
1951	9	26	-.25	241
1966	24	26	-.85	127
1972	30	26	-.75	86.5
12/43-2/44	1	29	[3] 0	168
1951	9	29	+.20	165
1966	24	29	+.25	46.0
1972	30	29	+1.30	50.0
12/43-2/44	1	33	[3] 0	201
1951	9	33	-.65	130
1966	24	33	-.40	99.5
1972	30	33	-.45	59.0
12/43-2/44	1	36	0	110
1951	9	36	-.15	75.5
1966	24	36	-.20	56.5
1972	30	36	-.20	59.0

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Missouri River, Montana, Fort Peck Dam				
Year of dam closure 1937[6]				
1936	0	9.2	0	348
1950	13	9.2	-.80	398
1955	18	9.2	-.65	402
1956	19	9.2	-.70	402
1958	21	9.2	-.70	408
1960	23	9.2	-.65	408
1966	29	9.2	-.75	408
1973	36	9.2	-.90	408
1936	0	13.0	0	234
1950	13	13.0	-.65	238
1955	18	13.0	-.80	238
1956	19	13.0	-.75	238
1958	21	13.0	-.60	236
1960	23	13.0	-.75	236
1966	29	13.0	-1.00	238
1973	36	13.0	-1.05	238
1936	0	16.5	0	248
1950	13	16.5	-1.00	304
1955	18	16.5	-1.20	336
1956	19	16.5	-1.00	336
1958	21	16.5	-1.00	336
1960	23	16.5	-1.05	336
1966	29	16.5	-1.15	340
1973	36	16.5	-1.75	340
1936	0	23	0	256
1950	13	23	-.50	262
1955	18	23	-.70	268
1956	19	23	-1.00	268
1958	21	23	-1.05	272
1960	23	23	-1.15	272
1966	29	23	-1.15	272
1973	36	23	-1.50	274

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Missouri River, Montana, Fort Peck Dam--Continued				
Year of dam closure 1937[6]				
1936	0	45	0	190
1950	13	45	-.15	202
1955	18	45	-.45	212
1956	19	45	-.60	212
1958	21	45	-.10	212
1960	23	45	-.20	216
1966	29	45	-.40	238
1973	36	45	-.75	238
1936	0	75	0	274
1950	13	75	-.20	286
1955	18	75	-.40	286
1956	19	75	-.25	288
1958	21	75	+.05	290
1960	23	75	-.10	292
1966	29	75	-.20	292
1973	36	75	-.25	298
Missouri River, North Dakota, Garrison Dam				
Year of dam closure 1953				
1946	(0)	2.7	0	530
1954	1	2.7	-.20	550
1960	7	2.7	[7] -1.35	505
1964	11	2.7	[7] -1.60	505
1970	17	2.7	[7] -2.30	505
1976	23	2.7	[7] -2.80	500
1946	(0)	6.4	0	450
1954	1	6.4	-.45	525
1960	7	6.4	[7] -2.10	388
1964	11	6.4	[7] -2.75	390
1970	17	6.4	[7] -3.65	392
1976	23	6.4	[7] -3.95	402

Table 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Missouri River, North Dakota, Garrison Dam--Continued				
Year of dam closure 1953				
1946	(0)	8.0	0	458
1954	1	8.0	-.65	424
1960	7	8.0	-1.70	428
1964	11	8.0	-2.20	428
1970	17	8.0	-2.70	428
1976	23	8.0	-3.25	428
1946	(0)	10.5	0	585
1954	1	10.5	-.75	520
1960	7	10.5	-1.35	525
1964	11	10.5	-1.60	540
1970	17	10.5	-2.35	555
1976	23	10.5	-2.75	565
1946	(0)	12.0	0	492
1954	1	12.0	+.05	520
1960	7	12.0	-1.00	520
1964	11	12.0	-1.35	530
1970	17	12.0	-1.50	545
1976	23	12.0	-2.10	540
1946	(0)	15.0	0	505
1948	(0)	15.0	-.35	535
1954	1	15.0	+.05	580
1960	7	15.0	-.65	630
1964	11	15.0	-.75	715
1970	17	15.0	-1.15	790
1976	23	15.0	-1.25	835
1946	(0)	17.5	0	310
1954	1	17.5	0	570
1960	7	17.5	-.65	600
1964	11	17.5	-.15	610
1970	17	17.5	-1.45	680
1976	23	17.5	-.90	705
1946	(0)	21	0	895
1954	1	21	-.35	915
1960	7	21	+.65	925
1964	11	21	+.45	930
1970	17	21	+.10	945
1976	23	21	+.05	960

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Missouri River, North Dakota, Garrison Dam--Continued				
Year of dam closure 1953				
1946	(0)	24	0	--
1954	1	24	-.80	1,295
1960	7	24	-1.60	1,300
1964	11	24	-1.60	1,305
1970	17	24	-1.90	1,310
1976	23	24	-1.95	1,315
1949	(0)	28	0	300
1954	1	28	-1.00	300
1960	7	28	-.70	296
1964	11	28	-1.05	298
1970	17	28	-2.15	300
1976	23	28	-3.05	306
1949	(0)	32	0	1,290
1954	1	32	-.40	1,395
1960	7	32	-.35	1,425
1964	11	32	-.50	1,430
1970	17	32	-.65	1,435
1976	23	32	-.80	1,430
1949	(0)	36	0	1,325
1954	1	36	-.35	865
1960	7	36	-1.00	855
1964	11	36	-.90	885
1970	17	36	-1.60	955
1976	23	36	-1.50	1,005
1949	(0)	38	0	448
1954	1	38	-.20	520
1960	7	38	-.30	525
1964	11	38	-.40	540
1970	17	38	-.70	555
1976	23	38	-1.50	595
1949	(0)	44	0	462
1954	1	44	+.10	505
1960	7	44	-.20	685
1964	11	44	-.05	740
1970	17	44	-.20	790
1976	23	44	-.85	805

Table 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Missouri River, North Dakota, Garrison Dam--Continued				
Year of dam closure 1953				
1949	(0)	47	0	525
1954	1	47	+.45	710
1960	7	47	+.45	930
1964	11	47	+.25	1,140
1970	17	47	-.35	1,145
1976	23	47	-1.05	1,150
1949	(0)	51	0	840
1954	1	51	+.05	845
1960	7	51	-1.05	488
1964	11	51	-.85	550
1970	17	51	-1.05	600
1976	23	51	-1.65	625
1949	(0)	54	0	376
1954	1	54	+.90	645
1960	7	54	+.65	690
1964	11	54	+.95	700
1970	17	54	+.35	725
1976	23	54	-.25	790
1949	(0)	58	0	635
1954	1	58	+.25	680
1960	7	58	-.45	715
1964	11	58	-.15	725
1970	17	58	-.35	740
1976	23	58	-.50	765
1949	(0)	61	0	565
1954	1	61	0	510
1960	7	61	+.30	595
1964	11	61	+.30	620
1970	17	61	-.45	635
1976	23	61	-.30	670
1949	(0)	70	0	416
1954	1	70	+.05	420
1960	7	70	+.25	424
1964	11	70	-.15	422
1970	17	70	-.45	428
1976	23	70	-.50	430

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Missouri River, North Dakota, Garrison Dam--Continued				
Year of dam closure 1953				
1949	(0)	78	0	448
1954	1	78	+.45	490
1960	7	78	+.45	505
1964	11	78	+.25	525
1970	17	78	-.20	545
1976	23	78	-.35	560
1946	(0)	87	0	434(?)
1954	1	87	+.75	595
1960	7	87	+.65	605
1964	11	87	+.60	605
1970	17	87	+.10	610
1976	23	87	+.20	615
Missouri River, South Dakota, Fort Randall Dam				
Year of dam closure 1952				
1952	0	1.6	0	484
1954	2	1.6	-1.00	484
1957	5	1.6	-1.30	472
1960	8	1.6	-.85	448
1962	10	1.6	-.80	458
1967	15	1.6	-.90	458
1970	18	1.6	-.25	585
1975	23	1.6	-.45	590
1952	0	3.1	0	645
1954	2	3.1	-.35	645
1957	5	3.1	-.70	650
1960	8	3.1	-.60	650
1962	10	3.1	-.95	650
1967	15	3.1	-.90	655
1970	18	3.1	-1.00	655
1975	23	3.1	-1.45	655
1952	0	4.2	0	675
1954	2	4.2	-.25	675
1956	4	4.2	-.65	675

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
	Missouri River, South Dakota, Fort Randall Dam--Continued			
	Year of dam closure 1952			
1962	10	4.2	-0.90	685
1967	15	4.2	-.90	690
1970	18	4.2	-1.05	695
1975	23	4.2	-1.35	690
1952	0	5.1	0	720
1954	2	5.1	+.20	745
1957	5	5.1	-.40	730
1960	8	5.1	-.40	735
1962	10	5.1	-.60	740
1967	15	5.1	-.60	750
1970	18	5.1	-.80	755
1975	23	5.1	-.80	755
1952	0	6.6	0	1,060
1954	2	6.6	-.20	1,075
1956	4	6.6	-.50	1,095
1960	8	6.6	-1.15	1,115
1962	10	6.6	-1.30	1,130
1967	15	6.6	-1.15	1,130
1970	18	6.6	-1.15	1,135
1975	23	6.6	-1.85	1,165
1952	0	7.7	0	1,070
1954	2	7.7	-.25	1,115
1957	5	7.7	-.75	1,130
1960	8	7.7	-1.10	1,145
1962	10	7.7	-1.35	1,160
1967	15	7.7	-1.15	1,245
1970	18	7.7	-1.05	1,260
1975	23	7.7	-1.60	1,280
1952	0	11.0	0	404
1954	2	11.0	-1.30	406
1956	4	11.0	-1.75	406
1960	8	11.0	-1.50	408
1962	10	11.0	-1.50	410
1967	15	11.0	-1.65	420
1975	23	11.0	-2.60	462

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
	Missouri River, South Dakota, Fort Randall Dam--Continued			
	Year of dam closure 1952			
1952	0	12.5	0	565
1954	2	12.5	0	565
1956	4	12.5	-.60	570
1960	8	12.5	-.75	570
1962	10	12.5	-.80	575
1967	15	12.5	-.80	585
1975	23	12.5	-1.40	605
1952	0	14.5	0	1,080
1954	2	14.5	+.50	1,070
1957	5	14.5	+.20	1,060
1960	8	14.5	+.25	1,065
1962	10	14.5	+.35	1,065
1967	15	14.5	+.20	1,065
1970	18	14.5	+.10	1,065
1975	23	14.5	0	1,035
1952	0	19.0	0	366
1954	2	19.0	-.10	366
1957	5	19.0	-.05	406
1960	8	19.0	-.45	645
1962	10	19.0	-.20	700
1967	15	19.0	+.35	735
1975	23	19.0	-.15	750
1952	0	24	0	640
1954	2	24	-.30	640
1957	5	24	+.10	650
1960	8	24	+.30	645
1962	10	24	+.25	645
1967	15	24	-.35	645
1975	23	24	-.75	645
1952	0	29	0	1,040
1954	2	29	-.45	1,070
1956	4	29	-.50	1,075
1960	8	29	-.50	1,070

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
	Missouri River, South Dakota, Fort Randall Dam--Continued			
	Year of dam closure 1952			
1962	10	29	-0.50	1,065
1967	15	29	-.50	1,075
1970	18	29	-.75	1,075
1975	23	29	-.65	1,075
1952	0	35	0	695
1954	2	35	+.05	695
1957	5	35	+.10	695
1960	8	35	+.05	695
1962	10	35	-.10	695
1967	15	35	-.25	695
1970	18	35	0	695
1975	23	35	-.45	695
1952	0	43	0	760
1954	2	43	+.35	895
1957	5	43	-.55	1,035
1960	8	43	-.45	1,050
1962	10	43	-.05	1,055
1965	13	43	+.20	1,060
1967	15	43	+.10	1,060
1970	18	43.	+.70	1,070
1975	23	43	+.10	1,115
1952	0	53	0	685
1954	2	53	+.35	690
1957	5	53	+.60	690
1960	8	53	+.60	700
1962	10	53	+.70	705
1965	13	53	+.75	705
1967	15	53	+.70	705
1970	18	53	+1.00	710
1975	23	53	+.60	710
1952	0	58	0	810
1954	2	58	+.50	835
1957	5	58	+.25	835
1961	9	58	+.50	845

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
	Missouri River, South Dakota, Fort Randall Dam--Continued			
	Year of dam closure 1952			
1962	10	58	+0.70	845
1967	15	58	+.75	860
1970	18	58	+.75	870
1975	23	58	+.85	885
	Missouri River, South Dakota, Gavins Point Dam			
	Year of dam closure 1955[8/]			
1955	0	2.3	0	374
1960	5	2.3	-1.30	374
1965	10	2.3	-1.50	380
1970	15	2.3	-2.15	380
1974	19	2.3	-2.50	374
1955	0	3.4	0	525
1960	5	3.4	-1.00	525
1965	10	3.4	-1.50	525
1970	15	3.4	-2.00	525
1974	19	3.4	-2.30	525
1955	0	4.3	0	344
1960	5	4.3	-.25	416
1965	10	4.3	-1.20	420
1970	15	4.3	-1.45	420
1974	19	4.3	-1.90	426
1955	0	5.3	0	630
1960	5	5.3	-.55	645
1965	10	5.3	-1.20	650
1970	15	5.3	-1.50	655
1974	19	5.3	-2.00	660
1955	0	6.8	0	980
1960	5	6.8	-.40	1,155
1965	10	6.8	-.60	1,160
1970	15	6.8	-.80	1,170
1974	19	6.8	-1.25	1,175

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Missouri River, South Dakota, Gavins Point Dam--Continued				
Year of dam closure 1955[8/]				
1955	0	7.9	0	885
1960	5	7.9	-.55	885
1965	10	7.9	-.80	885
1970	15	7.9	-1.35	885
1974	19	7.9	-1.50	885
1955	0	8.4	0	478
1960	5	8.4	-1.10	478
1965	10	8.4	-.65	478
1970	15	8.4	-1.05	478
1974	19	8.4	-1.80	478
1955	0	8.5	0	366
1960	5	8.5	-.25	368
1965	10	8.5	-.80	366
1970	15	8.5	-1.70	368
1974	19	8.5	-2.05	362
1955	0	9.5	0	464
1960	5	9.5	-.45	456
1965	10	9.5	-.65	464
1970	15	9.5	-1.15	466
1974	19	9.5	-1.55	466
1955	0	11.0	0	880
1960	5	11.0	-.50	1,020
1965	10	11.0	-.50	1,035
1970	15	11.0	-.90	1,060
1974	19	11.0	-1.05	1,065
1955	0	12.5	0	348
1960	5	12.5	-.45	412
1965	10	12.5	-.65	438
1970	15	12.5	-.50	446
1974	19	12.5	-1.35	470
1955	0	14.5	0	790
1960	5	14.5	0	880
1965	10	14.5	+.45	880
1970	15	14.5	-.45	1,045
1974	19	14.5	-.50	1,050

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Missouri River, South Dakota, Gavins Point Dam--Continued				
Year of dam closure 1955[8/]				
1955	0	16.5	0	845
1960	5	16.5	-1.00	850
1965	10	16.5	-.50	1,125
1970	15	16.5	-.45	1,160
1974	19	16.5	-.90	1,190
1955	0	18.0	0	905
1960	5	18.0	+.05	905
1965	10	18.0	-.20	920
1970	15	18.0	-.20	920
1974	19	18.0	-.25	930
1955	0	22	0	615
1960	5	22	+.10	625
1965	10	22	+.15	635
1970	15	22	-.25	645
1974	19	22	-.60	645
1955	0	23	0	520
1960	5	23	+.05	605
1965	10	23	+.50	780
1970	15	23	+.05	950
1974	19	23	+.10	975
1955	0	26	0	326
1960	5	26	+.65	466
1965	10	26	+.50	480
1970	15	26	+1.30	675
1974	19	26	+.80	690
1955	0	27	0	960
1960	5	27	+.40	1,165
1965	10	27	+.10	1,215
1970	15	27	-.20	1,215
1974	19	27	-.05	1,220
1955	0	28	0	805
1960	5	28	-1.05	975
1965	10	28	-.05	1,050
1970	15	28	-.10	1,080
1974	19	28	-.25	1,095

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Missouri River, South Dakota, Gavins Point Dam--Continued				
Year of dam closure 1955[8/]				
1955	0	30	0	460
1960	5	30	+.15	570
1965	10	30	-.15	575
1970	15	30	+.35	575
1974	19	30	+.35	580
1955	0	32	0	505
1960	5	32	+.25	585
1965	10	32	+.50	600
1970	15	32	+.60	620
1974	19	32	+.05	625
1955	0	34	0	790
1960	5	34	-.25	845
1965	10	34	+.05	880
1970	15	34	+.05	910
1974	19	34	-.20	980
1955	0	36	0	1,780
1960	5	36	-.60	1,785
1965	10	36	-1.20	1,815
1970	15	36	-.80	1,835
1974	19	36	-1.30	1,840
1955	0	38	0	655
1960	5	38	+.05	660
1965	10	38	-.10	665
1970	15	38	+.30	670
1974	19	38	+.10	680
1955	0	39	0	368
1960	5	39	+.25	378
1965	10	39	+.40	380
1970	15	39	+.35	380
1974	19	39	-.10	380
1955	0	41	0	890
1960	5	41	-.10	890
1965	10	41	-.15	905
1970	15	41	-.20	925
1974	19	41	-.60	935

Year of data collection		Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Year	Years after dam closure			
Missouri River, South Dakota, Gavins Point Dam--Continued				
Year of dam closure 1955[8/]				
1955	0	44	0	1,600
1960	5	44	-.25	1,600
1965	10	44	-.35	1,600
1970	15	44	-.45	1,605
1974	19	44	-.45	1,605
1957	2(0?)	46	[3/]0	945
1960	5	46	-.45	960
1965	10	46	-.45	970
1970	15	46	-.35	975
1974	19	46	-1.00	975
1957	2	48	[3/]0	895
1960	5	48	+.15	1,080
1965	10	48	+.35	1,145
1970	15	48	-.10	1,180
1974	19	48	+.15	1,190
1958	3	52	[3/]0	1,040
1960	5	52	-.10	1,125
1965	10	52	+.15	1,290
1970	15	52	-.05	1,415
1974	19	52	-.60	1,440
1957	2	55	[3/]0	675
1960	5	55	-.05	755
1965	10	55	+.20	1,030
1970	15	55	+.25	1,105
1974	19	55	-.30	1,130
1957	2	57	[3/]0	--
1960	5	57	+.20	--
1965	10	57	+.10	--
1970	15	57	-.35	--
1974	19	57	-.50	--
1958	3	61	[3/]0	865
1960	5	61	-.35	865
1965	10	61	-.20	925
1970	15	61	-.20	935
1974	19	61	-.80	940

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
		Missouri River, South Dakota, Gavins Point Dam--Continued		
		Year of dam closure 1955 8/		
1959	4	64	3/ 0	960
1960	5	64	+.05	975
1965	10	64	+.05	1,110
1970	15	64	+.10	1,140
1974	19	64	+.75	1,140
1958	3	69	3/ 0	755
1960	5	69	-.45	785
1965	10	69	-1.00	785
1970	15	69	-1.85	795
1974	19	69	-1.45	840
1959	4	72	3/ 0	1,415
1960	5	72	+.10	1,445
1965	10	72	-.20	1,555
1970	15	72	-.35	1,640
1974	19	72	-.65	1,645
1959	4	78	3/ 0	535
1960	5	78	-.25	535
1965	10	78	-.30	535
1970	15	78	-.65	545
1974	19	78	-1.15	545
1959	4	82	3/ 0	1,300
1960	5	82	-.05	1,300
1965	10	82	+.05	1,335
1970	15	82	+.25	1,365
1974	19	82	+.20	1,390
1959	4	85	3/ 0	1,355
1960	5	85	+.20	1,535
1965	10	85	+.65	1,905
1970	15	85	+.40	1,925
1974	19	85	-.10	1,935
1959	4	89	3/ 0	680
1960	5	89	+.30	685
1965	10	89	-.35	765
1970	15	89	+.25	865
1974	19	89	+.35	895

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
		Missouri River, South Dakota, Gavins Point Dam--Continued		
		Year of dam closure 1955 8/		
1959	4	93	3/ 0	330
1960	5	93	-.15	392
1965	10	93	+1.70	710
1970	15	93	+1.15	740
1974	19	93	+.85	755
		Medicine Creek, Nebraska, Medicine Creek Dam		
		Year of dam closure 1949		
1950	(0)	0.8	0	83.5
1952	3	.8	-.10	93.0
1962	13	.8	-.20	107(?)
1963	14	.8	-.20	91.5
1971	22	.8	-.20	99.0
1977	28	.8	-.20	107
1950	(0)	13.0	0	30.5
1952	3	13.0	-.05	32.0
1962	13	13.0	+.50	38.5
1963	14	13.0	+.30	36.5
1971	22	13.0	+.45	36.5
1977	28	13.0	+.40	35.5
1950	(0)	16.0	0	--
1952	3	16.0	-.55	20.5
1962	13	16.0	-.30	21.0
1964	15	16.0	-.25	20.5
1971	22	16.0	+.20	21.5
1978	29	16.0	+.25	21.0
1950	(0)	16.5	0	25.5
1952	3	16.5	-.25	25.5
1962	13	16.5	+.30	26.0
1964	15	16.5	-.10	25.5
1971	22	16.5	+.45	25.5
1978	29	16.5	+.15	25.5

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
		Middle Loup River, Nebraska, Milburn Dam		
		Year of dam closure 1955		9/
1950	(0)	0.2	9/ 0	7.6
1955	.2	.2	-.60	29.0
1956	1.3	.2	-1.20	44.5
1957	2.3	.2	-2.30	44.5
1957	2.7	.2	-2.30	
1957	2.8	.2	-1.35	57.5
1961	6.3	.2	-1.45	96.5
1961	6.6	.2	-1.80	96.5
1962	7.5	.2	-1.90	109
1964	9.3	.2	-2.15	110
1964	9.7	.2	-2.15	111
1967	12.3	.2	-2.65	114
1969	14.3	.2	-2.15	117
1971	16.3	.2	-2.40	124
1961	6.3	1.6	3/ 0	230
1962	7.5	1.6	-.35	234
1964	9.3	1.6	-.60	232
1964	9.7	1.6	-.60	238
1967	12.3	1.6	-1.00	234
1969	14.3	1.6	-1.10	234
1971	16.3	1.6	-1.20	234
1964	9.3	3.1	3/ (0)	118
1964	9.7	3.1	0	118
1967	12.3	3.1	-.20	120
1969	14.3	3.1	-.15	118
1971	16.3	3.1	-.25	123
1961	6.3	5.6	3/ (0)	90.5
1962	7.5	5.6	-.40	91.0
1964	9.3	5.6	-.65	91.0
1964	9.7	5.6	-.70	91.0
1967	12.3	5.6	-.90	92.0
1969	14.3	5.6	-.90	91.5
1971	16.3	5.6	-1.05	92.0
1967	12.3	7.4	3/ (0)	163
1969	14.3	7.4	-.05	166
1971	16.3	7.4	-.25	174

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
		Smoky Hill River, Kansas, Kanopolis Dam		
		Year of dam closure 1948		
1946	(0)	0.8	0	46.5
1951	3	.8	-.80	45.0
1952	4	.8	-1.10	44.5
1961	13	.8	-1.30	45.0
1971	23	.8	-1.45	48.0
1946	(0)	2.9	0	41.0
1951	3	2.9	-.20	42.0
1952	4	2.9	-.35	42.0
1961	13	2.9	-1.05	41.0
1971	23	2.9	-1.05	45.0
1946	(0)	4.8	0	40.0
1951	3	4.8	+.05	40.5
1952	4	4.8	+.15	39.0
1961	13	4.8	-.50	39.5
1971	23	4.8	-.50	42.0
1946	(0)	6.8	0	50.0
1951	3	6.8	-.05	49.5
1952	4	6.8	0	49.5
1961	13	6.8	-.45	46.5
1971	23	6.8	-.20	47.0
1946	(0)	8.7	0	39.5
1951	3	8.7	+.25	41.5
1952	4	8.7	0	46.0
1961	13	8.7	-.25	47.0
1971	23	8.7	-.20	50.0
1946	(0)	13.0	0	34.5
1951	3	13.0	-.05	38.5
1952	4	13.0	-.10	39.0
1961	13	13.0	-.25	39.5
1946	(0)	16.5	0	39.5
1951	3	16.5	+.35	41.0
1952	4	16.5	+.25	41.0
1961	13	16.5	+.35	40.5

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Smoky Hill River, Kansas, Kanopolis Dam--Continued				
Year of dam closure 1948				
1946	(0)	18.5	0	39.5
1951	3	18.5	+.10	39.5
1952	4	18.5	+.15	35.5
1961	13	18.5	+.10	38.0
1946	(0)	23	0	35.5
1951	3	23	-.05	38.0
1952	4	23	+.15	37.0
1961	13	23	-.10	36.5
1946	(0)	25	0	38.5
1951	3	25	-.05	39.5
1952	4	25	-.15	40.0
1961	13	25	-.25	41.5
1946	(0)	35	0	36.5
1951	3	35	+.05	36.0
1952	4	35	+.20	34.5
1961	13	35	+.15	37.0
1946	(0)	42	0	30.0
1951	3	42	+.05	30.0
1952	4	42	0	33.5
1961	13	42	-.10	32.5
1946	(0)	50	0	36.5
1951	3	50	-.05	36.5
1952	4	50	-.25	35.0
1961	13	50	--	--
1946	(0)	56	0	54.5
1951	3	56	+.05	34.0
1952	4	56	--	63.0
1961	13	56	+.05	33.0
1946	(0)	73	0	34.0
1951	3	73	+.05	38.0
1952	4	73	-.15	39.0
1961	13	73	-.20	39.5

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Smoky Hill River, Kansas, Kanopolis Dam--Continued				
Year of dam closure 1948				
1946	(0)	92	0	35.0
1951	3	92	0	35.0
1952	4	92	-.20	40.0
1961	13	92	--	--
1946	(0)	108	0	30.0
1951	3	108	+.25	30.0
1952	4	108	+.20	29.5
1961	13	108	+.25	31.0
Republican River, Kansas, Milford Dam				
Year of dam closure 1967				
1967	0	2.7	0	156
1974	7	2.7	-.85	165
1967	0	4.0	0	98.0
1975	8	4.0	-.15	116
Wolf Creek, Oklahoma, Fort Supply Dam				
Year of dam closure 1942				
1944	2	.3	0	242
1949	7	.3	-2.05	26.5
1961	19	.3	-3.15	32.5
1969	27	.3	-3.40	23.0
1944	2	1.0	0	137
1949	7	1.0	-1.90	30.5
1961	19	1.0	-2.20	56.0
1969	27	1.0	-2.00	57.5
1944	2	1.3	0	158
1949	7	1.3	-1.40	46.0
1961	19	1.3	-2.10	63.5
1969	27	1.3	-2.60	28.5
1944	2	1.6	0	172
1949	7	1.6	-.25	163
1961	19	1.6	-1.50	90.0
1969	27	1.6	-2.45	15.0

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Wolf Creek, Oklahoma, Fort Supply Dam--Continued				
Year of dam closure 1942				
1944	2	1.8	0	296
1949	7	1.8	--	--
1961	19	1.8	-1.35	191
1969	27	1.8	-2.30	20.0
1944	2	2.6	0	107
1949	7	2.6	-.45	88.5
1961	19	2.6	-1.05	120
1969	27	2.6	--	--
1944	2	2.9	0	242
1949	7	2.9	-.80	81.5
1961	19	2.9	-1.60	52.5
1969	27	2.9	-1.60	55.0
1944	2	3.9	0	246
1949	7	3.9	-1.20	79.0
1961	19	3.9	-1.45	84.5
1969	27	3.9	-2.00	24.5
1944	2	4.7	0	272
1949	7	4.7	-.45	166
1961	19	4.7	-1.15	97.0
1969	27	4.7	-1.50	26.0
1944	2	6.6	0	240
1949	7	6.6	-.35	121
1961	19	6.6	-1.15	38.0
1969	27	6.6	-1.30	30.0
North Canadian River, Oklahoma, Canton Dam				
Year of dam closure 1948				
1947	0	1.8	0	64.5
1949	1	1.8	-.90	61.0
1951	2.8	1.8	-1.20	62.0
1951	3.4	1.8	-1.55	67.0
1959	11	1.8	-2.90	29.5
1966	18	1.8	-2.75	17.5
1976	28	1.8	-3.00	18.5

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
North Canadian River, Oklahoma, Canton Dam--Continued				
Year of dam closure 1948				
1947	0	3.1	0	65.0
1949	1	3.1	-.60	53.0
1951	2.8	3.1	-1.00	47.0
1951	3.4	3.1	-1.30	56.5
1959	11	3.1	-1.50	55.5
1966	18	3.1	-1.20	56.5
1976	28	3.1	-1.50	48.0
1947	0	5.0	0	47.0
1949	1	5.0	-.60	48.5
1951	2.8	5.0	-.65	46.5
1951	3.4	5.0	-1.05	45.5
1959	11	5.0	-.80	49.0
1966	18	5.0	-.95	27.5
1976	28	5.0	-1.65	17.5
1947	0	5.6	0	45.5
1949	1	5.6	-.35	44.0
1951	2.8	5.6	-1.05	44.0
1951	3.4	5.6	-1.35	35.0
1959	11	5.6	-.85	29.5
1966	18	5.6	-1.60	16.5
1976	28	5.6	-1.50	20.0
1947	0	10.5	[10] 0	[10] 35.5
1949	1	10.5	+.75	53.5
1951	2.8	10.5	+1.05	91.5
1951	3.4	10.5	+1.05	91.5
1959	11	10.5	+.85	97.0
1966	18	10.5	+.90	76.0
1947	0	12.0	0	75.0
1949	1	12.0	-.15	77.0
1951	2.8	12.0	-.65	63.5
1951	3.4	12.0	-.75	61.0
1959	11	12.0	-.55	85.0
1966	18	12.0	-1.45	12.5

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
North Canadian River, Oklahoma, Canton Dam--Continued				
Year of dam closure 1948				
1947	0	14.5	0	93.0
1949	1	14.5	-.10	93.5
1951	2.8	14.5	-.35	74.0
1951	3.4	14.5	-.45	72.0
1959	11	14.5	-.85	42.0
1966	18	14.5	-.70	23.0
1947	0	27	0	105
1949	1	27	+.20	116
1951	2.8	27	+.05	105
1951	3.4	27	+.05	106
1959	11	27	-.65	39.5
1966	18	27	-.55	40.0
1947	0	35	0	52.5
1949	1	35	-.20	57.5
1951	2.8	35	-.25	57.5
1951	3.4	35	-.45	56.5
1959	11	35	-.35	49.5
1966	18	35	-.45	30.0
1947	0	50	0	76.0
1949	1	50	-.10	70.5
1951	2.8	50	-.10	69.0
1951	3.4	50	+.05	99.5
1959	11	50	+.45	100
1966	18	50	-.05	59.5
1947	0	58	0	96.5
1949	1	58	-.30	95.0
1951	2.8	58	-.10	113
1951	3.4	58	-.15	106
1959	11	58	-1.05	40.5
1966	18	58	-.85	39.5
1947	0	68	0	--
1949	1	68	+.45	--
1951	2.8	68	+.15	--

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
North Canadian River, Oklahoma, Canton Dam--Continued				
Year of dam closure 1948				
1951	3.4	68	-0.65	--
1959	11	68	+.05	--
1966	18	68	+.35	--
1947	0	92	0	--
1949	1	92	+.10	--
1951	2.8	92	+.10	--
1951	3.4	92	+.30	--
1959	11	92	-.30	--
1966	18	92	+.25	--
1947	0	104	0	--
1949	1	104	-.25	--
1951	2.8	104	-.20	--
1951	3.4	104	-.10	--
1959	11	104	-.50	--
1966	18	104	-.55	--
1947	0	114	0	44.5
1949	1	114	-.10	45.0
1951	2.8	114	-.20	44.0
1951	3.4	114	-.05	35.5
1959	11	114	-.05	31.5
1966	18	114	-.20	27.5
1947	0	125	0	38.5
1949	1	125	-.30	38.0
1951	2.8	125	-.50	38.5
1951	3.4	125	-.50	34.0
1959	11	125	-.65	26.5
1966	18	125	-.70	30.0
1947	0	134	0	40.0
1949	1	134	0	33.0
1951	2.8	134	+.10	36.5
1951	3.4	134	-.05	33.5
1959	11	134	-.35	33.0
1966	18	134	-.35	27.5

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
North Canadian River, Oklahoma, Canton Dam--Continued				
Year of dam closure 1948				
1947	0	154	0	39.0
1949	1	154	-.05	39.5
1951	2.8	154	+.05	39.5
1951	3.4	154	+.05	38.5
1959	11	154	-.35	28.5
1966	18	154	-.50	31.0
Canadian River, Oklahoma, Eufaula Dam				
Year of dam closure 1963				
1964	1	.8	0	252
1969	6	.8	-5.05	177
1977	14	.8	-4.95	234
1964	1	2.1	0	460
1969	6	2.1	-2.30	208
1977	14	2.1	-3.20	234
1964	1	3.4	0	284
1969	6	3.4	-2.10	183
1977	14	3.4	-2.80	220
1964	1	4.7	0	560
1969	6	4.7	-1.15	560
1977	14	4.7	-2.15	400
1964	1	6.6	0	218
1969	6	6.6	-.65	280
1977	14	6.6	-1.20	284
1964	1	8.0	0	362
1969	6	8.0	-.35	515
1977	14	8.0	-1.00	402
1964	1	11.5	0	446
1969	6	11.5	-.35	462
1977	14	11.5	-1.40	420
1964	1	14.0	0	505
1969	6	14.0	-.35	620
1977	14	14.0	-1.15	494

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Canadian River, Oklahoma, Eufaula Dam--Continued				
Year of dam closure 1963				
1964	1	16.0	0	422
1969	6	16.0	0	438
1977	14	16.0	-.60	374
1964	1	18.5	0	149(?)
1969	6	18.5	-.90	198
1977	14	18.5	-1.10	280
1964	1	20	0	446
1969	6	20	-.70	454
1977	14	20	-1.35	428
1964	1	23	0	400
1969	6	23	-.45	460
1977	14	23	-.60	580
1964	1	34	0	260
1969	6	34	-.30	260
1977	14	34	+.40	187
1964	1	37	0	360
1969	6	37	-.70	350
1977	14	37	0	346
1964	1	40	0	406
1969	6	40	+.05	470
1977	14	40	+1.20	478
Red River, Oklahoma-Texas, Denison Dam				
Year of dam closure 1942				
1942	0	.6	0	228
1945	3	.6	-1.25	244
1948	6	.6	-1.35	278
1958	16	.6	-1.45	280
1969	27	.6	-1.60	282
1942	0	1.1	0	236
1945	3	1.1	-1.40	230
1948	6	1.1	--	--
1958	16	1.1	-3.00	11/
1969	27	1.1	-2.40	11/

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
		Red River, Oklahoma-Texas, Denison Dam--Continued		
		Year of dam closure 1942		
1942	0	2.1	0	228
1945	3	2.1	-1.35	230
1948	6	2.1	--	--
1958	16	2.1	-2.45	240
1969	27	2.1	-2.40	238
1942	0	3.2	0	12/ 284
1945	3	3.2	-.80	284
1948	6	3.2	-1.60	284
1958	16	3.2	-2.40	284
1969	27	3.2	-2.00	284
1942	0	5.1	0	210
1945	3	5.1	-.45	218
1948	6	5.1	--	--
1958	16	5.1	-2.20	222
1969	27	5.1	-1.65	214
1942	0	7.2	0	274
1945	3	7.2	-.10	280
1948	6	7.2	-.75	280
1958	16	7.2	-1.30	280
1969	27	7.2	-1.30	296
1942	0	8.4	0	396
1945	3	8.4	-1.15	398
1948	6	8.4	--	--
1958	16	8.4	-1.45	400
1969	27	8.4	-1.75	400
1942	0	11.5	0	151
1945	3	11.5	-1.20	135
1948	6	11.5	--	--
1958	16	11.5	-1.85	--
1969	27	11.5	-2.10	140
1942	0	15.0	0	224
1945	3	15.0	-1.45	149
1948	6	15.0	-1.85	149
1958	16	15.0	-2.45	151
1969	27	15.0	-3.25	152

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
		Red River, Oklahoma-Texas, Denison Dam--Continued		
		Year of dam closure 1942		
1942	0	18.5	0	318
1945	3	18.5	+.15	324
1948	6	18.5	--	--
1958	16	18.5	-1.40	336
1969	27	18.5	-.60	342
1942	0	22	0	244
1945	3	22	-.20	244
1948	6	22	--	--
1958	16	22	-1.20	256
1969	27	22	-.70	246
1942	0	27	0	282
1945	3	27	-.30	328
1948	6	27	-.45	360
1958	16	27	-.40	382
1969	27	27	-.20	372
1946	4	34	3/ 0	218
1948	6	34	+.05	228
1958	16	34	-.25	292
1969	27	34	-.20	296
1946	4	41	3/ 0	308
1948	6	41	+.35	308
1958	16	41	-.45	292
1969	27	41	-.30	300
1946	4	48	3/ 0	376
1948	6	48	+.10	530
1958	16	48	+.75	775
1969	27	48	+.75	780
1946	4	65	3/ 0	480
1948	6	65	-.10	488
1958	16	65	-.10	630
1969	27	65	+.10	640
1946	4	80	3/ 0	705
1948	6	80	+1.05	1,050
1958	16	80	-.10	990
1969	27	80	+.35	1,025

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
		Red River, Oklahoma-Texas, Denison Dam--Continued		
		Year of dam closure 1942		
1946	4	90	3/ 0	191
1948	6	90	-.80	198
1958	16	90	-.70	226
1970	28	90	-.55	214
1946	4	101	3/ 0	368
1948	6	101	-.20	382
1958	16	101	+.45	408
1970	28	101	-.10	360
1946	4	109	3/ 0	234
1948	6	109	-.35	268
1958	16	109	-.65	262
1970	28	109	-.55	266
1946	4	122	3/ 0	1,085
1948	6	122	-1.00	1,195
1958	16	122	+.20	910
1970	28	122	-1.35	1,025
1946	4	132	3/ 0	312
1948	6	132	-.05	322
1958	16	132	+.30	366
1970	28	132	-.50	374
1946	4	142	3/ 0	464
1948	6	142	-.35	336
1958	16	142	-.10	452
1970	28	142	-.65	384
1946	4	150	3/ 0	270
1948	6	150	+.40	294
1958	16	150	+.10	324
1970	28	150	-.25	258
		Neches River, Texas, Town Bluff Dam		
		Year of dam closure 1951		
1951	0	.2	0	94.5
1965	14	.2	-2.25	127

Year of data collection: Year	Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
		Neches River, Texas, Town Bluff Dam--Continued		
		Year of dam closure 1951		
1951	0	1.4	0	111
1960	9	1.4	-.20	127
1965	14	1.4	-.90	127
1951	0	2.9	0	101
1960	9	2.9	-.10	100
1965	14	2.9	-.60	100
1951	0	4.7	0	90.5
1960	9	4.7	-.90	97.5
1965	14	4.7	+.50	101
1951	0	6.3	0	117
1960	9	6.3	-.60	133
1965	14	6.3	-.65	145
1951	0	8.0	0	121
1960	9	8.0	-.25	151
1965	14	8.0	-.05	157
		Des Moines River, Iowa, Red Rock Dam		
		Year of dam closure 1969		
1962	(0)	2.3	0	185
1978	9	2.3	-1.00	214
1962	(0)	4.7	0	155
1978	9	4.7	-1.15	162
1962	(0)	6.1	0	180
1978	9	6.1	-1.05	171
1962	(0)	12.0	0	184
1978	9	12.0	-1.75	--
1962	(0)	14.0	0	131
1978	9	14.0	-.60	145
1962	(0)	22	0	199
1978	9	22	+.20	212
1962	(0)	25	0	158
1978	9	25	+.05	168

TABLE 13.—*Data on channel features, as measured from resurveyed cross sections*—Continued

Year of data collection: Year	Year of data collection: Years after dam closure	Distance of cross section downstream from dam (kilometers)	Total change in mean bed elevation (meters)	Channel width (meters)
Des Moines River, Iowa, Red Rock Dam--Continued				
Year of dam closure 1969				
1962	(0)	29	0	153
1978	9	29	+.65	185
1962	(0)	33	0	160
1978	9	33	+.10	181
1962	(0)	36	0	154
1978	9	36	-.45	165
1962	(0)	38	0	146
1978	9	38	-.65	154
1962	(0)	40	0	200
1978	9	40	-1.85	146
1962	(0)	42	0	171
1978	9	42	-.35	172
1962	(0)	48	0	148
1978	9	48	-.45	155
1962	(0)	50	0	108
1978	9	50	-.60	110
1962	(0)	52	0	141
1978	9	52	-1.30	119
1962	(0)	55	0	129
1978	9	55	-.05	152
1962	(0)	62	0	206
1978	9	62	+.25	208
1962	(0)	68	0	179
1978	9	68	+1.00	185
1962	(0)	72	0	162
1978	9	72	+1.05	164
Chattahoochee River, Georgia, Buford Dam				
Year of dam closure 1956				
1956	0	.5	0	95.0
1963	7	.5	-.95	98.0
1964	8	.5	-1.00	98.5
Chattahoochee River, Georgia, Buford Dam--Continued				
Year of dam closure 1956				
1965	9	0.5	-0.95	99.0
1968	12	.5	-1.10	100
1971	15	.5	-1.00	103
1956	0	1.9	0	76.0
1963	7	1.9	-1.40	77.0
1964	8	1.9	-1.50	74.0
1965	9	1.9	-1.80	76.0
1968	12	1.9	-2.15	77.5
1971	15	1.9	-2.55	75.5
1956	0	2.9	0	71.5
1963	7	2.9	-.90	74.0
1964	8	2.9	-.95	79.5
1965	9	2.9	-1.30	74.0
1968	12	2.9	-1.60	74.5
1971	15	2.9	-1.85	76.0
1956	0	4.0	0	63.0
1963	7	4.0	-.75	67.0
1964	8	4.0	-.60	68.0
1965	9	4.0	-.90	68.5
1968	12	4.0	-1.35	67.0
1971	15	4.0	-1.45	--
1956	0	5.8	0	68.5
1963	7	5.8	-.30	67.0
1964	8	5.8	-.20	68.0
1965	9	5.8	-.45	67.0
1968	12	5.8	-.75	69.5
1971	15	5.8	-.70	69.0
1956	0	7.6	0	91.0
1963	7	7.6	+.05	93.0
1964	8	7.6	+.10	97.0
1965	9	7.6	-.05	95.5
1968	12	7.6	-.20	98.0
1971	15	7.6	-.30	--
Chattahoochee River, Georgia, Buford Dam--Continued				
Year of dam closure 1956				
1956	0	11.0	0	70.5
1963	7	11.0	-.90	70.5
1964	8	11.0	+.05	70.5
1965	9	11.0	+.05	71.5
1971	15	11.0	+.10	--
1957	1	13.5	[3] 0	69.5
1963	7	13.5	-.20	64.0
1964	8	13.5	-.10	67.5
1965	9	13.5	-.10	68.0
1968	12	13.5	-.35	72.0
1971	15	13.5	+.05	74.0
1957	1	16.5	[3] 0	59.0
1964	8	16.5	-.40	69.0
1965	9	16.5	-.60	67.0
1968	12	16.5	-.55	68.0
1957	1	18.0	[3] 0	57.5
1963	7	18.0	+.20	60.0
1964	8	18.0	+.20	61.0
1965	9	18.0	+.25	63.5
1968	12	18.0	+.15	62.0
1971	15	18.0	+.30	--
1957	1	21	[3] 0	57.0
1963	7	21	+.25	54.0
1964	8	21	+.15	55.0
1965	9	21	+.05	54.0
1968	12	21	+.15	55.0
1971	15	21	+.25	--
1957	1	24	[3] 0	60.5
1963	7	24	+.15	58.5
1964	8	24	+.25	59.0
1965	9	24	+.15	61.0
1968	12	24	+.10	60.0
1971	15	24	+.15	58.5

FOOTNOTES TO TABLE 13

[1] Cofferdam closure 1956; official closure of Glen Canyon Dam was 1963.

[2] Channel confined in rock-walled canyon. Widths, if listed, meaningful only for general order of magnitude.

[3] First measurement of this cross section was later than year of dam closure. Total changes in bed elevation were measured from this later year.

[4] Year of initial diversion. Official closure was in 1951.

[5] A diversion dam (Headgate Rock Dam), located about 24 kilometers below Parker Dam and closed in 1942, may have some unknown influence on the cross sections listed here from about 1942 on.

[6] Year storage began. Dam completed in 1939.

[7] Not all is bed degradation; arrival of bar or spit near left bank severed part of previous channel.

[8] Storage began 1952.

[9] All data for this cross section apply only to the thalweg rather than to the entire channel. During dam construction most of the flow was diverted into the thalweg, and it gradually grew to become the new main channel.

[10] Pronounced lateral migration of channel at this section at least from 1947 through 1966.

[11] Right bank washed out by tributary changing course in 1957.

[12] Bridge section; width constrained.

TABLE 14.—*Changes in streambed elevations as estimated from streamflow-gaging-station rating tables*

[Footnotes on last page of table]

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
	Colorado River, Arizona, Parker Dam Year of dam closure 1938			
Colorado River below Parker Dam	6.4	1/90.6	10/34-11/35	0
			12/35-2/37	+.18
			2/37-12/37	+.061
			12/37-3/38	+.18
			10/38-1/39	-.91
			1/39-12/39	-1.92
			1/40-12/40	-1.74
			1/41-9/41	-2.07
			10/41-5/42	-2.59
No suitable control station				
	Jemez River, New Mexico, Jemez Canyon Dam Year of dam closure 1953			
Jemez River below Jemez Canyon Dam	1.3	2/.034	4/51-3/52	0
			3/55-7/55	-.55
			8/55-9/55	-.95
			10/55-2/56	-.98
			2/56-8/56	-.73
			8/56-5/57	-.98
			5/57-10/57	-1.49
			10/57-3/58	-2.07
			3/58-6/58	-2.32
Jemez River near Jemez (control station)	43	.37	6/36-9/36	0
			10/36-5/37	-.18
			6/37-9/38	-.12
			10/38-9/39	-.061
			10/39-5/41	-.12
			8/49-5/52	-.40
			4/58-4/60	-.30
			10/60-5/61	-.43
			10/61-3/63	-.37

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
	Missouri River, Montana, Fort Peck Dam Year of dam closure 1937			
Missouri River below Fort Peck Dam	13	3/85.0	4/38-10/38	0
			10/38-4/39	-.030
			10/39-9/40	-.21
			10/40-9/41	-.24
			10/41-10/44	-.30
			10/44-9/45	-.52
			10/47-9/48	-.67
			10/48-9/51	-.85
			10/51-9/52	-1.01
			2/54-9/55	-1.19
			10/55-2/56	-1.25
			3/56-9/56	-1.37
			10/57-9/58	-1.31
			10/59-2/61	-1.34
			10/61-9/65	-1.37
			10/65-11/66	-1.46
			11/66-9/79	-1.49
No suitable control station				
	Missouri River, South Dakota, Fort Randall Dam Year of dam closure 1952			
Missouri River below Fort Randall Dam	11	4/464	5/47-9/51	0
			10/52-11/52	+.030
			3/53-5/53	+.030
			7/53-11/53	-.30
			5/54-9/54	-.30
			10/54-3/55	-.37
			3/55-9/55	-.24
			10/55-9/56	-.30
			10/56-9/59	-.24
			10/59-9/60	-.34

TABLE 14.—*Changes in streambed elevations as estimated from streamflow-gaging-station rating tables*—Continued

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
	Missouri River, South Dakota, Fort Randall Dam--Continued Year of dam closure 1952			
			10/60-12/63	-0.40
			12/63-9/64	-.43
			10/64-11/65	-.40
			11/65-10/67	-.43
			10/67-6/69	-.61
No suitable control station				
	Missouri River, South Dakota, Gavins Point Dam Year of dam closure 1955			
Missouri River at Yankton	8	5/312	3/32-9/33	0
			10/33-7/34	-.15
			8/34-3/37	-.061
			3/37-9/38	-.18
			10/38-5/39	-.15
			5/39-3/40	-.27
			3/40-3/41	-.15
			3/41-6/41	-.091
			6/41-9/41	-.061
			10/41-5/42	-.12
			5/42-3/43	-.34
			6/43-3/44	-.49
			10/45-3/47	-.61
			3/47-9/48	-.61
			10/48-3/51	-.37
			3/51-3/52	-.49
			5/53-11/54	-.58
			11/54-4/55	-.61
			5/55-9/55	-.46
			10/55-9/56	-.55
			10/56-9/57	-.67
			10/57-1/59	-.70
			1/59-12/60	-.76
			12/60-9/61	-.82
			10/61-9/62	-.88

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
	Missouri River, South Dakota, Gavins Point Dam--Continued Year of dam closure 1955			
			10/62-12/63	-0.98
			12/63-9/65	-1.01
			10/65-9/68	-1.19
			10/68-9/71	-1.25
			10/73-9/76	-1.92
			10/76-9/79	-2.16
No suitable control station				
	Smoky Hill River, Kansas, Kanopolis Dam Year of dam closure 1948			
Smoky Hill River near Langley	1.3	0.51	10/40-9/41	0
			10/41-9/42	+.12
			10/42-10/46	+.30
			10/46-5/47	+.12
			5/47-9/47	-.030
			10/47-3/49	0
			10/49-9/50	-.24
			9/50-3/51	-.40
			4/52-12/52	-.91
			10/53-6/54	-.91
			6/54-9/54	-.88
			10/54-10/55	-.91
			10/55-7/57	-.88
			10/59-4/60	-1.01
			4/60-6/61	-1.04
			10/61-9/64	-1.04
			10/64-9/68	-1.07
			10/68-5/70	-1.10
			10/70-10/71	-1.10
			10/71-3/73	-1.13
			3/73-10/73	-1.19
			10/73-10/74	-1.34
			10/74-9/76	-1.40
			10/76-12/77	-1.37

TABLE 14.—*Changes in streambed elevations as estimated from streamflow-gaging-station rating tables*—Continued

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
Smoky Hill River, Kansas, Kanopolis Dam--Continued Year of dam closure 1948				
Smoky Hill River at Ellsworth (control station)	48	0.43	7/40-9/45	0
			10/45-7/46	+.030
			7/46-9/49	0
			10/49-8/50	+.030
			8/50-4/51	-.061
			4/51-9/51	+.030
			10/51-9/53	0
			10/53-6/55	+.030
			10/56-7/57	-.030
			10/57-9/61	-.061
			10/61-9/62	-.030
			10/62-9/63	+.030
			10/63-6/64	-.030
			6/64-5/65	0
			7/65-11/65	+.15
			2/66-8/66	0
			7/67-11/68	+.030
			11/68-4/69	0
			6/69-12/69	+.12
			1/70-6/70	+.061
			6/70-10/70	+.21
			10/70-3/71	+.18
			7/71-1/72	+.061
			1/72-10/73	0
			2/75-?	+.091
Republican River, Kansas, Milford Dam Year of dam closure 1967				
Republican River below Milford Dam	2.7	1.2	10/63-9/64	0
			10/64-7/65	+.27
			7/65-2/66	+.15
			2/66-7/67	+.12
			7/67-11/67	+.091

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
Republican River, Kansas, Milford Dam--Continued Year of dam closure 1967				
			11/67-2/69	0
			2/69-5/70	-.27
			10/70-6/72	-.49
			6/72-4/73	-.58
			4/73-11/73	-.95
			11/73-4/74	-1.25
			4/74-6/75	-1.34
			6/75-1/76	-1.37
			1/76-9/77	-1.40
			10/77-6/78	-1.43
			6/78-3/79	-1.49
			3/79-1/80	-1.59
Republican River at Clay Center (control station)	49	3.4	10/53-2/55	0
			2/55-6/55	-.030
			6/55-9/55	-.061
			10/55-9/56	-.030
			10/56-9/58	-.061
			10/58-2/59	-.21
			2/59-9/59	-.18
			10/59-3/60	-.15
			3/60-9/62	-.18
			10/62-9/63	-.061
			10/63-1/68	-.091
			2/68-7/69	-.12
			10/69-5/71	-.15
			5/71-5/72	-.12
			5/72-9/73	-.15
			10/73-9/77	-.27
			10/77-1/80	-.34
North Canadian River, Oklahoma, Canton Dam Year of dam closure 1948				
North Canadian River at Canton	4.8	.031	10/37-9/41	0
			10/42-9/43	+.21
			11/46-5/47	+.21
			2/48-5/49	+.18
			6/49-9/50	-.43

TABLE 14.—*Changes in streambed elevations as estimated from streamflow-gaging-station rating tables*—Continued

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
North Canadian River, Oklahoma, Canton Dam--Continued Year of dam closure 1948				
			10/50-9/51	-0.73
			10/51-9/53	-1.01
			10/53-5/54	-.88
			5/54-9/54	-1.01
North Canadian River near Seiling (control station)	45	0.00057	7/46-2/48	0
			2/48-9/50	-.030
			5/51-3/53	-.030
			4/53-9/53	0
			10/53-9/54	-.27
			10/54-5/55	-.27
			5/55-9/65	-.30
Red River, Texas-Oklahoma, Denison Dam Year of dam closure 1943				
Red River near Colbert, Oklahoma	4.5	3.7	7/42-10/42	0
			11/42-4/44	-.37
			4/44-3/45	-.40
			10/45-6/46	-.88
			6/46-7/47	-1.01
			10/47-1/48	-.91
			1/48-7/48	-.98
			7/48-9/48	-1.04
			10/48-6/49	-1.16
			10/49-9/51	-1.16
			10/52-8/54	-1.13
			8/54-3/55	-1.16
			3/55-9/55	-1.19
			10/55-7/57	-1.13
			10/57-8/58	-1.31
			8/58-11/58	-1.34
			11/58-4/59	-1.28
			9/59-2/60	-1.28
			2/60-4/60	-1.34
			4/60-7/60	-1.37

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
Red River, Texas-Oklahoma, Denison Dam--Continued Year of dam closure 1943				
Red River near Gainesville, Texas (control station)	106	4.2	10/36-5/38	0
			5/38-5/40	+.21
			5/40-9/40	+.30
			10/40-5/41	+.37
			4/43-5/43	-.061
			10/43-4/44	-.061
			6/44-1/46	0
			6/46-7/47	+.24
			7/47-6/48	+.030
			7/48-10/49	+.27
			10/49-?	+.15
			10/50-5/51	+.30
			6/52-6/57	+.091
			6/57-11/57	+.37
			5/58-?	+.73
			10/58-5/59	+.70
			6/59-11/59	+.95
			12/59-5/62	+.70
Neches River, Texas, Town Bluff Dam Year of dam closure 1951				
Neches River at Town Bluff	.5	4.2	3/51-5/52	0
			5/52-11/54	-.061
			11/54-9/55	-.15
			10/55-9/58	-.37
			10/58-12/59	-.46
			12/59-9/62	-.55
			10/62-9/63	-.67
			10/63-9/70	-.73
			10/70-10/71	-.85
			10/71-	-.95
Village Creek near Kountze (control station)	6/	1.5	4/39-12/47	0
			12/47-9/49	-.061
			1/51-9/51	-.030
			10/51-2/56	0
			2/56-11/61	-.061
			11/61-9/66	-.15

TABLE 14.—*Changes in streambed elevations as estimated from streamflow-gaging-station rating tables*—Continued

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
Chattahoochee River, Georgia, Buford Dam Year of dam closure 1956				
Chattahoochee River near Buford	4.0	12.2	10/50-9/53	0
			10/53-9/55	-.061
			10/55-5/57	0
			5/57-9/57	-.091
			10/57-10/58	-.061
			10/58-9/59	-.12
			10/59-12/60	-.15
			1/61-5/61	-.24
			5/61-9/62	-.27
			10/62-11/63	-.40
			11/63-1/64	-.49
			1/64-2/64	-.40
			2/64-7/64	-.49
			7/64-3/65	-.55
			3/65-4/65	-.58
			4/65-5/65	-.52
			6/65-8/65	-.58
			8/65-10/66	-.67
			10/66-9/68	-.76
			10/68-1/70	-.88
			1/70-4/71	-.98
Chestatee River near Dahlonega (control station)	73	3.4	4/40-12/40	0
			3/41-12/42	+.15
			12/42-3/43	0
			3/43-10/43	-.061
			10/43-2/44	-.15
			2/44-11/44	-.24
			11/44-12/45	-.27
			1/47-11/53	-.31
			11/53-9/54	-.37
			10/54-9/71	-.40
			10/71-9/73	-.37

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
Rio Grande, New Mexico, Caballo Dam Year of dam closure 1938				
Rio Grande below Caballo Dam	1.3	[7]28.3	2/38-10/38	0
			10/38-12/39	0
			1/40-9/40	-.061
			1943	-.091
			1944	-.12
			1945	-.15
			1946-48	-.46
			3/55-12/55	-.40
			1957	-.43
			1958	-.40
			1959-60	-.64
			1961-62	-.70
			1963-64	-.73
			1965	-.70
			1966	-.76
			1967	-.70
			1972	-.67
			1974	-.76
			1979	-.76
No suitable control station				
Marias River, Montana, Tiber Dam Year of dam closure 1955				
Marias River near Chester	3.2	2.8	10/55-9/79	0
Marias River near Shelby (control station)	65	4.0	6/48-4/49	0
			4/49-4/50	-.030
			10/51-6/53	-.061
			10/54-?	-.15
			10/57-9/59	-.21
			10/59-9/61	-.24
			10/61-9/63	-.27
			10/63-6/64	-.21
			6/64-3/76	-.18

TABLE 14.—*Changes in streambed elevations as estimated from streamflow-gaging-station rating tables*—Continued

Name of downstream gaging station and control station	River distance of station from dam (kilometers)	Reference discharge (cubic meters per second)	Period	Change in streambed elevation = change from initial gage height (meters)
Frenchman Creek, Nebraska, Enders Dam Year of dam closure 1950				
Frenchman Creek near Enders	0.3	[1]1.3	2/46-9/48	0
			10/48-1/50	-.061
			1/50-9/51	-.15
			10/51-9/54	-.12
			10/54-1/59	-.18
			1/59-9/60	-.21
			10/60-4/62	-.27
			4/62-9/62	-.30
			10/62-9/63	-.34
			10/63-4/67	-.37
			4/67-5/68	-.43
			5/68-9/72	-.46
			9/72-10/78	-.49
No suitable control station				

[1]Lowest discharge common to all rating tables.

[2]The flow exceeded 75 percent of the time.

[3]The flow exceeded about 85 percent of the time.

[4]The flow exceeded about 68 percent of the time.

[5]The flow exceeded about 83 percent of the time.

[6]In adjacent drainage basin.

[7]The flow exceeded about 40 percent of the time.

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