95

Channel Changes of the Gila River in Safford Valley, Arizona 1846-1970

GEOLOGICAL SURVEY PROFESSIONAL PAPER 655-G

U.S. DEPARTMENT OF THE INTERIOR

March 3, 1849

Channel Changes of the Gila River in Safford Valley, Arizona 1846-1970

By D. E. BURKHAM

GILA RIVER PHREATOPHYTE PROJECT

GEOLOGICAL SURVEY PROFESSIONAL PAPER 655-G

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1972

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 2401-2065

CONTENTS

ILLUSTRATIONS

TABLES

GILA RIVER PHREATOPHYTE PROJECT

CHANNEL CHANGES OF THE GILA RIVER IN SAFFORD VALLEY, ARIZONA, 1846-1970

By D. E. Burkham

ABSTRACT

The stream channel of the Gila River in Safford Valley, Ariz., changed significantly from 1846 to 1970. The stream channel was fairly stable and narrow from 1846 to 1904 and meandered through a flood plain covered with willow, cottonwood, and mesquite. The average width of the stream channel was less than 150 feet in 1875 and less than 300 feet in 1903. During 1905–17 major destruction of the flood plain took place, and the average stream-channel width increased to about 2,000 feet. Reconstruction of the flood plain was underway during 1918–70; the stream channel narrowed, and the average width was less than 200 feet in 1964. The flood plain became densely covered with saltcedar during 1918–70. Minor widening of the stream channel occurred in 1965 and in 1967, and the average width of the channel was about 400 feet in 1968.

The major widening of the stream channel during 1905–17 was caused mainly by large floods, which carried small sediment loads. The period of flood-plain reconstruction was characterized by floods having relatively low peak discharges and large sediment concentrations. Primarily, the large sediment loads carried by these floods were the result of the erosion of alluvial deposits in the low-altitude drainage basins tributary to the Gila River. The small floods that originated in these tributary basins spread over the wide channel of the Gila River, lost kinetic energy, and sediment deposition resulted. During 1935–70 the average rates of sediment accretion along the bottom land in two reaches of the river were 0.03 and 0.08 foot per year. The dense cover of saltcedar and the cultivation of the bottom land may have been significant contributing factors to the rapid reconstruction of the flood plain.

The temporal distribution of flow and the average annual flow—about 260,000 acre-feet—at the head of Safford Valley during 1920–64 probably were about the same as those during 1800–1904. Based on this premise, the statement can be made that the flood of November 1905, which had a peak flow rate of about 150,000 cubic feet per second, probably was the largest flood in more than 170 years. The preceding statements are based on the fact that the channel width is governed mainly by rates of streamflow and that, even with the help of man, it took 50 years for the flood-plain development to approach that prior to 1905.

INTRODUCTION

Flood plains and streams are of prime interest to inhabitants of arid and semiarid regions in the United States because they offer, respectively, fertile level land and a water supply. Traditionally, development in these regions has centered along the flood plains, and changes in the flood plains and stream channels often result in loss of life, property, and water supply.

The natural processes involved when changes occur in flood plains and stream channels generally are complex and varied. Furthermore, data are seldom available to determine the influence of each of the many variables involved; the Gila River in the Safford Valley in southeastern Arizona (fig. 1) is an exception in that large quantities of historical data pertinent to the changes are available.

The present report gives a description of the natural flow-regime modification of the flood plain and stream channel of the Gila River in Safford Valley from 1846 to 1970. The spatial and temporal changes in stream-channel width, length, and sinuosity and in the areal extent of natural vegetation and cultivated land in the flood plain are described. The factors and conditions that influence these changes also are described. Finally, the hydrologic implications that pertain to aggradation and degradation in alluvial valleys, normal flows and frequencies of floods, hydraulics of flow, and the use of water by flood-plain vegetation are discussed. The present report is the result of studies of environmental factors that affect evapotranspiration in the Gila River Phreatophyte Project area (Culler and others, 1970). The studies are under the direct supervision of R. C. Culler, project chief, and the report was prepared under the general supervision of H. M. Bab-

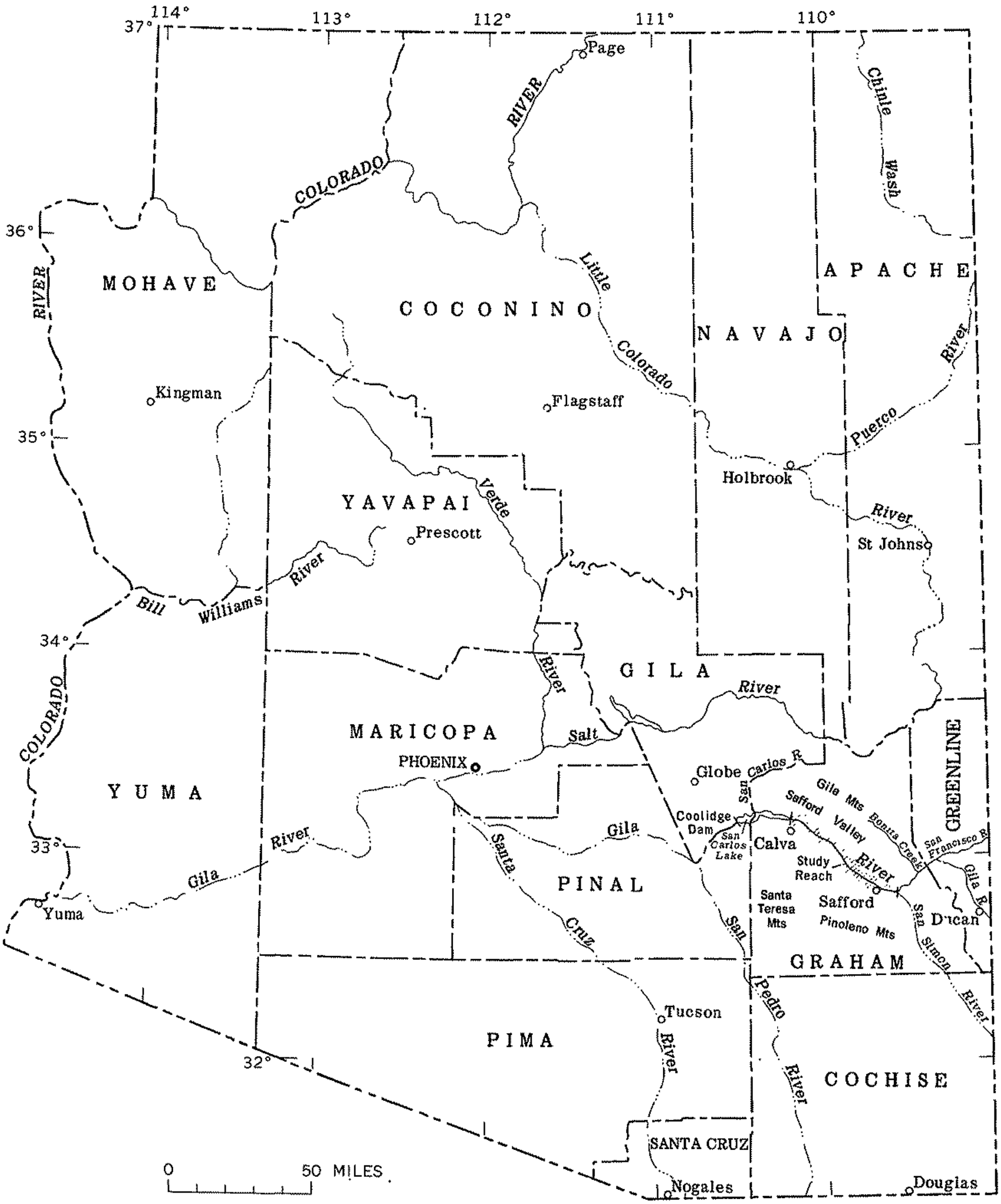


FIGURE 1.—Area of report.

cock, district chief of the Water Resources Division of the U.S. Geological Survey in Arizona.

The cooperation of the many people who supplied historical data vital to this investigation is gratefully acknowledged. Special thanks are due R. H. Rupkey, J. H. Jones, Jr., and Harold Johnson of the U.S. Bureau of Indian Affairs; D. M. Marshall of the U.S. Department of Justice; J. J. Turner of the U.S. Soil Conservation Service; and J. A. Lentz of the Phelps Dodge Corp. for assistance in furnishing data. The author appreciates the help of E. W. Scott of the U.S. Bureau of Land Management, who located the 1937 U.S. Soil Conservation Service cross sections in the field; Thomas Maddock, Sr., furnished profile data for the 1941 resurveys of the cross sections established by the Soil Conservation Service.

CHARACTERISTICS OF THE STUDY REACH

The Safford Valley, which extends from the confluence of the Gila River and Bonita Creek to Coolidge Dam, trends northwestward between the Gila Mountains on the northeast and the Pinaleno and Santa Teresa Mountains on the southwest (fig. 1). The valley is about 12 miles wide and 75 miles long and is filled with more than 1,000 feet of silt, sand, and gravel. The deposits have been classified informally as terrace gravel and alluvium, deformed conglomerate or gravel, and basin fill (Davidson, 1961, p. 151). Troughs incised in the basin fill are from 2,000 to 10,000 feet wide and are filled with as much as 100 feet of terrace gravel and alluvium. The Gila River enters the valley a few miles northeast of Safford and drains the area.

The study reach is about 45 miles long and extends from the confluence of the Gila and San Simon Rivers to Calva, Ariz. (pl. 1). The present report is concerned with the part of the alluvial area along the Gila River that underwent major changes from 1846 to 1970; in general, the area is included in the 1914–15 flood channel (pl. 1) as described by Olmstead (1919) and corresponds approximately to bottom land as defined by Gatewood, Robinson, Colby, Hem, and Halpenny (1950, p. 10). As herein used, the term "bottom land" refers to the area in the 1914–15 flood channel, and the term "flood plain" refers to the part of the bottom land not occupied by the stream channel. The term "stream channel" refers to the area that is generally void of vegetation and that has a definite bed in which flowing water is confined by banks.

The bottom-land area of the Gila River is from 1,000 to 5,000 feet wide, and the present (1970) stream channel is from 60 to 500 feet wide. The stream channel has an average slope of about 0.002 and is a pool-and-riffle type. During flows of less than about 500 cfs (cubic feet per second), the pools generally are full of sand, which is eroded easily at higher flows; the riffles are fairly stable gravel bars. The flood plain is densely covered with saltcedar, willow, and mesquite, except in areas where the vegetation has been removed by man.

The depth to ground water in the alluvium along the Gila River is less than about 20 feet below the land surface, and during flows of long duration, the water table intercepts the streambed. About 69,000 acres of land is under cultivation in the Gila River basin above Coolidge Dam; about 33,000 acres of the cultivated land is in Safford Valley (Barr, 1954, p. 14–17). The principal crops are cotton and alfalfa. Part of the irrigation water is diverted from the Gila River, and the rest is obtained from wells.

Climatically, the semiarid Safford Valley is in the Sonoran Border zone (Thomas, 1962, p. 13). The temperature extremes recorded at Safford, which is at an altitude of 2,900 feet above mean sea level in the upstream end of the valley, are 7° and 114° F (Sellers, 1960). The annual precipitation at Safford ranges from 3.0 to 17.5 inches and averages about 8.7 inches (Sellers, 1960).

An area of about 7,900 square miles contributes runoff to the Gila River at the head of Safford Valley. The drainage basin ranges in altitude from about 3,000 to 11,000 feet above mean sea level and extends eastward into the mountains in New Mexico.

The area tributary to the Gila River adjacent to the Safford Valley contains about 3,570 square miles and is drained by many ephemeral streams. The tributary basins typically are long and narrow, and the drainage areas are from less than 1 square mile to about 2,200 square miles. The altitudes of the basins range from about 2,500 to 11,000 feet above mean sea level. In general, the slopes of streams tributary to the study reach downstream from Fort Thomas are steep to the bottom land; in the bottom land the slopes of the streams abruptly decrease. The slopes of most of the tributaries upstream from Fort Thomas are relatively gentle to the bottom land.

Streamflow in the Gila River is classified as winter flow and as summer flow. Winter flow takes place from November through June, and summer flow takes place from July through October.

Winter flow is mainly from precipitation during frontal storms, snowmelt, or outflow from ground-water storage and often is a combination of the three. The flow rate may be fairly constant for several days, and the sediment concentrations are low. The causes of major winter floods are widespread heavy rainfall of long duration, warm weather after a large snow accumulation, or widespread rainfall on snow.

The main source of summer streamflow is local thunderstorms, which are especially prevalent in July and August. Individual summer thunderstorms characteristically produce high unit rates and unit volumes of flow from small watersheds, but only rarely do they produce high unit rates or unit volumes of flow from large watersheds. The crest of a flood from a thunderstorm typically is very sharp near the site of the thunderstorm, but it may become rounded or flattened downstream because of the dampening effects of temporary storage in the conveyance channels. During September and October, occasional frontal activity causes precipitation that produces widespread runoff. The combined runoff from the frontal storms and concurrent local thunderstorms is the most common cause of large flows of the summer season. Sediment concentrations generally are high during summer flows.

The annual surface-water inflow for the period 1938–61 averaged about 255,000 acre-feet for the reach that extends from the head of Safford Valley to Calva (Burkham, 1970, table 4). The inflow includes 230,000 acre-feet for the Gila River at the head of Safford Valley, 11,000 acre-feet for the San Simon River, and 14,000 acre-feet for ungaged tributaries. About 70 percent of the flow in the Gila River at the head of Safford Valley occurs in the winter, whereas the flows in the San Simon River and in the ungaged tributaries occur mainly in the summer.

The study reach is divided, in downstream order, into four subreaches (pl. 1)—A, from the confluence of the San Simon and Gila Rivers to the bridge at Pima; B, from the bridge at Pima to the east boundary of the San Carlos Indian Reservation; C, from the east boundary of the San Carlos Indian Reservation to the bridge on U.S. Highway 70 near Bylas; and D, from the bridge on U.S. Highway 70 near Bylas to the railroad bridge that spans the Gila River near Calva. Only a small amount of topographic data is available for subreach C, and data for this subreach are not included in the tables in this report. Subreach D is the same as subreach 1 in the Gila River Phreatophyte Project area (Culler and others, 1970). Spatial and temporal changes in the flood plain and stream channel are described for each subreach and for the entire study reach for the periods for which data are available.

DATA SOURCES

Diaries and journals written from 1846 to 1874 contain the first known descriptions of the Gila River in Safford Valley. A few of the diaries and journals, written by people in transit through the valley, include descriptions of the vegetation along the travel routes.

Cadastral surveys (data in files of U.S. Bur. Land Management, Phoenix, Ariz.) made during 1875–94 give detailed descriptions of stream-channel width, stream-channel meander, and vegetation along the stream. The cadastral surveys extended upstream from the east boundary of the San Carlos Indian Reservation to above the confluence of the Gila and San Simon Rivers.

The basic data for 1903 through 1917 are mainly from four sources—a soil survey made by Lapham and Neill (1904), photographs and topographic maps furnished by the U.S. Bureau of Indian Affairs (data in files of U.S. Bur. Indian Affairs, Phoenix, Ariz., and Washington, D.C.), Senate Document 436 (Olmstead, 1919), and U.S. Geological Survey Water-Supply Paper 450–A (Schwennesen, 1921). The soil-survey report covers a 2- to 6-mile-wide tract that extends from Solomon to Fort Thomas (pl. 1) and includes general descriptions of the Gila River and the vegetation along the bottom land in 1903 (Lapham and Neill, 1904). The topographic maps of Safford Valley were compiled in 1914–15, and the photographs showing views along the Gila River in the San Carlos Indian Reservation were taken during 1909–17 (data in files of U.S. Bur. of Indian Affairs, Phoenix, Ariz., and Washington, D.C.). The topographic maps, which are at a scale of 1:12,000, show altitude contours at 5-foot intervals, both banks of the Gila River, irrigation canals, diversion points, irrigated land, and land that could be supplied with water from the ditches in 1914–15.

Data for 1918–70 were obtained mainly from aerial photographs, topographic maps, and cross-sectional profiles. The aerial photographs were taken in 1935, 1942, 1947, 1954, 1957, 1964, 1966, 1967, and 1968. Data were taken from two sets of topographic maps One set was prepared by the U.S. Soil Conservation Service in 1935 at a scale of 1:7,200; the contours are at 2-foot intervals. The other set was prepared by the U.S. Geological Survey in 1960 at a scale of 1:62,500; the contours are at 40-foot intervals. Cross-sectional profiles are available for many sites along the study reach; most of the cross sections were established by the U.S. Soil Conservation Service in 1937 and by the Phelps Dodge Corp. in 1943. The cross sections used in the present report (pl. 1) were resurveyed by the author during 1965–70.

GILA RIVER BEFORE 1875

Francisco Vasquez de Coronado, in quest of the "Seven Cities of Gold," crossed the Gila River near the present town of Geronimo in 1540. According to Calvin (1946, p. 135), Coronado described the Gila River as " 'a deep and reedy stream'." The next known reference to the Gila River is by Emory (1848, p. 67), a U.S. Army topographical engineer, who described the Gila River near Bonita Creek as having a cross section of "about 70 feet by 4" on October 27, 1846. Emory (1848, p. 68) found cottonwood and willow close to the

Gila River near its confluence with the San Simon River, and farther downstream away from the Gila he noted that "the dust was knee deep in the rear of our trail; the soil appeared good, but, for whole acres, not the sign of vegetation was to be seen. Grass was at long intervals, and, when found, burned to cinder."

Johnston, who traveled in the same military expedition as Emory, substantiates Emory's description of the vegetation. Johnston (in Emory, 1848, p. 588) reported that

> the grass along the edge of the water on the river grows in a thin stripe very luxuriantly; there is usually a thicket of willows, about 10 yards deep, along the borders of the stream; then in the bottom, which is subject to overflow, cottonwoods grow of two and three feet in diameter; this strip is usually 200 or 300 yards wide.

Johnston implies that the banks of the Gila River in the Safford Valley were not high and related that the party crossed the Gila River several times without much difficulty.

On October 28, 1846, Dr. Griffin (1953, p. 27), en route to California, wrote that the Gila River near Mount Graham was "some 60 yards broad and very rapid and quite deep." Evidently, the river was at flood stage at this time and had received runoff from tributaries as a result of storms on the previous day (Clarke, 1966, p. 94).

In 1849 the Gila River probably was much the same as it was in 1846. Chamberlin (1945, p. 164) described the bottom land near the base of Mount Graham on July 15, 1849, as follows: "The bank of the river is so beset with underbrush and drift that we cannot get a supply of water without extreme difficulty." He reported that the sand and dust along the trail in the valley were very deep.

According to Chapin (copies of correspondence between Chapin, Commander of Camp Goodwin in 1867, and his superiors in files of U.S. Bur. Land Management, Phoenix, Ariz.), in 1867 the Gila River near Geronimo was "sandy under smooth stretches of water while slight rapids occur at intervals of one or two miles—no rocks in place are found in the river, the channel of water being 50 feet broad with an average depth of 2 feet." He also stated: "The mesquite trees are found in the low grounds, and the cottonwoods upon the banks of the Gila." Weech (1931, p. 23) related that the Gila River "was fringed on both sides with cottonwoods and willow trees" in 1867. On crossing the river at a point near Fort Thomas, Weech stated: "The river was swollen by the melting snow and to cross it we had to swim our horses. The Gila then was a stream with well defined banks and sloping graveled bottom. It was about four to six rods wide."

In summary, before 1875 the Gila River probably was less than 150 feet wide and 10 feet deep at bankfull stage. The river meandered through a flood plain covered with willow, cottonwood, and mesquite.

GILA RIVER FROM 1875 TO 1970

The channel changes of the Gila River in Safford Valley may be grouped into three distinct periods—1846–1904, 1905–17, and 1918–70. The size of the stream channel and the vegetation in the flood plain apparently were about the same in 1875 as they were during the previous few decades. In 1875 the average width of the stream channel, determined from maps made during the cadastral surveys, was about 150 feet for subreaches A and B (table 1); however, the width ranged from about 70 to 220 feet. The average stream-channel width was obtained by dividing the plan area of the channel by the length measured along the axis of the channel. The sinuosity of the stream channel in subreach A was about 1.20 (table 1). Sinuosity is the ratio between stream-channel length and valley length, in which valley length is taken as the flood-channel length in 1914–15.

TABLE 1.—*Characteristics of subreaches A, B, and D of the Gila River, Safford Valley*

[Location and extent of subreaches shown on pl. 1]

Year	History of the bottom land[1]			Stream channel				
	Vegetated area	Cultivated area	Stream channel	Area eroded beyond the bottom land	Total area	Length	Average width	Sinuosity
	Acres			Acres	Acres	Miles	Feet	Foot/foot
Subreach A								
1875	2,760	0	220	70	290	15.34	160	1.20
1903	2,540	0	370	71	441	14.30	250	1.12
1914	0	0	2,980	0	2,980	12.74	1,930	1.00
1935	2,050	253	673	163	836	13.82	500	1.08
1957	1,440	1,220	320	240	560	14.42	320	1.13
1966	870	1,320	790	280	1,070	12.84	690	1.01
1967	790	1,180	1,000	160	1,160	12.90	740	1.01
1968	970	1,200	810	20	830	12.80	530	1.01
Subreach B								
1875	4,550	0	380	0	380	[2] 22.90	137	----------
1894	[3] 795	0	[3] 450	0	[3] 450	[3] 7.44	[3] 500	1.12
1903	[3] 1,740	0	[3] 448	0	[3] 448	[3] 13.9	[3] 270	1.16
1914	0	0	4,900	0	4,900	20.2	2,000	1.00
1935	3,340	330	1,230	220	1,450	22.6	530	1.12
1942	3,420	470	1,000	290	1,290	23.1	460	1.14
1957	3,500	1,090	310	280	590	24.1	200	1.19
1966	2,290	2,070	540	270	810	22.9	290	1.13
1967	2,390	1,170	1,340	240	1,580	23.0	570	1.13
1968	3,040	1,030	830	70	900	22.8	330	1.13
Subreach D								
1914	827	0	503	0	503	6.09	907	1.09
1935	1,010	0	320	0	320	6.20	420	1.12
1942	1,100	0	225	0	225	6.56	280	1.17
1947	1,210	0	70	0	70	6.91	80	1.24
1954	1,270	0	59	0	59	7.05	70	1.26
1964	1,260	0	70	0	70	7.32	80	1.31
1967	----------	----------	122	----------	122	6.80	150	1.22
1968	----------	----------	238	----------	238	6.80	290	1.22

[1] The term "bottom land" refers to the area in the 1914–15 flood channel (pl. 1).

[2] Stream length was not measured in 1875; the length was "sketched in" by the field party.

[3] Map covered only part of reach.

The average width of the stream channel probably increased from 1875 to 1894 and decreased from 1894 to 1903. The average width for the section of the river from Fort Thomas to the boundary of the San Carlos Indian Reservation—an area that includes about a third of subreach B—was about 140 feet in 1875, 500 feet in 1894, and 260 feet in 1903.

The vegetation along the Gila River from 1875 to 1904 probably was about the same as it was in previous years (fig. 2). The banks of the Gila River were densely covered with willow, cottonwood, and mesquite in 1875, 1883, 1894 (vegetation notes made by cadastral engineers in files of U.S. Bur. Land Management, Phoenix, Ariz.), and 1903 (Lapham and Neill, 1904).

Widening of the Gila River stream channel began in 1905 and continued intermittently through 1917. The average width of stream channel in subreaches A and B increased from about 260 feet in 1903 to nearly 2,000 feet in 1914–15 (table 1; pl. 2). In 1914 the average stream-channel width in subreach C was about 1,600 feet and was about 900 feet in subreach D. Although it is known that the average width of stream channel in the study reach continued to increase during 1915–17 (Olmstead, 1919, p. 9), the amount of increase is unknown.

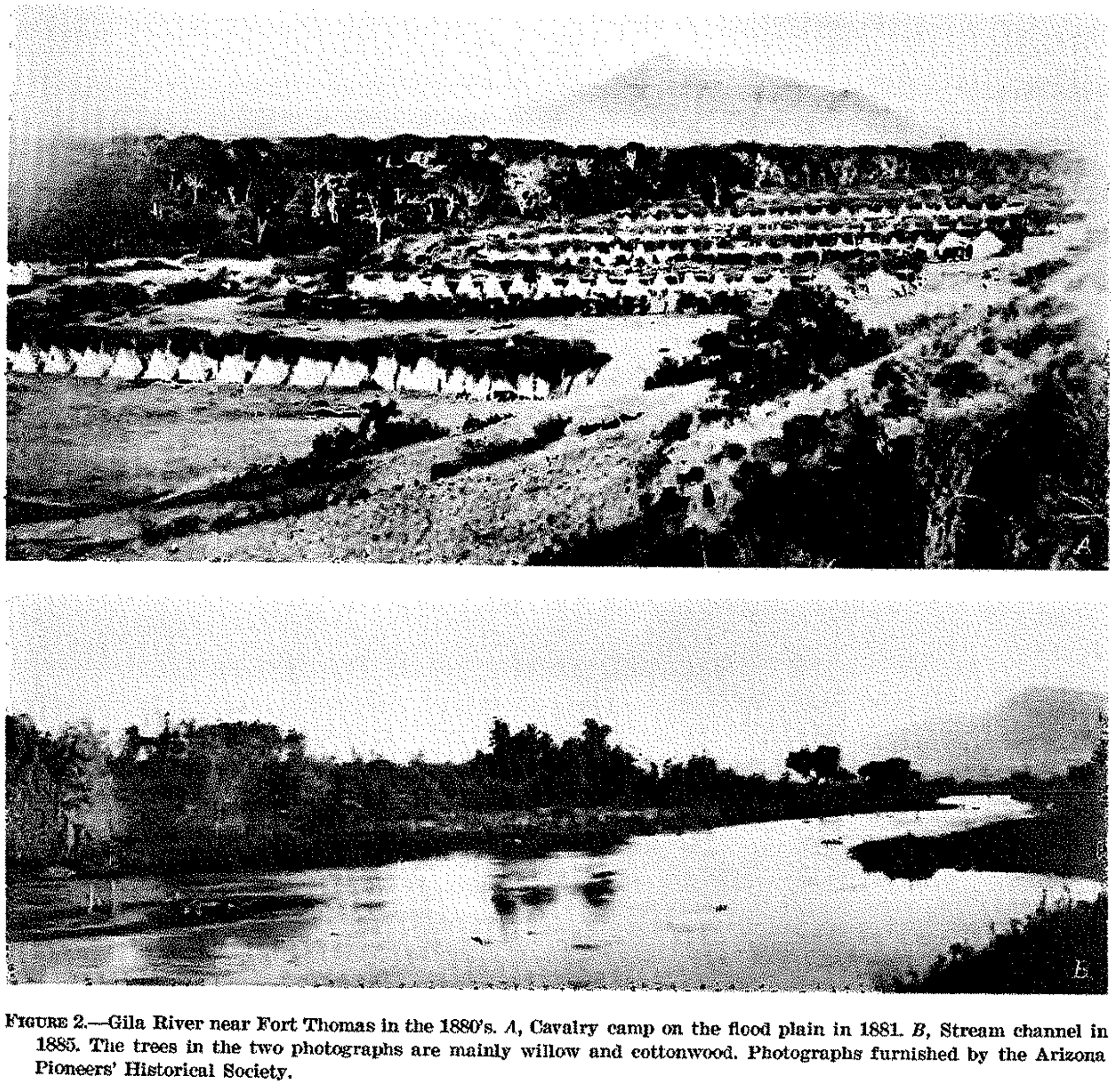


FIGURE 2.—Gila River near Fort Thomas in the 1880's. *A*, Cavalry camp on the flood plain in 1881. *B*, Stream channel in 1885. The trees in the two photographs are mainly willow and cottonwood. Photographs furnished by the Arizona Pioneers' Historical Society.

Most of the dense stands of willow and cottonwood that grew along the Gila River prior to 1905 were destroyed during 1905–17 (fig. 3). The stream channel was relatively barren in 1909 (fig. 4); therefore, most of the destruction probably occurred during 1905–9.

Redevelopment of the flood plain in the Safford Valley occurred during 1918–70; the stream channel became narrower, the meander of the stream channel became progressively greater, and the vegetative cover in the flood plain became more dense. The rate of redevelopment varied, and there were definite breaks in 1941 and during 1965–67, when minor stream-channel widening occurred. The average stream-channel width in subreaches A and B had decreased to about 500 feet by 1935; in subreach D the width had decreased to about 420 feet (table 1). By 1964, the average stream-channel width in the study reach had decreased to less than 200 feet. During two major floods—one in December 1965 and one in August 1967—the average width of the stream channel in the study reach increased to about 400 feet.

The sinuosity of the stream channel in Safford Valley increased from about 1.0 in 1918 to about 1.1 in 1957 and was about 1.2 in 1964. During the December 1965 and August 1967 floods, however, the sinuosity decreased to about 1.1.

Saltcedar became the dominant tree type in the bottom land during 1920–30. The saltcedar, a plant brought into Texas and New Mexico from the Mediterranean region, apparently was introduced into the Safford Valley in the second decade of the 20th century (Gatewood and others, 1950, p. 11). Conditions for the growth of the saltcedar were ideal, and it spread rapidly along the flood plain. The saltcedar, which consumes large amounts of water, reached its maximum areal extent in the study reach during 1945–55; after 1955, farmers began to clear large areas of saltcedar for the cultivation of crops (fig. 5).

STREAM-CHANNEL WIDENING, 1905–17

As indicated in a foregoing section, widening of the stream channel of the Gila River in Safford Valley occurred during 1905–17. The following discussion of the stream-channel widening is based primarily on comparisons between the different topographic maps, on analysis of streamflow data, on comparisons between the maps and the photographs that were taken before and after widening, and on observations by the author during the major floods of December 1965 and August 1967.

FACTORS AND MECHANICS INVOLVED

The widening of the stream channel occurred because the forces applied along the stream-channel boundary produced stresses greater than the banks could withstand. The effects of major floods and grazing and of flood-plain vegetation and cultivation are discussed below.

MAJOR FLOODS AND GRAZING

Major floods were a primary cause of the widening of the stream channel of the Gila River; the widening events in 1891, 1905–17, 1941, and 1965–67 were coincident with major floods (pl. 3; Burkham, 1970, p. 20–30). Most of the floods originated in the mountainous part of the headwaters area as a result of frontal storms, which moved into the area from the southern Pacific Ocean. Except for the flood of August 1967, the major floods occurred from September through February. The peak discharges ranged from about 30,000 to 150,000 cfs. Eight major floods occurred during 1905–17, which is the "wettest" period in Safford Valley since the beginning of record. According to Stockton and Fritts (1968, p. 18–20), 1905–17 may have been the wettest period since 1650.

Major floodflows exert great force on the stream-channel banks and on objects in the main-flow path and cause channels to enlarge. During a major flood, the main-flow path generally is straight down the valley, and, in many places, the banks of the meandering stream channel constitute objects in the main-flow path. While the meander pattern is intact, part of the flow is directed along the meandering stream, and large turbulence is developed along the streambanks. Eventually, as a result of the stresses produced by the turbulent forces along the streambanks and around other stationary objects, changes take place—stream-channel banks erode, trees are uprooted and flushed downstream, protective grasses are removed, alluvial fans at the mouths of the tributaries are destroyed, and dikes protecting cropland are breached. The result of these changes is additional debris in the flowing water.

Most, but apparently not all, of the stream-channel widening during 1905–17 occurred in 1905 and 1906. According to Olmstead (1919, p. 9): "From October, 1915, to September, 1916, by actual plane table survey, * * *, there was washed away by the Gila River, 1,155 acres in Safford Valley and 990 acres in the San Carlos Reservation, or 2,145 acres in all." Olmstead (1919, p. 10) further stated that the flood in October 1916 washed out "perhaps some 400 acres more along this Safford Valley reach."

The high flows during 1905–17 probably carried relatively small sediment loads at the head of Safford Valley, which may have been a significant factor in causing the widening of the stream channel of the Gila River. Studies based on the meager data available prior to 1905 (U.S. Army Corps Engineers, 1914, p. 30) and on

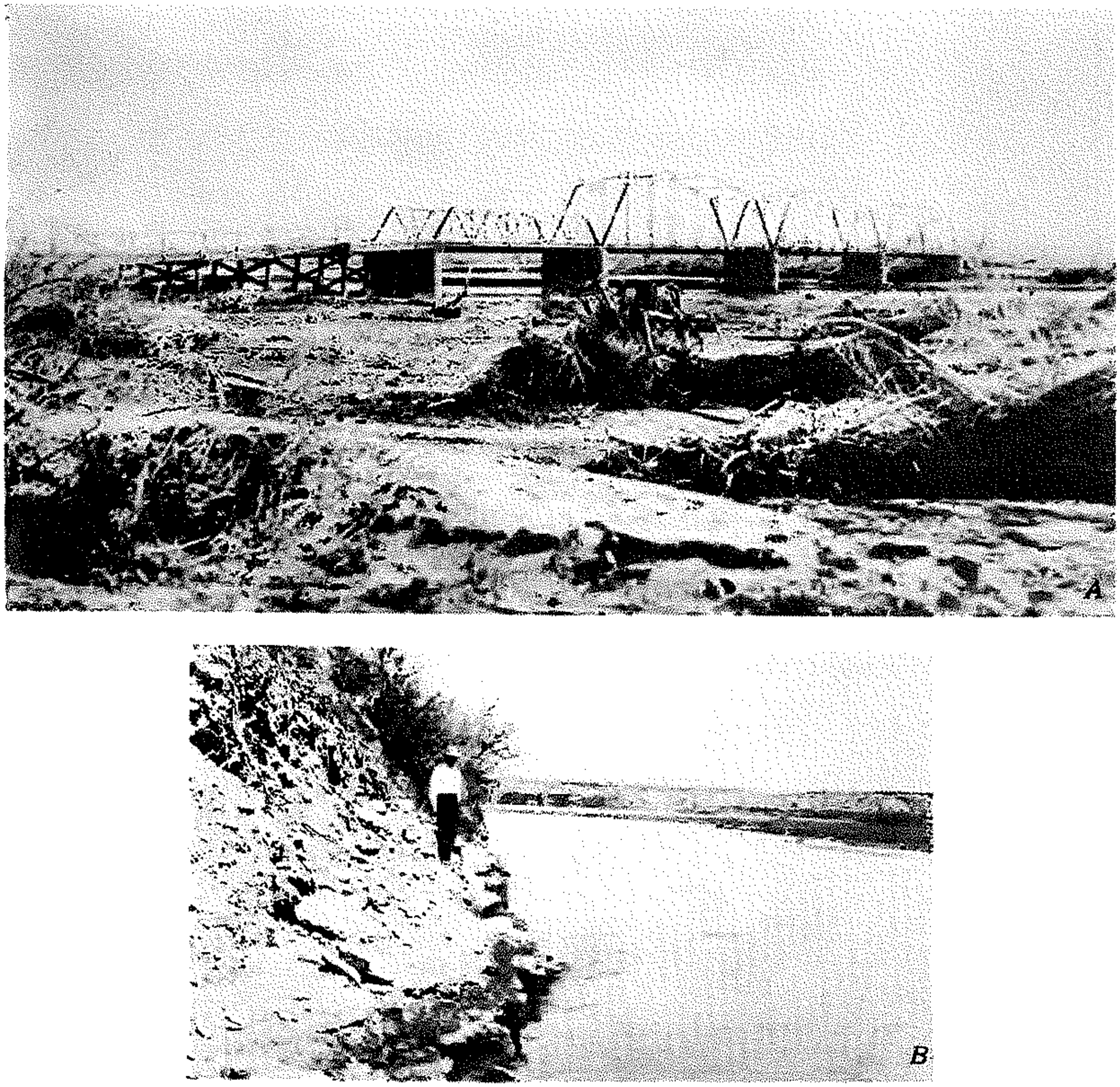
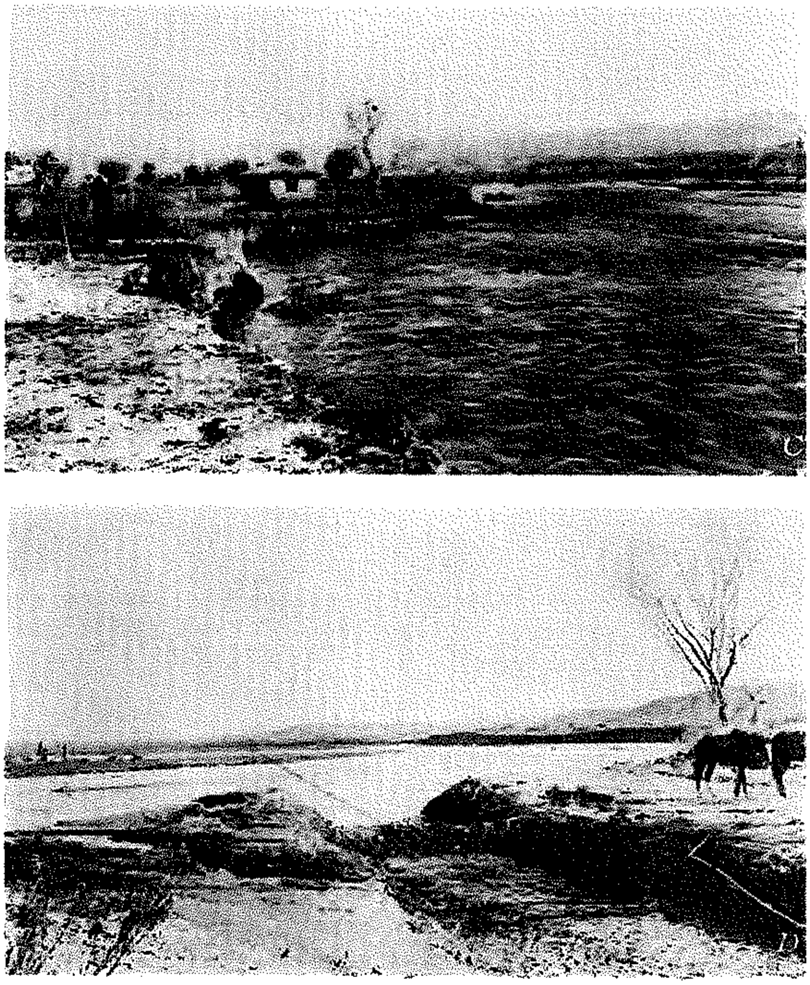


FIGURE 3.—Gila River in 1916. *A*, Looking upstream at the bridge at Pima; the drift in the foreground probably is cottonwood. *B*, Looking downstream at Black Point near Bylas; the trees in the background across the river probably are cottonwood. *C*, Erosion on the left bank of the river at Bylas; the alluvial fan on the right side of the river at the mouth of Salt Creek (not shown in photo-

data for 1965–70 (U.S. Geol. Survey, issued annually) indicate that the sediment concentration for a given flow rate in the winter in the Gila River at the head of Safford Valley is less than 20 percent of the average concentration for the same flow rate in the summer. Most of the winter flow originates in mountainous terrain, which does not erode easily. The sediment load does not increase with increasing discharge because of the lack of transportable material. Large flows having relatively low sediment yields are conducive to erosion.

Grazing apparently did not have a significant influence on the major floods during 1905–17 and, therefore, probably had no effect on the widening of the stream channel. Large-scale grazing began in about 1872 in the Gila River drainage (Calvin, 1946, p. 136), and, by 1890, the area apparently was "overstocked." A few



graph; see pl. 1) is causing a realinement of the river. *D*, Gila River near Bylas; debris in the left background is uprooted cottonwood. Photograph *A* is from Olmstead (1919, pl. 11); photographs *B*, *C*, and *D* furnished by the U.S. Bureau of Indian Affairs, Phoenix, Ariz.

years later, many of the cattle starved or were shipped to eastern markets (Calvin, 1946, p. 139; Rowalt, 1939, p. 7). Since about 1905, the number of cattle in the area has been small compared to the number in 1890. The parts of the Gila River drainage that were overstocked in 1890 were in the valleys below the shaded mountain forests and below the area that produced most of the floodwater; grass was the dominant vegetation in these areas. If there had been large areas of grass in the flood-producing area, the floods probably would have been slightly more severe.

FLOOD-PLAIN VEGETATION AND CULTIVATION

Although the trees along the river contributed to the stability of the flood plain during small and moderate floods, the trees may have had a minor influence on the

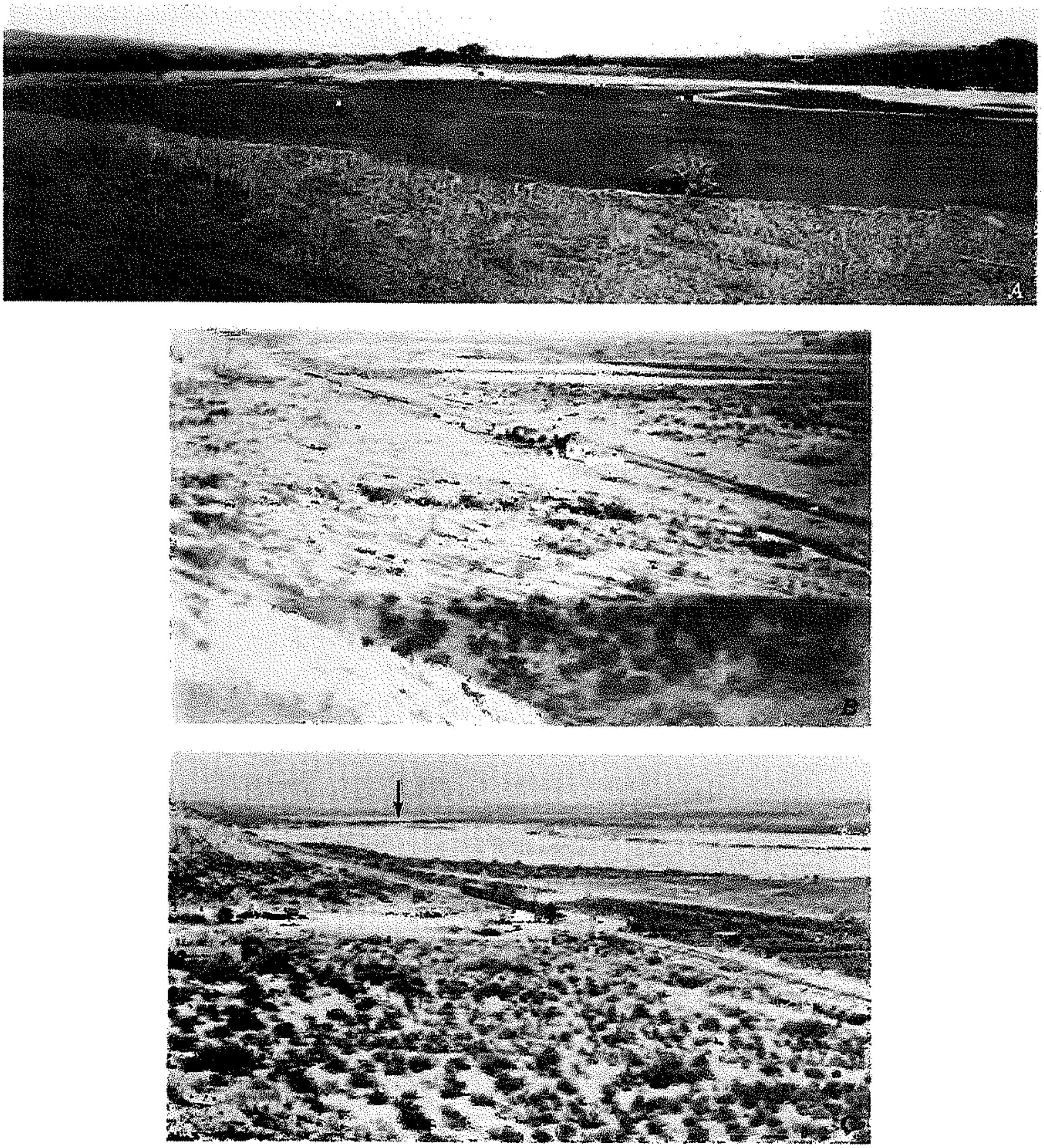


FIGURE 4.—Gila River in 1909 and 1969. *A*, Looking downstream near Geronimo in May 1909. *B*, Looking downstream near the railroad siding at Calva in 1909. *C*, Looking downstream near the railroad siding at Calva in 1969 (arrow indicates location of railroad bridge); the bottom-land vegetation was eradicated in 1966 to control evapotranspiration, and the photograph in figure 6 shows the same area before eradication. Photographs *A* and *B* furnished by the U.S. Bureau of Indian Affairs, Phoenix, Ariz. Photograph *C* furnished by Mr. R. M. Turner, Tucson, Ariz.

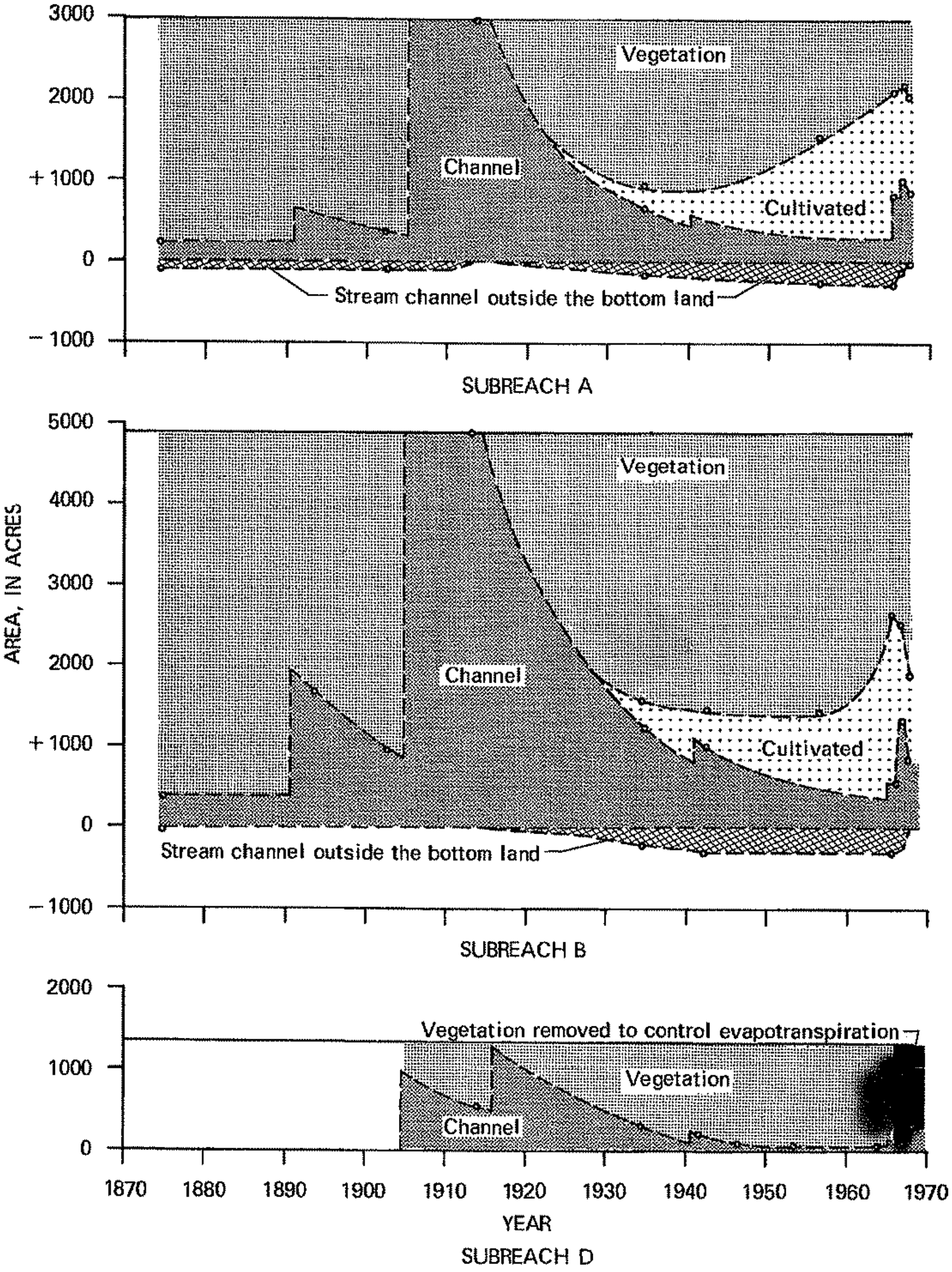


FIGURE 5.—Historical changes in the bottom land in subreaches A, B, and D. The increases in channel width are the result of the major floods in 1891, 1905–17, 1941, 1965, and 1967 (pl. 8). Data plotted from table 1.

widening of the stream channel during the major floods of 1905–17. The trees restricted the flow of water onto the flood plain and concentrated flow in the stream channel. The concentrated flow increased stresses along the stream-channel banks, which may have influenced erosion of the original stream channel. The cottonwood trees may have contributed to the widening in another way. During the major floods, floating debris hung on the trees, which resulted in an increase in turbulence and erosion. Because the trunks of cottonwood trees are very rigid, the forces applied to the trees created torsion at the ground. The combination of torsion and erosion caused the trees to overturn; the trees usually took large chunks of alluvium with them, which left the easily erodible material exposed. The unanchored trees became a part of the floating debris and may have hung on other trees farther downstream, which caused them to be uprooted.

Cultivation of the flood plain probably was not an important factor in causing the widening of the stream channel during 1905–17 because only a small amount of land was cleared for farming. Lapham and Neill (1904, p. 1059) stated that only "a small proportion of the Pecos sand is at present cultivated, mainly because of the difficulty and expense of clearing off the willow, cottonwood, and mesquite, and leveling the land for irrigation. Small tracts are, however, being cleared * * *." The areal extent of the Pecos sand and the areal extent of the flood plain were about the same in 1903.

The small dams and canals used to divert irrigation water from the Gila River probably did not influence the stream-channel widening greatly because of their temporary nature. The diversion dams and canals generally were cheaply built and readily failed during floods.

The author concludes that the large floods having low sediment concentrations were the main cause of the widening of the stream channel. Flood-plain vegetation, however, may have been a minor contributing factor.

EFFECTS OF STREAM-CHANNEL WIDENING ON STREAM GRADIENTS

As the stream channel of the Gila River widened, it straightened, and the channel length decreased and its gradient increased. Before the floods of 1905–17, the stream channel was about 20 percent longer than the valley; following the floods, however, the stream channel was only slightly longer than the valley (table 1). Available data indicate that the altitude of the stream-channel floor did not change appreciably during the periods of major stream-channel widening and flood-plain reconstruction. Therefore, the straightening of the stream channel increased the gradient about 20 percent. The widening of the stream channel of the river decreased the length of most of the tributary streams and resulted in an increase in the stream gradients at their confluence with the Gila River.

FLOOD-PLAIN RECONSTRUCTION, 1918–70

The reconstruction of the Gila River flood plain apparently began soon after the major flood of October 14, 1916; however, erosion continued in places along the flood channel through the fourth decade of the 20th century. High flows could take any one of several paths in the wide flood channel, causing local damage to canals, dikes, and cultivated land along the banks of the flood channel. Generally, however, erosion of the bank in one area made more sediment available for deposition in the flood channel in another area, and the rate of reconstruction of the flood plain was rapid. The reconstruction was accomplished almost entirely by the accretion of sediment. Conditions favoring the rapid accretion of sediment were a large sediment inflow and the inability of the Gila River to move the sediment through the valley.

SEDIMENT INFLOW

In the third and fourth decades of the 20th century, the floods in the Gila River in Safford Valley carried large sediment concentrations (Rowalt, 1939, p. 45; Calvin, 1946, p. 135). The large sediment loads originated mainly from the erosion of alluvium in the lower altitudes of the watersheds tributary to the Gila River above Coolidge Dam. The erosion was triggered mainly by the major floods of 1905–17, although the lack of precipitation and extensive grazing in earlier periods may have contributed to the erosion. The high flows in the Gila River drainage during 1905–17 accelerated erosion in the tributaries of the Gila River by increasing the gradient of most of the tributaries at their confluence with the Gila River and by providing the motive power necessary to start the erosion.

Generally, the areal extent of the channel erosion in the steep streams that drain the mountainous terrain near the Gila River was small because of the small areal extent of the easily erodible alluvium that underlies these streams (pls. 4, 5). Man's use of the steep watersheds was insignificant. However, the alluvial valleys drained by gently sloping streams apparently were very vulnerable to erosion, and erosion in some of the valleys was severe.

The lack of precipitation and the extensive grazing prior to 1905 may have contributed to the susceptibility of the alluvial valleys to erosion during high flows. The period 1870–89 was one of the driest periods of comparable length since 1650 (Stockton and Fritts, 1968, p.

20–21), and 1895–1904 was another period having very little precipitation. The years having small amounts of precipitation coincided with the years in which large numbers of cattle were brought into the area. The combination of little precipitation and extensive grazing caused a deterioration in the vegetation of the valley, which may have made the alluvium more susceptible to erosion.

The San Simon River (pl. 1) is an example of a gently sloping stream that has undergone severe channel erosion since 1905. The San Simon River drains an area of about 2,200 square miles, and its valley covers most of the watershed. Apparently, debris from side tributaries had been collecting in the alluvial-filled valley for centuries, and in 1905 it was poorly drained and relatively unstable. In 1903 the San Simon River was an insignificant and poorly defined watercourse (Lapham and Neill, 1904, p. 1050). When severe erosion began, probably during the major floods of 1905, deep channels were cut and eventually became large; erosion then spread to the side tributaries. According to Olmstead (1919, p. 79), there was 60 miles of eroded channel along the San Simon River in about 1919; by 1960, there was more than 100 miles of gullied channel from 10 to 40 feet deep (Peterson, DeJulio, and Rupkey, written commun., 1960) and from 20 to 500 feet wide. The gullied channels captured runoff that, prior to the erosion, would have spread over the valley and replenished soil moisture necessary for plant growth. As the water flowed into the deep channels, additional erosion occurred; however, the eroded material, generally of small size, was easily moved downstream because the flow was confined.

According to Olmstead (1919, p. 79), a ditch dug at the mouth of the San Simon River may have influenced channel erosion in that stream. The ditch was dug by settlers prior to 1900 to divert floods in the San Simon River away from the cultivated land. Because severe erosion took place at the same time in other gently sloping streams, the author assumes that the erosion in the San Simon River basin would have occurred even if the ditch had not been dug.

DEVELOPMENT PROCESS

Sediment accretion in alluvial flood plains may occur in five general ways: (1) by the development of islands in the stream channel and their subsequent attachment to one bank by channel abandonment, (2) by direct deposition on the flood plain, (3) by deposition in the stream channel along the banks, (4) by formation of natural levees, and (5) by deposition on alluvial fans at the mouths of tributary streams. The processes of deposition overlap, and it is often difficult to determine the method of deposition by observing a sediment deposit in the field. Nevertheless, the methods are different, and examples of each are found in the study reach. The characteristics of methods 1–4 are described in the section "Stream-Channel Development," and the characteristics of method 5 are described in the section "Alluvial-Fan Development."

STREAM-CHANNEL DEVELOPMENT

Low-flow channels that developed during the floods of 1905–6 and 1915–17 were the beginning of the present (1970) stream channel. The small channels meandered between sediment islands that were formed during the floods. The sediment islands were remnants of the old flood plain and sandbars and dunes that formed in the areas of low velocity. At first, the sediment islands were small, but they increased in size as a result of successive additions of sediment, mainly at the downstream ends. In time, vegetation became established, and the islands became fairly stable (fig. 6).

The development of the islands reduced the width of the surrounding channels, and deposition often occurred in one of the channels. One channel generally will carry a larger part of the sediment load than the other channel (Lindner, 1952); in this instance, the channel that carries the largest part of the load generally will aggrade until it carries only a small percentage of the streamflow, and eventually the channel is abandoned, except during floods (Schumm and Lichty, 1963, p. 82–84). The islands were united by this process and formed a flood plain paralleling a low-flow channel. In the beginning, almost all the flows overtopped the low-flow channel and deposited sediment on the flood plain. Because of the absence of large floods, vegetation became fairly permanent. Successive depositional events have resulted in a flood plain at a level several feet above the present (1970) streambed.

The deposition along the banks in the stream channel may be described as lateral deposition. This type of deposition occurs in places where stream velocities are relatively low; along the inside banks at bends; at downstream ends of objects protruding into the flow; and, in some instances, in straight channels without protruding objects. Lateral deposits generally occur at all levels below the top of the channel banks. If lateral deposits are not disturbed by floods, they increase in thickness with each successive addition of sediment until the top level reaches that of the original banks. The higher deposits are more stable, owing to less frequent disturbance by floods and to the protective vegetation.

When flow overtops the banks, deposition often takes place just outside the stream channel and forms natural levees. As the flow leaves the stream channel, the veloc-

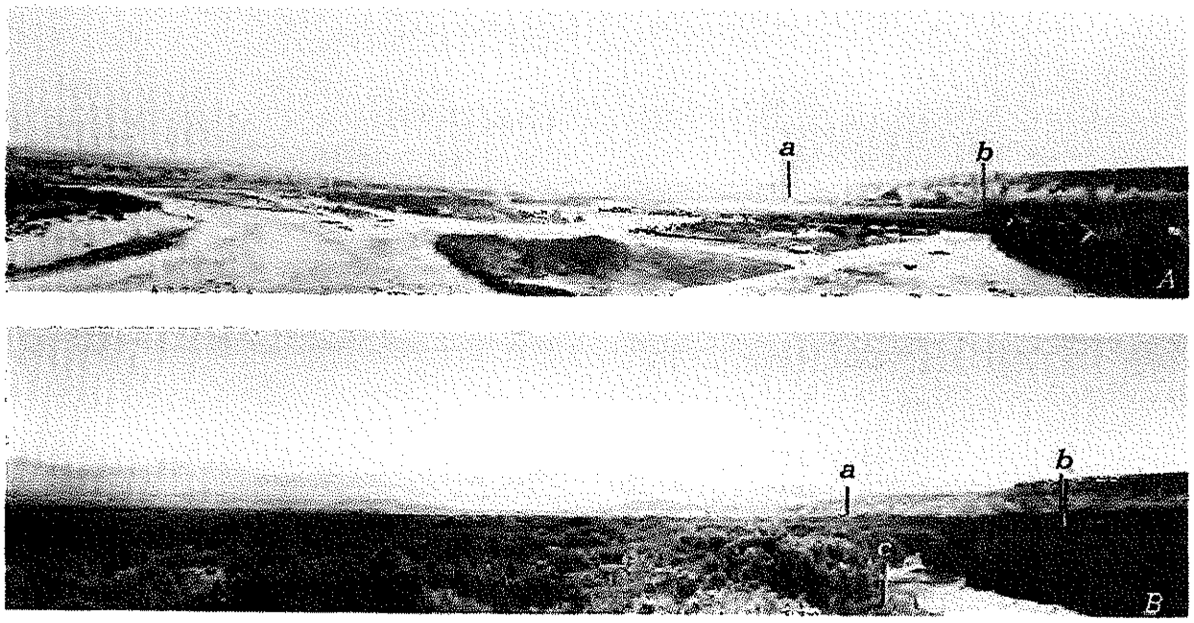


FIGURE 6.—Saltcedar encroachment along the Gila River between 1932 and 1964. *A*, Looking upstream from the railroad bridge near Calva in 1932; the braided stream probably is typical of the Gila River in most of the Safford Valley in the third and early fourth decades of the 20th century. *B*, Looking upstream from the railroad bridge near Calva in 1964. Leaders indicate: *a*, location of railroad siding at Calva (fig. 4*B*, *C*); *b*, location of alluvial fan shown on plate 4; *c*, location of stream channel in 1964.

ity is reduced and sediment is deposited adjacent to the banks. The deposition is aided by the retarding action of the vegetation along the banks. Natural levees occupy only a small part of the flood plain at present (1970); however, in places, the levees are more than 3 feet high. The natural levees and the retaining dikes constructed by farmers keep median flows—flows below about 5,000 cfs—from spreading over the flood plain. Conversely, during high flows, water that flows over the levees and water from the tributary streams often are retained in basins formed by flood-channel banks, alluvial fans, and the natural levees, which results in deposition of sediment.

ALLUVIAL-FAN DEVELOPMENT

In the bottom land, alluvial fans generally are limited to the reach downstream from Fort Thomas (pl. 1). Because of the steep slopes, flows in streams tributary to this part of Safford Valley usually travel at relatively high velocities, carry large sediment loads, and move large amounts of coarse material along the channel bed. Upon reaching the wide flat bottom land along the Gila River, the material carried by the tributary flows is deposited as alluvial fans.

The development of an alluvial fan is depicted on plate 4. The floods of 1905–6 in the Gila River apparently washed out the alluvial fan at the mouth of a tributary stream near Calva and eroded a low-flow channel. Removal of the fan caused an increase in the gradient at the mouth of the tributary channel and augmented erosion. Subsequently, another fan developed at the site, forcing the Gila River stream channel toward the opposite side of the flood plain. Development of the fan has caused a progressive aggradation in the tributary stream; the deposit is about 17 feet thick at the mouth and about 5 feet thick at the railroad bridge spanning the tributary (pl. 4). The alluvial fan and the tributary stream apparently are reverting to a natural state similar to that existing prior to 1905.

Alluvial fans at the mouths of a few tributary streams have caused striking shifts in the course of the Gila River. For example, at the mouth of Salt Creek at Bylas (pl. 1), the fan, which probably developed after the floods of 1905–6, shifted the Gila River channel southward during the major flood of December 1914 (Burkham, 1970, p. 25), causing flood damage in Bylas. According to C. R. Oldberg (written commun., January

1916, in files of U.S. Bur. Indian Affairs, Phoenix, Ariz.):

> For several years previous to 1914, however, the stream channel seemed to hug the north bank of the river * * *. In December 1914, the river attacked the south bank in three places * * *. In July 1915, another flood, although not so great as the one in December 1914, eroded the [south] river bank for about 6,600 feet * * * at the same time cutting the channel deeper on the south side of the river and building up on the north side. * * * The channel is now headed directly towards the school [in Bylas] * * *.

In February 1920, H. V. Clotts (written commun., March 1920, in files of U.S. Bur. Indian Affairs, Phoenix, Ariz.) found that "the wide detour of the [Gila River] channel * * * has been gradually approaching the school [in Bylas] * * *. While the river has been cutting in the Southside, it has been depositing a bar on the Northside on the inside of the curve."

The meager topographic data indicate that the alluvial fan at the mouth of Salt Creek at Bylas retarded flow in the Gila River and caused the deposition of sediment in the backwater areas during the major floods of 1905–17. Some of the sediment deposited during the floods was removed later by smaller flows.

Plate 5 shows the horizontal and vertical changes in the Gila River near Fort Thomas as a result of two alluvial fans and high flows. The fans, which formed at the mouths of two tributaries, apparently were removed during the floods of 1905–17; however, a deep channel did not erode in the smaller tributary until subsequent years (pl. 1). As the alluvial fans re-formed, there was keen competition for the space occupied by the flood plain between the alluvial fans on the north and the cultivated land on the south. The alluvial fans caused a bend to develop in the Gila River and caused the erosion of the cultivated land during the floods of 1965–67.

In summary, the alluvial fans that formed at the mouths of the steep streams have affected the reconstruction of the Gila River flood plain in several ways. The fans occupy space and, therefore, retard floodflow, which results in the deposition of sediment in the backwater areas. The fans furnish a supply of easily erodible material that is redistributed to other parts of the flood plain by floods. The fans also have forced the Gila River into a meandering course through the bottom land.

RATES OF SEDIMENT ACCRETION

The amount of sediment accreted for each of the five processes of deposition is unknown. In subreaches A and B, however, the composite accumulation as a result of all processes is well documented through the periodic surveys that have been made at several cross sections (pl. 1).

The average change in the altitude of the bottom land at each cross section for a given time increment was obtained as follows: (1) The measured profiles at each cross section were plotted on graphs; (2) the vertical area between plotted profiles was obtained from the graph; and (3) the change in altitude was obtained by dividing the vertical area by the horizontal length of the cross section. These data are for the bottom land within the end points of the cross sections as initially established (table 2). The profile data were obtained from field surveys, except the data for 1914–15 and 1935, which were scaled from contour maps. A positive change in altitude for a time increment indicates a larger area of fill than of scour in the section. In many places there is fill in part of a cross section and scour in the rest (pl. 5*A*).

TABLE 2.—*Changes in the altitude of the bottom land at cross sections along the Gila River, Safford Valley*

Cross section No.: See plate 1 for locations of cross sections.
Change in altitude: Change in altitude for a cross section is averaged by dividing the change in vertical area by the horizontal width of the section.
Rate of change in altitude: Total change in altitude divided by the number of years between the first survey and the last, but data for 1914–35, 1914–37, and 1914–43 were not used in calculating the rate of change.

Cross section No.	Period between surveys	Change in altitude (feet)	Rate of change in altitude (feet per year)
SCS 18	July 1937 [1] to July 1965	−1.22	−0.03
	July 1965 to July 1966	+.27	
17	July 1937 [1] to July 1965	−1.60	−.04
	July 1965 to July 1966	+.44	
16	July 1937 [1] to July 1965	−.98	−.03
	July 1965 to July 1966	+.24	
15	July 1937 [1] to July 1965	−0.78	−.09
	July 1965 to July 1966	−1.80	
14	July 1937 [1] to July 1965	+1.37	+.04
	July 1965 to July 1966	−.31	
13	July 1937 [1] to July 1965	−.07	−.02
	July 1965 to July 1966	−.79	
12	July 1937 [1] to July 1941	−.28	−.03
	July 1941 to July 1965	+.21	
	July 1965 to July 1966	−.79	
11	July 1937 [1] to July 1941	−1.00	−.06
	July 1941 to July 1965	−.71	
	July 1965 to July 1966	−.02	

[1] Date that the cross section was established.

TABLE 2.—*Changes in the altitude of the bottom land at cross sections along the Gila River, Safford Valley*—Continued

Cross section No.	Period between surveys	Change in altitude (feet)	Rate of change in altitude (feet per year)
SCS 10	July 1937[1] to July 1941	+0.04	+0.03
	July 1941 to July 1965	+.09	
	July 1965 to July 1966	+.77	
9	July 1937[1] to July 1941	+.15	0
	July 1941 to July 1965	+.07	
	July 1965 to July 1966	+.46	
	July 1966 to Dec. 1968	−.67	
8	July 1937[1] to July 1941	+.49	+.05
	July 1941 to July 1965	+1.61	
	July 1965 to July 1966	−.59	
7	July 1937[1] to July 1941	−.05	+.02
	July 1941 to July 1965	+.81	
	July 1965 to July 1966	−.09	
6	July 1914 to July 1937[1]	+.60	
	July 1937[1] to July 1941	+.48	+.02
	July 1941 to July 1965	+.56	
	July 1965 to July 1966	−.50	
5	July 1914 to July 1937[1]	−1.30	
	July 1937[1] to July 1941	+.95	+.01
	July 1941 to July 1965	+.92	
	July 1965 to July 1966	−1.60	
4	July 1914 to July 1937[1]	−.77	
	July 1937[1] to July 1941	+.10	+.03
	July 1941 to July 1965	+1.11	
	July 1965 to July 1966	−.42	
3	July 1914 to July 1937[1]	+.94	
	July 1937[1] to July 1941	+.54	+.05
	July 1941 to July 1965	−.05	
2	July 1914 to July 1937[1]	+.85	
	July 1937[1] to July 1965	+.62	+.03
	July 1965 to July 1966	−.60	
1	July 1914 to July 1937[1]	+.31	
	July 1937[1] to July 1965	+.40	+.01
	July 1965 to July 1966	−.17	
	July 1966 to Dec. 1968	−.26	
GS (Safford bridge).	Dec. 1942[1] to Nov. 1967	+1.80	+.06
	Nov. 1967 to Jan. 1969	−.25	
PD 224	Oct. 1914 to July 1935	+3.56	
	July 1935 to June 1943[1]	−.78	−.07
	June 1943[1] to Oct. 1969	−1.70	
223	Oct. 1914 to July 1935	+2.51	
	July 1935 to June 1943[1]	−1.87	−.07
	June 1943[1] to Oct. 1969	−.54	
PD 222	Oct. 1914 to July 1935	+.88	
	July 1935 to June 1943[1]	+.53	−.01
	June 1943[1] to Oct 1969	−.97	
216	Oct. 1914 to July 1935	−.49	
	July 1935 to June 1943[1]	−.35	+.05
	June 1943[1] to Sept. 1969	+1.92	
215	Oct. 1914 to July 1935	−2.11	
	July 1935 to June 1943[1]	+1.10	+.03
	June 1943[1] to Sept. 1969	+.01	
214	Oct. 1914 to July 1935	+.15	
	July 1935 to June 1943[1]	+1.60	+.04
	June 1943[1] to Sept. 1969	−.21	
209	July 1935 to June 1943[1]	+.93	+.07
	June 1943[1] to Dec. 1969	+1.37	
208	July 1935 to June 1943[1]	+1.07	+.07
	June 1943[1] to Dec. 1969	+1.28	
207	July 1935 to June 1943[1]	+.20	+.04
	June 1943[1] to Dec. 1969	+1.23	+.04
196	July 1914 to July 1935	−0.32	
	July 1935 to June 1943[1]	+.10	+.10
	June 1943[1] to July 1966	+2.73	
GS (Pima bridge).	Oct. 1914 to July 1935	−.16	+.08
	July 1935 to Feb. 1968[1]	+2.57	
PD 185	Mar. 1915 to July 1935	−.18	
	July 1935 to June 1943[1]	+1.09	+.06
	July 1943[1] to Jan. 1970	+.99	
184	Mar. 1915 to July 1935	+1.12	
	July 1935 to June 1943[1]	+.89	+.04
	June 1943[1] to Jan. 1970	+.62	
183	Mar. 1915 to July 1935	+1.65	
	July 1935 to June 1943[1]	+.81	+.03
	June 1943[1] to Jan. 1970	+.27	
177	Mar. 1915 to July 1935	−1.39	
	July 1935 to June 1943[1]	−.43	+.03
	June 1943[1] to Dec. 1966	+1.42	
176	Mar. 1915 to July 1935	−2.22	
	July 1935 to June 1943[1]	+1.84	+.07
	June 1943[1] to Dec. 1966	+.23	
175	Mar. 1915 to July 1935	−1.25	
	July 1935 to June 1943[1]	−1.74	−.07
	June 1943[1] to Dec. 1966	−.89	
	Dec. 1966 to Dec. 1968	−.12	

---

[1] Date that the cross section was established.

TABLE 2.—*Changes in the altitude of the bottom land at cross sections along the Gila River, Safford Valley*—Continued

Cross section No.	Period between surveys	Change in altitude (feet)	Rate of change in altitude (feet per year)
SCS 145	Mar. 1915 to July 1937 [1]	−2.82	+0.09
	July 1937 [1] to July 1965	+2.40	
146	Mar. 1915 to July 1937 [1]	−4.68	+.06
	July 1937 [1] to July 1965	+2.19	
	July 1965 to Dec. 1968	−.38	
PD 148	Mar. 1915 to Sept. 1935	+1.66	+.08
	Sept. 1935 to June 1943 [1]	+.12	
	June 1943 [1] to Dec. 1967	+2.25	
147	Mar. 1915 to Sept. 1935	+2.27	+.08
	Sept. 1935 to June 1943 [1]	−.15	
	June 1943 [1] to Dec. 1967	+2.54	
146	Mar. 1915 to Sept. 1935	+2.28	+.12
	Sept. 1935 to June 1943 [1]	+1.33	
	June 1943 [1] to Dec. 1967	+2.62	
144	Mar. 1915 to Sept. 1935	+1.11	+.15
	Sept. 1935 to June 1943 [1]	+1.41	
	June 1943 [1] to Dec. 1967	+3.56	
	Dec. 1967 to Dec. 1968	−.15	
141	Mar. 1915 to Aug. 1935	+1.73	+.06
	Aug. 1935 to June 1943 [1]	+.49	
	June 1943 [1] to Dec. 1967	+1.35	
118	Feb. 1915 to Sept. 1935	−1.12	+.10
	Sept. 1935 to June 1943 [1]	+.82	
	June 1943 [1] to Dec. 1968	+2.37	
117	Feb. 1915 to Sept. 1935	−.51	+.06
	Sept. 1935 to June 1943 [1]	−.13	
	June 1943 [1] to Jan. 1968	+2.21	
116	Feb. 1915 to Sept. 1935	−.37	+.09
	Sept. 1935 to June 1943 [1]	+.51	
	June 1943 [1] to Dec. 1966	+2.37	
115	Feb. 1915 to Sept. 1935	−1.23	+.09
	Sept. 1935 to June 1943 [1]	+.39	
	June 1943 [1] to Dec. 1966	+2.29	
	Dec. 1966 to Dec. 1968	+.24	
114	Feb. 1915 to Sept. 1935	−2.47	+.04
	Sept. 1935 to June 1943 [1]	−.10	
	June 1943 [1] to Dec. 1966	+1.24	
113	Feb. 1915 to Sept. 1935	−1.46	+.11
	Sept. 1935 to June 1943 [1]	−.09	
	June 1943 [1] to Dec. 1966	+3.42	
112	Feb. 1915 to Sept. 1935	−.07	+.08
	Sept. 1935 to June 1943 [1]	+.30	
	June 1943 [1] to Dec. 1966	+2.18	
PD 111	Feb. 1915 to Sept. 1935	−0.13	+0.08
	Sept. 1935 to June 1943 [1]	−.59	
	June 1943 [1] to Dec. 1966	+3.05	
110	Feb. 1915 to Sept. 1935	+.97	+.06
	Sept. 1935 to June 1943 [1]	−1.54	
	June 1943 [1] to Dec. 1966	+3.37	
109	Feb. 1915 to Sept. 1935	+.03	+.14
	Sept. 1935 to June 1943 [1]	−.66	
	June 1943 [1] to Dec. 1966	+3.97	
	Dec. 1966 to Dec. 1968	+1.20	
108	Feb. 1915 to Sept. 1935	−.56	+.10
	Sept. 1935 to June 1943 [1]	−.68	
	June 1943 [1] to Dec. 1966	+3.89	
107	Feb. 1915 to Sept. 1935	+1.52	+.13
	Sept. 1935 to June 1943 [1]	−1.17	
	June 1943 [1] to Jan. 1968	+4.45	
106	Feb. 1915 to Sept. 1935	+.17	+.17
	Sept. 1935 to June 1943 [1]	+.23	
	June 1943 [1] to Jan. 1968	+5.23	
105	Feb. 1915 to Sept. 1935	−.81	+.17
	Sept. 1935 to June 1943 [1]	+.48	
	June 1943 [1] to Jan. 1968	+4.83	
GS 1	Nov. 1964 [1] to June 1966	−.83	+.31
	June 1966 to June 1968	+2.08	
3	Nov. 1964 [1] to June 1966	+.94	+.55
	June 1966 to June 1968	+1.25	
5	Nov. 1964 [1] to June 1966	−.17	+.08
	June 1966 to June 1968	+.48	
7	Nov. 1964 [1] to June 1966	−.09	+.04
	June 1966 to June 1968	+.21	
9	Nov. 1964 [1] to June 1966	−.09	+.20
	June 1966 to June 1968	+.89	

The sediment-accretion data for 1914–35, 1914–37, and 1914–43 are of poor quality for two reasons. First, several of the cross sections established in 1937 and 1943 did not extend across the entire bottom land, and the amount of fill or scour in the unsurveyed areas could not be determined; however, the amount in the unsurveyed areas may have been a large part of the fill or scour during these periods. Secondly, the small scale (1:12,000) and large contour intervals (5-ft) for the 1914–15 topographic map resulted in limited accuracy of the cross-sectional profiles. Although these data may have limited hydrologic value today, they do indicate

---

[1] Date that the cross section was established.

the areas of aggradation and degradation. The sediment-accretion data collected from 1935–70 are of better quality. Since 1935 most of the changes in the altitude of the bottom land are assumed to have occurred in the surveyed areas.

From 1935 to 1970, the net change in the altitude of the bottom land has been an increase at 45 of the 57 cross sections in subreaches A and B, although data show short periods of scour at some of the other sections (table 2; fig. 7). The author hypothesizes that the increase in sediment accretion in the downstream direction occurred because more coarse material is deposited in the bottom land in the lower part of the valley than in the upper part and because streamflow is depleted by infiltration and diversion. Coarse material originating in steep watersheds tributary to subreaches D and C and part of subreach B is deposited directly in the bottom land. In subreach A and in the other part of subreach B, only the fine material makes its way to the bottom land, and most of the fine material is carried through the valley and is deposited in the San Carlos Reservoir.

The data for cross sections where scour is indicated in figure 7 may be grouped for (1) cross sections at bends in the stream channel where bank erosion is occurring and (2) cross sections where the stream channel has been enlarged to improve the conveyance capacity. Examples of the data in group 1 are those for cross sections PD 222, PD 223, PD 224, and PD 175. The erosion on the outside of the bends in the stream channel at these sections apparently has been greater than the fill on the inside. Data for cross sections SCS 11 through SCS 18 are examples of group 2 (table 2; pl. 1; fig. 7). A decrease in the average altitude of the bottom land is shown by 16 of the 22 sets of sediment data for 1965–66 (table 2), which indicates a net scour of the bottom land in the valley in 1965–66.

The volume of coarse material being deposited annually on the bottom land is unknown, but data obtained from periodic surveys of five alluvial fans (pl. 1) in and near the lower part of the study reach indicate that the amount is large. The volumes of the alluvial fans were determined from a topographic map for 1914 and from a field survey made in 1968. The sizes of the contributing watersheds and the increases in volumes of the five fans for 1914–68 are given below.

Alluvial fan number	*Size of watershed (square miles)*	*Increase in volume of fan (acre-feet)*
1	0. 31	2. 2
2	1. 78	5 5
3	2. 37	140
4	10. 2	187
5	2. 56	36 6

The volumes of coarse material moving toward the bottom land from the five tributaries undoubtedly were greater than those indicated above because some of the fan material probably was eroded during major floods subsequent to those of 1914.

The data given in tables 1 and 2 were used to estimate the volume of sediment accretion for the subreaches in the Safford Valley for 1935–70 (table 3). The estimates of sediment accretion in subreaches A and B were taken as the product of the average annual change in altitude of the bottom land (0.03 ft per yr for subreach A and 0.08 ft per yr for subreach B), the average area of uncultivated bottom land in 1935–68 (2,390 acres for subreach A and 4,360 acres for subreach B), and the number of years in the period (35 yr). Estimates of sediment accretion in subreaches C and D were obtained

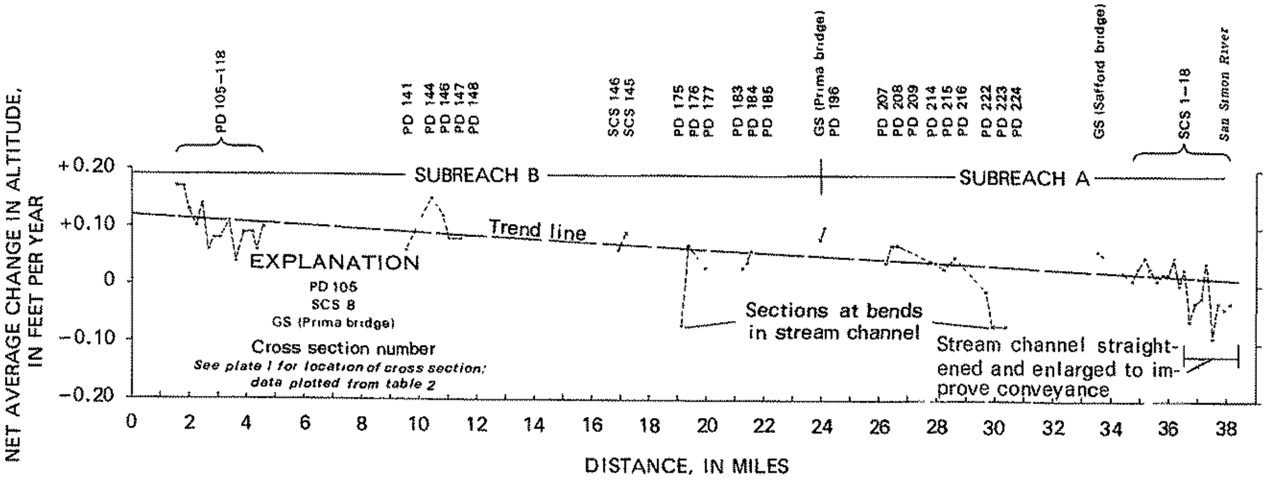


FIGURE 7.—Net average change in the altitude of the bottom land, 1935–70, at cross sections in subreaches A and B of the Gila River. Distance was measured along the centerline of the stream channel (1960).

by multiplying the length of the subreach (7.2 miles for subreach C and 6.1 miles for subreach D), measured along the center of the bottom land, by the per-mile volume of sediment accretion in subreach B (604 acre-ft per mile).

TABLE 3.—*Estimated volume of sediment accretion for subreaches in Safford Valley, 1935–70*

Location	Sediment-accretion volumes	
	Acre-feet, 1935–70	Acre-feet per year
Subreach:		
A	2,500	70
B	12,200	350
C	4,350	120
D	3,680	110
Total for study reach	22,730	650
San Carlos Reservoir	[1] 61,000	2,000
Total	83,730	2,650

[1] Sediment accretion for 1935–66; data furnished by F. P. Kipple (written commun., 1970).

The value of 2,650 acre-feet per year (table 3) probably is a conservative estimate for the amount of sediment moving toward the bottom land because the accretion of the sediment in the cultivated part of the bottom land and the amount of sediment moving through the San Carlos Reservoir are not included. The accretion of sediment in the cultivated area probably is significant in only a few places; however, the farmers make no special effort to keep suspended sediment from moving onto the cultivated land during the diversion of river water for irrigation because the sediment has a high nutritive value. At times, floodwater is ponded temporarily on the cultivated land and is desilted. The amount of sediment that moves through the San Carlos Reservoir is assumed to be small. It is of interest to note that about 75 percent of the annual sediment volume that moves onto the bottom land moves through the bottom land and is deposited in the San Carlos Reservoir. The sediment in the reservoir is mainly of small diameter, which indicates that most of the material that is eroded from the gently sloping alluvial valleys is deposited in the reservoir and most of the material that is eroded from steep streams is deposited in the flood plain.

INFLUENCE OF WIDE FLOOD CHANNEL AND LOW-FLOW RATES

The wide flood channel and low-flow rates probably were the most important factors influencing the deposition of sediment during 1918–70. The natural development of the flood channel took place in order to accommodate the large flows of fairly clear water from major winter floods that originated in the mountains. Since 1917 the flow rates have been relatively small in comparison with those of 1905–17 (pl. 3), and the flashy sediment-laden summer flows have contributed much of the total flow. Summer flows—about 25 percent of which come from watersheds tributary to the study reach—spread over the wide flood channel, losing kinetic energy and depositing their sediment loads. Owing to the absence of the flushing action of the large flows of fairly clear water, the accreted sediment becomes relatively stable. When major floods having low sediment contents occur, however, extensive erosion results.

The effects of streamflow depletion on sediment-accretion rates in Safford Valley are unknown. However, the inflow to the valley is greater than the outflow from the valley (Burkham, 1970, p. 6–10), and streamflow depletion is known to influence the rate of deposition.

INFLUENCE OF STREAM-CHANNEL TREATMENT PRACTICES AND FLOOD-PLAIN VEGETATION

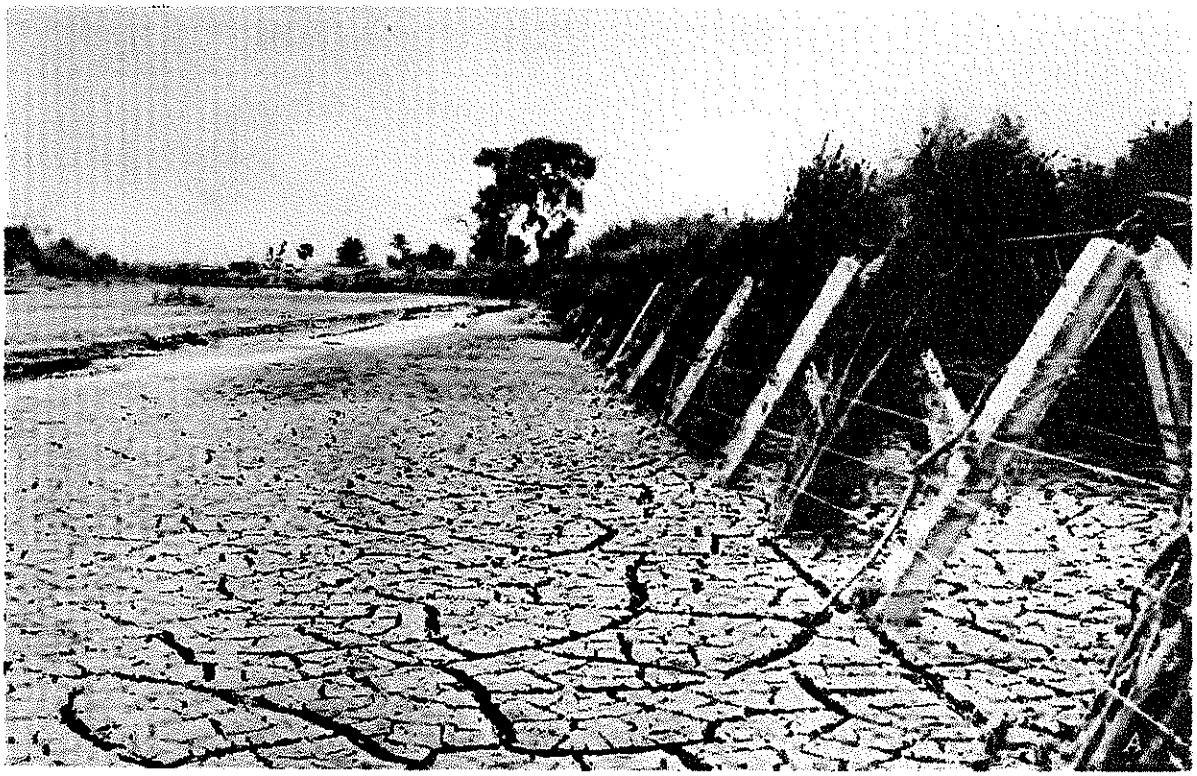
Stream-channel treatment practices in the Gila River include those designed to reduce erosion and those designed to increase conveyance. The two treatment practices are dynamically opposed—the first tends to cause deposition, and the second tends to cause erosion.

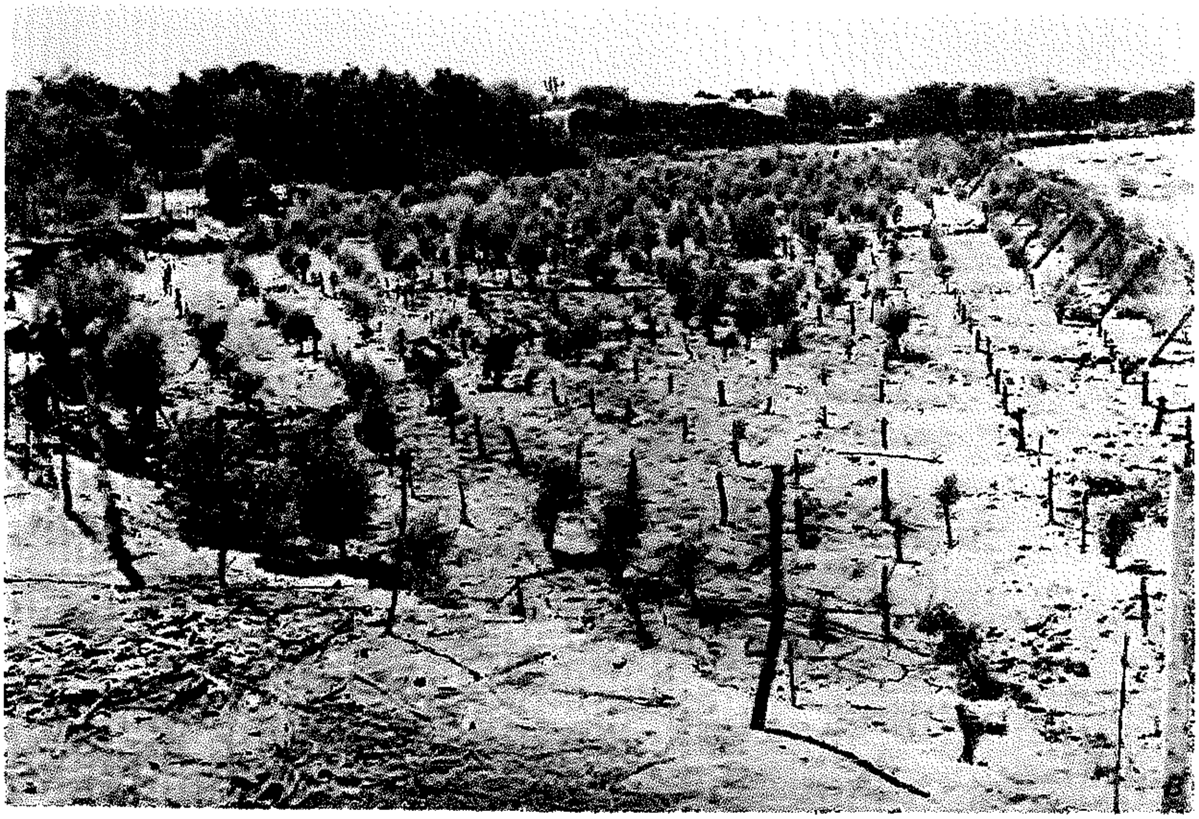
As discussed on page 12, erosion of the farmland was occurring in places along the Gila River in the second, third, and fourth decades of the 20th century. The U.S. Soil Conservation Service initiated an erosion-control program in the 1930's to stabilize the streambanks and slow the movement of floodwater in the badly eroding areas. According to Rowalt (1939, p. 46):

> The program is primarily vegetative in character, which is nature's way, with here and there some mechanical reinforcement to enable nature to work with less interference. * * * The native black willow is used. Black willow cuttings about the size of fence posts are set 4 or 5 feet apart under the banks. * * * In the more vulnerable places the willows are planted behind brush and cable revetments. Mechanical protection is also provided on the outside banks of curves. Usually this consists of cable and log jetties placed across the bow of the channel, or cable and brush anchored at both ends under high-cut banks. Rail tetrahedron lines have been used, and these are effective but expensive.

The erosion-control treatment used by the Soil Conservation Service (fig. 8) undoubtedly had some short-term local effects because it was applied during a period having few major floods; however, saltcedar became established naturally, and any reduction in erosion effected by the willow probably would have occurred later as a result of the saltcedar.

Vegetation was sparse in the flood plain through the second and third decades of the 20th century, but, once saltcedar was established, it spread rapidly and became the dominant vegetation (Gatewood and others, 1950, p. 11). Saltcedar reached its maximum areal extent


A


B

during 1945–55 (fig. 5). At present (1970), saltcedar is very dense in most places where the black willow was planted, and most of the mechanical devices are buried under the alluvium.

Flood-plain vegetation affects sediment accretion in three general ways: (1) it retards flow, which results in the deposition of sediment in backwater areas; (2) it aids in the stabilization of the deposits; and (3) it concentrates flow in the stream channel, thus increasing erosion tendencies in the channel during floods. Therefore, during the periods when there are few major floods, the trees in the flood plain aid in flood-plain building and stream-channel maintenance. During major floods, however, the trees in the flood plain may cause the volume of erosion in the stream channel to exceed the volume of fill deposited on the flood plain; the author believes that this phenomenon is most likely to occur during floods carrying very small sediment loads. For example, the trees in the flood plain probably contributed to the erosion in the Gila River channel during the floods of 1965–66 (fig. 3) and to the major widening of the stream channel during 1905–17. Unlike the cottonwood, the saltcedar is not a rigid tree and will bend during large floods, thus releasing hanging debris. Saltcedars were not uprooted during the floods of 1965 and 1967, except where bank erosion occurred along the stream channel.

Since 1950, farmers have altered short sections of the channel in several places in an attempt to improve its conveyance capacity. The usual alterations are straightening and enlarging of the channel, which create temporary increases in the sediment-carrying capacity of the flow. Any increase in sediment load in the treated section, however, generally leads to additional deposition in the adjoining downstream section; also, some erosion generally takes place in the adjoining upstream section. Eventually, through the process of erosion in the upstream section and filling in the downstream section, the treated area returns to a fairly stable state similar to that before the treatment.

INFLUENCE OF FLOOD-PLAIN CULTIVATION

Cultivation of the bottom land is limited almost entirely to subreaches A and B, where large-scale cultivation began in the fourth decade of the 20th century; the land was stripped of natural vegetation and leveled, and dikes were built to protect the cropland from floods. Initially, only the outer edges of the bottom land were cultivated, but during extended periods of low flow (pl. 3) in the Gila River and as heavy equipment became available for vegetation removal, additional bottom land was converted to cropland (fig. 5). At the same time, the stream channel was becoming narrower, and the uncultivated part of the flood plain was becoming heavily congested with vegetation.

FIGURE 8.—Erosion controls established in the 1930's by the U.S. Soil Conservation Service in the stream channel of the Gila River. *A*, Mechanical device in stream channel near Safford, November 1935. Note vegetation staves. *B*, Willows in stream channel near Fort Thomas; the willows were planted in March 1938, and the photograph was taken in June 1938. Photographs furnished by the U.S. Soil Conservation Service.

In times of moderate floods, the dikes prevented the water from spreading onto the cropland and concentrated flow in the stream channel. The concentrated flow increased stresses along the channel boundary, which may have led to erosion. The dikes probably contributed to the erosion in the stream channel during the floods of 1965–67. Once the dikes were breached by floodflows, however, the cropland acted as a relief valve; large amounts of water flowed into the fields, where they were temporarily impounded and desilted.

The dams, which were built to divert irrigation water, may have caused accretion of sediment locally in the channel upstream from the dams. The dams usually are built on gravel bars and generally are unstable. In 1969 only three of the 14 dams were of a more permanent type. The accretions of sediment caused by the dams are small and generally are flushed downstream during major floods.

CHANGES IN STREAM-CHANNEL LENGTH AND SLOPE

Since 1917, significant changes have taken place in the length and slope of the stream channel of the Gila River—the length has increased and the slope has decreased. In 1920 the low-flow channel, which is described in the section "Stream-Channel Development," was slightly longer than the flood channel, and its length increased steadily through 1964 (fig. 9). The length increased simultaneously with the development of the sediment islands, the attachment of the islands to the banks, and the development of the alluvial fans. Further increases in the length of the stream channel occurred as a result of erosion on the outside and filling on the

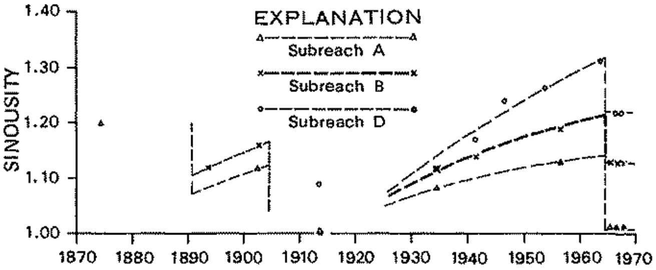


FIGURE 9.—Sinuosity of the stream channel of the Gila River in Safford Valley, 1875–1970.

inside of bends. Because the altitude of the streambed has not changed significantly, the increase in channel length has resulted in a decrease in stream-channel slope. The author hypothesizes that an increase in the number of alluvial-fan deposits and the depletion of streamflow in the downstream direction caused the increase in sinuosity in the downstream direction (fig. 9).

HYDROLOGIC IMPLICATIONS

Several interesting hydrologic implications were brought out during this study. The implications are in relation to aggradation and degradation in alluvial valleys, normal flows and frequency of floods, hydraulics of flow in the Gila River, and use of water by bottom-land vegetation.

Gilbert's theory (in Chorley and others, 1964, p. 562) of the translation of the effects of variation of erosive power to all parts of the river system apparently applies to the erosion of the alluvium that occurred in the Gila River watershed above Coolidge Dam as a result of the major floods of 1905–17 and to the redevelopment of the flood plain during periods having no major floods. According to Gilbert (in Chorley and others, 1964, p. 562):

> Of the main conditions which determine the rate of erosion, namely, quantity of running water, vegetation, texture of rock, and declivity, only the last is reciprocally determined by rate of erosion. * * * Wherever by reason of change in any of the conditions the erosive agents come to have locally exceptional power, that power is steadily diminished by the reaction of rate of erosion upon declivity. Every slope is a member of a series, receiving the water and the waste of the slope above it, and discharging its own water and waste upon the slope below. If one member of the series is eroded with exceptional rapidity, two things immediately result: first, the member above has its level of discharge lowered, and its rate of erosion is thereby increased; and second, the member below, being clogged by an exceptional load of detritus, has its rate of erosion diminished. The acceleration above and the retardation below, diminish the declivity of the member in which the disturbance originated; and as the declivity is reduced the rate of erosion is likewise reduced.

The author believes that the erosion and the subsequent filling in the lower altitudes of the Gila River watershed is a repetitive process that occurs naturally. The severity of erosion has not been the same in all the alluvial deposits, however, because of anomalies in the amounts of flowing water, vegetation, texture of rock, and declivity.

The temporal distribution of flow and the average annual flow—about 260,000 acre-feet—at the head of Safford Valley during 1920–64 probably were about the same as those during 1800–1904. The preceding statement is based on the following: The stream-channel width is governed mainly by rates of streamflow; the stream channel was narrow and fairly stable during 1846–1904; and, subsequent to the channel-widening floods of 1905–17, it took 50 years for the flood-plain development to approach that prior to 1905. Large-magnitude floods equal to those that destroyed the Gila River flood plain during 1905–17 apparently did not occur in the 19th century. If large-magnitude floods had occurred during 1800–46, the stream channel probably would have been wider than that described by travelers in 1846. Based on the preceding assumptions, the November 1905 flood of 150,000 cfs (Smith and Heckler, 1955, p. 61) and the December 1906 flood of 140,000 cfs (Olmstead, 1919, p. 64) may have been the largest floods for more than 170 years; according to Stockton and Fritts (1968), the floods may have been the largest for more than 300 years.

The major stream-channel widening during 1905–17 caused changes in the amounts of surface-water storage available for all subsequent flow events in the Gila River, except perhaps for the large floods and low flows. The changes in storage probably resulted in reductions in peak flows as the water moved down the river; however, the effects of channel widening on the peak flows became less significant as the flood plain was reconstructed.

A net decrease in evapotranspiration in the bottom land along the Gila River may have occurred as a result of cultivation. The amount of water saved annually is unknown; however, it probably ranged from almost zero in 1920, when only a few acres was cultivated, to as much as 10,000 acre-feet in 1964, when about 3,700 acres was cultivated (fig. 5). The reduction in evapotranspiration losses in 1964 was calculated using values of 5 acre-feet per year per acre for evapotranspiration by saltcedar (Gatewood and others, 1950) and 2 acre-feet per year per acre for evapotranspiration by cotton (Blaney and Criddle, 1962).

SUMMARY

Changes in the Gila River in Safford Valley were grouped into three periods for this study—1846–1904, 1905–17, and 1918–70. From 1846 to 1904, the stream channel was narrow and meandered through a flood plain covered with willow, cottonwood, and mesquite. Only moderate changes occurred in the width and sinuosity of the stream channel in this period; the average width of the stream channel was less than 150 feet in 1875 and less than 300 feet in 1903.

During 1905–17 the average width of the stream channel increased to about 2,000 feet, mainly as a result of large winter floods that carried small sediment loads. The meander pattern of the stream and the vegetation in the flood plain were destroyed completely by the floods. The trees on the flood plain may have had a minor influence on the widening in two ways. First, the trees restricted the flow of water onto the flood plain during the major floods and concentrated the flows in the stream channel; the concentrated flow increased stresses along the stream-channel banks, which may have caused erosion. Second, during the major floods, floating debris hung on the fairly rigid cottonwood trees, and the forces applied to the trees created torsion at the ground; eventually the trees were uprooted, carrying large chunks of alluvium with them and leaving the easily erodible material exposed.

During 1918–70 the stream channel narrowed, and the average width was less than 200 feet in 1964. The stream channel developed a meander pattern, and the flood plain became densely covered with vegetation. Saltcedar became well established in the fourth decade of the 20th century, and it was the dominant vegetation type. Minor widening of the stream channel occurred in 1965 and in 1967, and the average width of the channel was about 400 feet in 1968.

During 1918–70 reconstruction of the flood plain was accomplished almost entirely by the accretion of sediment, which occurred in five general ways: (1) by the development of islands in the stream channel and their subsequent attachment to one bank by channel abandonment, (2) by direct deposition on the flood plain, (3) by deposition in the stream channel along the banks, (4) by formation of natural levees, and (5) by deposition on alluvial fans at the mouths of tributary streams. In subreaches A and B the volume of sediment accretion by all the different methods is well documented for 1935–70. The average annual change in altitude of the bottom land was 0.03 foot per year for subreach A and 0.08 foot per year for subreach B. Much of the sediment accreted in subreach B is coarse material from steep side tributaries. For 1935–70 the accretion of sediment in the 45-mile-long study reach of the Gila River is estimated to be about 650 acre-feet per year.

The most important factors influencing the deposition of sediment during 1918–70 were the wide flood channel and the small floods that carried large sediment loads. The large sediment loads resulted mainly from the rapid erosion of the alluvial deposits in the watersheds tributary to the Gila River. The small floods originated in the tributary watersheds and spread over the wide flood channel, losing kinetic energy and depositing their sediment loads. The major floods of 1905–17 probably were the main cause of the rapid-erosion era in the tributary basins; however, periods of drought and extensive grazing prior to the floods may have been contributing factors.

The natural vegetation and cultivation in the flood plain may have had a significant influence on the reconstruction of the flood plain. The trees retarded floodflow, which resulted in the deposition of sediment in backwater areas, aided in the stabilization of the deposits, and concentrated the flow in the stream channel that helped maintain the stream channel. Large-scale cultivation of the bottom land began in the fourth decade of the 20th century; the land was stripped of natural vegetation and leveled, and dikes were built to protect the cropland from floods. In times of moderate floods, the dikes prevented the water from spreading onto the cropland and concentrated flow in the stream channel, which helped maintain the stream channel. Once the dikes were breached by floodflows, however, large amounts of water flowed into the fields, which reduced the stresses in the stream channel. In places, the small unstable dams, which were built to divert irrigation water, may have influenced sediment accretion. The accretions of sediment caused by these dams are small, however, and generally are flushed downstream during major floods.

The temporal distribution of flow and the average annual flow—about 260,000 acre-feet—at the head of Safford Valley in 1920–64 probably were about the same as those during 1800–1904. Based on this premise, the flood of November 1905, which had a peak flow rate of about 150,000 cfs, probably was the largest flood in more than 170 years. The preceding statements are based on the following facts: The stream-channel width is governed mainly by rates of streamflow; during 1846–1904 the stream channel was narrow and fairly stable and meandered through a densely vegetated flood plain; and, subsequent to the channel-widening floods of 1905–17, it took 50 years for the flood-plain development to approach that prior to 1905.

REFERENCES CITED

Barr, G. W., 1954, Arizona agriculture 1954: Arizona Univ., Agr. Expt. Sta. Bull. 252, 18 p.

Blaney, H. F., and Criddle, W. D., 1962, Determining consumptive use and irrigation water requirements: U.S. Dept. Agriculture Tech. Bull. 1275, 59 p.

Burkham, D. E., 1970, Precipitation, streamflow, and major floods at selected sites in the Gila River drainage basin above Coolidge Dam, Arizona: U.S. Geol. Survey Prof. Paper 655–B, 33 p.

Calvin, Ross, 1946, River of the sun—Stories of the storied Gila: Albuquerque, New Mexico Univ. Press, 153 p.

Chamberlin, W. H., 1945, From Lewisburg to California in 1849—Notes edited by L. B. Bloom: New Mexico Historical Rev., v. 20, no. 2, p. 144–180.

Chorley, R. J., Dunn, A. J., and Beckinsale, R. P., 1964, The history of the study of landforms or the development of geomorphology—Volume 1, Geomorphology before Davis: Methuen and Co., and John Wiley & Sons, 678 p.

Clarke, D. L., 1966, The original journals of Henry Smith Turner: Norman, Oklahoma Univ. Press, 173 p.

Culler, R. C., and others, 1970, Objectives, methods, and environment—Gila River Phreatophyte Project, Graham County, Arizona: U.S. Geol. Survey Prof. Paper 655–A, 25 p.

Davidson, E. S., 1961, Facies distribution and hydrology of intermontane basin fill, Safford basin, Arizona, *in* Geological Survey research 1961: U.S. Geol. Survey Prof. Paper 424–C, p. C151–C153.

Emory, W. H., 1848, Notes of a military reconnaissance, from Fort Leavenworth, in Missouri, to San Diego, in California, including part of the Arkansas, Del Norte, and Gila Rivers: U.S. 30th Cong., 1st sess. Ex. Doc. 41, 614 p.

Gatewood, J. S., Robinson, T. W., Colby, B. R., Hem, J. D., and Halpenny, L. C., 1950, Use of water by bottom-land vegetation in lower Safford Valley, Arizona: U.S. Geol. Survey Water-Supply Paper 1103, 210 p.

Griffin, J. S., 1953, A doctor comes to California—The diary of John S. Griffin, assistant surgeon with Kearny's Dragoons, 1846–1847: San Francisco, California Hist. Soc., 97 p.

Lapham, M. H., and Neill, N. P., 1904, Soil survey of the Solomonsville area, Arizona: U.S. Dept. Agriculture, Bur. Soils 5th Rept., p. 1045–1070.

Lindner, C. P., 1952, Diversions from alluvial streams: Am. Soc. Civil Engineers Proc., v. 78, no. 112, 25 p.

Olmstead, F. H., 1919, Gila River flood control—a report on flood control of the Gila River in Graham County, Arizona: U.S. 65th Cong., 3d sess., S. Doc. 436, 94 p.

Rowalt, E. M., 1939, Soil defense of range and farm lands in the Southwest: U.S. Dept. Agriculture Misc. Pub. 338, 51 p.

Schumm, S. A., and Lichty, R. W., 1963, Channel widening and flood-plain construction along Cimarron River in southwestern Kansas: U.S. Geol. Survey Prof. Paper 352–D, p. 71–88.

Schwennesen, A. T., 1921, Geology and water resources of the Gila and San Carlos Valleys in the San Carlos Indian Reservation, Arizona: U.S. Geol. Survey Water-Supply Paper 450–A, 27 p.

Sellers, W. D., ed., 1960, Arizona climate: Tucson, Arizona Univ. Press, 60 p.

Smith, Winchell, and Heckler, W. L., 1955, Compilation of flood data in Arizona, 1862–1953: U.S. Geol. Survey open-file report, 113 p.

Stockton, C. W., and Fritts, H. C., 1968, Conditional probability of occurrence for variations in climate based on widths of annual tree rings in Arizona: Arizona Univ., Laboratory of Tree-ring Research Ann. Rept., 24 p.

Thomas, H. E., 1962, The meteorologic phenomenon of drought in the Southwest: U.S. Geol. Survey Prof. Paper 372–A, 43 p.

U.S. Army Corps of Engineers, 1914, San Carlos Irrigation Project, Arizona: U.S. 63d Cong., 2d sess., H. Doc. 791, 168 p.

U.S. Geological Survey, issued annually, Water resources data for Arizona—Part 2, Water quality records: U.S. Geol. Survey open-file reports.

Weech, Hiram, 1931, Autobiography: Hollywood, Calif., Lee Printing Co., 46 p.

U. S. GOVERNMENT PRINTING OFFICE : 1972 O - 450-345