Lateral Migration of the Middle Sacramento River California

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 77-43

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By James Brice

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UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

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LATERAL MIGRATION OF THE MIDDLE SACRAMENTO RIVER, CALIFORNIA

By James Brice

ABSTRACT

Rates and processes of lateral erosion were studied for the middle Sacramento River between Chico Landing and Colusa, a river distance of about 50 miles along which the river is bordered by valuable agricultural land. The study is based on comparison of maps made during the period 1867-1949, and on aerial photographs made during the period 1924-74. Meander loops migrate by downstream translation in a direction nearly perpendicular to the loop axis. Loops are cut off by straight or diagonal chutes across the meander neck, rather than by gradual closure of the neck. The sinuosity of the river has gradually decreased from a value of 1.56 in 1896 to 1.35 in 1974.

The morphology and curvature of meander loops cut off before white settlers came to the area indicate that the river was more stable, as well as more sinuous, then than now; subsequent morphologic changes are attributed mainly to the clearing of riparian vegetation and the effects of levees in reducing the area of overflow. The bank-erosion rate, as measured by shift of the channel centerline between successive times of survey, is 1.82 acres per year per stream mile or about 15 feet per year per stream foot for the period 1896-1974. Before 1948, cumulative bank erosion increased at about the same rate as cumulative discharge above mean annual, but it has increased at a lesser rate since 1948, probably because of flow regulation by Shasta Lake.

INTRODUCTION

The purpose of this study is to document changes, particularly in plan view, of the middle Sacramento River during the past hundred years and to describe the rates and processes of lateral migration, chute cutoff, and meander cutoff by which the present course has evolved. Information on rates and processes of erosion during the past few decades provides a basis for estimating future behavior of the river and hence is useful for planning purposes.

The reach of the river from Chico Landing to Colusa, in this report called the middle Sacramento River, is only one-sixth of the total length, but it is important because of the agricultural value of the bordering land, the high rate of bank erosion, and a change in river pattern and behavior that occurs transitionally within this reach.

The origin of the Sacramento River is west of Mount Shasta in northern California (fig. 1). A short distance south of its origin, it flows into Shasta Lake which is formed by Shasta Dam, completed in 1944. Most of the drainage area of the upper Sacramento is that of its tributary, the Pit River, which also flows into Shasta Lake. The length of the Sacramento River as measured from Keswick Dam (fig. 2) to the mouth at Collinsville is 302 river miles, according to the U.S. Army Corps of Engineers (1973a).

Col. Albert McCollam, Chief Engineer of the California State Reclamation Board until 1975, provided encouragement for the project, as did Mr. Amalio Gomez, who also provide a useful bibliography on history of the river. Personnel of the U.S. Army Corps of Engineers, including Margaret Peterson, gave helpful information and publications that proved very useful. Personnel of the California Department of Water Resources provided useful information and permission to photocopy the 1924 aerial photographs of the Sacramento River.

The results reported herein are based mainly on comparison of maps and aerial photographs made at different times in the past. The oldest maps, on which the river meanders were surveyed during the period 1867-72, are the land-plat surveys of the General Land Office. The river is also represented on U.S. Geological Survey topographic quadrangle maps surveyed during 1886-88 (scale 1:125,000), on other Geological Survey maps surveyed during 1904-10 (Scale 1:31,680), and on newer Geological Survey maps prepared by photogrammetric methods (scale 1:24,000) from photographs flown during 1947-49. Two of the newer maps have been photorevised to show the river course as it was in 1969. A map of the river as surveyed in 1935 (scale 1:4800), on which had been plotted the river banklines of 1896, 1908, 1946, 1955, and 1964, was obtained from the U.S. Army Corps of Engineers.

The oldest aerial photographs of the Sacramento River, which are of particular significance as a historical record, are dated 1924. The negatives of these photographs apparently have been lost, but prints on file at the California Department of Water Resources were copied on 35-mm film for this study. Aerial photographs from 1937, 1946, 1970, 1972, and particularly a set of high-altitude photographs dated January 21, 1974, taken from a U-2 aircraft, were also used.

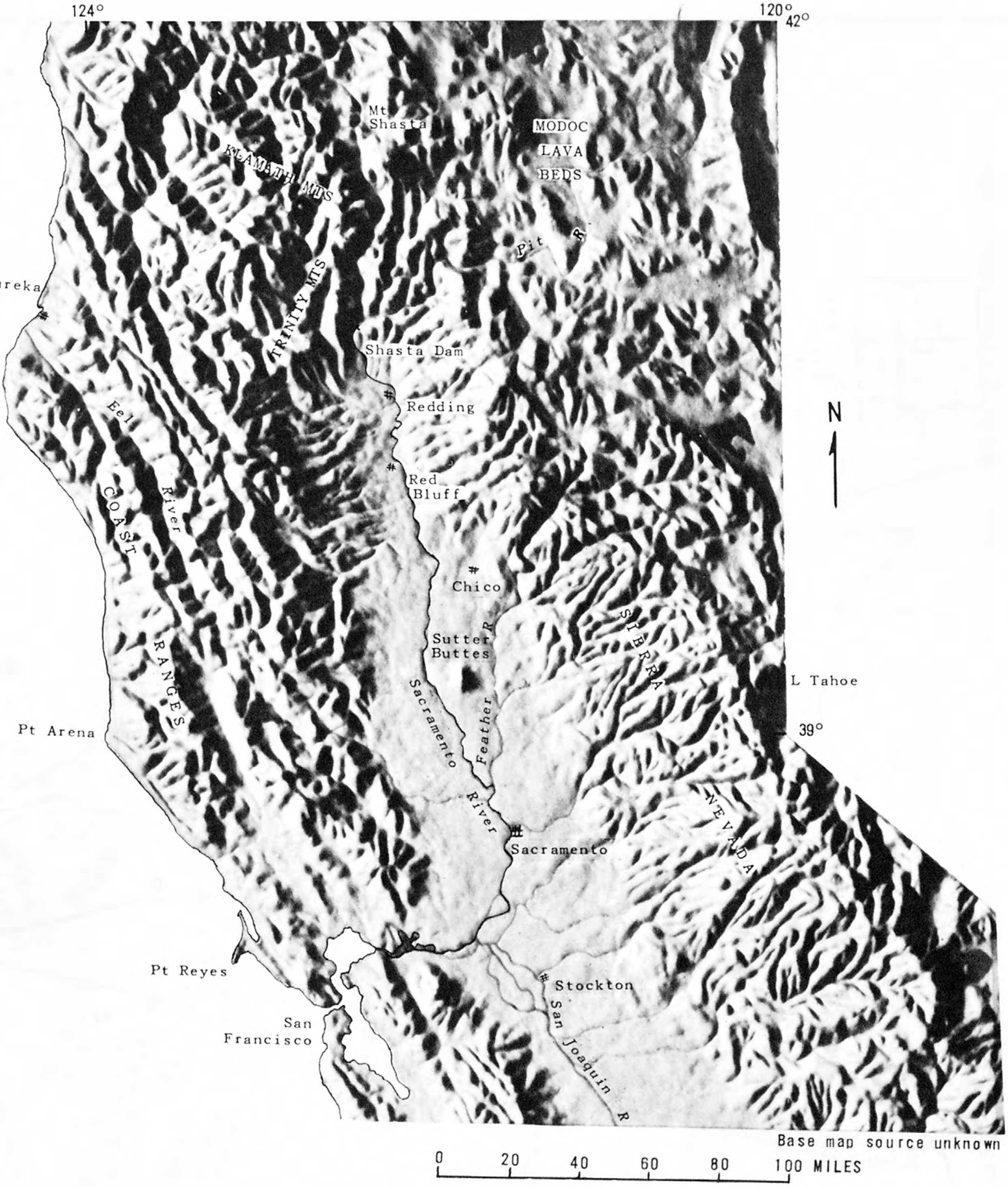
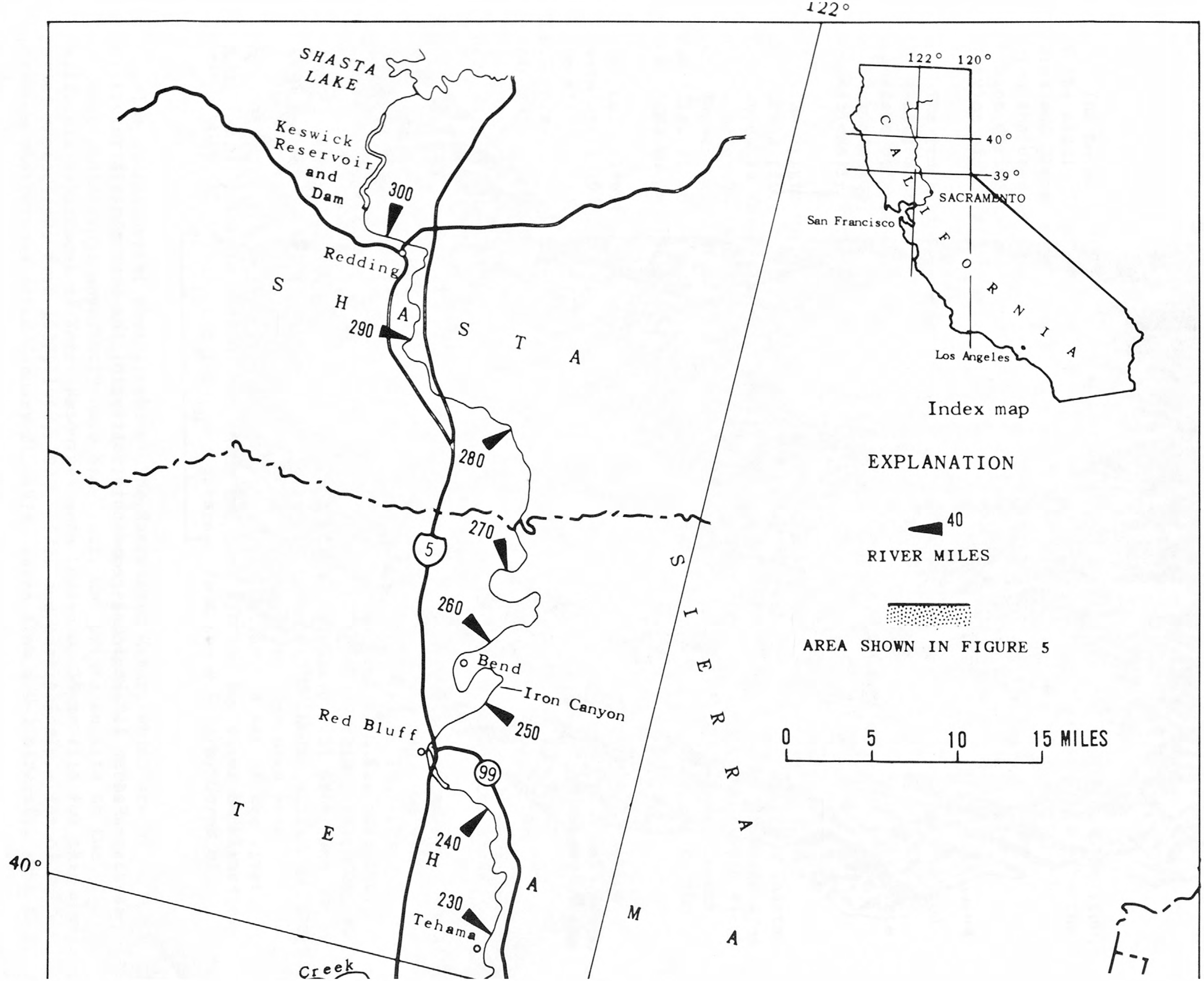


FIGURE 1.—Regional geomorphic setting of the Sacramento River.


122°
SHASTA LAKE
Keswick Reservoir and Dam
300
Redding
S H A S T A
290
280
270
5
260
Bend
Iron Canyon
250
Red Bluff
99
T E H A M A
240
230
Tehama
Creek
40°
S I E R R A
122° 120°
40°
39°
C A L I F O R N I A
SACRAMENTO
San Francisco
Los Angeles
Index map
EXPLANATION
40
RIVER MILES
AREA SHOWN IN FIGURE 5
0 5 10 15 MILES

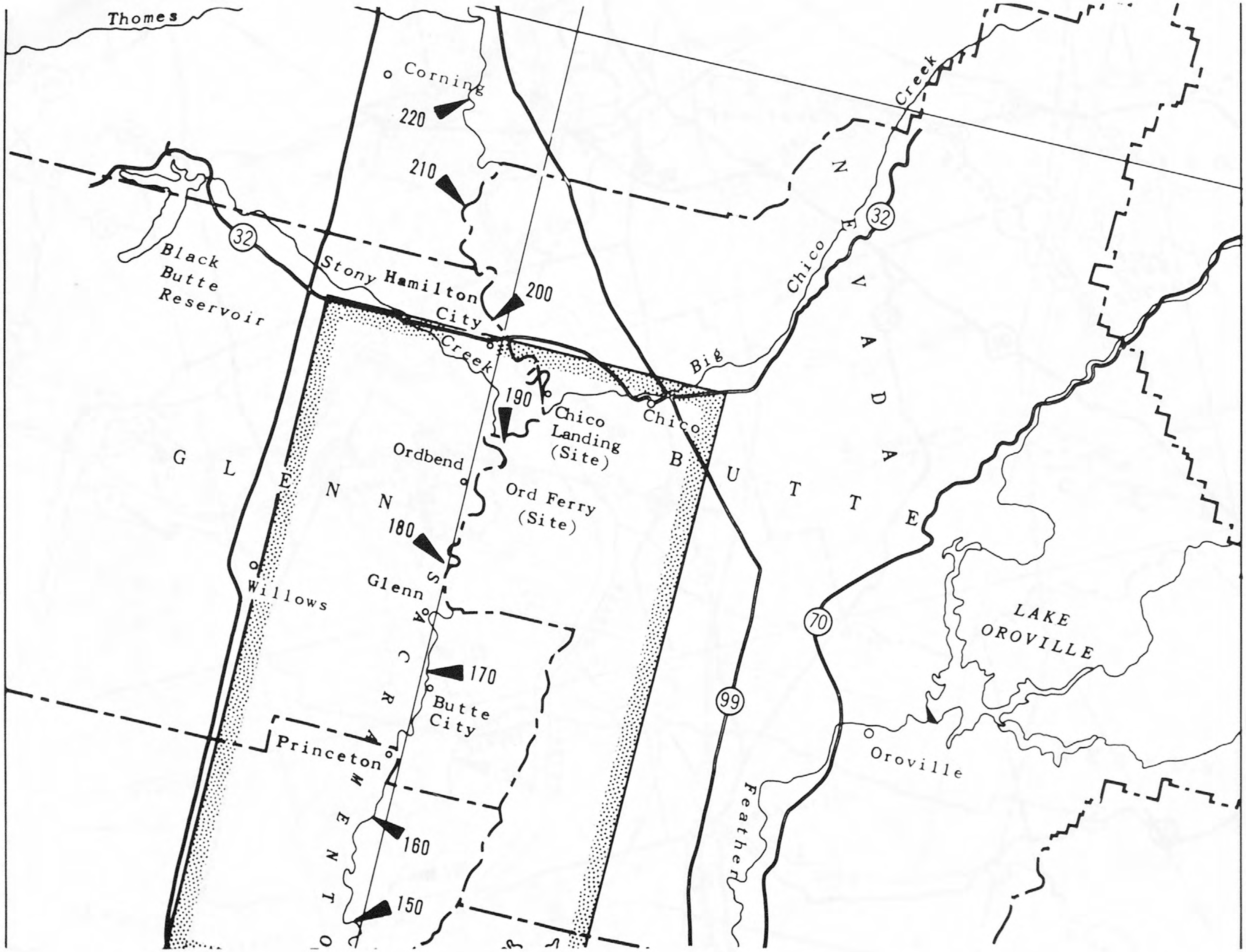
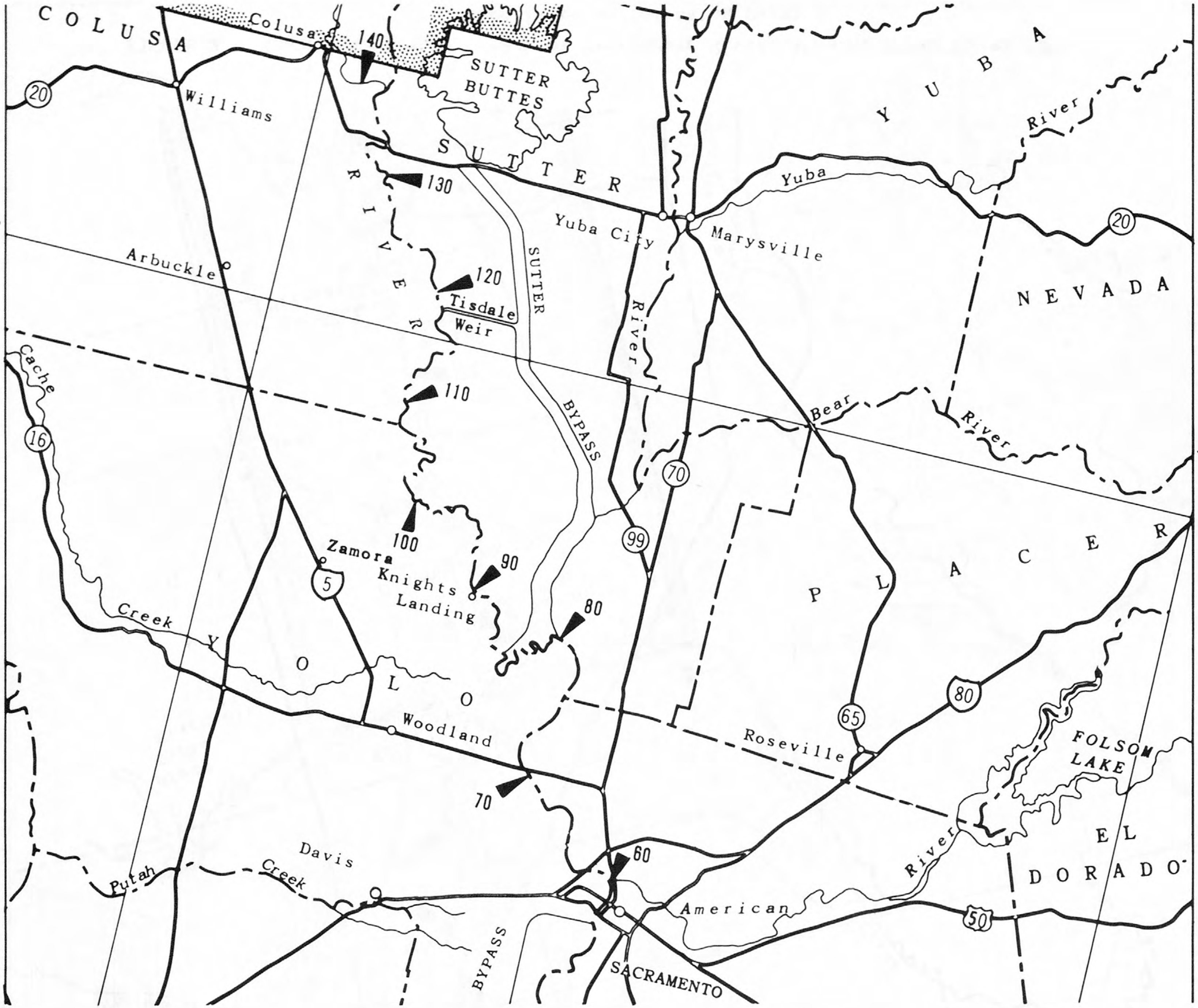


FIGURE 2.— Location of study reach of Sacramento River, showing River Miles (RM).
(Continued on following pages.)



COLUSA
Colusa
Williams
Arbuckle
SUTTER BUTTES
SUTTER
YUBA
NEVADA
PLACER
YOLO
EL DORADO
RIVER
SUTTER BYPASS
BYPASS
Yuba City
Marysville
Yuba
River
Feather River
Bear
River
Tisdale Weir
Cache
Creek
Zamora
Knights Landing
Woodland
Roseville
FOLSOM LAKE
Davis
Putah
Creek
American
River
SACRAMENTO
140
130
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50
39°
39°
121°

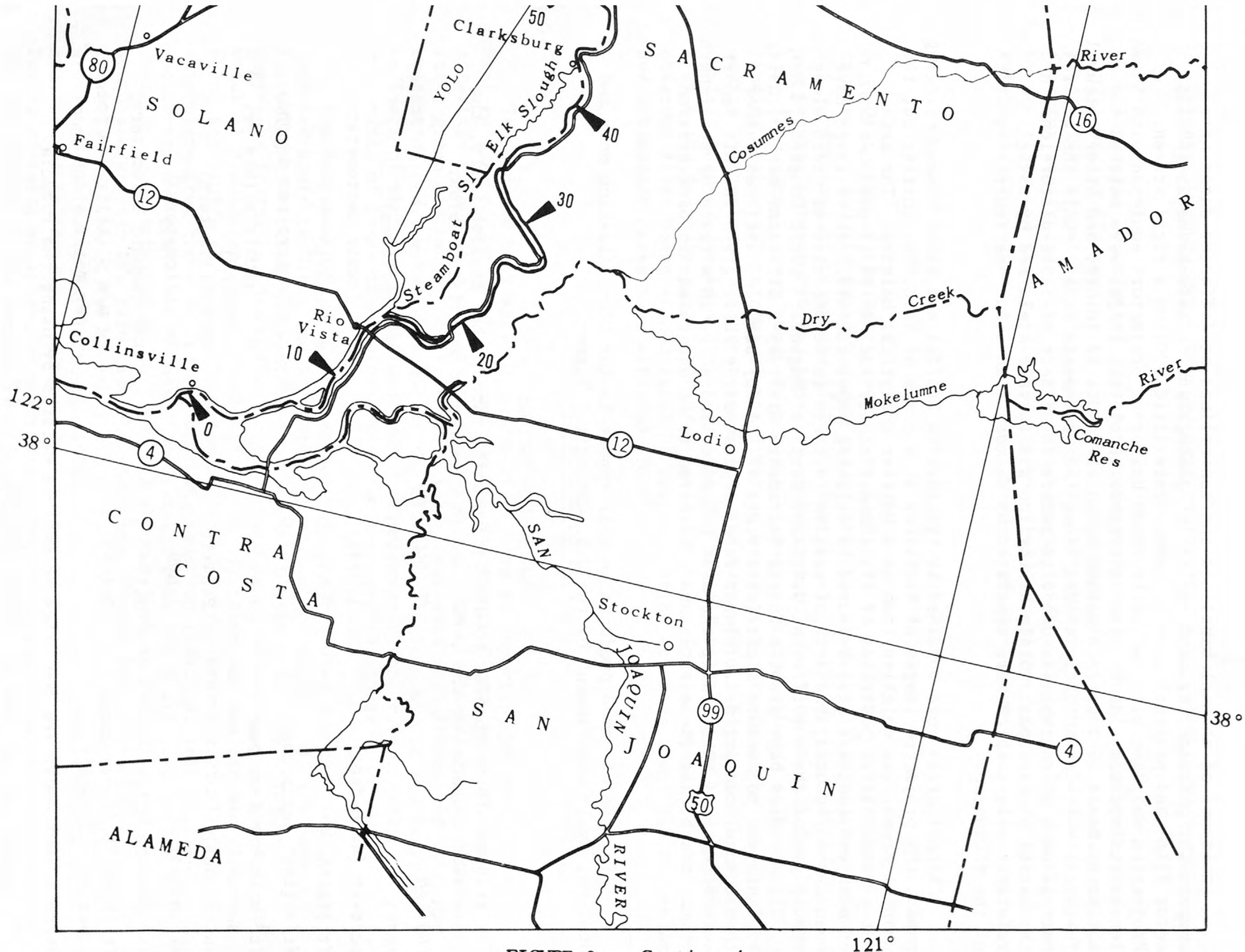

FIGURE 2.— Continued.

Positions of channel banklines and centerlines at different dates were compared by photocopying maps and aerial photographs on Kodachrome-25 (KR 135) color film[1] and projecting to a common scale (1:18,000) on a rigid screen. Projection was done with two Leitz Prado Universal projectors equipped with 50-mm lenses and mounted side by side on tracks. Projected images were matched two at a time by means of reference points, such as roads, buildings, and other cultural features, which are closely spaced along the Sacramento River. Only the central part of each photograph was used, to reduce the effect of scale distortions in the aerial photographs. Scale distortion was further minimized by using reference points which were separated by no more than about one-fourth the width of the photograph.

Channel areas were obtained by tracing, on Keuffel and Esser Albanene tracing paper, the projected images of banklines at a scale of 1:18,000, cutting out the channel areas, and weighing them on a Mettler analytical balance. The area between successive positions of the channel centerline, which is used as a measure of bank erosion, was also measured by weighing paper cutouts. Where loops have been cut off chutes, the area of erosion is taken to be one channel width along the length of the cutoff. The U.S. Army Corps of Engineers (U.S. Congress, 1960, p. 23) measured bank erosion on the Sacramento River by a different method, using a planimeter to measure areas (at a scale of 1:4800) between banklines rather than channel centerlines. Linear rates of centerline shift given in this report were determined by dividing the area of centerline shift in a reach by the length of the reach, and these rates are considered to be equivalent to bank-erosion rates.

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[1] The use of named products in this report is for identification only and does not imply endorsement by the U.S. Geological Survey.

CONVERSION FACTORS

For readers who may prefer to use metric units rather than English units, the conversion factors for the terms used in this report are listed below:

English	*Multiply by*	*Metric (SI)*
acres	4.047×10^{-1}	ha (hectares)
acre-ft (acre-feet)	1.234×10^{-3}	hm^3 (cubic hectometers)
ft (feet)	3.048×10^{-1}	m (meters)
ft/s (feet per second)	3.048×10^{-1}	m/s (meters per second)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meters per second)
in (inches)	2.54×10^{1}	mm (millimeters)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)
ft lbs/s ft (foot pounds per second foot)	0.4536	kg m/m s (kilograms meter per meter second)

Degrees Fahrenheit are converted to degrees Celsius by using the formula

$$°C=5/9\ (°F-32).$$

GENERAL MORPHOLOGIC AND HYDROLOGIC PROPERTIES OF THE SACRAMENTO RIVER

A general description of the Sacramento River has been given by Bryan (1923) and by Olmsted and Davis (1961). For most of its course, the Sacramento River flows through the Sacramento Valley, a structural trough whose nearly flat surface is underlain by deposits brought in from the adjoining mountains by the river and its tributaries. Bryan (1923) considered that the river enters the Sacramento Valley at the lower end of Iron Canyon (fig. 2).

Discharge

Discharge of the Sacramento River (table 1) is regulated by upstream reservoirs, and the following summary of its flow characteristics is from the U.S. Army Corps of Engineers (1973a). Diversions for irrigation and domestic use between Keswick Dam and the city of Sacramento amount to about 1.8 million acre-feet annually, or about 23 percent of the average discharge at Knights Landing. About 40 percent of the diverted water is returned to the river, mostly by canals entering between Colusa and Sacramento. Regulation by Shasta Dam has increased mean monthly flows at Red Bluff for June, July, and August from 6,190 ft^3/s (period 1889-1944) to 10,520 ft^3/s (period 1945-70). Maximum observed flood peaks at Red Bluff before regulation attained about 250,000 ft^3/s, and subsequent peaks have attained about 140,000 ft^3/s.

Bed and Bank Materials

The bed and bank materials of a river have an important effect on its pattern (see p. 26) and behavior. On the Sacramento River, bed and bank materials change in a downstream direction. Schumm (1971) has reported that, for a given discharge, the width of a river decreases with increasing silt-clay content of bed and banks, and that the silt-clay content of bed and banks is an index of the type of sediment being transported by the river. The resistance of banks to erosion also depends on vegetal cover.

The Sacramento River is tentatively characterized as a gravel-bed stream from Red Bluff to Glenn and as a sand-bed stream for the rest of its course. According to a brief and nontechnical summary by the U.S. Army Corps of Engineers (1973a, p. 31), "The riverbed composition of coarse sand and gravels, which is predominant above Red Bluff, gradually thins out and becomes finer below Red Bluff, and, about 25 miles below Ord Ferry, gravel virtually disappears from the riverbed." According to Bryan (1923, p. 78), "...the Sacramento has gravels 3-6 inches in diameter near Red Bluff, 2-3 inches at Hamilton, 1-2 inches at Butte City, and about 1 inch at Colusa. From Colusa southward gravels are rare, but the sands are in many places coarse and gravelly and even as far south as Rio Vista pebbles half an inch in diameter are found in the sands." Kresch (1970, table 3) gives 67 particle-size analyses of bed material samples from the Sacramento River at Colusa Weir. For 40 of these analyses, 90 percent or more of the sample was finer than 0.5 mm, but 27 of the samples contained particles in the 8-32 mm size range.

River miles[1] above Collinsville	River distance (miles)	Elevation of low-water surface (feet)	Longitudinal slope, in feet per 1,000 feet: River	Longitudinal slope, in feet per 1,000 feet: Valley	Channel sinuosity	Bank-to-bank width (feet)	Average discharge (ft^3/s)	Discharge equaled or exceeded 10 percent of time (ft^3s)	Stream power (foot pounds per second foot)	Channel pattern
RM 243-225, Red Bluff to Thomes Creek	18	230-178	0.558	0.775	1.39	500	11,650	19,000	918	Sinuous, slighty anabranching, variable width
RM 225-193, Thomes Creek to Chico Landing	32	178-110	.403	.597	1.48	525	11,650	19,000	707	Do
RM 193-169, Chico Landing to Butte City	24	110-67	.333	.479	1.44	500	12,700	24,000	717	Sinuous, variable width, discontinuous natural levees
RM 169-143.5, Butte City to Colusa	25.5	67-37	.228	.338	1.48	350	11,000	25,000	527	Sinuous, moderately variable width, continuous natural levees
RM 143.5-80, Colusa to Feather River	63.5	37-10	.080	.142	1.77	300	10,600	22,000	195	Meandering, uniform width, cramped loops, continuous natural levees
RM 80-61, Feather River to American River	19	10-2	.080	.106	1.33	600	19,100	48,000	317	Sinuous, broad curves, uniform width, continuous natural levees
RM 61-0, American River to Collinsville	61	2-0	.006	.008	1.33	650	22,750	54,000	--	Anabranched distributary system south of RM 44

The riverbanks were examined at seven localities between RM 188 and RM 165. They consist dominantly of silt, which has sufficient cohesion to maintain a vertical face. In places the silt is underlain by fine sand, and in other places it is interbedded with sand. Silt and sand are underlain by gravel at only one place. No systematic downstream change in texture could be discerned. An old map of the soils on the west side of the river from RM 137 to RM 209 (U.S. Dept. Agriculture, 1907) indicates that the soils along the river become somewhat finer in texture downstream. Upstream from RM 165, north of Princeton, the river is bordered mainly by "riverwash" and Sacramento silt loam. Downstream from RM 165, the river is increasingly bordered by the Sacramento silt clay loam. In the soil survey of Glenn County (Begg, 1968), Columbia silt loam is prominent along the river in the northern part of the county, near Hamilton City; whereas Zamora silty-clay loam is prominent in the southern part.

Useful but fragmentary information on the alluvial fill along the river between Colusa and Sacramento is provided by geologic sections and drillers' logs published by the California Department of Water Resources (1967). The fill is divided into (1) flood-plain deposits, characterized as brown, soft clay or silt to silty sand, (2) stream deposits of gray, loose, gravelly sand, and (3) flood-basin deposits of gray stiff clay. The stream deposits, which should more accurately be called channel deposits, are in the form of lenses having widths of a mile or two and maximum thicknesses of about 75 ft. These gravelly-sand lenses are inset into the flood-basin deposits and overlain by a top stratum of flood-plain deposits. The flood-basin deposits range in thickness from 10 to 30 ft and are probably natural-levee materials. Near RM 113, one well penetrated 15 ft of silty-clay top stratum before reaching channel sands; another well near the river, but half a mile downstream, penetrated only 8 ft of silty sand before reaching channel sands. At two wells near RM 71, the top flood-plain stratum consisted of interbedded silt and silty clay; but at wells near RM 69.5 it consisted mainly of silt, which is slightly plastic.

Data on sediment discharge and particle size of suspended sediment for high flows of the Sacramento River near Colusa (RM 146) and in the vicinity of Tisdale Weir (RM 119) were given by Kresch (1970, table 1). For 15 composite samples of suspended sediment, Kresch computed an average of 33 percent clay [less than 4 μm (micrometers)] and 68 percent silt-clay (less than 62 μm).

Longitudinal Slope

The longitudinal slope of a river is a determining factor in the flow velocity and, therefore, contributes to the potential of a river to erode its bank. The longitudinal slope of a river valley represents an upper limit for the longitudinal slope of a river, which is the valley slope divided by channel sinousity. River and valley slopes of the Sacramento River decrease in a downstream direction (fig. 3, table 1).

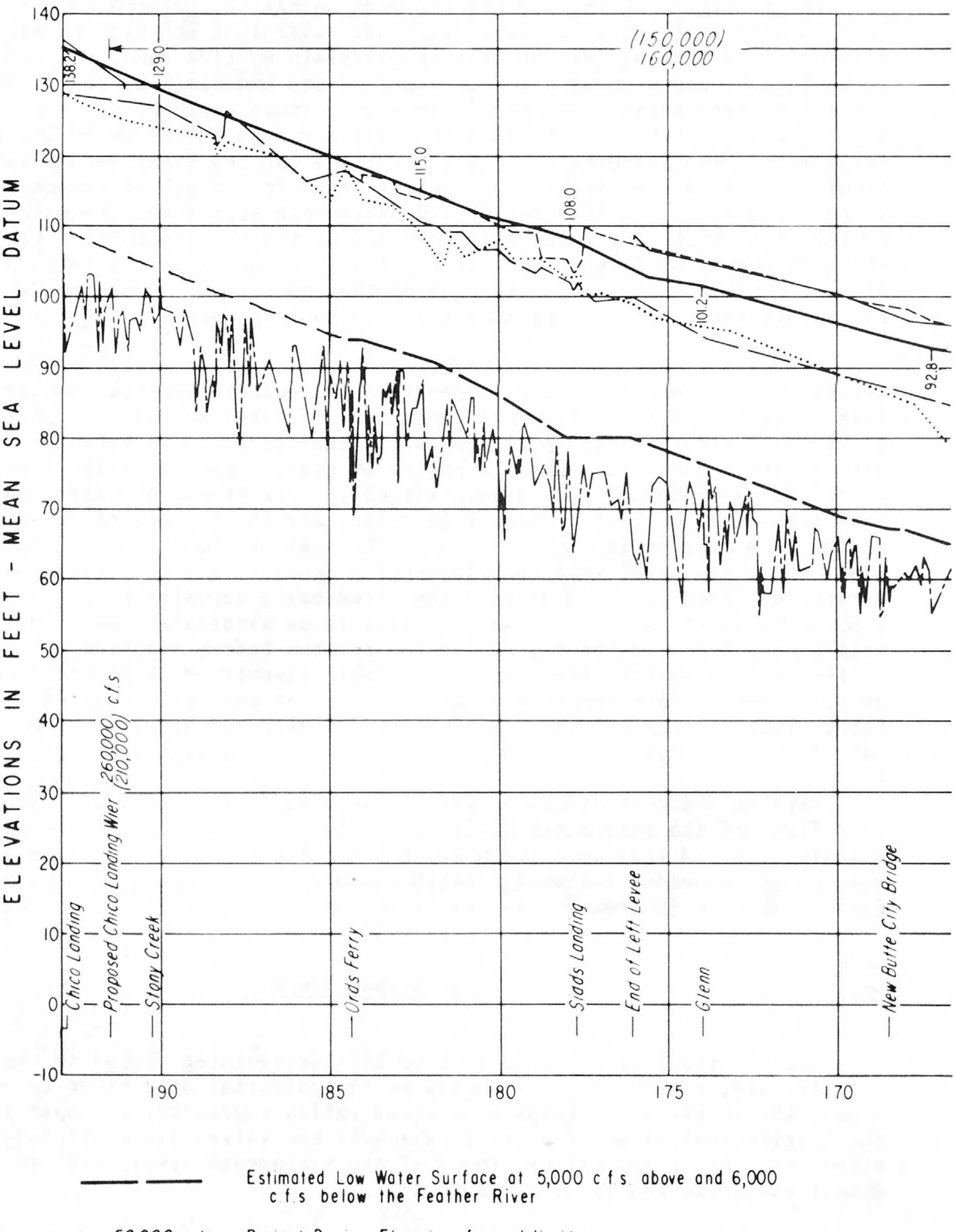
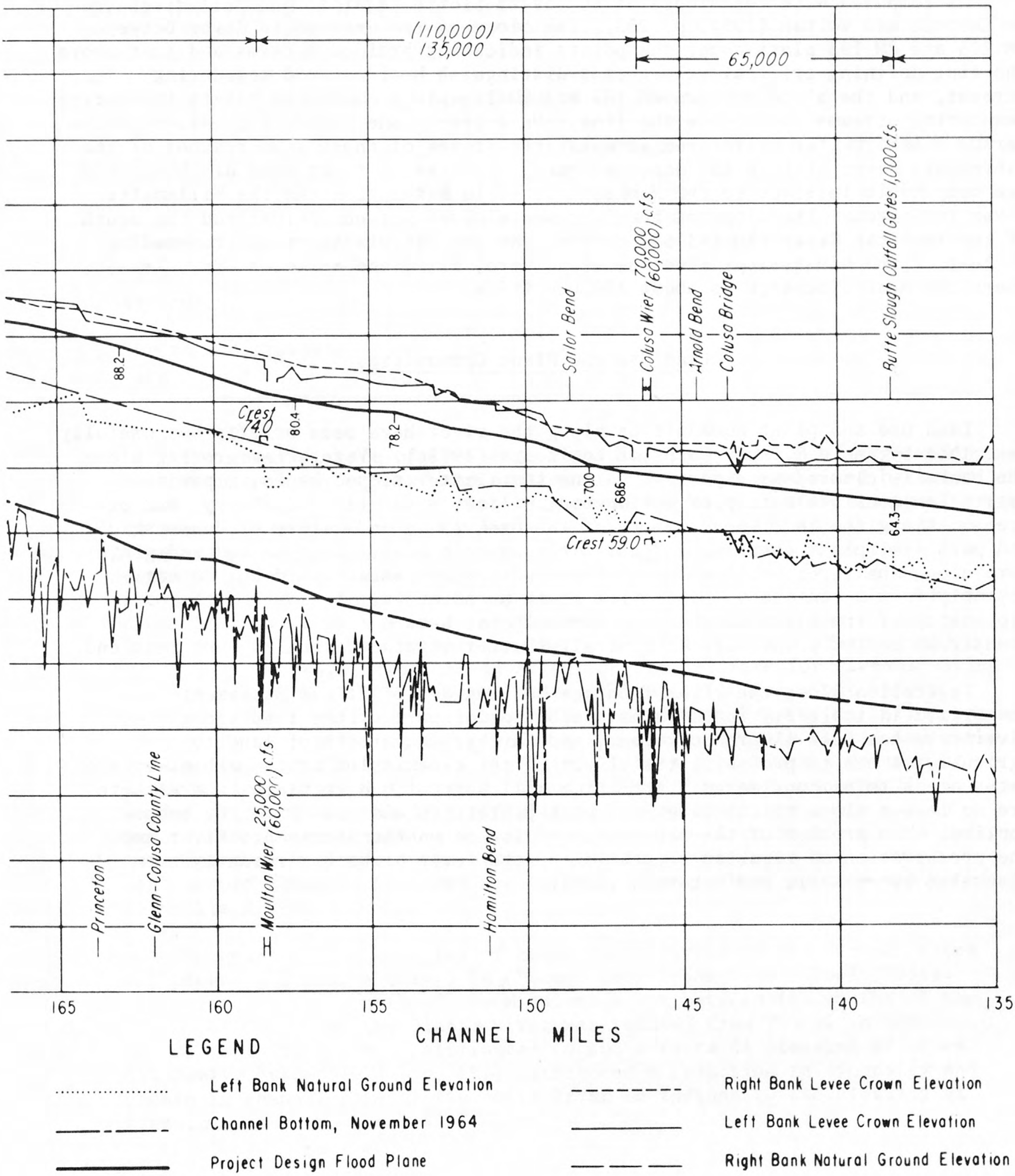


FIGURE 3.—Longitudinal profile of the Sacramento
From U.S. Army Corps of Engineers, Sacramento



River, RM 193 (Chico Landing) to RM 135.
District, 1973 – Sheet 3, Chart 3.

As compared with the slopes of 56 rivers plotted against bankfull discharge by Leopold and Wolman (1957, p. 293), the slope of the Sacramento River between RM 225 and RM 193 plots among the points indicating braided streams and just above the line defining critical values that distinguish braided from meandering streams, and the slope between RM 193 and RM 153 plots among the points indicating meandering streams just below the line. On a plot (Lane, 1957, fig. 4), of slope versus discharge for gravel-bed streams, the slopes of these same reaches of the Sacramento River plot in the expected range relative to their mean discharge and are comparable in slope to the Nooksack River in Washington and the Willamette River in Oregon. The slope of the Sacramento River between Colusa and the mouth of the American River (RM 143-61) is very low for its discharge, corresponding to that of the Mississippi River between Cairo, Ill., and Arkansas City, Ark., where the mean discharge is about 450,000 ft^3/s.

Land Use and Plant Communities

Land use and plant communities along the river have been briefly but usefully described by the U.S. Army Corps of Engineers (1973a). Vegetation growing along the banks is classed as riparian. Along the flatter sloped banks, riparian vegetation consists mainly of cottonwood, willow, sycamore, elderberry, and oak trees. Along the less wooded parts of the bank is an understory of dense shrub and perennial plant cover extending to the water's edge. On the sand and gravel bars along the river, willows and cottonwoods become established but do not commonly form a continuous protective cover on point bars because of the propensity of the river for cutting across point bars during floods. The downstream end of point bars is generally better vegetated than the upstream end.

Vegetation along the river frontage between Red Bluff and Sacramento is summarized in table 2. Inasmuch as a substantial part of the land along the riverbanks has been cleared of trees, and further conversion of land to agricultural use is probable, the effect of the clearing of trees on bank-erosion rates needs to be considered. Attention will be confined to places where there are no levees close to the river and bank-protection measures have not been applied. The problem of the protection of levees on the Sacramento River and the preservation of riparian vegetation on the levee berms has recently been discussed by Mifkovic and Petersen (1975).

Table 2.--*Land use along the banks of the Sacramento River*

[From U.S. Army Corps of Engineers, 1973a]

Vegetal cover	Percentage of frontage (left and right banks) Red Bluff to Ord Ferry (RM 243-184.2)	Ord Ferry to Colusa (RM 184.2-145.5)	Colusa to Sacramento (RM 145.5-61)
Agriculture	13	9	5
Trees	35	34	40
Shrubs and grasses	37	35	49
Barren	15	22	6

The general state of knowledge regarding the relation of vegetation to the channel pattern and bank erosion of rivers was summarized by Lane (1957, p. 13), who believed that vegetation had a great stabilizing effect on small streams and an important effect even on streams as large as the Mississippi and the Missouri. On large streams, vegetation on the narrow necks of meanders inhibits the development of chute cutoffs, and thus promotes a higher degree of sinuosity. Lane does not discuss the relation of vegetation to bank erosion on the outside of meander loops. From a study of small streams in northern Vermont, Zimmerman and others (1967) concluded that vegetation had an effect on channel form for streams having average annual high flows in the range of 100 to 150 ft^3/s but only a marginal effect on larger streams. They noted that vegetation influences channel form by altering the roughness and shear strength of bed and banks. From a study of the Kaskaskia River in Illinois (which has a meandering pattern, an average discharge of about 2,000 ft^3/s, and a dominantly wooded flood plain), Shifflett (1973) concluded that trees were easily undercut by lateral erosion at vertical banks 10-15 ft high. When a large undercut tree falls into the river, it sets up turbulence and induces bank scour; thus, large trees may actually promote bank erosion along the Kaskaskia River.

In general, the clearing of trees along rivers in the United States has probably caused a change in channel length and form. Towl (1935) reported that the length of the Missouri River between the mouths of the Big Sioux River and the Platte River was reduced from 250 mi in 1804 to 150 mi in 1935, which he attributed to the effects of clearing of trees. Similarly, Brice (1974a, p. 191) attributed a reduction in sinuosity and change in channel form of the White River in Indiana to the clearing of trees.

On the Sacramento River there is some evidence that even the surviving fringes of riparian vegetation on the outside of meander loops, and particularly at the approaches to these loops, has an effect in inhibiting bank erosion. In figure 4A, at the point numbered 1, the bank is scalloped downstream from a narrow fringe of vegetation. The fringe of vegetation at point 2 appears to have deflected the flow at its upstream end, and the bank shows some indentation at its downstream end, an effect that is much more apparent in both the 1970 and the 1972 aerial photographs. In figure 4B, at point 3, the indentation of the bankline seems to be clearly associated with the downstream termination of a fringe of vegetation.

On the necks of meander loops the role of vegetation in inhibiting chute cutoffs is probably quite important. It seems likely, for example, that the large patch of vegetation opposite point 2 in figure 4A has served to inhibit a chute cutoff at the point where the inside of the bend is flooded, and it may also have served to deflect the flow to the opposite side of the river, thus forming a new loop downstream from the cutoff at Murphys Slough. Furthermore, if the ground around Murphys Slough had not been cleared, the cutoff there probably would not have occurred. On the other hand, the recent loop cutoff at left in figure 4B seems not to be related to the clearing of vegetation on the inside of the bend, but rather to an insufficiency of natural vegetation.

It is unlikely that vegetation could be reestablished at vertical banks on the outside of loops, or that it would have any great effect in preventing bank erosion if it could be established, but the maintenance of a strip of riparian vegetation on sloping banks at the approaches to meander loops would serve to inhibit erosion and deflect the flow away from the outside of loops. Riparian vegetation on the inside of a loop serves to inhibit the downstream migration of the loop and to prevent cutoffs. Vegetation can be more easily established and protected there than at the outside of loops, and it should not be cleared.

Natural Levees

The origin and occurrence of natural levees have not been well explained in the literature on river morphology. Natural levees on the lower Mississippi River and its tributaries have been described by Fisk (1944), who observed that the width of levees tends to increase with stream size and with concentration of suspended sediment. Leopold and others (1964, p. 317) note that most natural levees contain "coarser materials deposited as flood flows over the top of the channel banks", and that streams transporting only fine-grained materials may not have natural levees. Bryan (1923) attributed the deposition of natural levees along the Sacramento River to a reduction in velocity as water spread a smooth sheet over the riverbanks during flood.

A. RM 191.5 - 183.5

FIGURE 4.— Vertical aerial photographs of the Sacramento River at flood stage, January 21, 1974

B. RM 177 - 171

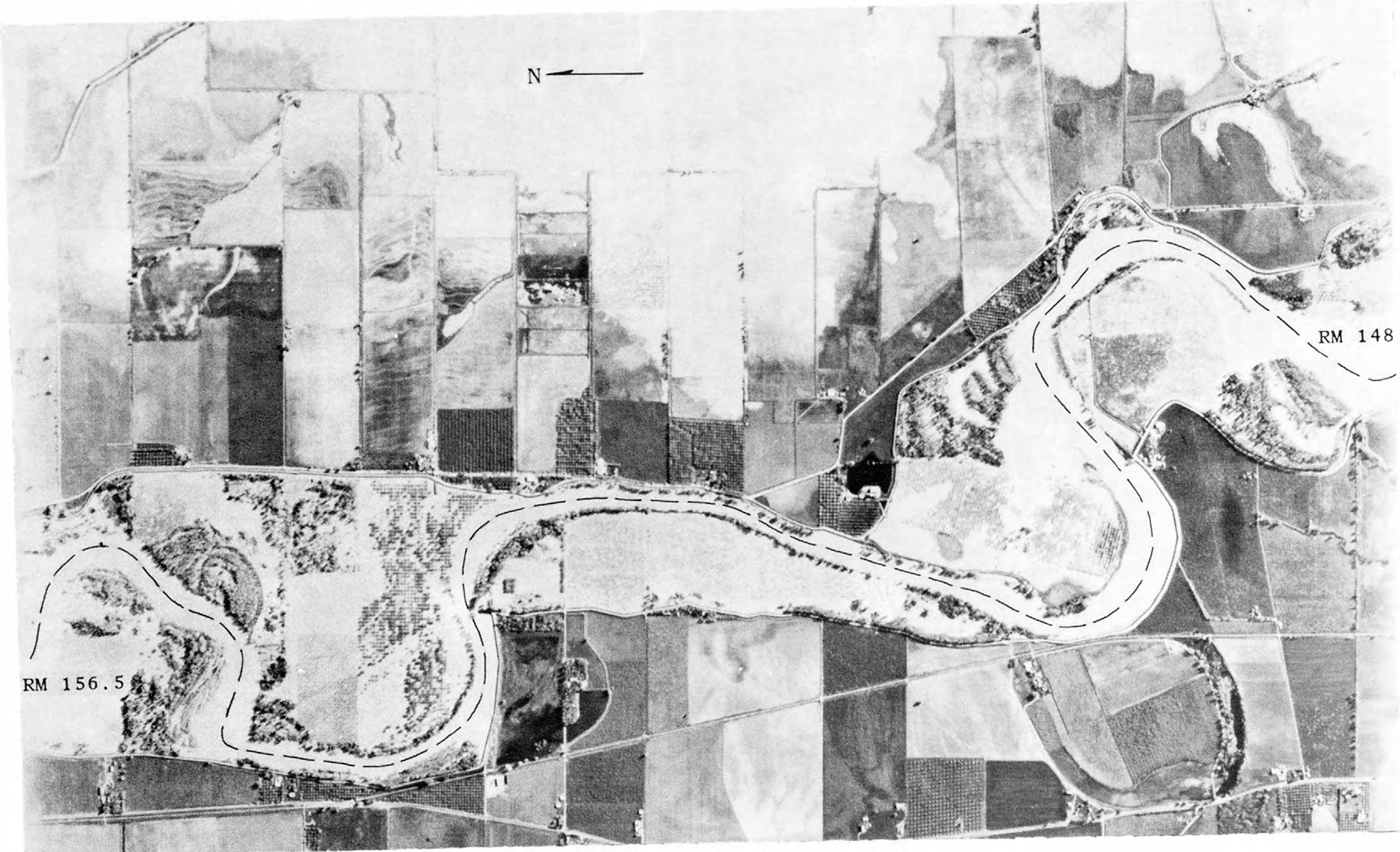
FIGURE 4.—continued

If natural levees occur along a stream, they are normally along its lower course where the valley slope is lowest and the duration (but not necessarily the frequency) of overbank flow is highest. This suggests that natural levees, rather than being deposited by a sheet of water flowing overbank, may be mostly deposited when water moving at high velocity through a stream channel is flanked by rather deep water on the flood plain. Perhaps the clearest example of natural levees in process of formation is at the mouth of distributaries on the Mississippi Delta, where they are formed laterally along a jet of moving turbid river water that enters the standing water of the Gulf of Mexico (Bates, 1953).

Along major streams, natural levees rarely have the form of narrow ridges but are typically broad surfaces that slope gently away from the stream. They are most easily discerned during flood stages, when a strip of ground on either side of the river stands above the flood. In figures 4C and 4D, the emerged ground north of the river is natural levee, but its extent immediately along the river, as well as its extent south of the river, cannot be discerned because of the ponding of water by artificial levees. Other criteria for recognizing natural levees include the flow of small drainage channels away from the streambanks, and differences in soil type between the natural levee and the adjacent flood basin. On an accurate topographic map with a small contour interval, natural levees can be discerned by the downstream curve of a contour line along a river course, as by the 60-ft and 70-ft contour lines (fig. 5).

The position of the river at Chico Landing is fixed between rather narrow limits by side slopes that represent the alluvial fan of Big Chico Creek on the east and the fan of Stony Creek on the west (fig. 5). The fan and prominent levee ridge of Stony Creek cuts off overbank flow on the west side of the valley and diverts it to the east side, where it has formed an anabranching network of ephemeral channels (figs. 4A and 5). Bryan (1923, p. 35) observed that no natural levees are present along these channels and he attributed this to "a balance between erosion and depositon." More accurately, it seems that neither erosion nor depositon is significant along the well-established channels, although new channels may be scoured from time to time. In an effort to determine changes in the channels with time, a comparison was made between aerial photographs flown in 1939 with others flown in 1970. The drainage has been disturbed by cultivation, but in general the pattern of channels, both large and small, tended to remain remarkably constant over the 30-year period, except that smaller channels adjacent to the river had changed locally. The soils of the channeled area are of the Zamora Series (Begg, 1968) and the erosion hazard for this series is characterized as very slight.

According to Bryan (1923) and Olmsted and Davis (1961, p. 22-23), natural levees along the Sacramento River begin at Hamilton City and form a strip of land 3 to 5 mi wide between Hamilton City and Colusa; however, the levees are discontinuous for several miles south of Stony Creek. This would be an academic matter, except that crevassing of natural levees along this segment of the river might divert the Sacramento River into Butte Basin. In the absence of the levees such diversion becomes less probable, because the water surface of the river is not elevated above the surrounding land.



C. RM 156.5 - 148

FIGURE 4.—continued

U.S. National Aeronautics and Space Administration photographs

D. RM 146 - 136

FIGURE 4.—continued

Natural levees at Hamilton City are indicated on the U.S. Geological Survey Chico Map (15' series, scale 1:62,500) by downstream point lobes in the 140-ft contour line on both sides of the river; the total width of levee is about 1.5 mi. The 130-ft contour line near Chico Landing (fig. 5) also trends downstream and can be taken to indicate natural levees. Downstream from this contour line, however, diversion of overbank flow by the Stony Creek fan and levee ridge apparently has interfered with the deposition of levees. Levees are not found on the west side of the river downstream from Stony Creek; the indentation of the 120-ft and 110-ft contours on the east side is attributed to a broad swale formed by scour. Moreover, the drainage channels on the east side of the river show no trend away from the river. The area has the morphologic character of an ordinary flat flood plain marked by scour channels. Natural levees are again indicated by the 90-ft contour, and they become higher and somewhat broader downstream (fig. 6, secs. B-B' and C-C').

The increased width of the meander belt between Ord Ferry and Glenn, and the restriction of meander scars to the east side of the river, is attributed to the absence or insignificance of natural levees on the east side. As valley slope decreases downstream, and the duration and depth of overbank flooding increases, conditions for the formation of levees have been more favorable and the Butte and Colusa flood basins are clearly defined.

It is reasonable to assume that the probability of diversion increases with increasing elevation of a streambed relative to the adjoining land surface; although, except for ephemeral streams on alluvial fans, this has not been clearly demonstrated. The bed of the Sacramento River is about 25 ft lower than the flood-plain scour channel at section A-A' (figs. 5 and 6), about 15 ft lower than the bottom of Angel Slough at section B-B', and about 5 ft lower than Butte Creek at section C-C'. Under natural conditions, diversion by crevassing of the natural levees at section C-C is conceivable, particularly if some aggradation occurred on the riverbed. Such diversion would be inhibited by the system of artificial levees and flood-bypass weirs already constructed along the Sacramento River.

According to Olmsted and Davis (1961), the natural levees widen 5 to 10 mi south of Colusa, especially east of the river. Downstream from the mouth of the Feather River (RM 80), the natural levees are well defined but narrower, averaging about 2 mi in width. This narrowing of the levees is tentatively attributed to upstream deposition of most of the coarser suspended load from which natural levees are constructed.

Width, Depth, and Channel Pattern

Along many rivers, bank-to-bank width is difficult to define for purposes of measurement because one of the banks is indefinite. This is particularly true at bends, where the outside bank is likely to be vertical and sharply defined but the inside bank slopes gradually up to flood-plain level. The position of the line of permanent vegetation on the inside bank is the best available indicator of the bankline, and it tends to be rather sharply defined along many rivers in humid regions. Stevens and others (1975, p. 124) have defined the width of the middle Mississippi as "the distance from tree line to tree line, irrespective of bank height, measured normal to the general direction

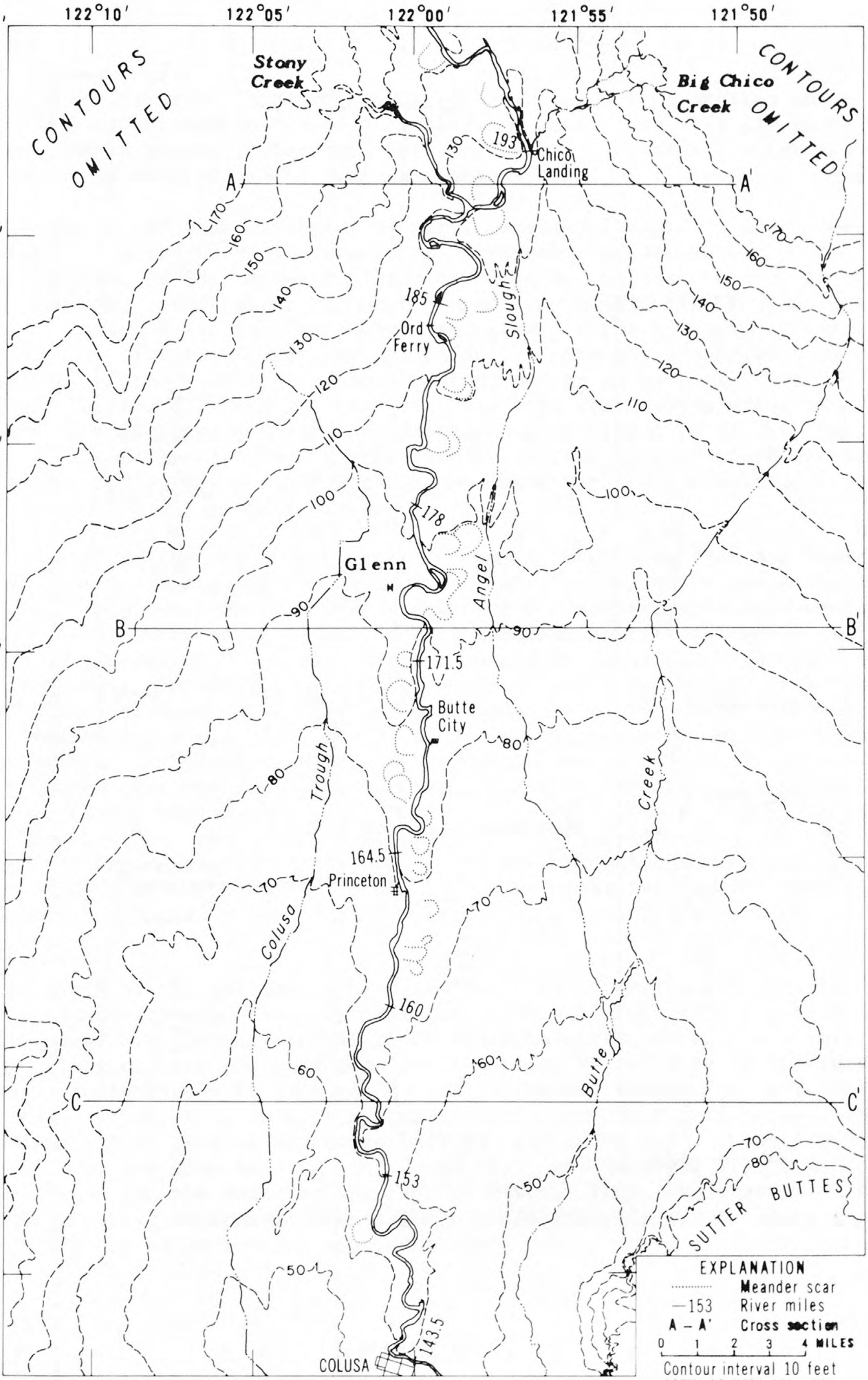


FIGURE 5.—Configuration of the Sacramento Valley between Chico Landing (RM 193) and Colusa (RM 143.5).

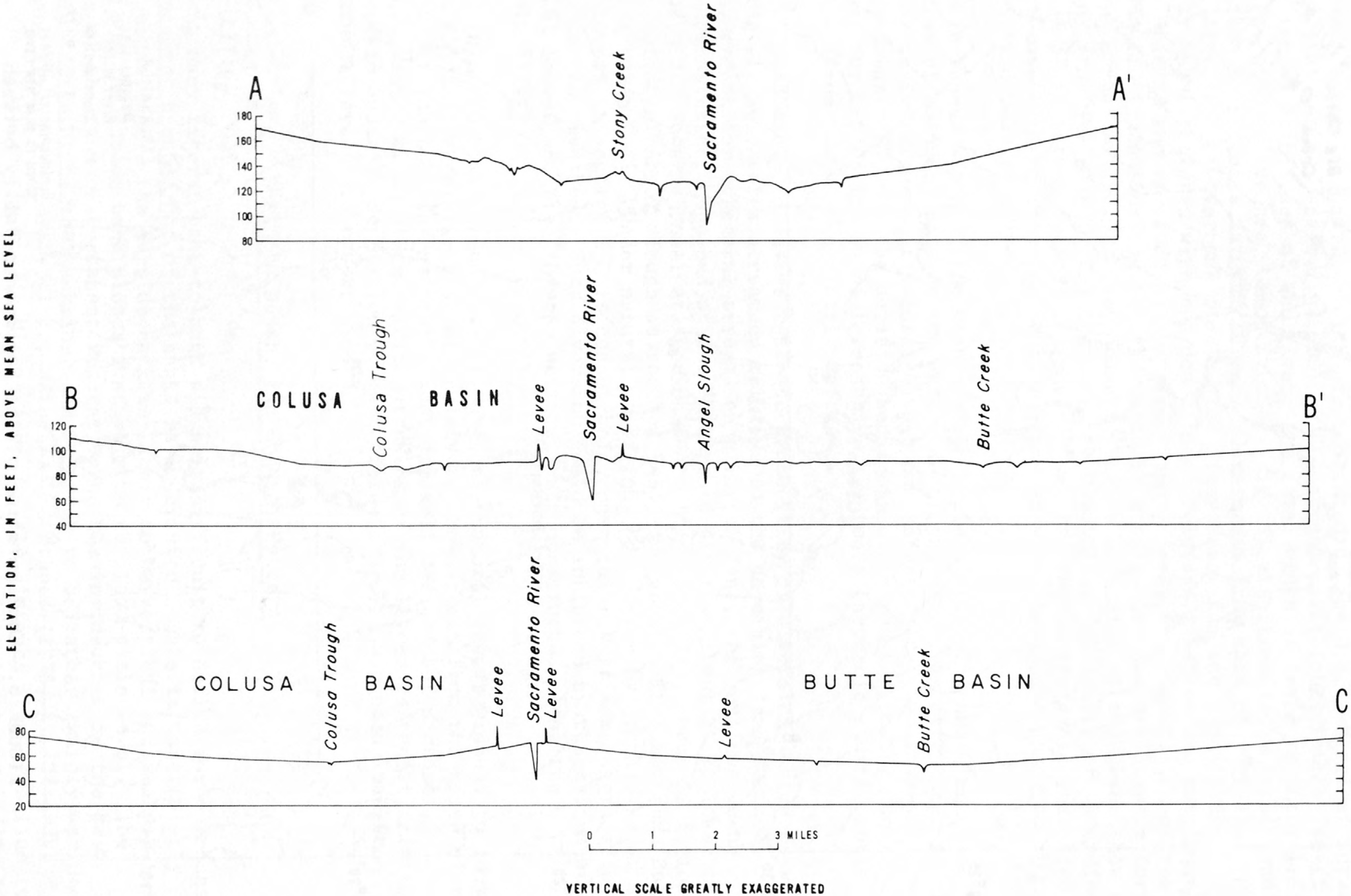


FIGURE 6.—Cross profiles of the Sacramento Valley between Chico Landing (RM 193) and Colusa (RM 143.5).

of flow of the river." This definition, however, cannot be applied where banks are bordered by cultivated ground or grassland. The width of a stream can be measured along a perpendicular draw between its opposing banks, which are defined either by their form or as the riverward edge of a line of permanent vegetation.

Measurement of width at bends is particularly difficult for the Sacramento River north of Butte City. Vegetation is irregularly distributed on the inside of bends because of the tendency of the river to cut across them during high stage and of the erratically channeled ground. Consider, for example, the problem of locating the inside bankline at either of the two large meander loops in figure 4A. Different observers may differ by as much as several hundred yards in placement of the bankline in those places, and by as much as 100 acres in measuring the area of the river channel. For this reason, measurements of bank erosion on the Sacramento River that depend upon the location of both banklines can never be consistent. On the other hand, the tree-to-tree width of the river at crossings and straight reaches can be measured with fair consistency, and it is this width that is given in table 1.

The width of the Sacramento River decreases downstream from Red Bluff to the mouth of the Feather River, although the discharge remains about the same (table 1). This decrease in width accompanies the downstream development of the natural levees. More striking is the fact that variability in width, as measured by the ratio of width at bends to width at crossings, decreases sharply downstream until the river has a nearly constant width downstream from Colusa. At some places between Colusa and the mouth of the Feather River, the width of the Sacramento River at the apexes of bends is slightly narrower than its average width. This narrowing of width might be attributed to artificial levees and associated bank-protection works. but it also occurs along low-gradient rivers not having artificial constraints; for example, the Wabash River in Indiana and the Red Lake River in Minnesota. Constancy of width and low rates of bank erosion are characteristic of rivers having continuous natural levees (Melton, 1936; Speight, 1965). In addition, the cross sections of such rivers are typically deep and narrow and more symmetrical than for rivers of variable width.

The depth of the Sacramento River between Chico Landing and RM 135 relative to an estimated low-water surface is shown in figure 3. Maximum depths at low flow are in the range of 20-25 ft along this section of the river, but between Colusa and the mouth of the Feather River (RM 143.5 to RM 80) they gradually increase to a maximum of 35-40 ft. Minimum depths, as measured from the average elevation of submersed shoals to the low-water surface, are about 3 ft between Chico Landing and Butte City (RM 193 to RM 169), about 5 ft between Butte City and Hamilton Bend (RM 169 to RM 153), and increase from 6 ft to 10 ft between Colusa and the mouth of the Feather River. Thus, the average depth of the river gradually increases downstream with decrease in width, along a section in which the discharge remains about constant.

Stream power was proposed by Langbein (1964) as a measure of the energy expended by a stream on its boundary, and hence as a major determinant of channel dimensions and cross-sectional forms. He expressed stream power per unit length by the equation $\omega = \gamma QS$, where ω is stream power, γ is the specific weight of water, Q is discharge, and S is water-surface slope.

The values for stream power of the Sacramento River are based on valley slope and on the discharge equaled or exceeded 10 percent of the time (table 1). Stream power does not correlate directly with width, because both bed material and channel pattern change downstream along the Sacramento River, but it may explain the decrease in width in the reaches between Butte City and the mouth of the Feather River, where the Sacramento River is a sand-bed stream.

According to the usage of Leopold and Wolman (1957), the term "channel pattern" applies to the plan view of a stream reach, and channels are described according to pattern as meandering, braided, or straight. More recently Schumm (1968) and Mollard (1973) have, in effect, distinguished two kinds of braided streams. The term "braided" is restricted to channels that are divided mainly by unvegetated bars, and the term "anabranching" is applied here to channels that are divided mainly by large vegetated islands. Most anabranching streams have gravel beds, and the islands that divide them are more stable than the smaller unvegetated bars of braided streams.

Meandering streams have some arbitrary degree of sinuosity, which is the ratio of reach length as measured along the channel centerline to reach length as measured along the valley centerline. Streams having a numerical value of sinuosity greater than 1.5 are regarded as meandering by Leopold and others (1964, p. 295): If this criterion is applied, only one of the Sacramento River reaches indicated in table 1 would be termed meandering, and the rest may be termed sinuous. At several places within these reaches the Sacramento River has a sinuosity of less than 1.05 for distances ranging from 1 to 3 mi; these parts of the river are not divided to a significant degree and their pattern is described as "straight." Even where no control by levees is apparent, straight reaches on the Sacramento River are remarkably persistent if they are downstream from a stable loop of large radius or if the entering flow is alined along the reach.

From Red Bluff Diversion Dam to the mouth of Thomes Creek, the Sacramento River is sinuous with a tendency toward anabranching around large islands. These islands are fairly stable as indicated by comparison of 1946 and 1972 aerial photographs which show that not much change had occurred in 26 years. The comparison also shows that the islands were more heavily vegetated in 1972 than in 1946, possibly indicative of the moderating effect of Shasta Dam on peak flood flows. Large islands in this reach form by chute cutoff at a meander neck, or by the gradual growth and stabilization of midchannel bars. Isolated small midchannel bars occur from place to place, but the numerous unvegetated bars that characterize braided streams are not typical of the Sacramento River there or elsewhere.

The flood plain, which has an average width of 2.5 mi, is flat and inset by lateral planation below the adjoining piedmont slopes, which may indicate that the recent regimen of the river has been degradational rather than aggradational. From place to place, and particularly for the first 5 mi downstream from Red Bluff, the flood plain is marked with a distinct anabranching pattern of channels formed by scour during overbank flow. Elsewhere the flood plain is marked by the scars of abandoned meander loops, within which are irregular meander scrolls. These loops are adjacent to the present river, which thus has a very narrow meander belt, and the form of the loops indicates that they were made by chute cutoff across the meander neck, rather than by gradual closing of the neck.

From Thomes Creek to Chico Landing, the sinuosity of the river increases slightly, and the flood-plain width increases to 4.5 mi. Between 1964 and 1970 a large loop was cut off at Wilson Landing, and between 1970 and 1973 another loop was cut off between RM 212 and RM 215; thus sinuosity has decreased during the past decade. At RM 195, one of a pair of large loops (Jenny Lind Bend) was cut off between 1910 and 1937, and the second was cut off between 1936 and 1937, forming a straight segment about 18,000 ft in length. The river has widened in this length and assumed a somewhat braided pattern, but an exceptional amount of bank erosion is apparent. The two large islands now present along the reach, one at RM 207 and the other at RM 205.5, were formed by chute cutoff. Islands named on the 1904 U.S. Geological Survey topographic maps (Snaden Island, Foster Island, Gazelle Island) are no longer separated from the flood plain by an active channel. The point bars in this reach and the next bars downstream have a shape described by Melton (1936) as "tongue-like;" they are formed by a chute that separates the upstream part of the bar from the mainland but leaves the downstream part attached.

From Chico Landing to Butte City, the variability in width of the river gradually decreases, as does the measured width at crossings, and islands of the sort found upstream no longer occur. Most of the large islands in the Sacramento River are formed by chute cutoff, either across a point bar or a meander neck. The cutoff part of the channel fills more quickly as the sediment load becomes finer downstream. Compared with the reaches upstream, the river in this reach tends to be more distinctly sinuous as indicated by a more concentric development of scrolls on the inside of meander loops and also by the larger number of abandoned loops on the flood plain. The most distinctive feature of this reach is the gradual downstream development of natural levees, which have already been described.

From Butte City to Colusa, the width and variability of width of the river decrease further as the natural levees increase in height and width, and the river gradually loses any tendency toward anabranching or braiding. The loops are confined by artificial levees and tend to be distorted for this reason, but their smaller radius relative to upstream loops is apparent (figs. 4A-D). Abandoned cutoff loops on the flood plain are infrequent, and these loops tend to be narrow and elongated, as is characteristic of the cutoff loops of natural-leveed streams. These tendencies are continued in the reach between Colusa bridge and the mouth of the Feather River, where the meander loops decrease further in radius and have the cramped shape of loops associated with continuous natural levees. For example, nearly identical loops occur on the Ouachita River at Monroe, La.; and the loops of the Mississippi River at New Orleans, though much larger, have similar shape.

Between the mouth of the Feather River and the mouth of the American River, the Sacramento River is markably constant in width, and it curves in gentle arcs of very large radius, only two of which (located just upstream from Sacramento) appear to be meander loops in the usual sense. Apparently the stream power is too low, relative to bank resistance, for meanders to develop. This same explanation is offered for the randomly curving course of the river downstream from Sacramento; but it must be noted that Elk Slough (formerly Elkhorn Slough), a distributary that leaves the river at Clarksburg, has a definitely meandering pattern although it flows on the same valley slope as the randomly curving reach of the Sacramento River main stem. Although values for width of channel are given in table 1 for the reach from the American River to Collinsville, the Sacramento River is actually an anabranching distributary system downstream from Clarksburg.

ANALYSIS OF CHANNEL FORM AND MIGRATION, CHICO LANDING TO COLUSA

Method

For purposes of analysis, the Sacramento River between Chico Landing and Colusa was arbitrarily divided into seven reaches between points indicated by the appropriate river mile (fig. 5). U.S. Geological Survey topographic maps of the 7.5-minute series, scale 1:24,000 and prepared by photogrammetric methods from aerial photographs flown in 1947 and 1949, were used as a base for the preparation of figures 7 through 13. These maps were photocopied and projected on a rigid screen at a scale of 1:18,000 and the centerlines and banklines from all other dates and sources were matched by projection onto this scale and base.

The centerline of flowing water in a river shifts with river stage, but for any given stage below bankfull the centerline can be drawn for the Sacramento River with greater consistency than can the banklines. The centerlines of this study (figs. 7A-13A) are intended to represent the river at the stage at which the Topographic Division of the U.S. Geological Survey attempts to represent rivers, the so-called "normal" stage that prevails during part of the year. A centerline diagram has the advantage of showing clearly the position of the river at different times, and an analysis of the form and migration of meander loops can be made from it. The centerlines for 1896 and 1908 are approximations, interpreted from bankline diagrams but confirmed to some degree by the river as represented on Geological Survey maps of 1904 and 1910. The centerlines for 1924 are from aerial photographs; for 1947-49, from Geological Survey topographic maps; and for 1974, from aerial photographs. The 1870 centerline (fig. 9A) is from a General Land Office survey, and the 1969 centerlines (figs. 7A and 8A) are from the photorevised edition of 1947-49 topographic maps. From the goodness of fit for reference points superimposed by projection, the centerlines for dates prior to 1947 are estimated to have maximum errors in the range of ±200 ft and the later centerlines, in the range of ±75 ft.

The banklines for 1896 and 1908 (figs. 7B-13B) are from U.S. Army Corps of Engineers plots on a detailed map of the river surveyed during the period 1927-37. The banklines for 1947 and 1949 were interpreted from Geological Survey 1:24,000 maps, and the banklines for 1974 were interpreted from aerial photographs flown on January 21, 1974, scale about 1:32,500. As previously noted, the banklines on the inside of bends cannot be consistently and objectively defined. Personnel of the Corps of Engineers evidently took land utility as a principal criterion for defining banklines and considered land on the inside of bends that seemed unfit for agricultural use as part of the river channel. This is probably the best criterion for the Sacramento River in places where no well-defined line of permanent vegetation can be discerned.

Form and Behavior of Meander Loops

Terms used here for the description and measurement of meander loops are illustrated in figure 14. The chord is drawn between inflection points with adjoining loops, and the axis is a perpendicular that bisects the chord. The point of intersection of the axis with the loop is termed its apex. Radius is measured by superimposing on the loop a transparent template on which closely spaced circles of known radii are inscribed.

A variety of loop forms can be distinguished (Brice, 1974b), but for bank-erosion studies it is the behavior of loops (movement and form changes with time) that matters. Major alternatives in the behavior of common loop types, with particular reference to loops on the Sacramento River, are illustrated in figure 15. Extension of a loop (fig. 15A) refers to outward movement of the apex along the axis. Translation (fig. 15B) refers to movement of the apex at right angles to the axis. Clearly, all gradations may occur between pure extension and pure translation. In ideal rotation, the axis of a loop is rotated, while the inflection points stay fixed, but some translation usually accompanies rotation (fig. 15C). As indicated in figure 15D, new loops have formed on the limbs of an elongated loop whose behavior can no longer be analyzed as a single unit.

A loop may be cut off by gradual closure of its neck as adjacent, differently oriented, loops encroach on it (fig. 15E). Alternatively, it may be cut off by a chute across the meander neck, either diagonally (fig. 15F) or straight (fig. 15G). On the present Sacramento River, loop cutoffs take place entirely by means of chutes. Loops upstream and downstream from a cutoff are usually much affected by the change in stream alinement that attends a cutoff.

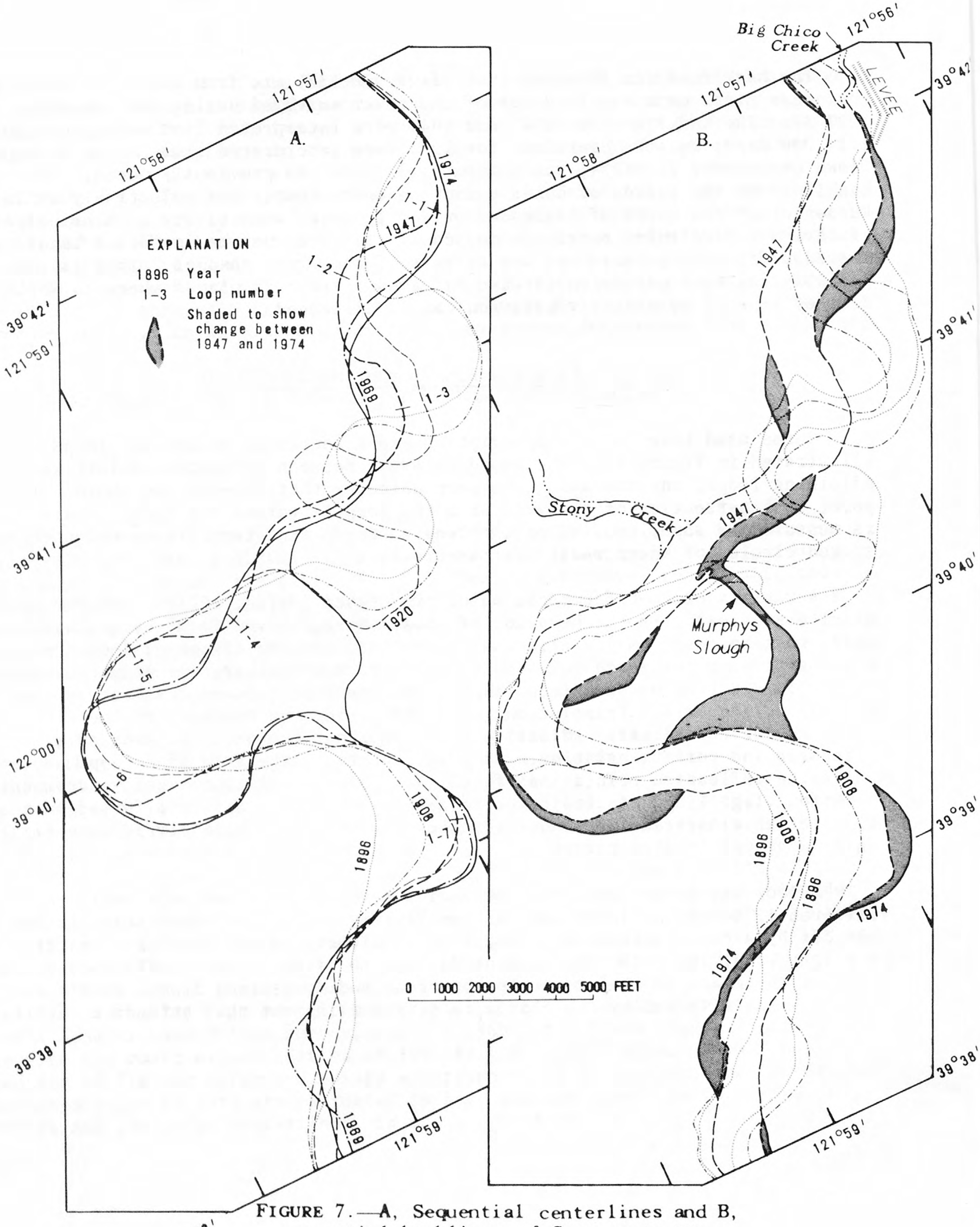


FIGURE 7.—A, Sequential centerlines and B, sequential banklines of Sacramento River, Reach 1, RM 193 - 185.

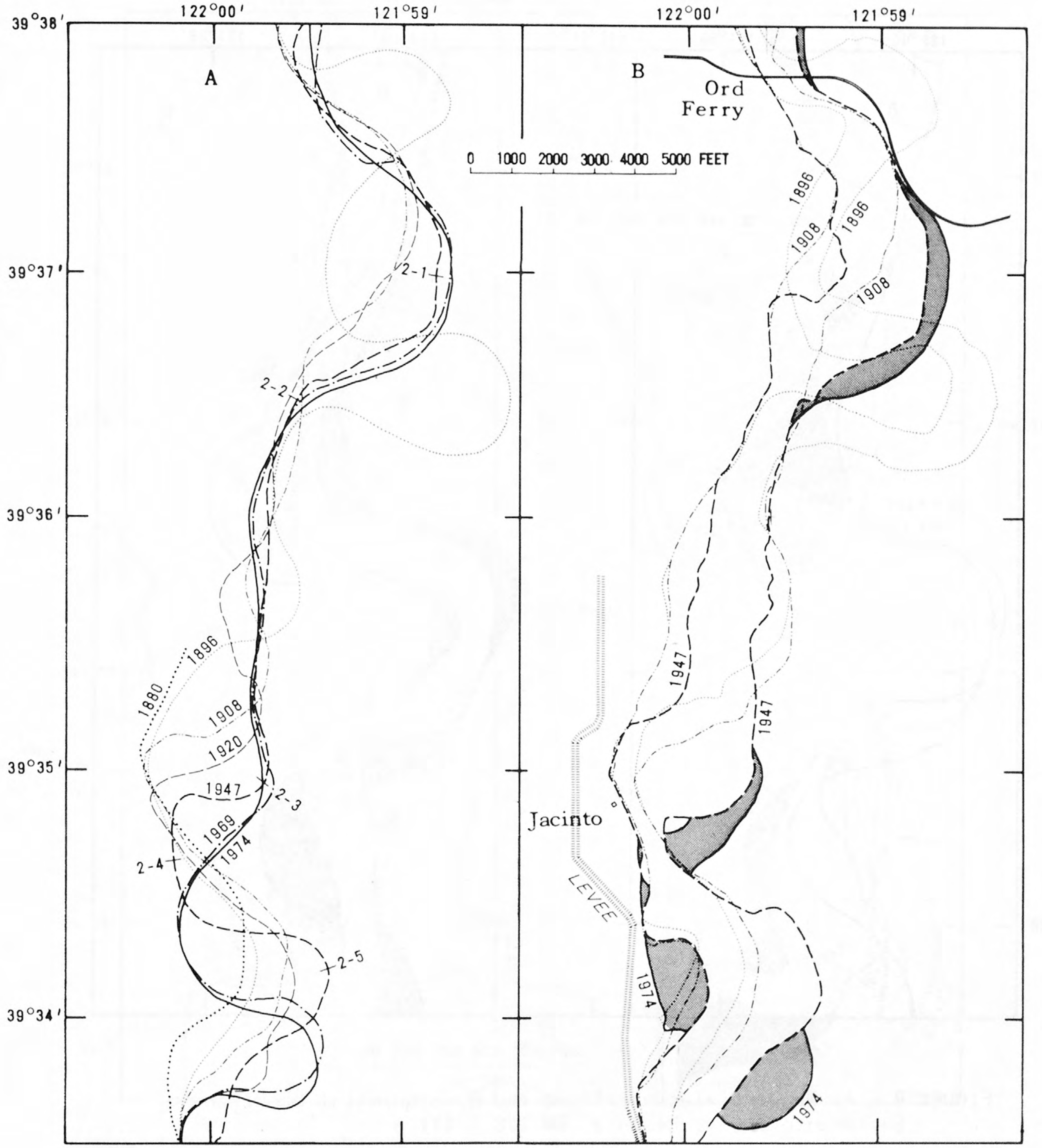


FIGURE 8.—A, Sequential centerlines and B, sequential banklines of Sacramento River, Reach 2, RM 185 - 178.

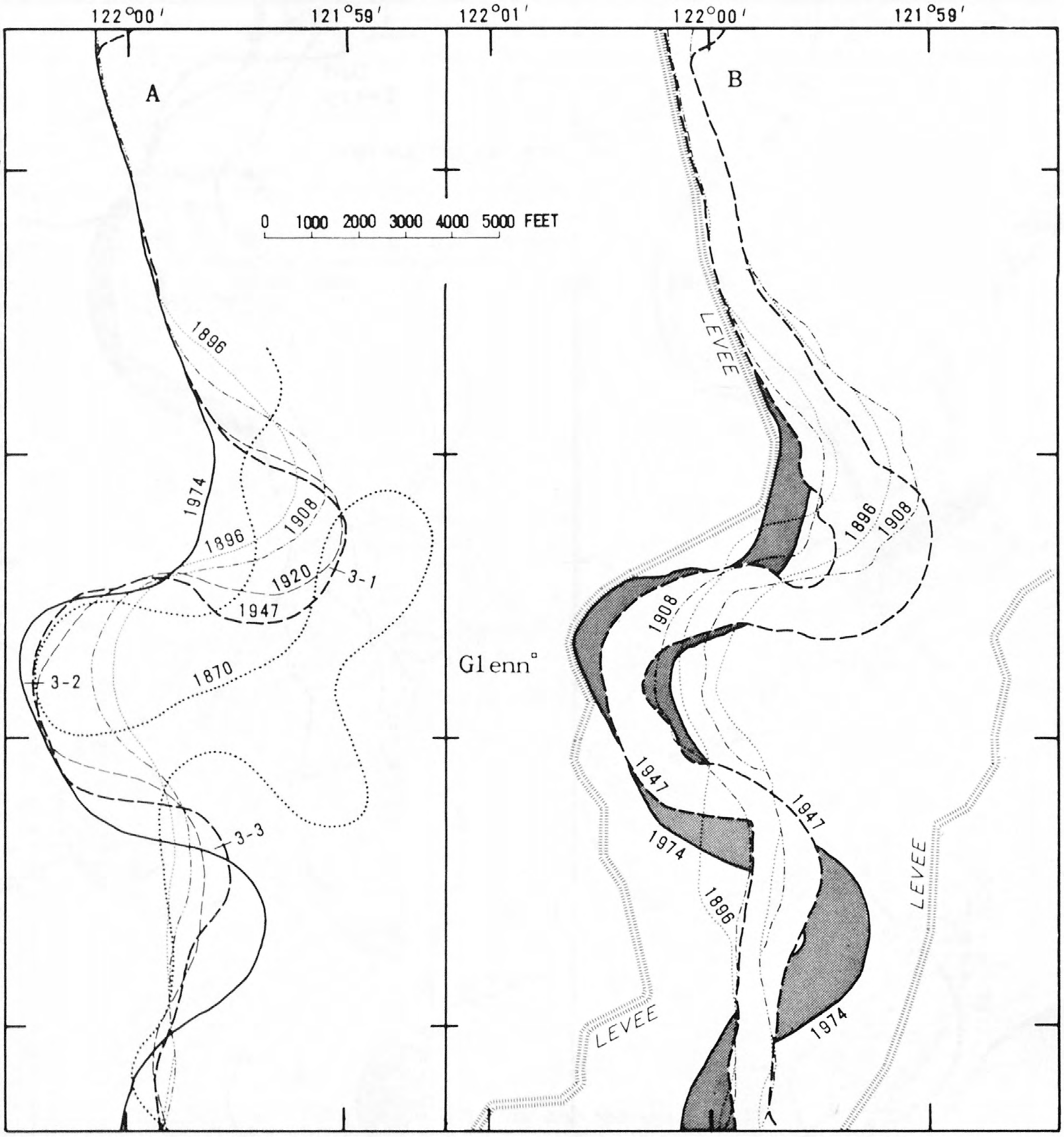


FIGURE 9.—A, Sequential centerlines and B, sequential banklines of Sacramento River, Reach 3, RM 178 - 171.5.

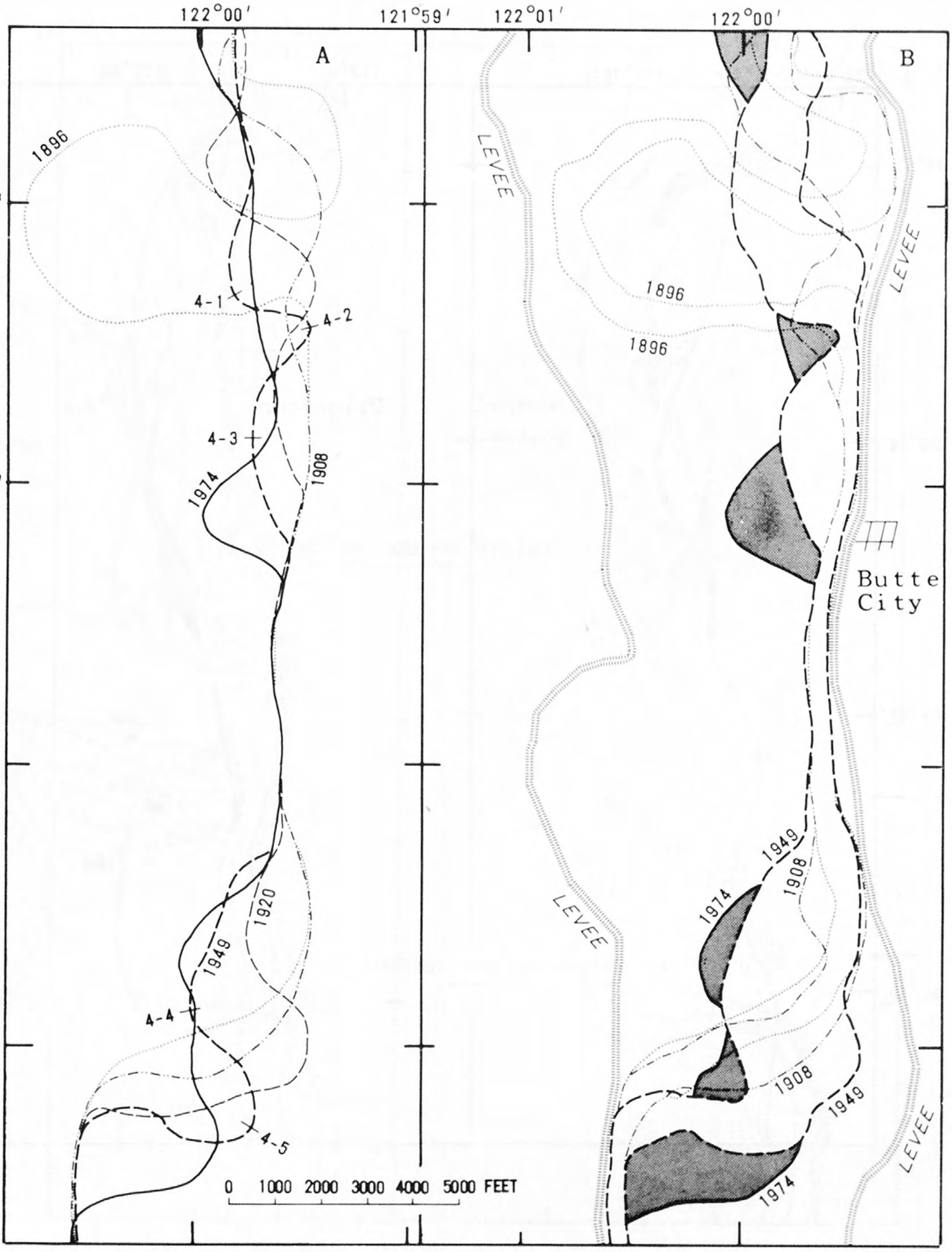


FIGURE 10.—A, Sequential centerlines and B, sequential banklines of Sacramento River, Reach 4, RM 171.5 - 164.5.

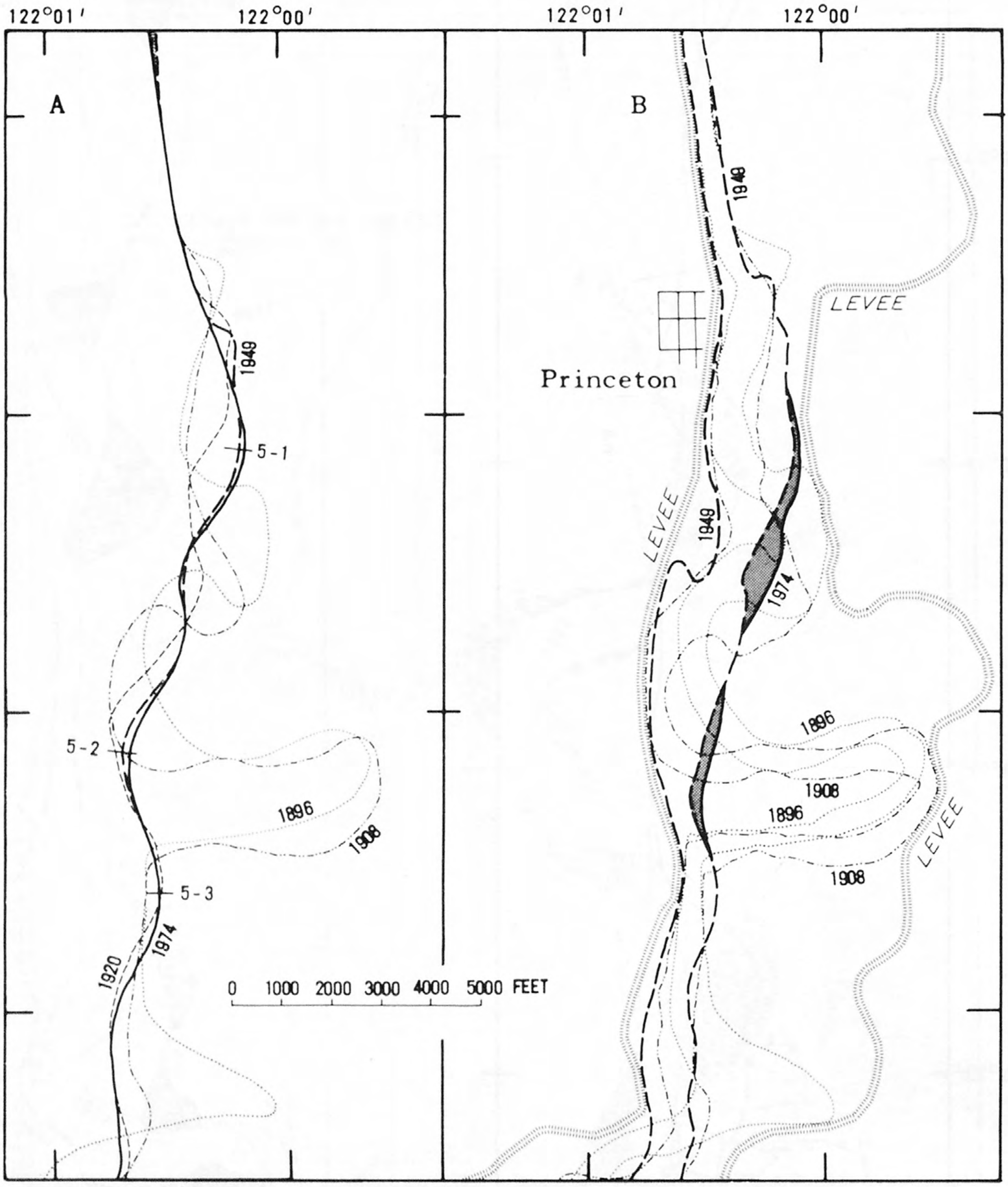


FIGURE 11.—A, Sequential centerlines and B, sequential banklines of Sacramento River, Reach 5, RM 164.5 - 160.

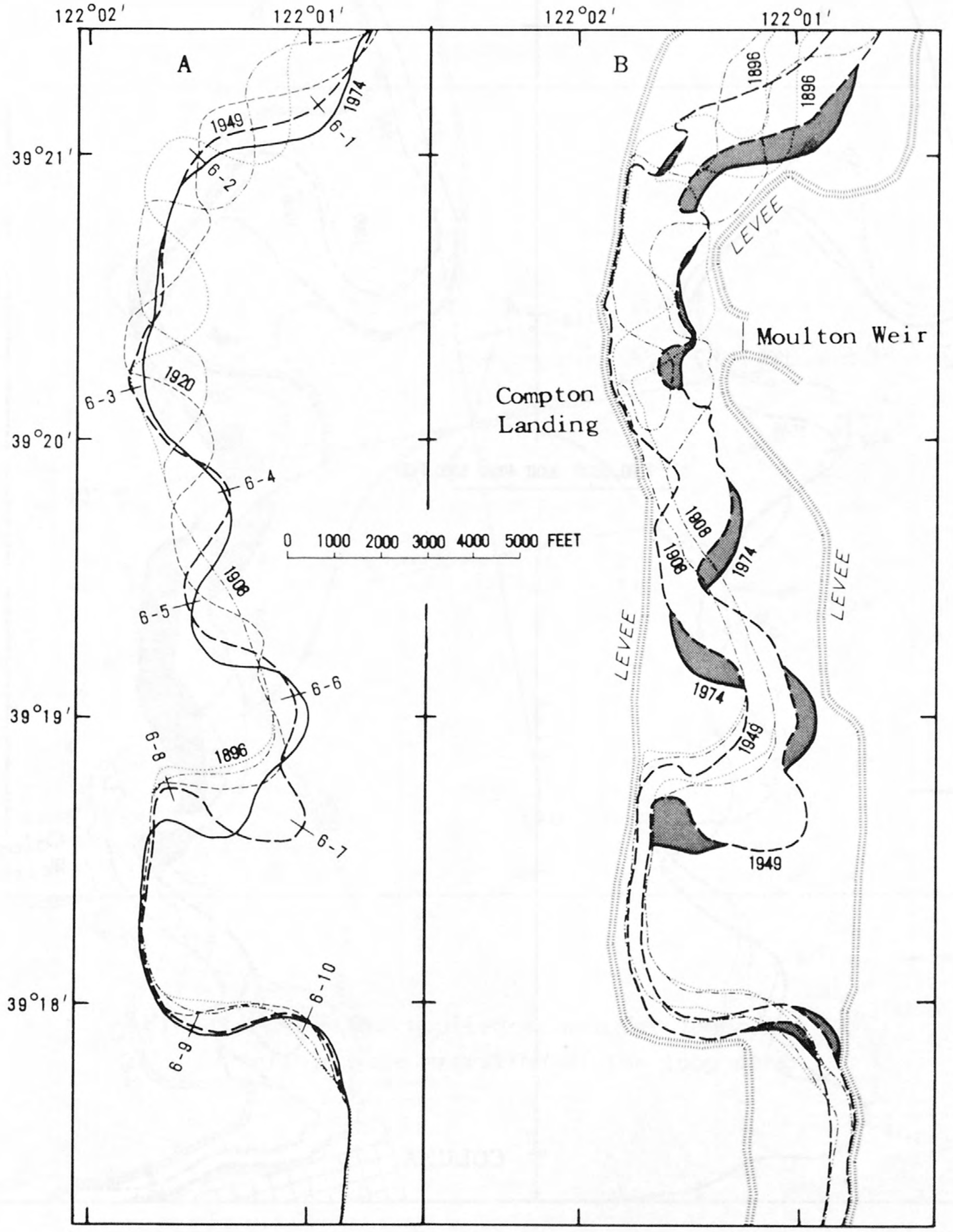


FIGURE 12.—A, Sequential centerlines and B, sequential banklines of Sacramento River, Reach 6, RM 160 - 153.

FIGURE 13.—

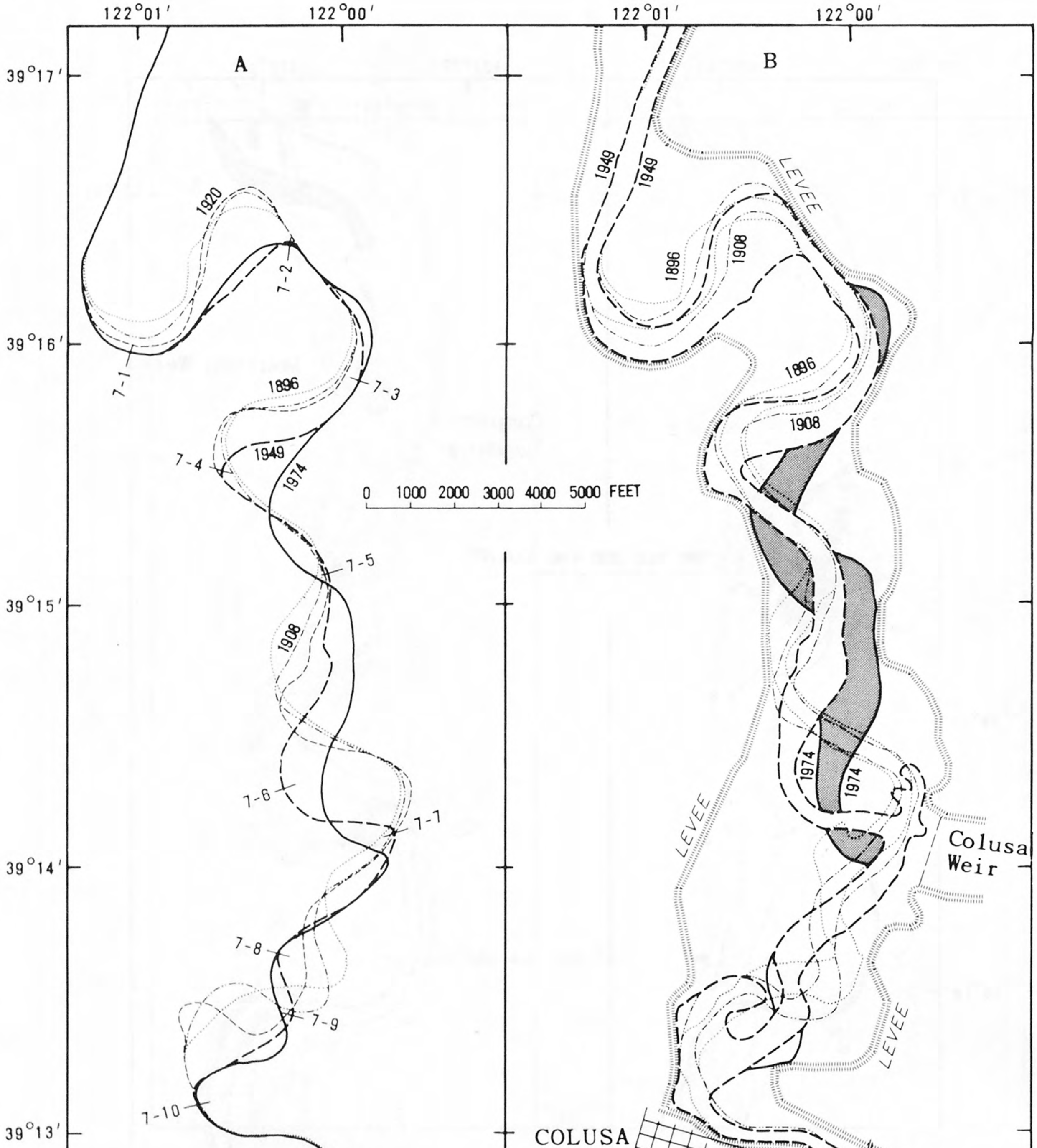


FIGURE 13.— A, Sequential centerlines and B, sequential banklines of Sacramento River, Reach 7, RM 153 - 143.5.

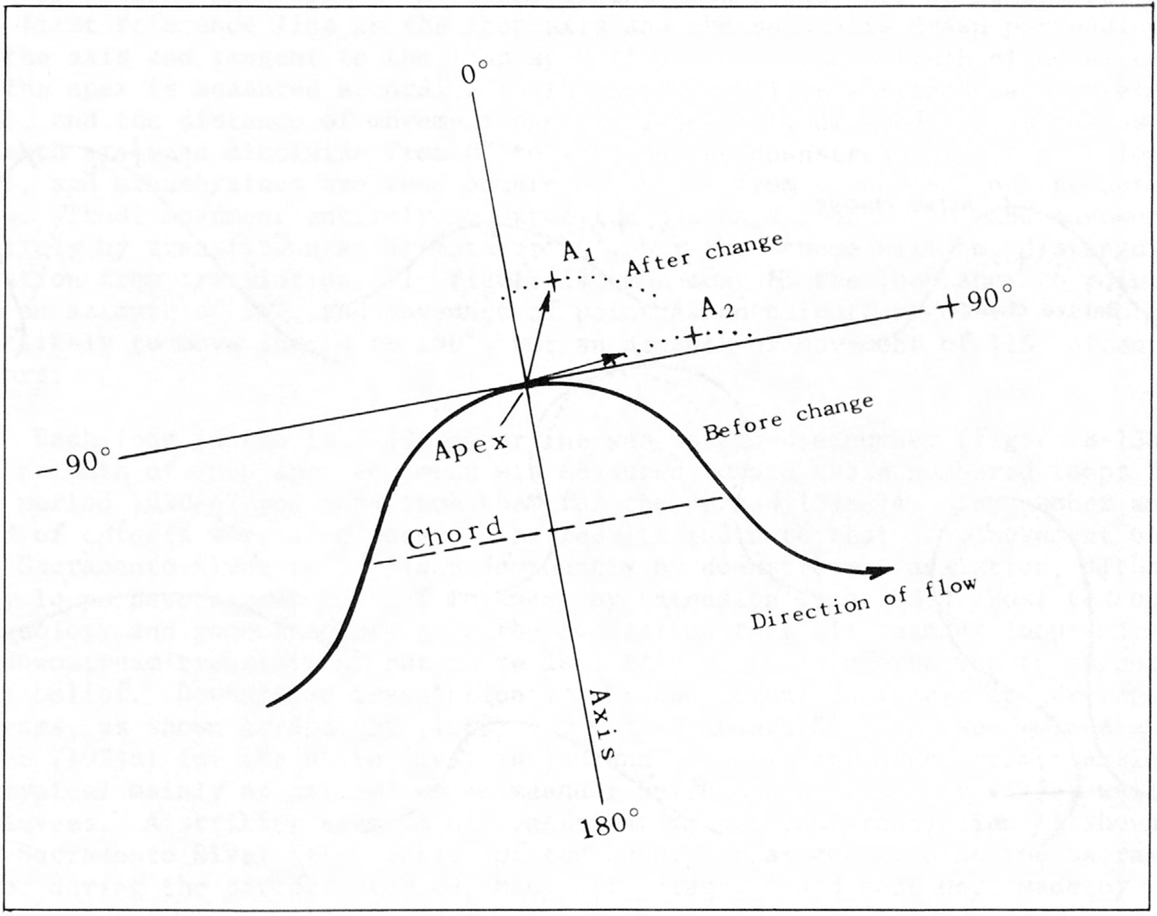


FIGURE 14.—Terms applied to meander loops and for describing the migration of the loop apex.

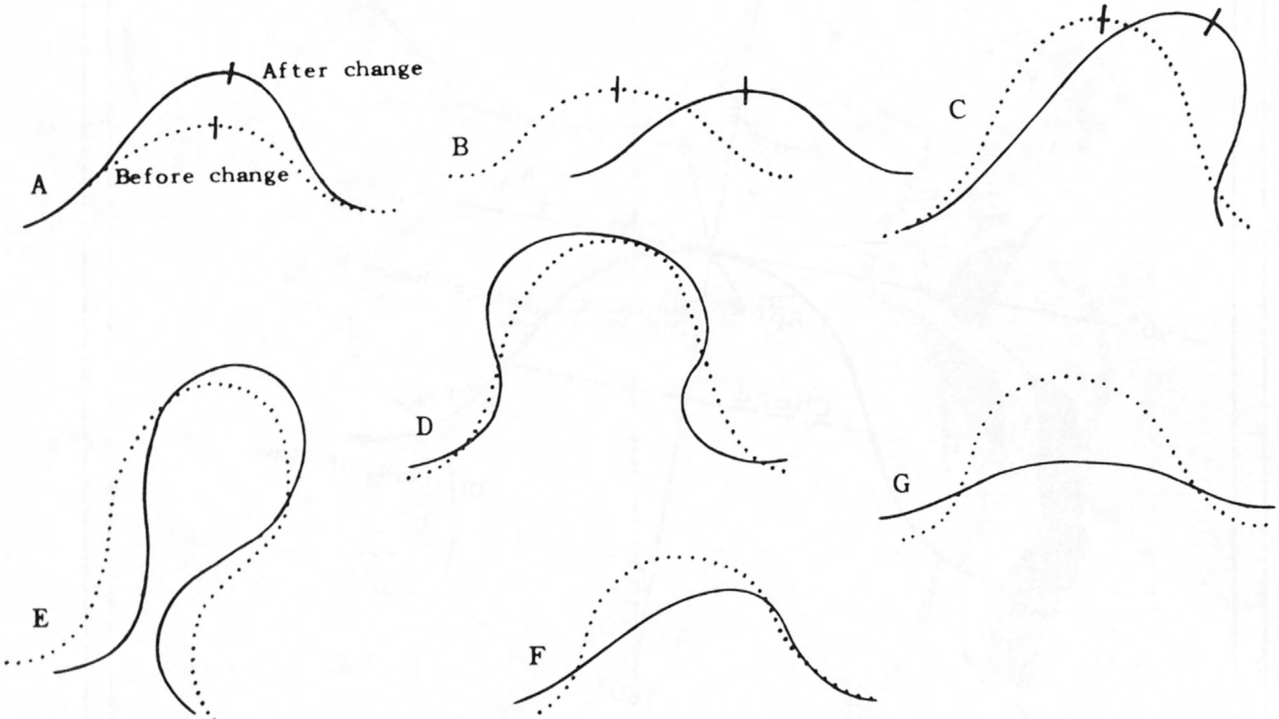


FIGURE 15.—Some major alternatives in the behavior of meander loops on the Sacramento River. A, Extension; B, Translation; C, Rotation; D, Conversion to a compound loop; E, Neck cutoff by closure; F, Diagonal cutoff by chute; G, Neck cutoff by chute.

The behavior of meander loops has been analyzed according to different methods by Daniel (1971), Hickin (1974), and Brice (1974a). The analysis becomes complicated if it includes movement and change in form of an entire loop, and for present purposes the movement of the apex alone will be considered. The first reference line is the loop axis and the second is drawn perpendicular to the axis and tangent to the loop apex (fig. 14). The azimuth of movement of the apex is measured according to the azimuth values assigned each reference line, and the distance of movement can be measured if desired. Plus values of azimuth are read clockwise from 0° to 180° on the downstream side of the loop axis, and minus values are read counterclockwise from 0° to 180° on the upstream side. Thus, movement entirely by extension has an azimuth of 0° and movement entirely by translation an azimuth of 90°, but the scheme will not distinguish rotation from translation. In figure 14, movement of the loop apex to point A_1 has an azimuth of 25°, and movement of point A_2 an azimuth of 85°. A loop is not likely to move inward to 180°, but an azimuth of movement of 115° often occurs.

Each loop in the 1947-49 centerline was assigned a number (figs. 7B-13B). The azimuth of loop-apex movement was measured toward these numbered loops for the period 1920-47 and away from them for the period 1948-74. The number and kind of cutoffs were also noted. The results indicate that loop movement on the Sacramento River takes place dominantly by downstream translation, although many loops have a component of movement by extension (table 3). Most textbooks in geology and geomorphology give the impression that all meander loops migrate by downstream translation, but there is little factual information to support this belief. Downstream translation is not consistent on freely meandering streams, as shown by Speight (1965) for the Angabunga River in New Guinea and by Brice (1974a) for the White River in Indiana. Consistent downstream translation is typical mainly of streams whose meander belts are confined by valley walls or by levees. A striking example of consistent downstream translation is shown on the Sacramento River (fig. 12B). Of the cutoffs that occurred on the Sacramento River during the periods studied, many were diagonal and none were made by closure.

Table 3.--*Azimuth of loop apex migration and number of loop cutoffs during the periods 1920-47 and 1947-74*

	Number of loops	
	1920-47	1947-74
Azimuth of apex migration:		
75° - 105°	15	10
45° - 74°	6	9
<45°	1	1
Neck cutoff by chute	2	5
Diagonal cutoff by chute	4	2
No change	0	2
Total	28	29

To investigate any systematic change in loop radius with time along the Sacramento River, the radius of all loops in 1920, 1947, and 1974 was measured. Loop radii have a fairly symmetrical normal size-frequency distribution, with a range from about 300 to 2,600 ft and a median of 1,400 ft (fig. 16). There has been a general trend toward increase in loop radius between 1920 and 1974, which is related to the trend toward decreased sinuosity. Loops of small radius, or with narrow necks, do not now survive because they were cut off by chutes.

Hickin and Nanson (1975) have proposed (for the Beatton River in Canada) a relation between average migration rate of a loop and the radius of curvature/channel width ratio. Maximum migration rates on the Beatton occur when this ratio has a value of 3, and lesser rates as the ratio becomes greater or less than 3. A major difficulty in applying this relation to the Sacramento River is the difficulty of measuring the river width at bends. If the mean channel width as determined from area/length is used (about 1,000 ft) loops having a radius of 3,000 ft would have the greatest migration rate, but no loops are this large. If the width as measured at crossings and straight reaches is used (about 450 ft), loops having a radius of 1,350 ft would have the greatest migration rate. Loops of large radius (greater than 2,000 ft) tend to have relatively slow migration rates, but loops of radius smaller than 1,200 ft tend to be cut off before they have migrated very far.

The behavior of meander loops on the middle Sacramento River is sufficiently consistent that short-term predictions can be made. In figure 17, a prediction is made for the large loop that has recently been partly cut off at Murphys Slough (fig. 4A; fig. 7B, loops 1-6) on the assumption that the cutoff chute will be artificially closed. This loop is compound, and the simple loops on its periphery will move by downstream translation as indicated. The rate of movement shown is based on the assumption that flow trends of the past 10 years will be continued; however, a meander neck as narrow as this will soon be cut off by a chute, probably in the vicinity shown in figure 17.

Changes in Sinuosity, Channel Area, and Width

From the channel and the valley centerline plots, the sinuosity of each reach was computed (table 4). The sinuosity for reaches 1-7 (figs. 7-13), considered as a whole, decreased steadily from 1.56 in 1896 to 1.35 in 1974, or to 1.29 in 1974 if the cutoff at Murphys Slough (fig. 7B) is considered to be the main river channel. The sinuosity of reach 3 (fig. 9A) decreased from 2.12 in 1870 to 1.16 in 1896. Sinuosity of other reaches for the period 1867-72 is uncertain, because the river is crudely represented on the relevant land-plat surveys. Reach 3 is exceptional because the river was accurately surveyed in T. 19 N., R. 1 W.; the river position on the land-plat of this township corresponds closely with the position of now-abandoned meander loops on aerial photographs (fig. 4B).

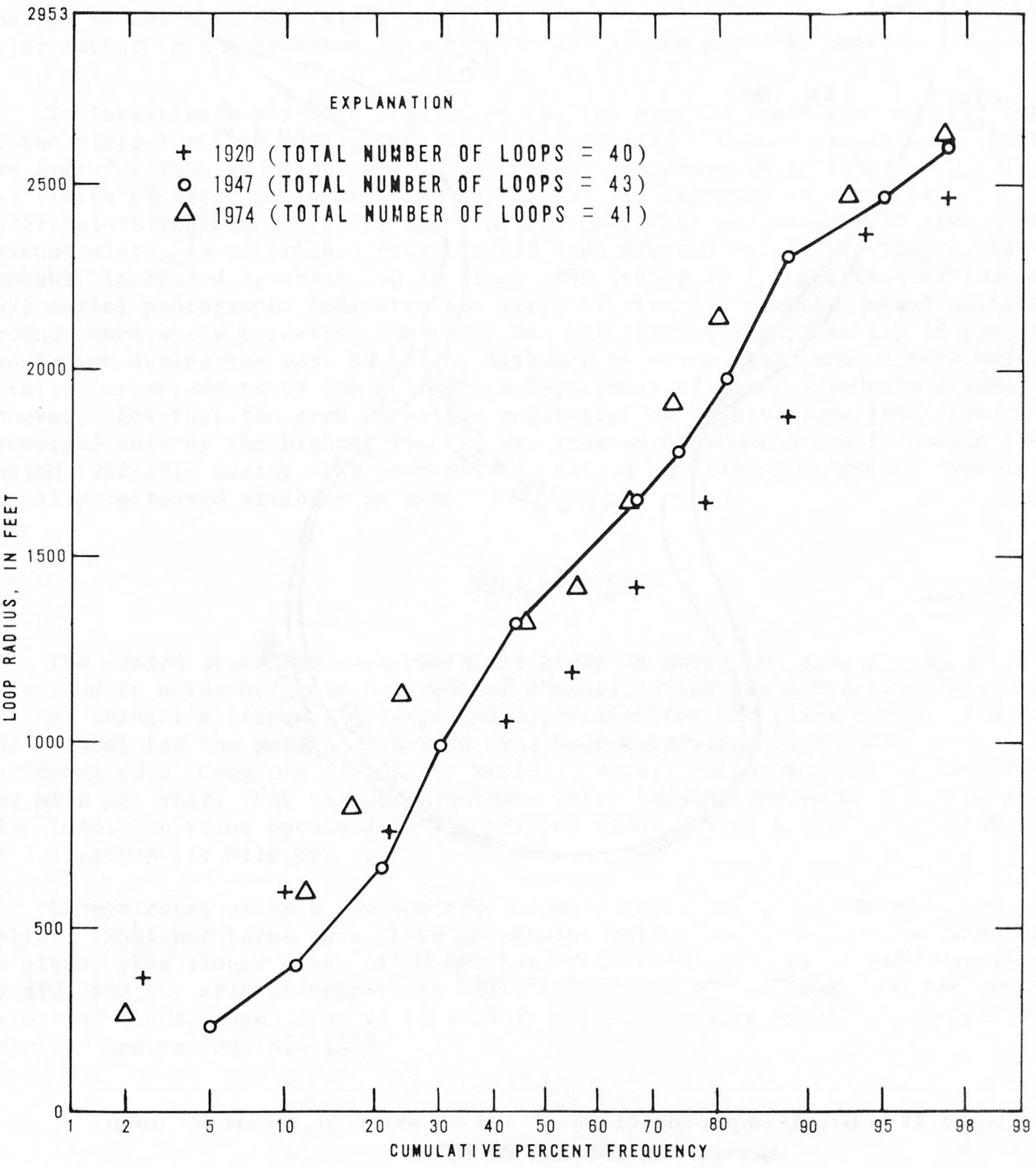


FIGURE 16.—Size-frequency distribution of meander loop radii for 1920, 1947, and 1974, Sacramento River between Chico Landing and Colusa.

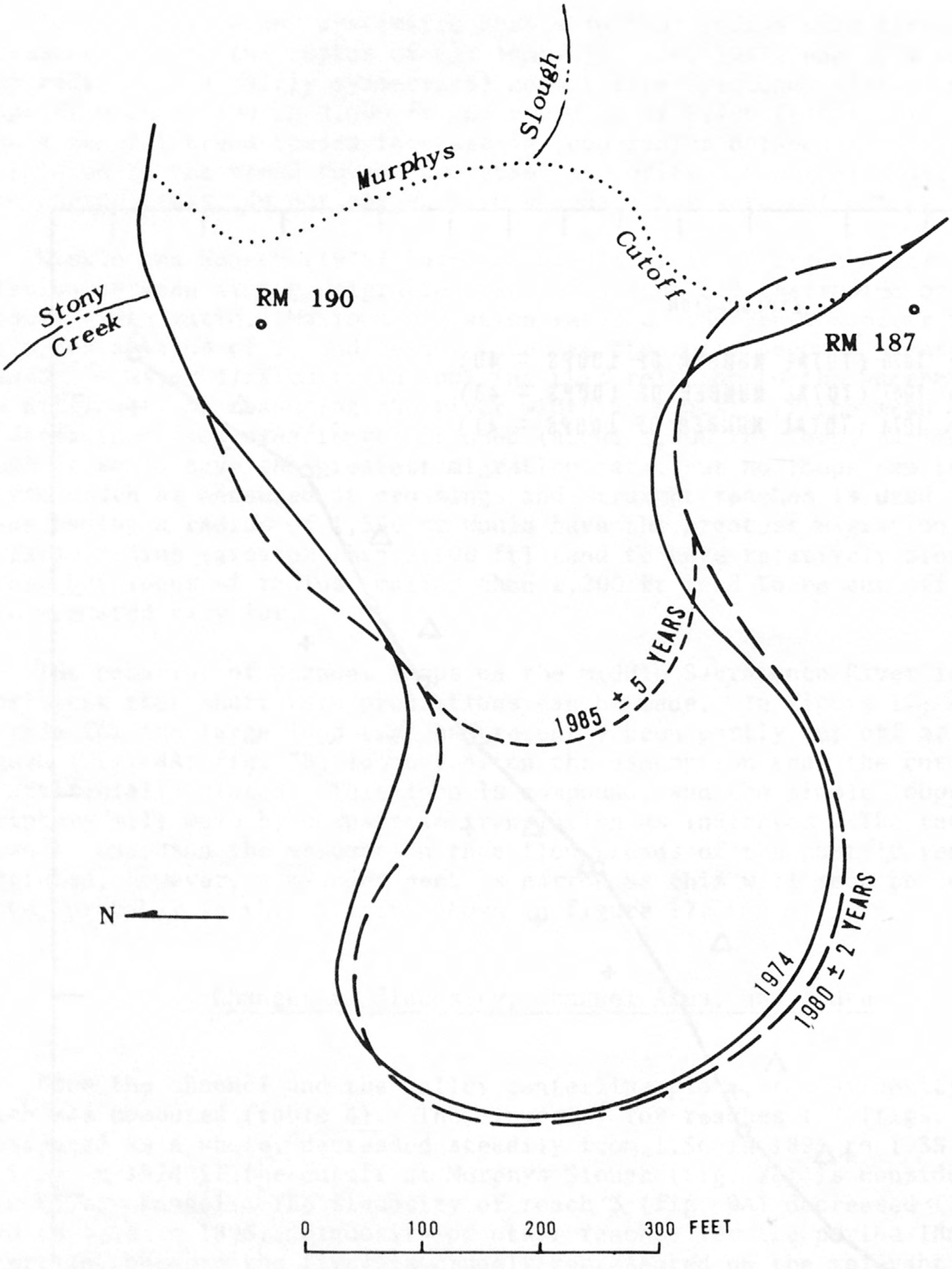


FIGURE 17.—Short-term prediction of the behavior of a meander loop between RM 190 and RM 187.

Abandoned meander loops along the river have a further significance in evaluating channel changes during the past 100 years. Their curvature indicates that they were cut off by gradual closure at the neck, rather than by chute cutoff; and their regular concentric internal markings (meander scrolls) indicate that they grew slowly, probably bordered on opposing banks by a rather continuous plant cover. Decrease in plant cover may be partly caused by climatic change, rather than entirely by man, but decrease in plant cover is probably a major factor in the decrease in sinuosity during the past 100 years.

To investigate possible changes during the past 50 years, the channel areas of the river for 1896, 1924, and 1974 were measured. Channel areas were about the same for 1896 and 1920, and the 10 percent increase in 1974 may be within the limits of error in location of banklines. An increase in width is nevertheless indicated because the channel length has decreased with time. Mean channel width, as determined from channel area divided by channel length, has probably increased by about 200 ft since 1896 (table 4). Comparison of 1924 and 1972 aerial photographs indicates the strip of riparian vegetation and cultivated ground immediately bordering the river has not changed significantly in aspect or proportion during the past 50 years, although no exact measurements were made. Detailed measurements by the California Department of Water Resources (1975), however, show that the area of native vegetation on high-terrace land (land submerged only by the highest floods) was reduced by about one-half during the period 1952-72. During this same period, native vegetation on ground flooded annually decreased slightly in area.

Bank Erosion

The eroded areas for each reach are given in acres in table 5 and are also expressed in acres per year per mile of channel, using the centerline length in 1947 as channel distance. Average annual erosion for the river between Red Bluff and Colusa, for the period 1896-1946, has been determined by the Corps of Engineers (U.S. Congress, 1960), to be 193.7 acres, which amounts to 1.94 acres per mile per year. For the reach between Chico Landing and Colusa, for the period 1896-1948, the value obtained in the present study, using a different method, is 2.11 acres per mile per year.

Linear rates of bank erosion are commonly quoted (as, for example, by Weller, 1965) but these rates have no meaning unless the method of measurement is given. The linear rates of centerline shift given in table 5 were determined by dividing the area of centerline shift in a reach by the length of the reach. Values obtained ranged from 10 to 20.4 ft of bank erosion per ft of channel per year for the period 1896-1974.

Table 4.--*Channel dimensions and slope for reaches 1 through 7, Sacramento River between Chico Landing and Colusa*

Reach	Stream centerline length in 1947 (ft)	Sinuosity value			Channel area, in acres			Mean channel width (area/length), in feet			Stream slope in 1947	Valley slope
		1896	1920	1974	1896	1920	1974	1896	1920	1974	(ft/1,000 ft)	
1	48,800	1.65	1.87	[1](1.23) 1.67	1,154	1,306	1,329	1,024	1,019	1,160	0.286	0.471
2	36,050	1.62	1.26	1.30	1,114	893	991	1,095	1,127	1,205	.346	.457
3	34,500	1.16	1.37	1.28	570	768	710	909	1,038	1,024	.333	.489
4	33,250	1.68	1.21	1.16	660	584	743	642	788	1,047	.300	.375
5	24.100	1.71	1.06	1.04	584	370	489	645	658	887	.311	.326
6	38,250	1.36	1.43	1.42	479	579	698	600	688	838	.235	.351
7	46,900	1.72	1.86	1.62	557	636	718	523	551	715	.191	.333
1-7	261,850	1.56	1.43	[1](1.29) 1.35	5,118	5,136	5,678	779	840	986	--	--

[1]Cutoff at Murphys Slough considered as main channel.

Table 5.--*Bank erosion as measured by shift of channel centerline, Sacramento River between Chico Landing and Colusa*

Reach	Area of centerline shift, in acres					Areal rate of centerline shift, 1896-1974		Linear rate of centerline shift, 1896-1974
	1896-1908	1900-1920	1921-1948	1949-1974	1896-1974	Acres per year	Acres per year per river mile	(ft per ft per year)
1	447	445	429	488	1,809	22.8	2.46	20.4
2	374	248	359	327	1,308	16.5	2.41	20.0
3	131	268	132	224	755	9.5	1.45	12.1
4	192	268	337	313	1,110	14.1	2.24	18.4
5	251	151	87	19	508	6.4	1.40	11.6
6	183	237	272	122	814	10.3	1.42	11.7
7	158	148	342	205	853	10.8	1.21	10.0
1-7	1,736	1,765	1,958	1,698	7,157	90.4	1.82	15.1

Study of bank erosion on the Sacramento River by the Corps of Engineers (U.S. Congress, 1960) indicated that the rate of erosion had generally decreased between 1896 and 1955. The Corps of Engineers also reported that significant bank erosion begins when the mean water velocity in the channel reaches 4.1 to 4.4 ft per second, values that correspond to a discharge of 22,000 ft^3/s at Red Bluff, 32,000 ft^3/s at Hamilton City, 24,000 ft^3/s at Colusa, and 35,000 ft^3/s at Sacramento. Bank erosion was found to be roughly related to stage duration, in foot-days per year, for the time that the discharge exceeds the values given above.

In figure 18 a comparison is shown between cumulative area of bank erosion and cumulative discharge above mean annual, for the periods 1908-20 and 1921-48. For the period 1948-74, the rate of bank erosion remains about the same as that for the preceding period, but it decreases in relation to flow. This decrease is attributed to reduction of peak discharges by storage in Shasta Lake and perhaps to depletion of the river by diversions for irrigation. Bank-erosion control measures in this reach are not of sufficient extent to have had a significant effect.

Because of the strong tendency toward downstream translation of meander loops and the development of chute cutoffs, bank stabilization of the Sacramento River between Chico Landing and Colusa would probably require continuous river-training and bank-protection measures such as those that have been used effectively along reaches of the Missouri River (Ruhe, 1975, p. 66). It would not be sufficient to provide bank protection for the outside of meander loops, because the necks of loops are also subject to erosion and to channeling by chutes. Furthermore, partial bank protection on the outside of one loop can deflect the flow and cause bank erosion downstream. The present artificial levees have caused distortion or confinement of many meander loops and consequent severe bank erosion at several places, most notably at loop 4-5 (fig. 10).

As a river migrates laterally, it erodes land on the outside of a bend and forms an approximately equal amount of land on the inside; the river width remains about the same. Thus, it is sometimes argued that bank erosion does not destroy land for agricultural purposes, but only transfers it to the other side of the river. In response to this argument, the Corps of Engineers (U.S. Congress, 1960, p. 25) investigated the use of land formed on the inside of bends along the Sacramento River. They concluded that during the 50 years prior to 1955 the new land amounted to about two-thirds of that lost by bank erosion; but that the cost of leveling it and preparing it for agricultural purposes nearly equaled its value. By comparing figures 4B and 9B, it can be seen that some land that was under the river in 1870, and some that was formed on the inside of loop 3-2 between 1896 and 1908, is now being used for agricultural purposes. In general, it seems that a period greater than 50 years must elapse before the new land can be used, but the length of period would depend on the irregularity of the surface, the texture of the soil, and the probability of flooding.

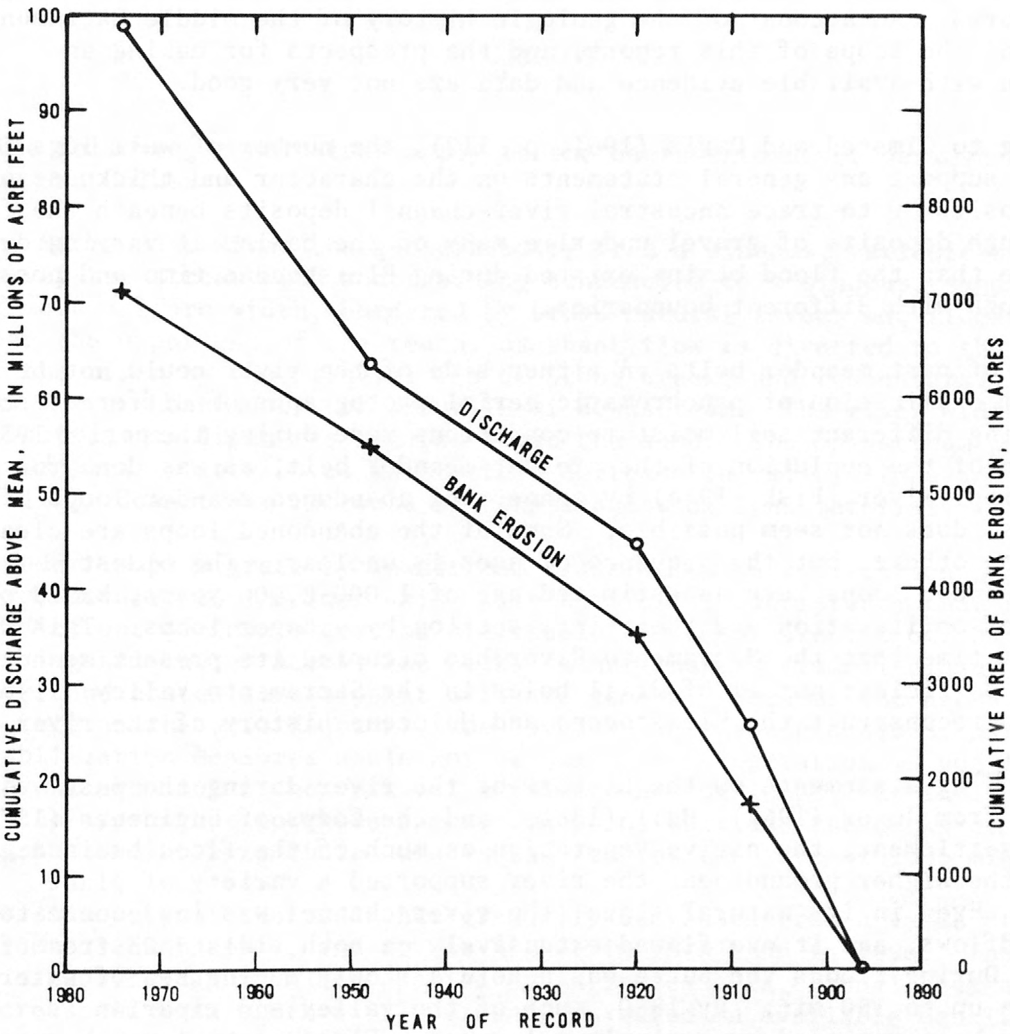


FIGURE 18.—Cumulative area of bank erosion in relation to cumulative discharge above mean annual, for the Sacramento River between Chico Landing and Colusa.

RIVER HISTORY RELEVANT TO PRESENT CHANNEL FORM AND MIGRATION

The geomorphic history of a river is interpreted from existing landforms and from the stratigraphy of alluvial fills. For example, Fisk (1944) distinguished 20 stages in the evolution of the present meander belt of the lower Mississippi River from interpretation of flood-plain forms on aerial photographs, and he interpreted the Pleistocene history from terraces and from thousands of logs of drill holes. Similarly, Schlemon (1971) has interpreted the Quarternary history of the California Delta in the central part of the Great Valley from well logs and surface forms. An account of the geologic history of the middle Sacramento River is beyond the scope of this report, and the prospects for making an interpretation with available evidence and data are not very good.

According to Olmsted and Davis (1961, p. 112), the number of well logs is inadequate to support any general statements on the character and thickness of the river deposits or to trace ancestral river-channel deposits beneath the flood basins, although deposits of gravel underlie many of the basins at varying depths. They speculate that the flood basins existed during Pleistocene time and possibly before, although with different boundaries.

Evidence of past meander belts on either side of the river could not be discerned from examination of panchromatic aerial photographs of different scales and representing different soil-moisture conditions made during the period 1939-74. Reconstruction of the evolution of the present meander belt, as was done for the lower Mississippi River (Fisk, 1944) by connecting abandoned meander loops of different ages, does not seem possible. Some of the abandoned loops are clearly much older than others, but the sequence of ages is unclear. The oldest discernible meander loops have an estimated age of 1,000-2,000 years, based on their degree of obliteration and their intersection by younger loops. This would be the minimum time that the Sacramento River has occupied its present meander belt. With a sufficient number of drill holes in the Sacramento Valley, it may be possible to reconstruct the Pleistocene and Holocene history of the river.

The following statements on the history of the river during the past 150 years are from Jones (1967), Hall (1881), and the Corps of Engineers (1973a). Before white settlement, the native vegetation on much of the flood-basin areas was tule and the higher ground near the river supported a variety of plant associations. Even in its natural state, the river channel was inadequate to transmit floodflows, and it overflowed extensively on both sides downstream from Stony Creek. During floods the Butte basin held a slowly moving sea of water having an area up to 150 mi^2. By 1850, much of the valley and riparian vegetation had been replaced by agricultural crops. Flood control was begun in an unsystematic manner by individual private landowners, and by 1894 levees had been extended for many miles along the stream channels. Detritus from hydraulic mining in the Sierra Nevada, during the period 1869-1900 approximately, did not significantly aggrade the Sacramento River upstream from the American River, although the water depth was generally increased by the downstream aggradation.

According to Jones (1967) the construction of levees along the Sacramento River and the reclamation of areas of natural inundation restricted more and more of the floodwater to the main river channel, with the result that water velocities increased and the channels were scoured wider and deeper. In the reach from Chico Landing to Colusa described in the present study, the levees are located mainly downstream from Ord Ferry, although there is a levee at Chico Landing. The increase in channel width and decrease in length (sinuosity) between 1896 and 1974 is here attributed to the clearing of native vegetation and to the effects of levees, but the relative importance of these parameters could not be assessed.

CONCLUSIONS

The following conclusions apply to the Sacramento River between Chico Landing and Colusa:

1. The Sacramento River changes gradually from a sinuous, variable-width, gravel-bed stream with anabranching tendencies to a sinuous, sand-bed stream of more uniform width, bordered by broad natural levees and flood basins. Near the upper end of the reach, overbank flow is diverted to the east side of the river by the alluvial fan of Stony Creek, and the natural levees are low and discontinuous for about 15 mi downstream. The river width decreases downstream as discharge remains about the same. The downstream change in river form is attributed mainly to a decrease in valley slope and partly to a slight downstream increase in cohesiveness of bank material.

2. Meander loops migrate by downstream translation in a direction nearly perpendicular to the loop axis, with sufficient consistency that short-term predictions of loop migration are feasible. Loops are cut off by straight or diagonal chutes across the neck, rather than by gradual closure of the neck, and chutes across point bars are common. Because the necks of loops, as well as the outside banks, are involved in these processes, partial bank-stabilization measures would not be suitable. Vegetation is not likely to prevent erosion at the vertical outside banks of loops, but it is effective on the approaches to these banks. On point bars and the necks of loops, vegetation inhibits chute cutoffs and reduces the rate of loop migration.

3. The sinuosity of the river has gradually decreased from a value of 1.56 in 1896 to 1.35 in 1974, and it was higher in 1870 than in 1896. The decrease in sinuosity has been accompanied by an increase in channel area and by an increase in mean width of 27 percent, as based on available bankline plots. These changes are attributed to the clearing of riparian vegetation along the river and to the effects of levees in reducing the area of overflow. They are not attributed to flow regulation by Shasta Lake because erosion rates have not increased during the period of regulation.

4. The bank erosion rate, as measured by the shift of the channel centerline between 1896 and 1974, was 1.82 acres per year per stream mile or about 15 ft per year per stream foot. Before 1948, cumulative bank erosion increased at about the same rate as cumulative discharge above mean annual discharge, but it has increased at a lesser rate since 1948, probably because of flow regulation by Shasta Lake.

5. If the condition of the river in 1870 is regarded as "natural," the present river is substantially modified from nature, both in form and behavior. Besides the gradual changes in sinuosity and width, manmade levees have in places produced awkward and unstable bends by deflection of flow. Continuous river-training and bank-protection measures, in connection with channel realinement, would probably be required for stabilization of the channel. Some judicious artificial alinement of the river, perhaps in broad curves, might contribute both to its stability and its aesthietic qualities.

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