UNITED STATES
DEPARTMENT OF THE INTERIOR
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CHANNEL CHANGES OF POWDER RIVER BETWEEN MOORHEAD AND BROADUS, MONTANA, 1939 to 1978

By Holly A. Martinson

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COVER: Powder River. View upriver (SW) from section 28, T8S, R.48E. Newly formed cutoff channel across meander neck will have become the main channel when floodwaters have receded. May 25, 1978. Rendering by Bobbie Myers, U.S. Geological Survey, Vancouver, Washington.

For additional information write to:

U.S. Geological Survey
Water Resources Division
Mail Stop 413, Box 25046
Denver Federal Center
Denver, Colorado, 80225

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CONVERSION FACTORS

Multiply inch-pound units	By	To obtain metric units
inch (in.)	25.4	millimeter (mm)
	2.84	centimeter (cm)
	0.0254	meter (m)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.0929	square meter (m^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1233.6	cubic meter (m^3)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per second (f/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

CHANNEL CHANGES OF POWDER RIVER BETWEEN MOORHEAD AND BROADUS, MONTANA, 1939 to 1978

By Holly A. Martinson

ABSTRACT

Aerial photographs taken during 1938-39, 1944, 1954, 1967, 1973, and 1978 are the basis for a series of maps of the bankfull channel of the Powder River between Moorhead and Broadus, Montana. The bankfull channel is mapped by the position of the cutbank and the distribution of vegetation on the point bars. Comparing the maps provides measurements of bank erosion and changes in channel width, length, and pattern. The record of daily-mean and peak-discharges at Moorhead for water years 1939 through 1978 provides the hydrologic framework within which the measurements of bank erosion and changes in channel characteristics are interpreted.

Comparisons of magnitude and frequency of daily mean and peak flows to the area of bank erosion that occurred during each interval between photographs show that the area of bank erosion is related to the number of days that mean discharge was equal to or greater than bankfull (the 1.5-year flood, or 5,600 ft^3/s). No relation was found between area of bank erosion and the occurrence or exceedence of effective discharge (2,200 ft^3/s).

Mean channel width measured from the maps ranged from 260 ft (1973) to 415 ft (1967). The channel (mapped from the position of the cut bank and the distribution of vegetation) appeared wider after periods of higher annual peak flows. The channel lengthened between 1939 and 1978, although cutoffs eliminated several miles of channel. Variable rates of lengthening in the reach reflect the degree of bedrock control in the valley and local variations in valley slope.

Optimum values of channel sinuosity for a given valley slope were identified from the range of sinuosities for each reach during the 40-yr period covered by the maps. Meander-bend cutoffs occurred naturally in those reaches where channel sinuosity had exceeded the optimum value. These data from the Powder River verify the concept of thresholds of channel-pattern stability demonstrated experimentally.

INTRODUCTION

Statement of the Problem

Changes in river channel width, depth, bank retreat, point-bar growth, scour and fill, aggradation and degradation can be measured at discrete sites by repetitive surveys of channel cross sections. The survey data provide the basis for quantifying changes and rates of change in channel dimensions, but these rates cannot necessarily be extrapolated in time or be applied to long sections of channel.

Detailed measurements of changes over a prolonged period of time can be obtained from old discharge-measurement notes, or bridge or reservoir surveys, but these are not available for most river reaches. When few previous measurements are available, channel changes may be described from old maps, aerial photographs, and narrative accounts. Comparing recent photographs to previous photographs or to old maps may reveal channel-pattern changes, meander-bend development and cutoffs, significant widening or narrowing of the channel, and the relative activity of reaches.

When aerial photographs of suitable quality are available, changes and rates of change may be measured. If records of precipitation, water, or sediment discharge coincide with the period of photographic coverage or cross-section measurements, the magnitude and frequency of flows associated with the channel changes can be identified.

The objectives of this study were to measure planimetric changes in channel dimensions and pattern of the Powder River between Moorhead and Broadus, Montana using historic channel maps and aerial photographs, to identify reaches that are most susceptible to change, to interpret the patterns of this change relative to the available water-discharge and sediment-discharge data, and to test the threshold concept of channel-pattern stability previously demonstrated experimentally (Schumm and Khan, 1972).

Suitability of the Powder River for Studies of Channel Processes

Six sets of aerial photographs taken periodically since 1938 form a data base for measuring planimetric changes of channel characteristics for a 65-to-70-mi reach of the Powder River in southeastern Montana. More than 40 yr (years) of concurrent daily flow data and about 4 yr of daily sediment-load data (1975 to 1978) provide the hydrologic data needed to reconstruct the pattern of discharge for each period between photographic coverage. The relation between measured channel change and the magnitude and frequency of water and sediment discharge can, therefore, be examined.

Data from the Powder River are ideally suited to studies of natural channel processes because there are no large diversions or reservoirs, only a fraction of the valley bottom bordering the channel is irrigated, and land use (primarily grazing and alfalfa production) has changed little during the past 40 yr. Therefore, flow of water through the channel is virtually unregulated. Although the Powder River basin is least developed of the smaller basins of the Yellowstone River system, it is an area with significant potential for future development. The recent coal-resources assessment within the basin indicates the water resources soon may be used or augmented for energy development (Keefer and Schmidt, 1973). Thus, data for the Powder River can be used to assess and monitor the impact of changes caused by energy development in water and sediment loads in the channel.

Previous channel locations and configurations have been mapped for the 120-mi reach between Moorhead and Powderville, Montana (Martinson and Meade, 1983), but measurements of channel change have been restricted in this report to the 65-to-70-mi reach between Moorhead and Broadus (fig. 1) for several reasons. No major tributaries enter the Powder River between Moorhead and Broadus; thus the morphometric and hydrologic analyses are limited to a single data base affected by similar water and sediment loads. Furthermore, historical photographic coverage is more complete for the reach between Moorhead and Broadus than for the reach between Broadus and Powderville. In addition, streamflow-gaging stations at Moorhead and Broadus provide a record of the movement of water and sediment through the study reach. The Moorhead gaging station at the upstream end of the study reach has been operated almost continuously since 1928. Consequently, the record of daily mean discharge and peak flows available from U. S. Geological Survey files includes the period of photographic coverage. The gaging station at Broadus has been operated since 1975. Suspended-sediment samples have been collected daily at both stations since 1975. Finally, the reach between Moorhead and Broadus contains 20 channel cross sections that have been resurveyed every year or two since 1975 to show short term changes in the channel resulting from flows between surveys. These survey measurements also provide empirical data with which to evaluate the accuracy of measurements made from aerial photographs.

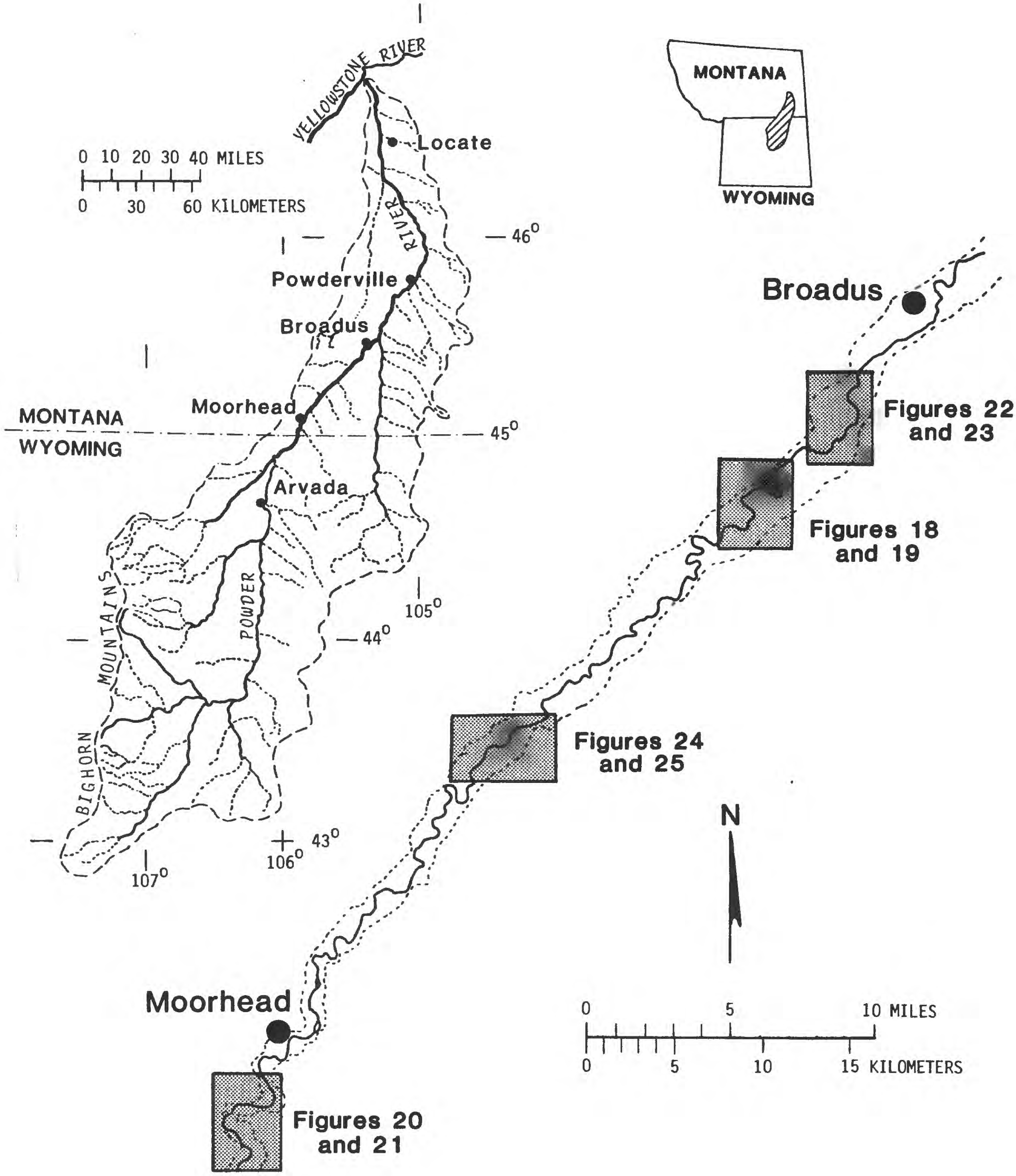

FIGURE 1.--Location of Powder River drainage basin in Montana and Wyoming, the study reach, and the locations of figures 18-25 within the study reach.

Approach

The objectives outlined above were achieved by: (1) Preparing maps at a common scale from all photographs using a photogrammetric stereoplotter; (2) mapping the channel on the basis of geomorphic or hydrologically significant criteria rather than by instantaneous discharge (water surface) at the time photographs were taken; (3) constructing maps using scale-stable materials and base maps for horizontal control; (4) defining geomorphically significant discharges for the study reach; (5) correlating magnitude and rate of channel changes measured from the maps to daily mean and peak flow and sediment discharge data for the study reach; (6) identifying channel reaches that have changed the most (by meander-bend development or cutoffs) from the maps; and (7) testing for thresholds of channel-pattern stability using valley-slope and channel-sinuosity measurements from the maps.

Acknowledgments

R.H. Meade supervised this investigation from inception to completion. In its final form, this paper bears the imprint of both his fertilizing and pruning efforts. S.A. Schumm, W.W. Emmett and C.F. Nordin provided suggestions, criticisms, encouragement and technical review. J. L. Derick, H. K. Fuller, and P. L. Wilber spent many hours orienting stereographic pairs of photographs to base-map control points so that channels could be mapped from aerial photographs.

POWDER RIVER STUDY AREA

Geographic Setting

The Powder River, tributary to the Yellowstone River, originates on the eastern flanks of the Bighorn Mountains of Wyoming and flows about 500 mi northeast before joining with the Yellowstone River downstream from Locate, Montana (fig. 1). Although most of the basin lies within the Great Plains physiographic province, the 13,400 mi^2 drainage encompasses terrain ranging from the rugged mountains of the headwaters to semiarid plains. The headwaters are underlain by Precambrian crystalline rocks and Paleozoic sandstones and limestones that are relatively resistant to erosion. Sedimentary rocks of Mesozoic and younger age dominate the near-surface geology of the drainage basin and are the primary source of sediment to the Powder River.

Annual precipitation varies from less than 15 in. on the plains to more than 30 in. at some mountain localities, and therefore, depending on location, average annual runoff varies from less than 1 in. to more than 15 in. Most of the runoff and the peak discharges occur between May and July during a typical year. Occasionally, an early thaw or rain on snowpack results in an earlier peak flow. The distribution of precipitation and runoff is governed primarily by altitude and topography. Previous investigation (Hembree and others, 1952) shows that most of the discharge, but very little of the sediment load, originates in the mountains. Hembree and others (1952) give a detailed description of drainage-basin characteristics, sedimentation, and the chemical quality of streamflow.

Map Coverage

The earliest maps that depict the Powder River (excluding those produced during early explorations and military campaigns through the area) are the cadastral-survey maps completed between 1890 and 1911. The channel was transferred from the cadastral-survey maps to a 1:24,000 scale base map and portrayed with the other historic channels. Because the cadastral-survey maps show only the approximate location, pattern, and width of the Powder River circa 1900, they were not used in the measurements of bank erosion and channel change.

Topographic maps of the Powder River published during 1944 and between 1969 and 1973 were not used in the present study because scale instability of the paper prevented the scaling of accurate distances from the maps; furthermore, channels portrayed on these maps were defined using criteria inconsistent with those used for this study, in which mapped channels were adjusted to bankfull stage to normalize flow conditions for comparative measurements. These earlier topographic maps depict the channels as a function of stage at the time photographs used to prepare the maps were taken; edges of the mapped channel commonly were determined by the edges of water, rather than by morphologic features of the channel such as banklines. No information was lost by excluding previously published topographic maps because photography was available to remap the channel for 1944 and 1973 using the criteria of this study.

Photographic Coverage

Since 1939, eight configurations of parts of the Powder River have been documented through aerial photography. Six of these sets of photographs were used to construct historic-channel maps of the Powder River. Source, dates flown, scale, and coverage of the photographs are summarized in table 1. Several criteria were used to select those sets of photographs from which maps could be constructed for this study. Photographs had to show features clearly and be suitable for stereographic viewing, consisting of stereographic pairs with at least 60 percent overlapping coverage taken along approximately parallel, overlapping flight lines. Furthermore, regardless of scale, photographs had to be 9-in. prints with fiducial marks for orienting stereographic pairs on a stereoplotter. Finally, time between photographs had to be sufficiently long that the channel configuration had an opportunity to change discernibly.

In the analysis, each set of photographs was treated as a single data base in time. If two sets of photographs were taken at about the same time, the set photographed during the shorter period was used.

Table 1.--Summary of aerial-photograph source data

Year	Dates flown	Approximate scale	Source	Coverage
1939	5/27/38-6/28/39	1:20,000	USFS[1]	Moorhead to Broadus.
1944	7/28/44-10/8/44	1:40,000	Aero Service[2]	Moorhead to Powderville.
1954	8/27/54-9/26/54	1:20,000	ASCS[3]	Do.
1967	6/21/67-8/15/67	1:20,000	ASCS	Do.
1973	7/4/73-7/5/73	1:24,000	Intrasearch[4]	Moorhead to Broadus.
1978	7/26/78	1:40,000	ASCS	Moorhead to Powderville.

[1]U.S. Department of Agriculture, Forest Service, Division of Engineering, Fort Missoula, Mont.
[2]Western Geophysical Co. of America, Aero Service Division, Houston, Tex.
[3]U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service, Aerial Photography Field Office, Salt Lake City, Utah.
[4]Intrasearch, Inc., Denver, Colo.

CONSTRUCTING CHANNEL MAPS FROM AERIAL PHOTOGRAPHS

Previous Approaches to the Study of Historic-Channel Changes

With historical photography and maps, the criteria used to define channels and channel movement or change, and the techniques used to map channels and measure channel changes have varied. Brice (1973) projected aerial photographs onto earlier aerial photographs and compared channel centerline positions in order to map the development of meander patterns and erosion in meander bends for the White River in Indiana. Similarly, he studied rates and processes of lateral erosion for the Middle Sacramento River in California between Chico Landing and Colusa (Brice, 1979). Lewin (1977) and Lewin and Hughes (1976) have mapped channels from aerial photographs to monitor cutbank development and channel shift for Welsh Rivers. Their measurements were based on channels mapped from the cutbank on one side to the edge of water on the other side. Only the cutbank side of the channel was used to assess channel shift. Changes in channel area for "moderately low-flow conditions" of the Missouri River in Iowa were quantitatively documented by Hallberg and others (1979). Noninterpretive atlases of historic-channel locations recently have been compiled from maps and aerial photographs of the White River in the eastern Uinta Basin in Utah and Colorado (Jurado and Fields, 1978) and the Kansas River in eastern Kansas (Dort and others, 1979).

Earlier investigations of channel morphology and channel shift from historic maps and aerial photographs commonly have documented rather than precisely quantified channel changes. These previous studies that mapped and compared historic channels generally have used simple projection methods to map channels from aerial photographs. Generally, no attempt has been made to consider the effects of differences of river stage on channel morphology.

Criteria for Mapping the Channel

The channel mapped from the aerial photographs was defined by the positions of the banklines, rather than by the left and right edges of water. Daily mean discharge corresponding to the days on which aerial photographs of the channel were taken ranged from 1.4 to 3,430 ft^3/s (measured at the Moorhead gage). Therefore, the channel locations mapped as the edges of water for the different times would not be comparable to each other, because they represent different stages of the river. To minimize the extent to which measurements of the channel reflected a difference in stage rather than actual changes in channel dimensions or location, configurations of the channel were mapped for a comparable stage. Channels were mapped for bankfull stage, because bankfull discharge is a flow of hydrologic and geomorphic significance, and bankfull stage may be recognized on the basis of topographic and vegetational criteria.

Although the method is subjective, previous investigators have used the distribution of vegetation to locate banktops both in the field (Schumm, 1960; Sigafoos, 1964; Emmett, 1975) and from maps or photographs (Hallberg and others, 1979). Surfaces lower than the floodplain usually have little or no vegetation (Emmett, 1975; Williams, 1978). For the point-bar side of an active reach, the bankline was mapped where vegetation began to dominate the ground surface, or at the riverward limit of established vegetation. Primary drawbacks to defining bankfull stage by the distribution of vegetation include: (1) Patchy distribution of vegetation and sediment on point bars, (2) a possibility that the limit of vegetation may fluctuate landward or riverward on point bars, and (3) difficulty in distinguishing some perennial riparian species from herbaceous annuals that populate point bars and mid-channel bars during low flow. For changing reaches, the cutbank was used as the position of the bankfull channel on the outsides of the bends. For relatively stable reaches, the tops of the banks usually were identified by both a recognizable break in slope and a change in the distribution of vegetation.

Similarly, islands were distinguished from bars primarily on the basis of type of vegetation. Regular inundation of mid-channel bars and movement of sediment across their surfaces presumably would prevent the establishment of significant vegetation.

Map Construction

A map of the bankfull channel was constructed from each set of aerial photographs on an overlay to the corresponding 1:24,000 topographic base. Maps were constructed using a stereoplotter, which enabled accurate transfer of data from photographs to maps. Advantages in using this instrument include (1) direct viewing of the stereographic pair and clear optical resolution of the photographs permits identification and location of corresponding points on the photographs and base maps; and (2) the stereoplotter removes parallax errors and corrects mechanically for scale changes and displacement due to topography.

All base maps and overlays were constructed on mylar for scale stability to improve the accuracy for comparative measurements. Maps of the Powder River channel between 1939 and 1978 that provide the data base for this report are contained in a report by Martinson and Meade (1983). Representative reaches of channel from these maps have been reproduced to accompany the discussion of channel changes later in this report.

Measurements from the Maps

Channel area, island area, and channel length were measured from each channel map with a planimetric digitizer that was connected to a desk-top calculator. The calculator detects closure and computes areas or lengths from digitized data relayed from the cursor. Each area or length was measured at least twice with the cursor and the average value computed. Adjusted channel area was determined by subtracting total area of the islands from the total area measured between banks. Adjusted mean channel width was computed by dividing the adjusted channel area by the channel centerline length. Channel sinuosity was determined by dividing channel centerline length by the valley length measured between topographic contours on the base map. These data are summarized in table 2.

Chronologically consecutive maps of the historic channels were overlain, and areas of bank erosion were measured with the planimeter. Small areas eroded from discrete sites were summed together to measure total bank erosion from the study reach for each pair of maps. Average bank erosion per unit length of channel, for each pair of maps, was computed by dividing the total area eroded by the channel length of the earlier of the two maps.

Table 2.--Summary of historic-channel characteristics measured from maps, Powder River between Moorhead and Broadus, Montana, 1939 to 1978

Year of photo-graph	Channel area (square miles)	Channel length (miles)	Mean Channel width (feet)	Island area (square miles)	Adjusted area (square miles)	Adjusted mean width (feet)	Sinu-osity[1]
1939	5.065	65.444	408	0.452	4.613	372	1.40
1944	5.044	65.872	404	.575	4.469	358	1.41
1954	3.745	67.271	294	.416	3.329	261	1.44
1967	5.399	68.647	415	.437	4.962	382	1.47
1973	3.494	69.866	264	.139	3.355	253	1.50
1978	4.245	68.427	328	.192	4.053	313	1.47

[1]Sinuosity is the ratio of channel length to valley length. Valley length between Moorhead and Broadus is about 46.7 miles.

Accuracy of the Measurements

Ideally, each map represents the exact bankfull configuration at the moment the channel was photographed. However, error can be introduced during almost every step of the mapping process. Therefore, possible sources of error and their impact on measurements from the maps need to be evaluated.

The largest and most variable error may be the result of orientation of the stereographic photographs and scaling of the stereographic model. The national map-accuracy standards of the U.S. Geological Survey specify that for 7.5-minute maps, the maximum permissible horizontal error for 90 percent of the points checked is 1/52 in., corresponding to 40-ft distance at map scale. Should points selected for control be located imprecisely and the stereographic model oriented to the framework of those points, significant error could be introduced. Inexact orientation of the base map with respect to the photographs also would result in displacement of the mapped channel.

Other possible sources of error inherent in the method of map construction can be identified. At a scale of 1:24,000, a line drawn with a sharpened pencil point is about 5 to 10 feet wide, thus precluding exact measurements by that width. The digitizer used to measure areas and distances from the map is accurate to only the nearest 1/52 in., or about 40 ft at the scale of the maps. Unsteadiness of hand on the part of the illustrator may introduce some variable amount of wobble in the bankline during map construction. For discrete reaches, definition of a bankline using vegetational or topographic criteria may be difficult.

Many of these inadvertent inaccuracies introduced during mapping of the channel were random and assumed to be compensating. Displacement of the mapped channel due to thickness of the pencil point and illustrator were considered to be unbiased, occurring as much to one side of the actual bankline as to the other. The subjective element in mapping a bankline also was assumed to introduce only minor errors into the measurements. Usually, the cutbanks in areas of active channel, or the flood-plain vegetation in straight reaches, define a discrete bankline. Only on point bars, where distribution of vegetation and fluvial sediment is patchy rather than areal, was delineation of the bankline interpretive. It was assumed that, for a set of maps, if the position of the bank were incorrectly located on point bars, the errors were as many times landward as riverward. Therefore, the sum error in planimetric measurements of width and length due to difficulties in defining the bank around point bars should be negligible. Furthermore, the effect of this error on measured bank erosion should also be minimal, because measurable bank erosion occurred mostly along the cutbank, not the point-bar bank.

Only errors in model orientation were assumed to be noncompensating or nonrandom. Displacement of the mapped channel due to orientation of the stereographic model or inexact orientation of the base map would not significantly affect measured widths or lengths on a single map. However, when maps were overlain to measure bank erosion for periods between photographs, displacement of the channel would always result in an overestimate of the actual area of erosion (fig. 2). The degree of overestimation was determined from the following experiment, which was designed to evaluate the reproducibility of maps constructed for this study.

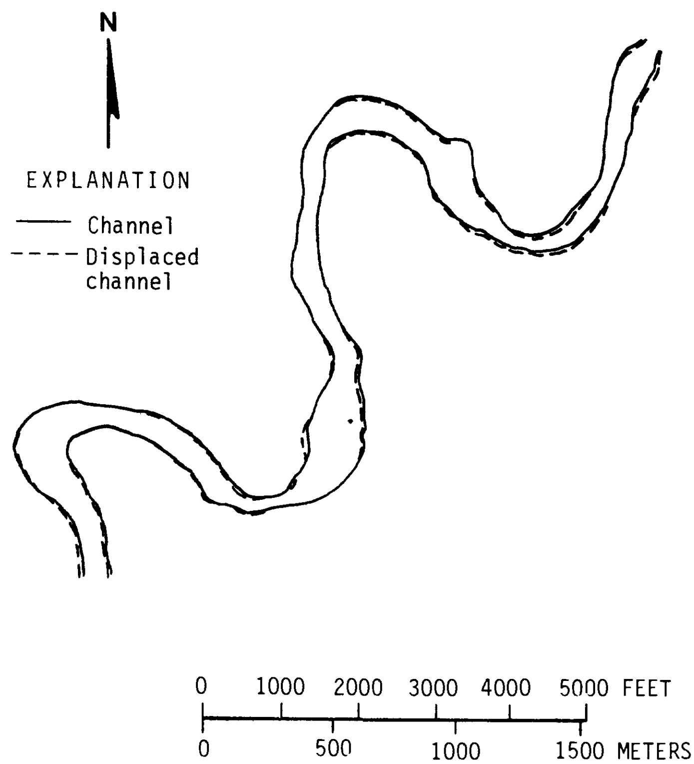

FIGURE 2.--Schematic illustration for a reach of the Powder River downstream from Moorhead, Montana, showing the mapped channel and apparent channel shift caused by slight displacement of the mapped channel, resulting in overestimation of bank erosion.

Reproducibility of the Maps

The maps constructed for this study were evaluated by how accurately maps constructed with the plotter could be reproduced. Reproducibility of the maps was tested by constructing duplicate maps for a reach of the Powder River several miles in length near Moorhead. This reach was selected because it was representative of a range of river environments (straight and meandering, and shifting and stationary), and the reach could be mapped from only a few stereographic pairs from each set of photographs. A series of maps of the channel, set A, was prepared from 1939, 1944, 1954, 1967, and 1978 photographs and a second series of maps, set B, was prepared using the same photographs that were used to make the initial maps (set A). The mapping techniques were the same as those already described.

The magnitude of apparent channel shift was evaluated by measuring only the area of "apparent erosion" from each pair of duplicate maps. To test the reproducibility of the maps, maps of set A were overlain on those of set B and apparent erosion was measured. If the maps were absolutely reproducible, bankfull channels of set A would coincide with those of set B. Set B maps then were overlain on set A maps and apparent erosion measured. When the maps were compared, erosion was always overestimated. This method defines the smallest area of erosion measurable using the techniques and mapping scale of this study. When chronologically consecutive maps were overlain, measured erosion that averaged 0.0041 mi^2 or less per mile of channel exceeded the limits of accuracy of the equipment and the measuring techniques.

Overestimation appeared to be independent of age or scale of the photography. Therefore, the measured value of erosion for the entire study reach for each set of historically consecutive channels was adjusted by 0.0041 mi^2 per mile of channel. The adjusted values for total erosion are summarized in table 3.

Table 3.--Summary of channel changes, Powder River between Moorhead and Broadus, Montana, 1939 to 1978

Variable	Time intervals				
	1939-44	1944-54	1954-67	1967-73	1973-78
Change in area (square miles)	-0.020	-1.300	+1.654	-1.904	+0.751
Change in length (miles)	.428	1.399	1.376	1.219	-1.439
Change in mean width (feet)	-4	-110	+121	-151	+64
Change in adjusted mean width (feet)	-14	-97	+121	-129	+60
Change in island area (square miles)	+.123	-.159	+.021	-.298	+.053
Bank erosion (square miles)	.520	.146	1.804	.007	.592
Point bar deposition (square miles)	.539	1.446	.150	1.915	-.163
Number of cutoffs	1	6	4	1	3

RELATION OF BANK EROSION TO DISCHARGE

Water-Discharge and Sediment-Discharge Data

Gaging stations at Moorhead and Broadus, Montana (fig. 1) provide a record of daily mean discharge, peak flow, and sediment load through the study reach. The Moorhead station was established during water year 1928 and was operated continuously until water year 1973. Records of daily sediment loads began during water years 1975 and 1976, when discharge measurement was resumed at Moorhead and begun at Broadus. Thus, there are 49 yr of daily mean-discharge and peak-flow data and about 5 yr of daily sediment-discharge and sediment-concentration data for the study reach.

Except for water years 1973 and 1974, which were years of about average flow as measured at the Arvada gaging station (about 50 mi upstream from Moorhead, fig.1), there is a record of daily mean and peak discharge for the time delimited by the aerial photographs. To reconstruct the missing record, a regression relation between daily mean discharge at the Moorhead gaging station and the Arvada gaging station was determined for 45 yr of contemporaneous record. The regression relation was used to synthesize peak flows and daily mean flows at Moorhead for water years 1973 and 1974 from the Arvada record. The synthesized values were included in order to complete the record of flow for the period delimited by the photography.

Annual discharge for the period of record has ranged from 3.4×10^9 ft^3 (78,053 acre-ft) during water year 1961 to 3.44×10^{10} ft^3 (789,715 acre-ft) during water year 1978 (fig. 3). Instantaneous peak flows for the same period have ranged from 1,320 ft^3/s during water year 1961 to 33,000 ft^3/s during water year 1978 (fig. 4). Periods of greater than average annual flows were recorded for water years 1943-48 and 1962-67. A prolonged period of lesser than average annual flows was recorded for water years 1949-61 (fig. 3). Comparison of figures 3 and 4 shows that many of the years of greater than average annual flow also were years of greatest peak flows.

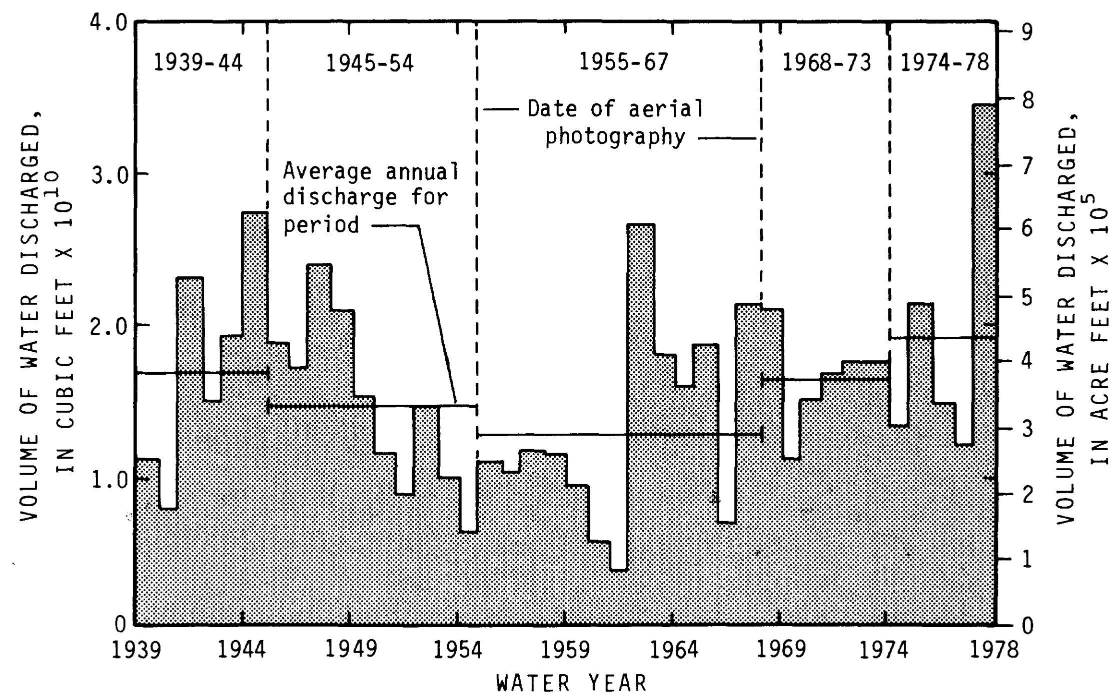

FIGURE 3.--Annual discharge, Powder River at Moorhead, Montana, water years 1939-78.

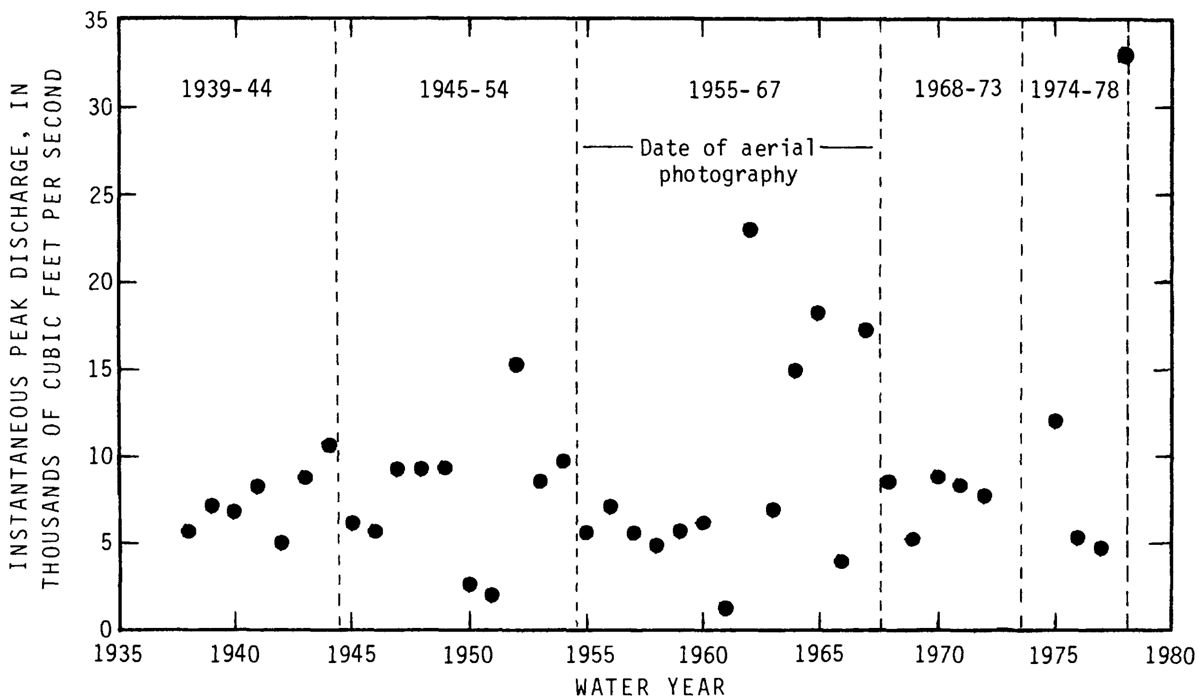

FIGURE 4.--Annual peak flows, Powder River at Moorhead, Montana, water years 1939-78.

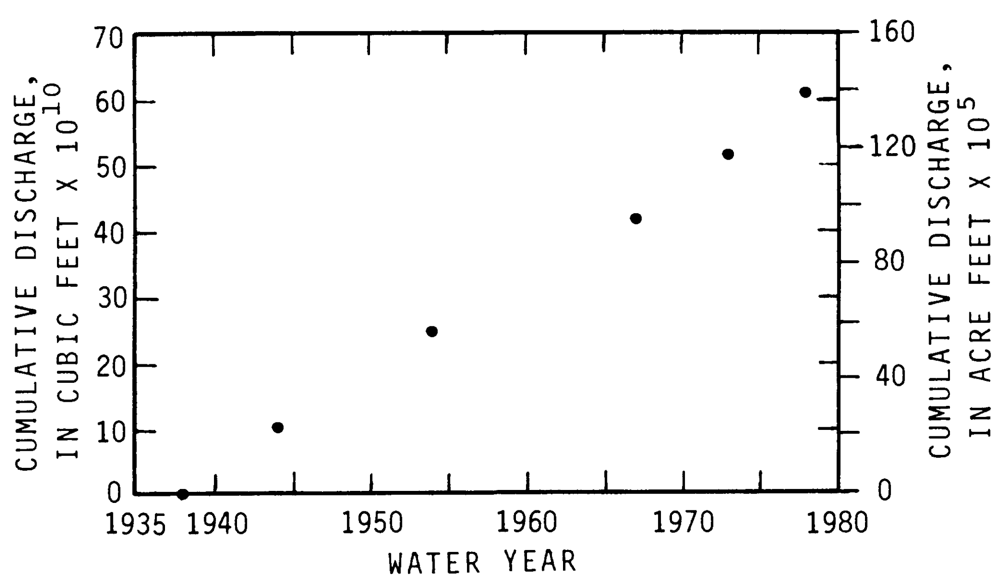

FIGURE 5.--Cumulative discharge, Powder River at Moorhead, Montana, 1938-78.

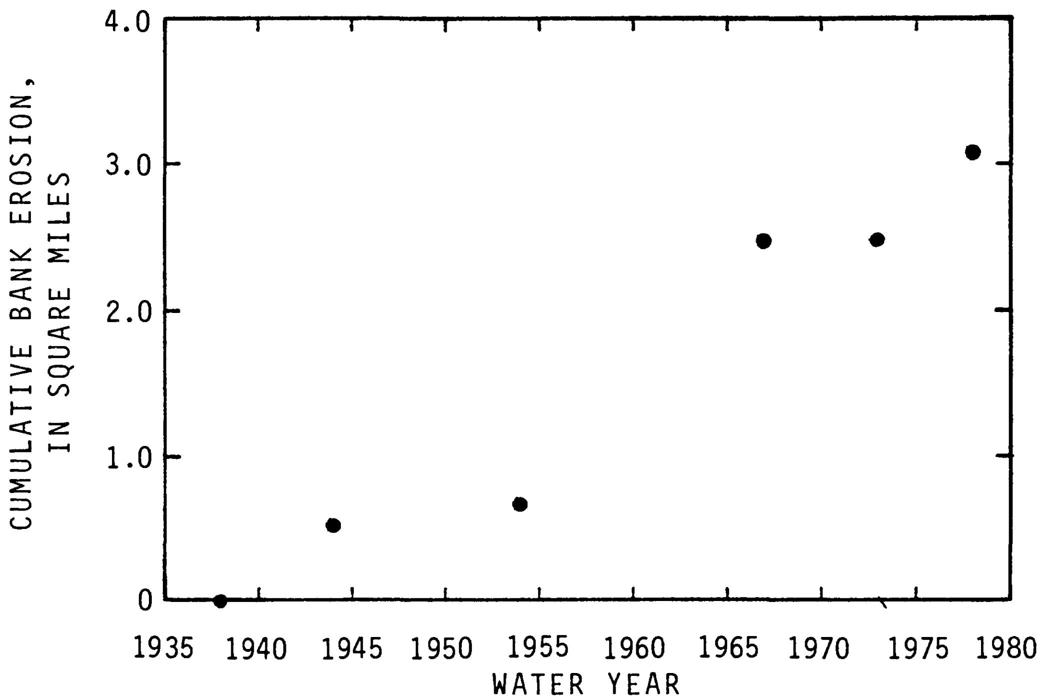

FIGURE 6.--Cumulative bank erosion, Powder River between Moorhead and Broadus, Montana, 1938-78.

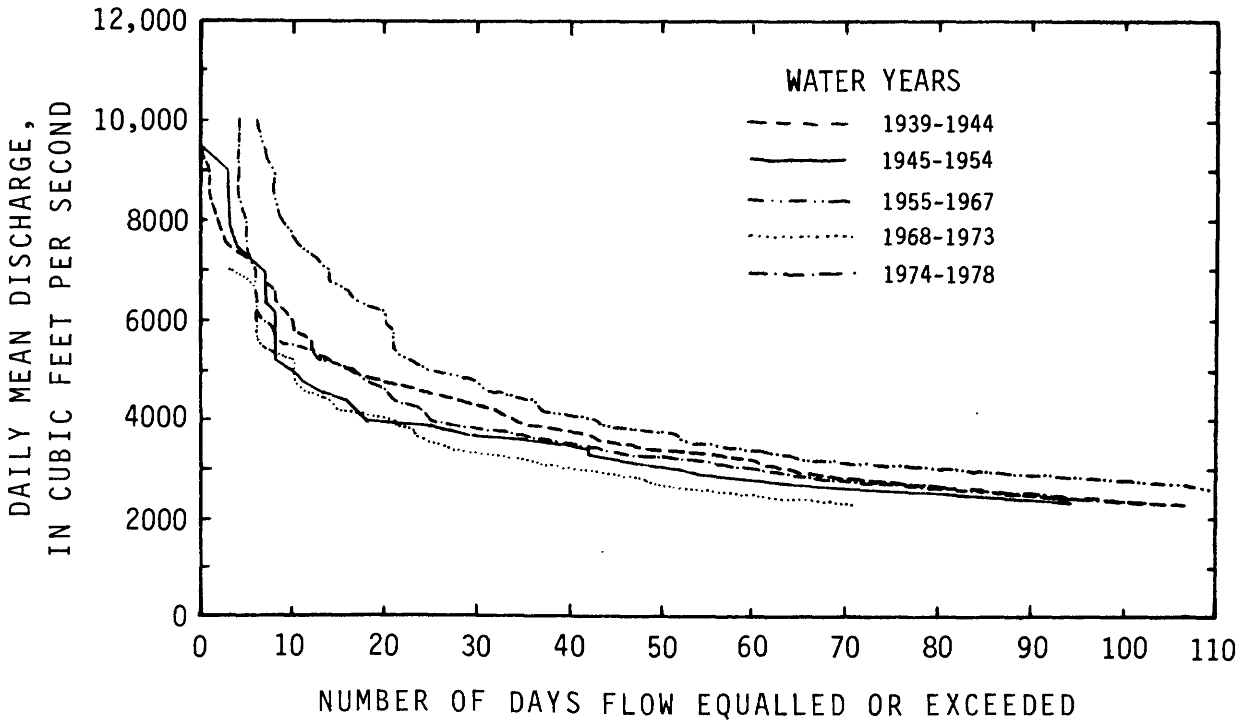

FIGURE 7.--Duration curves for time intervals delimited by aerial photographs, Powder River at Moorhead, Montana.

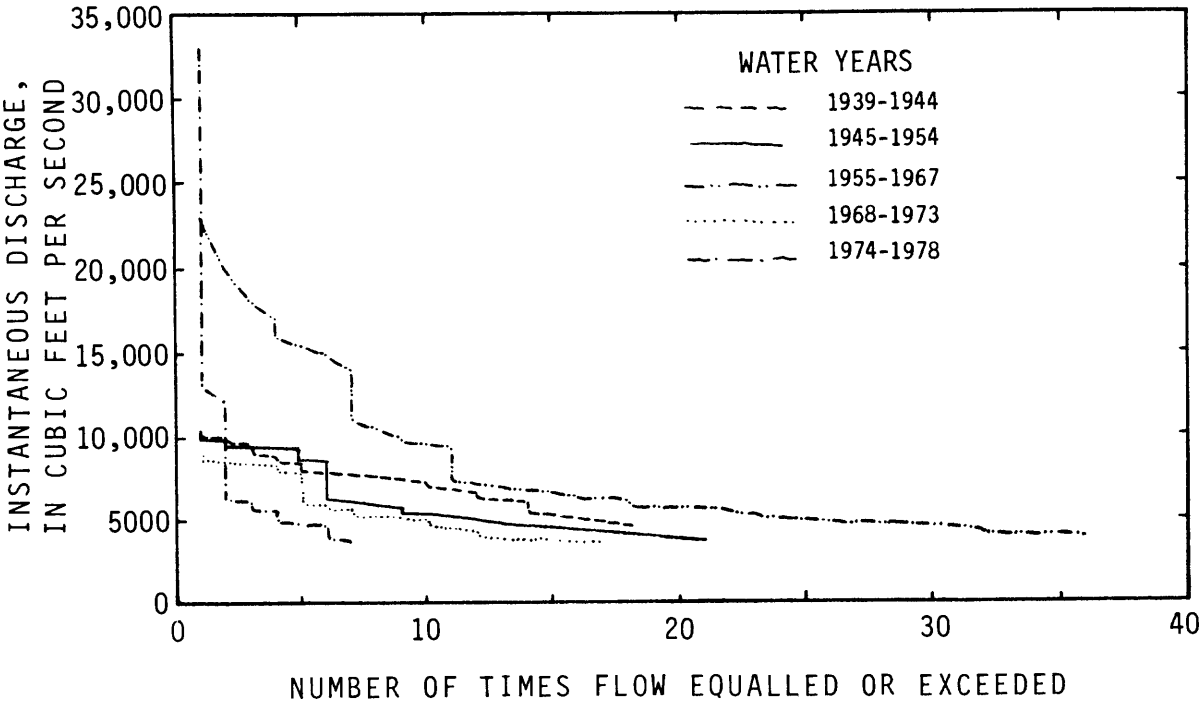

FIGURE 8.--Frequency curves of peak discharges for time intervals delimited by aerial photographs, Powder River at Moorhead, Montana.

Analysis of Discharge Data

The immediate effect on the channel of periods of greater or lesser than average flow cannot be assessed, because the aerial photography does not coincide with the beginnings or ends of these periods. Figures 3 and 4 show that each period delimited by aerial photographs had years in which the total- annual and instantaneous-peak flows were greater and lesser than average. The total amount of water discharged through time has been fairly constant (averaged for 5 to 13 years) as indicated by a plot of cumulative discharge for the five periods (fig. 5).

The magnitude and number of higher flows have varied for the five periods, as has bank erosion (fig. 6). Daily mean-discharge and peak-flow records for the Moorhead station were used to determine whether a relation exists between discharge and the extent of bank erosion for each period delimited by aerial photographs. The range of values for discharges between water years 1939 and 1978 at Moorhead was arbitrarily divided into classes by increments of 100 or 1,000 ft^3/s (by 100-ft^3/s increments for the lesser but more frequently occurring discharges, by 1000-ft^3/s increments for the greater, but less frequently occurring discharges). For the time intervals between aerial photographs, the number of days that mean flow and the number of times that peak flow occurred in each class was tabulated. The number of days that mean flow or times that peak flow were within or greater than each discharge increment was tallied.

Each period is distinctive in the number of days and number of times certain discharges, especially the greater discharges, have occurred. The number of days that mean discharge has equaled or exceeded a given discharge for each interval between photographs is shown in figure 7. Similarly, the number of times during each interval that certain discharge values have been equaled or exceeded also has varied (fig. 8).

Best fit lines determined by the least-squares technique were computed using standard equations from discharge and bank-erosion data as well as for their log-transformed values for each time interval. The relation between total area of bank erosion for each interval of time delimited by aerial photographs (y) and the following corresponding water and sediment discharges or volumes (x) for the time interval was examined: (1) the number of days that mean discharge was within or greater than a given discharge class, (2) the number of times that daily mean discharge was within or greater than a given discharge class, (3) the number of times that instantaneous peak discharge was within or greater than a given discharge class, and (4) the volume of sediment transported at discharges within or greater than a given discharge class.

Separate relations were examined for "number of days" and "number of times" that discharges equaled or exceeded certain values. The correspondence of bank erosion to the "number of days" that flow equaled or exceeded a given discharge would indicate that the bank erosion effected by a flow may be dependent on the duration as well as the magnitude of flow.

Correlation coefficients (r) for linear, exponential and power function regressions of the data were computed. Computations were based on only five paired data points. Therefore, F values were computed to evaluate sensitivity of the fit (Snedecor and Cochran, 1971, p. 117). Correlation coefficients (r) and F values are summarized in Appendix A at end of report.

Geomorphically Significant Discharges

The best agreement was found between the areal extent of bank erosion and (1) the number of days mean flows equaled or exceeded 5,400 ft^3/s, (2) the number of peak flows greater than 9,900 ft^3/s, and (3) the total volume of sediment discharged on days when mean flow equaled or exceeded 5,600 ft^3/s. Little or no agreement was found between bank erosion and the number of days mean flows were less than 5,400 ft^3/s or number of peak flows less than 9,900 ft^3/s that occurred in a given period. To evaluate the geomorphic significance of these flows (5,400 ft^3/s and 9,400 ft^3/s), they were compared with values of "bankfull", "effective", and "threshold" discharges identified from discharge data and bank erosion measurements for the Powder River. Previous investigators have found other rivers to be adjusted to these discharges, which will be discussed in the following section.

Bankfull Discharge

The discharge that fills the channel to the level of the flood plain is called the "bankfull discharge", and it is assigned special geomorphic significance (Leopold and others, 1964; Emmett, 1975; Pickup, 1976). Sometimes termed the "channel-forming" discharge, bankfull discharge has been measured or estimated by a number of methods. These are summarized and evaluated by Williams (1978).

Bankfull discharge is determined best by measurement of flow at a site when discharge is just to the top of definable banks. Alternatively, rating curves, hydraulic geometry, flow-recurrence frequencies, and flow equations can be used to estimate bankfull discharge. Several of these estimation techniques were used to calculate values for bankfull discharge for the Powder River study reach.

For gaged sites with an adequate water-discharge record, flow-frequency analysis can be used to estimate bankfull discharge. Leopold and others (1964) determined that in a frequency analysis of floods, bankfull discharge usually was the 1.5-year flood. Recurrence intervals for the Powder River study reach were computed from the records of peak flows and daily mean discharges at Moorhead. The peak discharge frequency curve is plotted along with the frequency curve for the annual maximum daily mean flows in figure 9. Bankfull discharge for the Powder River at Moorhead estimated by the 1.5-yr flood is 5,600 ft^3/s (fig. 9); the annual maximum daily mean discharge occurring with that frequency is about 3,200 ft^3/s.

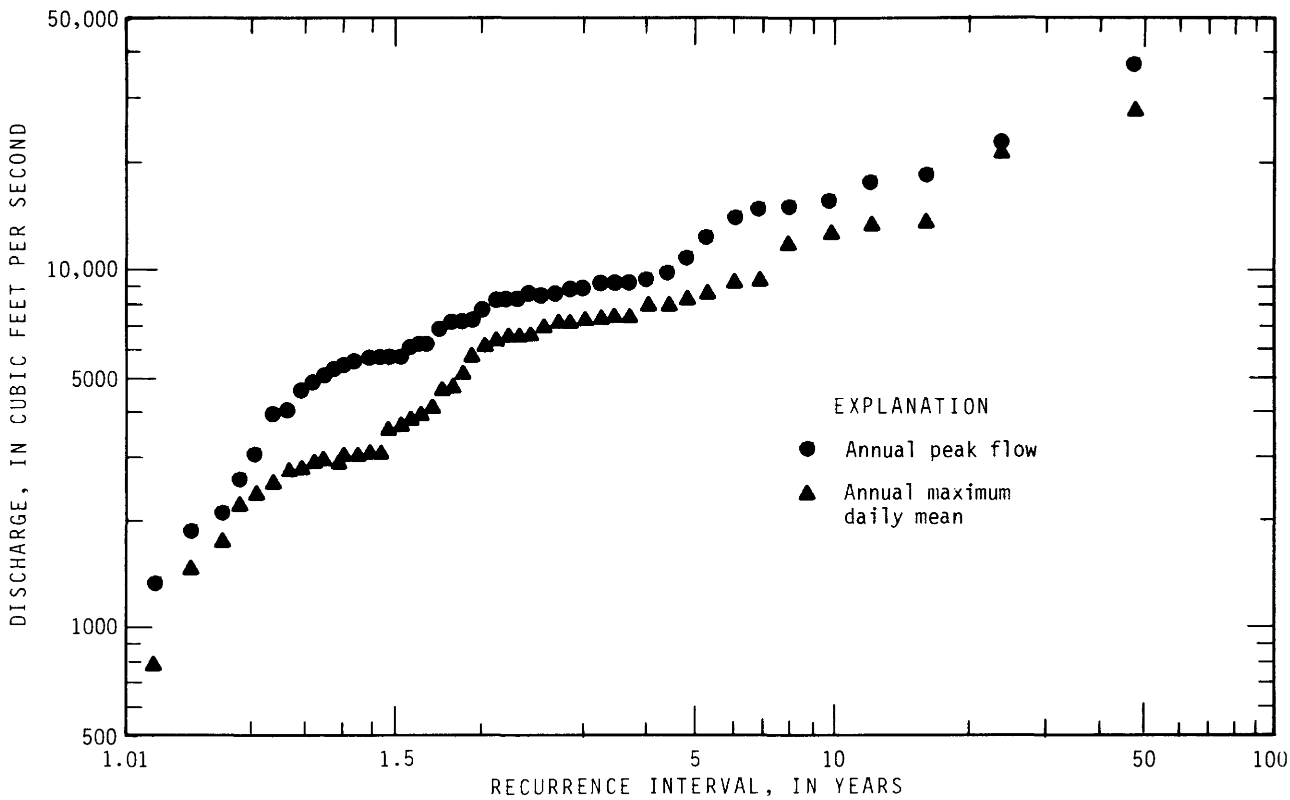

FIGURE 9.--Recurrence intervals for annual peak and annual maximum daily mean flows, Powder River at Moorhead, Montana, 1929-78.

At ungaged sites, flow equations provide estimates of bankfull discharge. The following equation proposed by Williams (1978) was used to approximate bankfull discharge (Q_b):

$$Q_b = 4.0A_b^{1.21}S^{0.28} \quad (1)$$

where A_b = bankfull cross-sectional area, in square meters; and
S = water surface slope.

Discharges were computed using map (approximately bankfull) and onsite (low flow) measurements of water-surface slopes and estimates of bankfull cross-sectional area determined from six of the cross sections surveyed during 1977. Bankfull area was defined in relation to the flood plain from cross-section plots; the flood plain was selected as the surface that was inundated during the 1978 flood (assuming that this highest flow recorded since 1923 at Moorhead would have exceeded the banks). Values for bankfull discharge computed for the measured cross sections between Moorhead and Broadus varied from about 4,500 to 5,900 ft^3/s.

A value of 5,600 ft^3/s was selected to approximate bankfull discharge for the study reach. This value corresponds to the 1.5-yr flood from flood-frequency analysis of the discharge record at Moorhead, and it is within the range of bankfull discharges estimated by the flow equation of Williams (1978).

Analysis of the water-discharge and bank-erosion data discussed earlier showed best agreement between bank erosion and the number of days mean discharge equaled or exceeded 5,600 ft^3/s, the bankfull discharge. Little agreement was found between bank erosion and the number of days mean discharge was less than bankfull. This indicates that bank erosion is measurable or systematic for discharges equal to or greater than bankfull, but not at smaller discharges.

Effective Discharge

In recent studies water-discharge and sediment-discharge records have been analyzed to identify the "effective discharge", the increment of discharge that transports the largest fraction of the total sediment load during a number of years. This computed value usually approximates the measured bankfull discharge or the annual flood determined by other means. Tributaries of the Yampa River in Colorado and Wyoming (Andrews, 1980) and Australian rivers (Pickup, 1976; Pickup and Warner, 1976) appear adjusted to the effective discharge.

Computations of effective discharge generally are based on total sediment load transport or bedload transport. No bedload data were available for the Powder River. Therefore, bedload transported for a range of discharges was computed using the following form of the equation of Meyer-Peter and Mueller (1948) modified by H.H. Stevens, Jr. (U.S. Geological Survey, written commun., 1981). The channel-wide bedload transport rate (I_b) is computed by the following equation:

$$I_b = (2.52\, D_{90}^{\,0.25}\, u^{1.5} S^{0.25} - 0.86 D_m)^{1.5} W \qquad (2)$$

where:

D_{90} = grain diameter of the 90th percentile fraction, in millimeters;
u = mean velocity, in feet per second;
S = water surface slope;
D_m = effective grain diameter, in millimeters; and
W = channel width, in feet

Values for width and velocity were obtained from water-discharge measurements at Broadus; bed-material-size data were obtained from Hembree and others (1952). The mean value of bankfull slope for the reach was determined from maps for the bankfull channel. The relation of computed bedload transport to discharge is plotted in figure 10.

Annually, bedload is about 1.7 percent of the total sediment discharge at Moorhead and Broadus. This varies from more than 10 percent at low discharges to about 1 percent at high discharges. The relation of bedload to total load computed for Moorhead is consistent with that determined for the Powder River at Arvada, Wyoming, by Hembree and others (1952), who found bedload was approximately 4 percent of the total annual load.

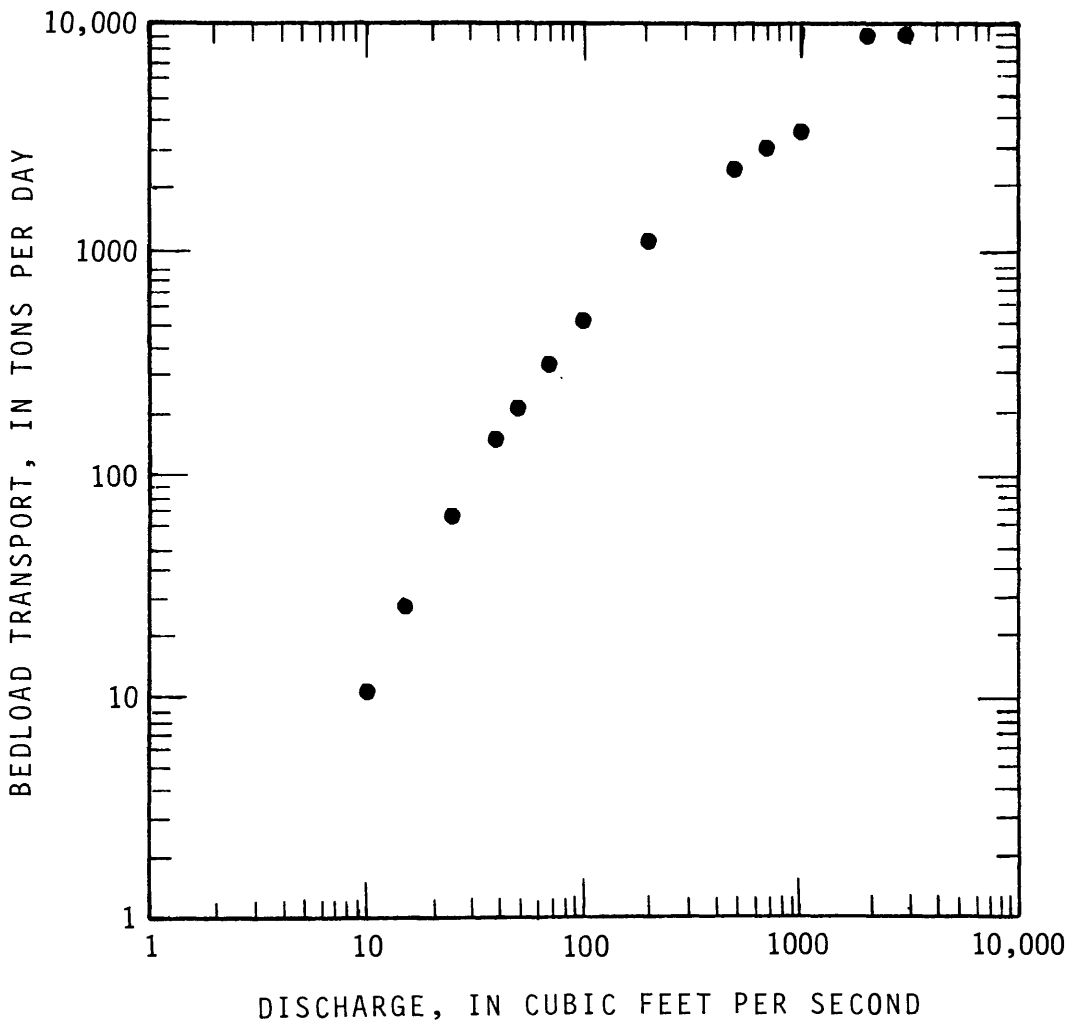

FIGURE 10.--Computed bedload discharge, Powder River at Broadus, Montana.

Effective discharge was computed from the almost 49 yr of daily mean flow records at Moorhead and the 1975-78 daily sediment data at Moorhead and Broadus using the technique summarized by Andrews (1980). Flow frequency was computed for the record of daily mean discharges at Moorhead. The range of discharge was arbitrarily sub-divided into increments of discharge. The number of days of flow in each increment was determined from the flow-duration curve. A suspended-sediment discharge curve (fig. 11) was constructed from the daily suspended-sediment records at Moorhead and Broadus; suspended-sediment transport for the mean discharge for each discharge increment was identified from the curve. Representative daily mean sediment discharge multiplied by the number of days of flow in each class yielded values for suspended-sediment load transported by each increment of discharge.

Suspended-sediment load computed from measured sediment-concentration data and computed estimates of bedload were combined to determine the total load transported by each increment of discharge for the 49 yr of water-discharge records at Moorhead. More sediment is transported at discharges between 1,000 and 3,000 ft^3/s than at any other increment of discharge (fig. 12). Effective discharge is the median value in that range of discharges; more specifically, it is the point of inflection (2,200 ft^3/s) on the plot of cumulative sediment transport (fig. 13).

Pickup and Warner (1976) used a technique to define effective discharge similar to that of Andrews (1980), but based on bedload rather than total-load transport. Effective discharge for the Powder River study reach computed from bedload transport alone (1,200 ft^3/s) is about the same as that computed from total-load data (fig. 13). Because most of the sediment transport in the Powder River occurs in suspension, effective discharge determined from total-load data was assumed to be a better value than one determined from bedload data alone.

There seems to be no relation between total area of bank erosion that occurred during an interval of time and the number of days or number of times that mean discharge for the same interval was equal to or greater than the effective discharge (2,200 ft^3/s). On days on which mean discharge equaled or exceeded effective discharge, either there was no bank erosion, or it was unsystematic or not measureable using photogrammetric techniques.

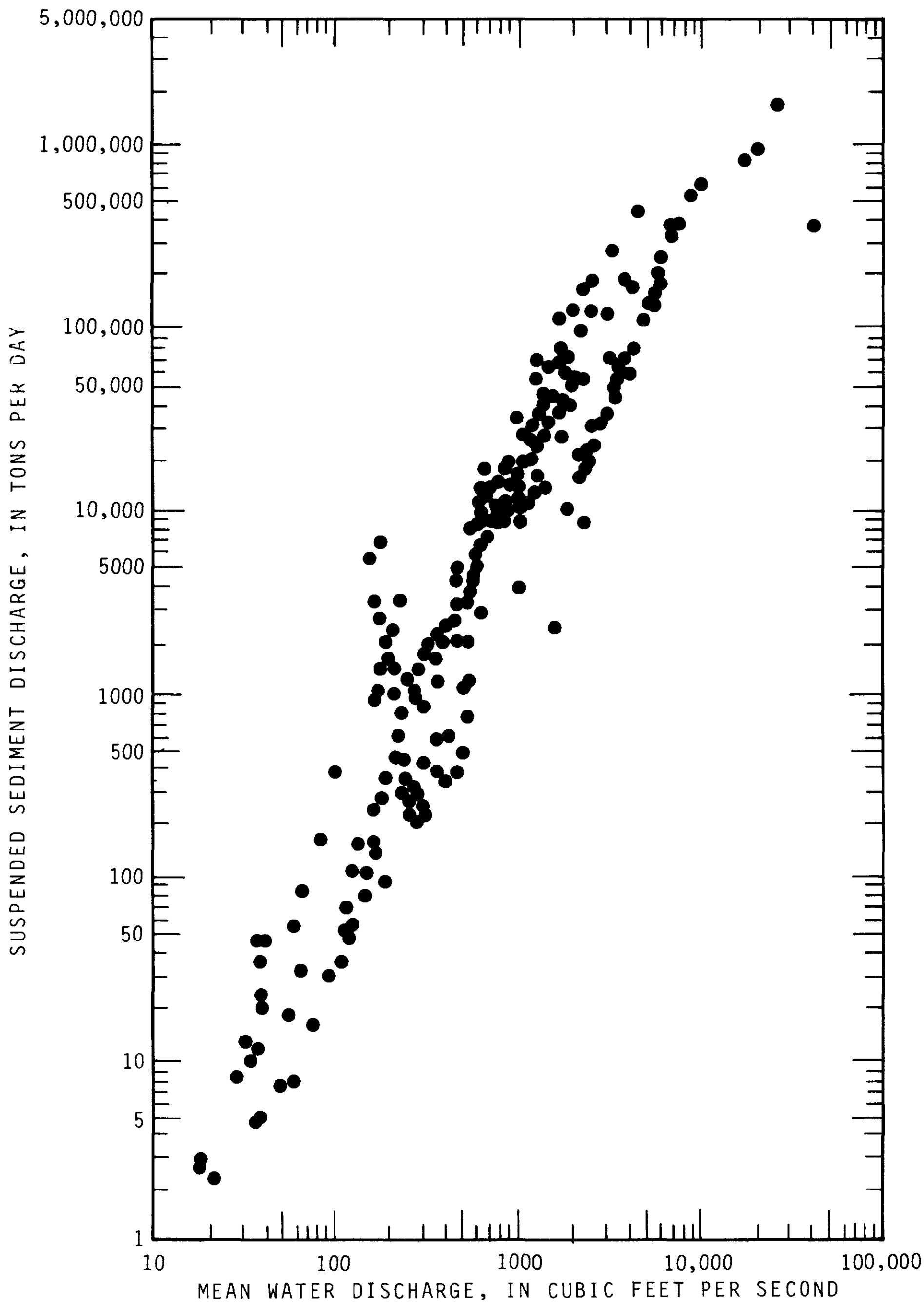

FIGURE 11.--Suspended-sediment discharge as a function of water discharge, Powder River at Moorhead and Broadus, Montana, 1975-78.

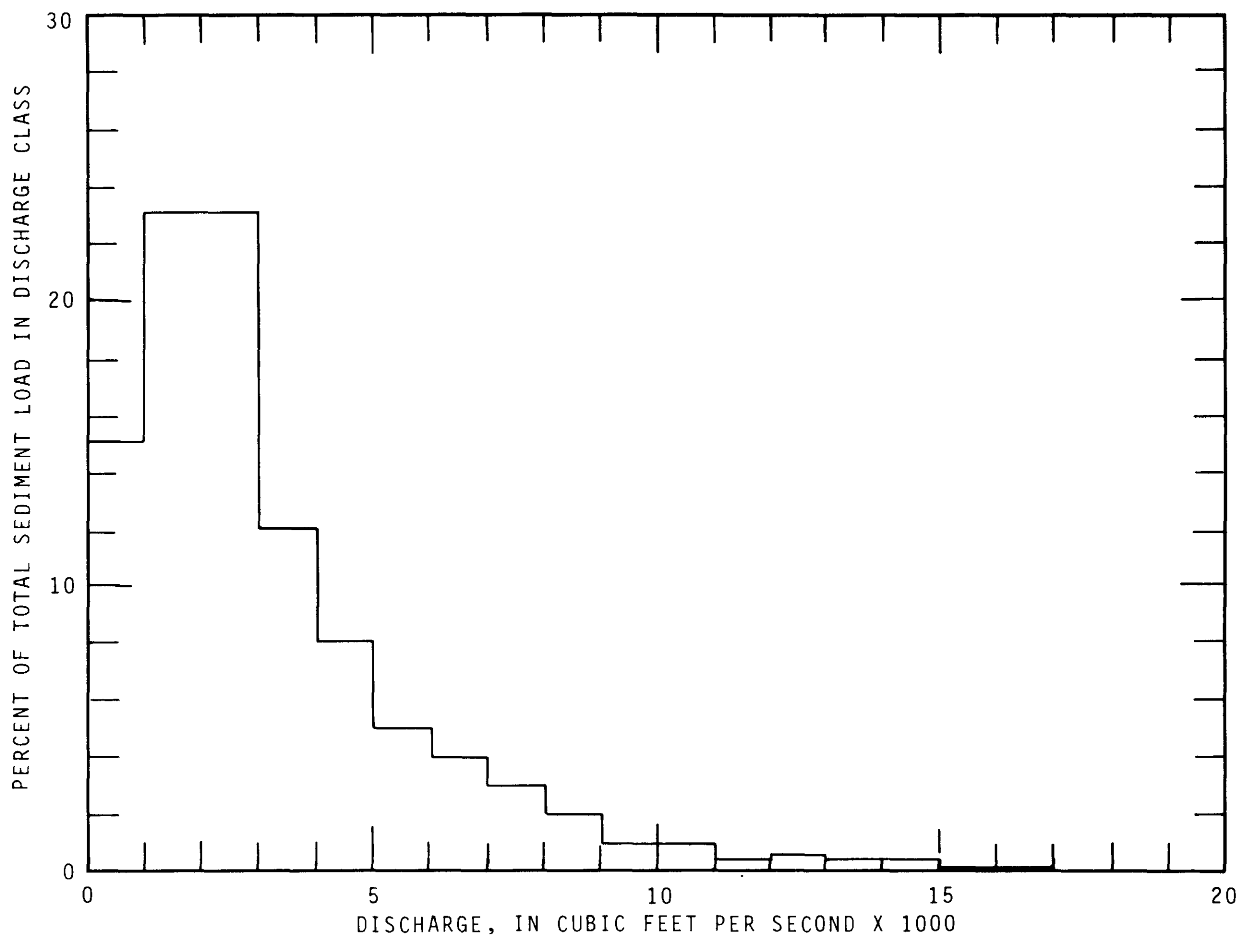

FIGURE 12.--Percentage of total-sediment discharge by discharge class, Powder River at Moorhead and Broadus, Montana, 1975-78.

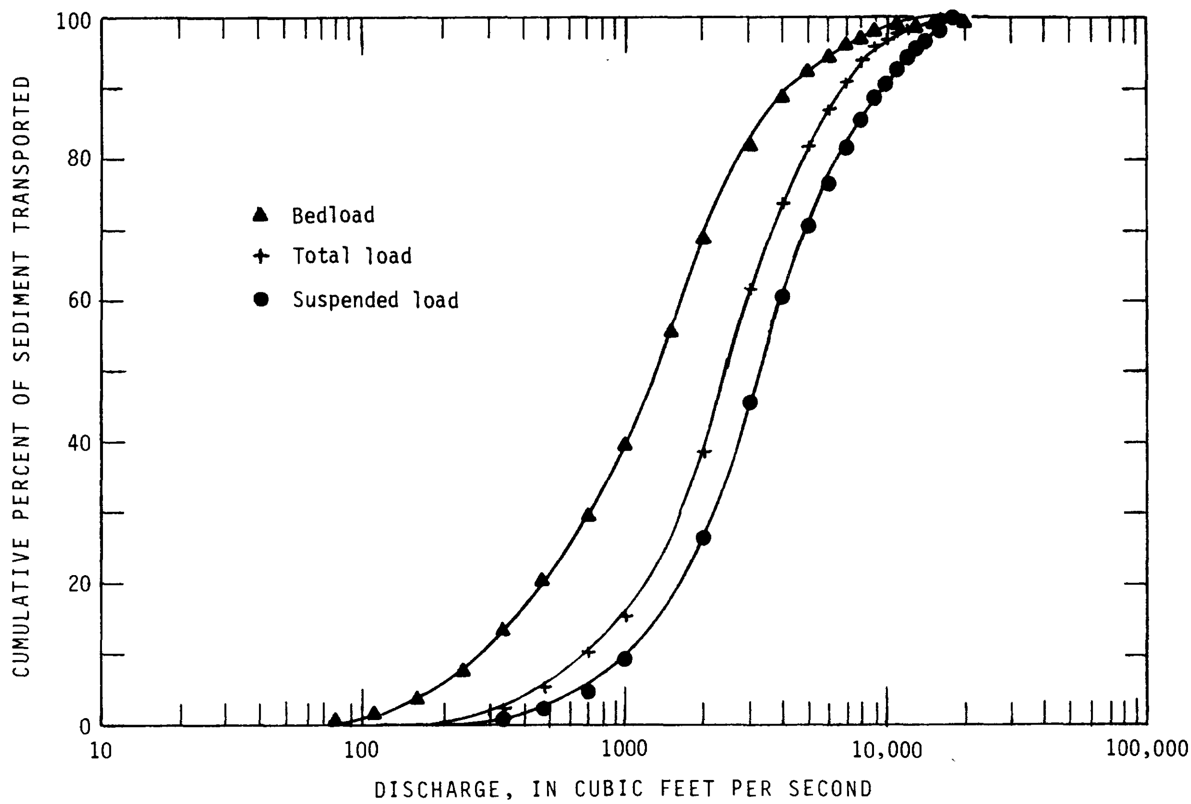

FIGURE 13.--Cumulative percentage of sediment load transported at discharges less than or equal to discharge indicated, Powder River at Moorhead and Broadus, Montana, water years 1939-78.

Relation of Bankfull to Effective Discharge

Both bankfull discharge and effective discharge have been referred to as the "channel-forming discharge." For streams in the Yampa River basin, Colorado and Wyoming, Andrews (1980) found that effective discharge, as computed from daily sediment records, corresponds to measurements of bankfull discharge. In other words, more of the annual sediment load is transported at bankfull discharge than at any other discharge. Therefore, streams are adjusted to the effective discharge, and bankfull discharge and the effective discharge appear to be geomorphically equivalent.

For streams in New South Wales, Australia, Pickup and Warner (1976) suggested that bankfull discharge (defined statistically as the 1.58-yr flood from the regional flood-frequency curve or derived using the Strickler equation with calculated or estimated roughness coefficients) was 2 to 12 times larger than the effective discharge. They suggest that channel incison may result in some overestimation of the bankfull discharge; whatever the reason, effective discharge is smaller than the bankfull discharge. When effective discharge is not equal to the bankfull discharge, the geomorphic significance of each flow needs to be examined.

For the Powder River study reach, bankfull discharge is two to three times larger than the computed effective discharge. That the value selected for bankfull discharge in this study has not been overestimated, and that bankfull discharge is geomorphically significant is inferred from the correspondence of the 1.5-yr flood (5,600 ft^3/s) to that discharge that fills the channel to the top of the banks, and agreement between area of bank erosion and the number of days that mean discharge equals or exceeds bankfull (5,600 ft^3/s) for a given period.

No relation was determined between area of bank erosion and the number of days mean discharge equaled or exceeded the effective discharge, which was considerably less than bankfull discharge. Plots of approximate water surfaces and cross-sectional areas for bankfull and effective discharges for several measured cross sections show effective discharge to fill the bottom of the bankfull channel (fig. 14). Thus, the effective discharge spans the "effective width" of the channel. Conceivably, by undermining the banks, the effective discharge should be capable of significant bank erosion and channel enlargement; erosion rates determined from historic maps and several years of empirical data indicate that it is not. Perhaps cohesiveness of the banks, or armoring of the streambed impedes significant bank erosion by effective discharge.

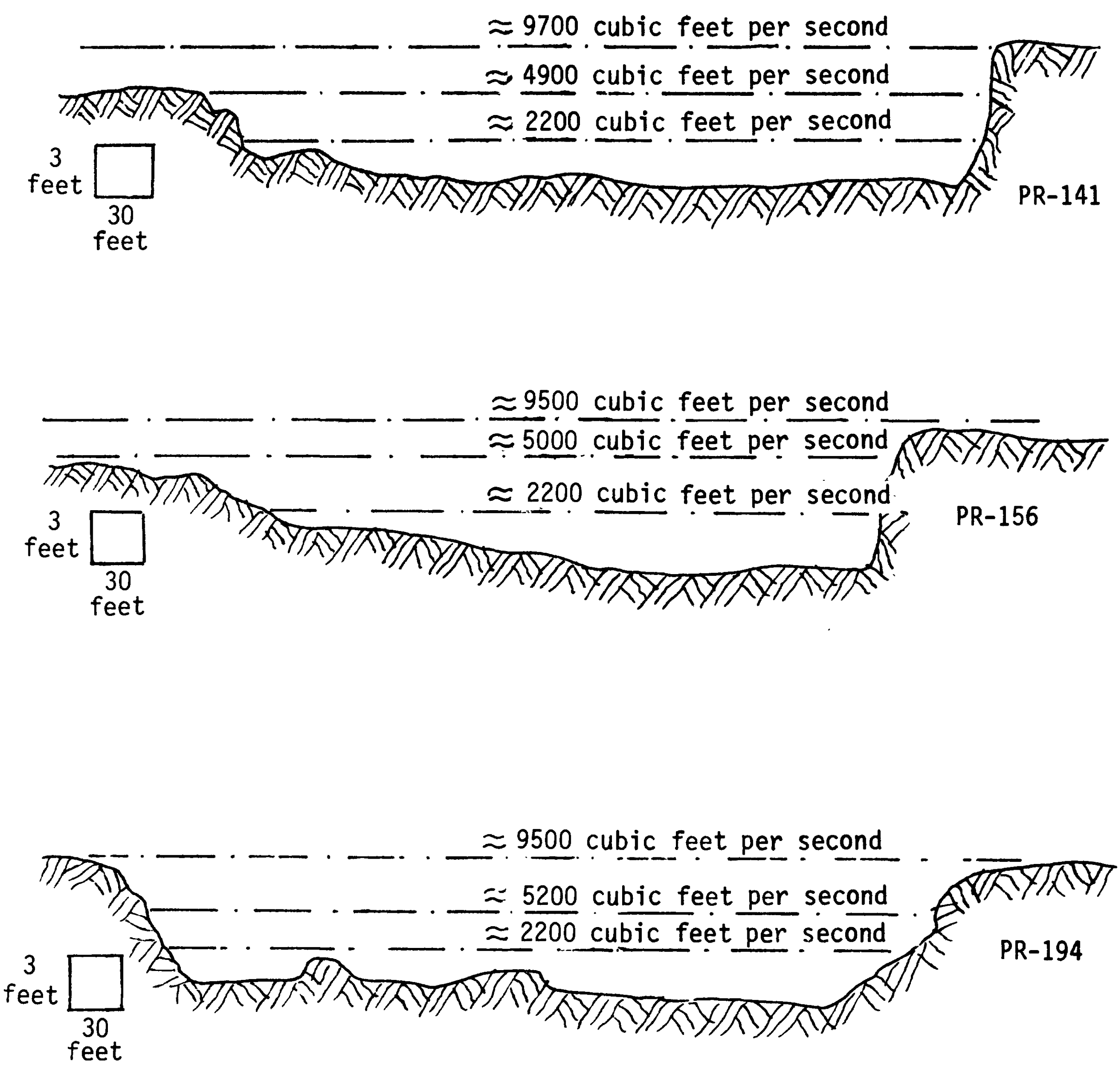

FIGURE 14.--Approximate cross-sectional areas and water surfaces for effective discharge, bankfull discharge, and a discharge flooding the channel to the level of the low terrace, at three cross sections of Powder River at distances of about 16 miles (top), 26 miles (middle) and 50 miles (bottom) downstream from Moorhead, Montana. Water level approximated by back-calculating from Williams (1978) equation to solve for mean depth.

Comparison of the relation of both flows to channel size and shape, and their effect on bank erosion and sediment transport indicates that both effective discharge and bankfull discharge have geomorphic significance and work together to maintain the channel. Most bank erosion, but only 15 percent of the mean annual sediment transport, occurs at flows equal to or greater than bankfull. However, almost 50 percent of the mean annual sediment load is transported during moderate flows about equal to the effective discharge. Effective discharge, then, may be important in channel maintenance, because more of the total annual sediment load is transported at that discharge than any other without significantly modifying the channel shape and capacity that are adjusted to bankfull discharge.

Threshold Discharge

When records of discharge accompany measurements of geomorphic processes or change, "threshold" values can be identified at which a change or process begins, maximizes, or occurs most rapidly. For example, recent studies of erosion rates (Hughes, 1977; Harvey and others, 1979; Pickup and Warner, 1976) have identified threshold values for discharge above which there is major bank erosion and below which there is no measurable erosion.

Between Moorhead and Broadus, monumented cross sections have been resurveyed several times between 1975 and 1980, providing measured rates of bank erosion to compare with the discharge record between surveys. Discharge thresholds of bank erosion then can be identified. Measurable bank erosion is systematic and significant at discharges greater than but not at discharges less than bankfull (5,600 ft^3/s); bankfull discharge, therefore, is the threshold discharge of bank erosion.

The extent of bank erosion measured at several cross sections that have been resurveyed every year or two since 1975 (R.H. Meade, U.S. Geological Survey, oral commun., 1981) was compared to the record of daily mean and peak flows with the following results. Streamflow generally was low during water years 1979 and 1980. Highest 1-day flows were 1,300 ft^3/s (1979) and 1,440 ft^3/s (1980), with peak flows of 3,700 ft^3/s (1979) and 1,700 ft^3/s (1980). Surveys of the cross sections indicate no measurable bank erosion during those 2 yr. Peak flows in 1979 and 1980 apparently did not exceed the minimum (threshold) discharge necessary to erode the banks.

Of the nine cross sections measured during 1975 and again during 1977, six showed no measurable bank erosion. Three sections averaged 1.3 ft of bank erosion. No significant modification of the banks occurred during this period at the study sites, as the average change in width for the measured sections was 0.6 ft, about 0.002 channel widths, or about 0.2 percent of the erosion measured from maps for the past 40 yr. Instantaneous peak discharges for water years 1976 and 1977 were 5,370 and 4,750 ft^3/s. Annual maximum daily mean flows for the same years were 3,100 and 3,080 ft^3/s. The effective discharge was exceeded 8 days during the 2 years, yet the majority of the measured sections was not measurably eroded. Therefore, the effective discharge is not a threshold of significant bank erosion. Peak discharge was less than bankfull both years.

The largest total annual flow for the 49 yr of record occurred during 1978. The flood of May 1978, the largest on Powder River since 1923, peaked at 33,000 ft^3/s and was preceded by a high flow that peaked at 5,520 ft^3/s during March and exceeded annual peaks of the previous 2 yr. Daily mean discharge exceeded 5,600 ft^3/s six days that year, about four times its usual annual occurrence. At the cross sections referred to above, average bank erosion during 1978 was 33.8 ft, about 0.11 channel widths or nearly 14 percent of the total bank erosion measured between 1939 and 1978.

Pickup and Warner (1976) and Hughes (1977) used bank-erosion pins to identify three degrees of bank erosion in response to discharge: (1) No measurable bank erosion at any site during a range of low discharges; (2) small, unsystematic bank erosion at a few sites for a range of moderate discharges; and (3) significant bank erosion for discharges exceeding a threshold value. A similar relation was identified for the Powder River. When daily mean discharge was less than about 2,200 ft^3/s (the effective discharge), there was no measurable bank erosion. Between discharges of 2,200 ft^3/s (effective discharge) and 5,600 ft^3/s (bankfull discharge), there was small, unsystematic, but measurable bank erosion. Significant bank erosion occurred after sustained flows greater than bankfull discharge.

CHANNEL CHANGES BETWEEN 1939 AND 1978

The following discussion of channel change is based on measurements and observations from the mapped configurations of the Powder River between 1939 and 1978 (Martinson and Meade, 1983). Modified parts of the maps have been included to illustrate points in the discussion. Stationing (in feet) used in the discussion below refer to valley floor elevation at the Powder River on the 7.5-minute topographic maps (1969-73) used for base maps.

Changes in Channel Dimensions

Changes in Width

Mean channel width was 15 percent less during 1978 than during 1939. However, this may not indicate channel narrowing through time, as mean width, as measured from the photographs, increased and decreased several times during the 40 yr of photographic coverage (table 2, fig. 15). The smallest measured mean width (1973) was about 60 percent of the greatest measured mean width (1967). This is on the same order as upstream-downstream variability in width for a single set of maps (fig. 16). The apparent variability of channel width needs to be interpreted cautiously because of difficulties in defining the bankfull channel using vegetation-cover criteria.

Nonetheless, changes in channel width could be related to antecedent hydrologic conditions. Following periods characterized by relatively high annual peak flows (1967, 1978), average channel width appeared to increase. Conversely, following periods characterized by lower annual peak flows (1954, 1973), average channel width decreased. This variability is expected, as channel dimensions reflect the volume of water passing through the channel; therefore, the channel might widen, if only temporarily, following large flows.

The channel was widest during 1967 and this did not coincide with the highest annual mean, annual maximum daily mean, or instantaneous peak flow (1978). Neither did mean width correlate closely with the peak flow during the last or next-to-last runoff season preceding the photography. Since 1944, the narrowest channels mapped have followed periods of least erosion, and the widest channels mapped have followed periods of greatest erosion. Perhaps then, the distribution of vegetation near the channel represents some cumulative response to the discharge preceding width measurement and not only to the most recent flows.

Changes in the width-depth ratio probably would be a better index of flood-induced modifications of channel morphology (Schumm, 1977). Depth data corresponding to earlier channels, however, are not available.

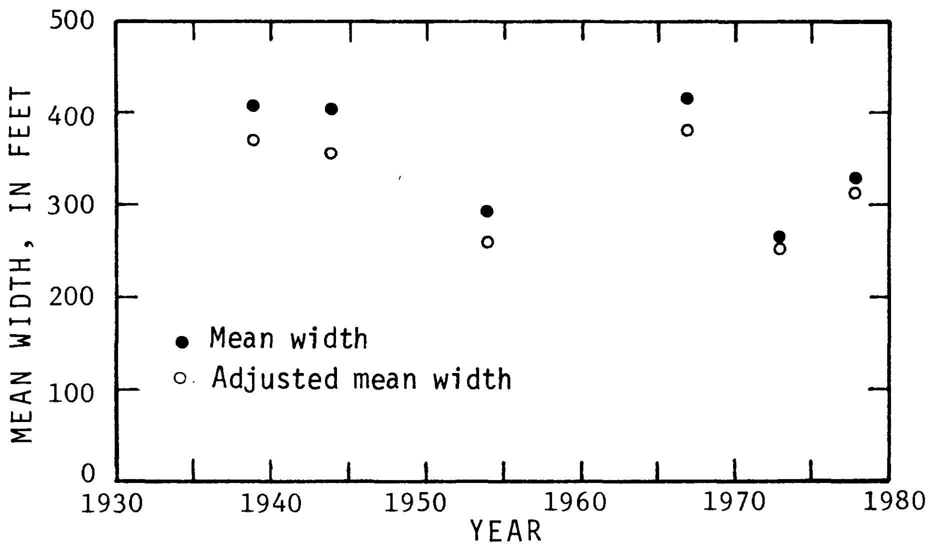

FIGURE 15.--Changes of mean width and adjusted mean width (adjusted area divided by length), Powder River between Moorhead and Broadus, Montana, 1939-78.

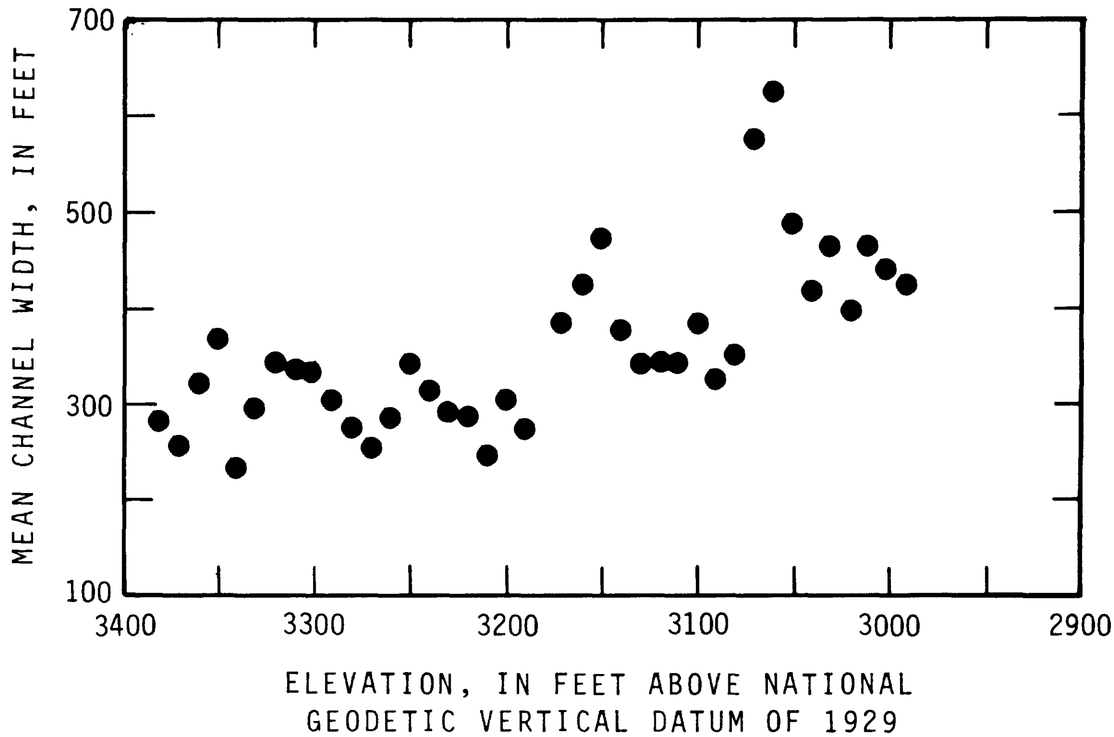

FIGURE 16.--Relation of mean channel width to elevation, Powder River between Moorhead and Broadus, Montana, 1944.

Increases and decreases in width were not distributed uniformly along the channel. During periods of relatively lower peak flows, the unvegetated distance between banks was relatively uniform along the reach. During periods of relatively higher peak flows the increase in width ranged from 20 to 70 percent (20 to 30 percent upstream from Moorhead and 60 to 70 percent near Broadus, fig. 17). The channel widened significantly in reaches where the channel was increasing in length (figs. 18 and 19), much more so than in the reaches where length remained constant (figs. 20 and 21). Variability in width reached a maximum between elevations of 3,070 and 3,030 ft in the reach characterized by meander bends that translated downstream with little increase in channel length (figs. 22 and 23). This is also the reach with the greatest measured rate of bank erosion per unit length of channel. The narrowest reaches, and those reaches that vary least in map width, commonly impinge at some point against the valley wall (figs. 20 and 21). The relative stability of these reaches, therefore, probably reflects the restricting effect of bedrock control on channel activity.

Width seems to reach minima and maxima at regular intervals (fig. 17). Minima (approximate valley floor elevations 3,030, 3,100, 3,190, and 3,270 ft) and maxima (approximate valley floor elevations 3,060, 3,150, 3,240, and 3,350 ft) occur about every 100,000 ft of channel, or every 60,000 ft of valley length, or an average of once every 7 to 10 valley widths. Perhaps the spacing reflects some relict configuration (pool and riffle spacing?) of the valley bottom established by prehistoric flows through the valley.

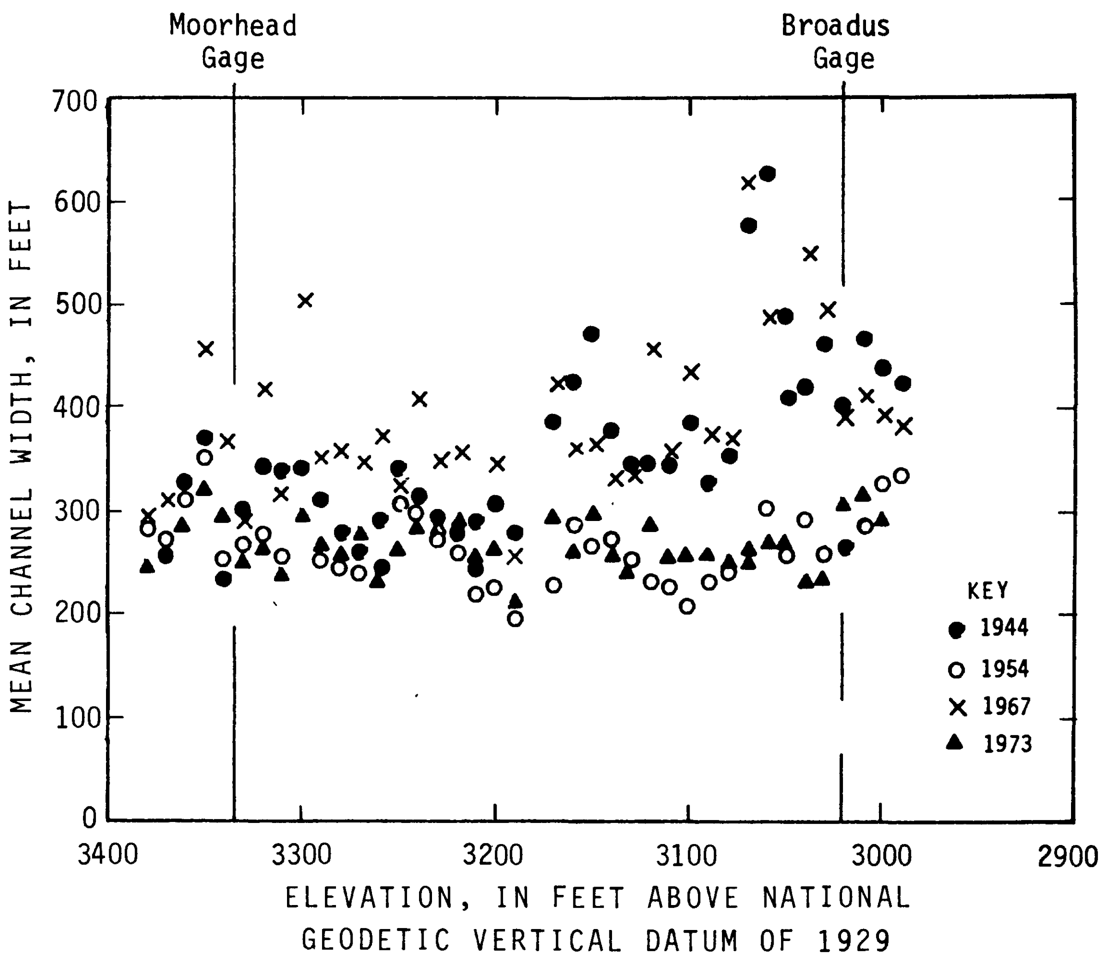

FIGURE 17.--Mean channel width (area of channel bounded by 10-foot contour interval divided by length of channel segment) plotted against elevation of downstream contour, Powder River between Moorhead and Broadus, Montana, 1944, 1954, 1967, 1973.

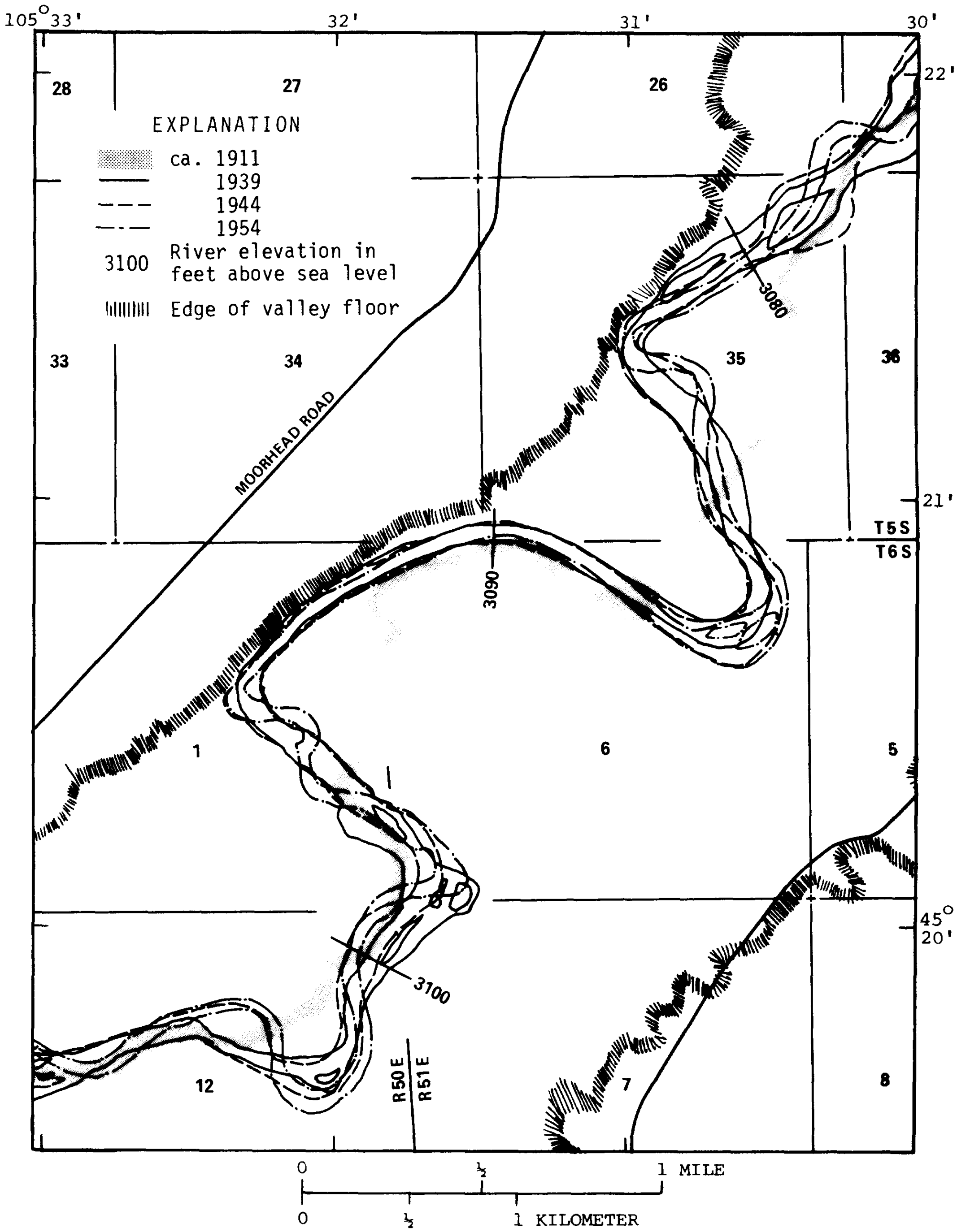

FIGURE 18.--Powder River, Montana, between about 3,110- and 3,080-foot elevation, with locations and configurations of the bankfull channel between about 1911 and 1954. The channel had consistently lengthened by lateral migration and development of meander bends, with negligible downstream translation of the meanders. The reach typifies changes along the Powder River between the 3,110- and 3,070-foot valley-bottom contours.

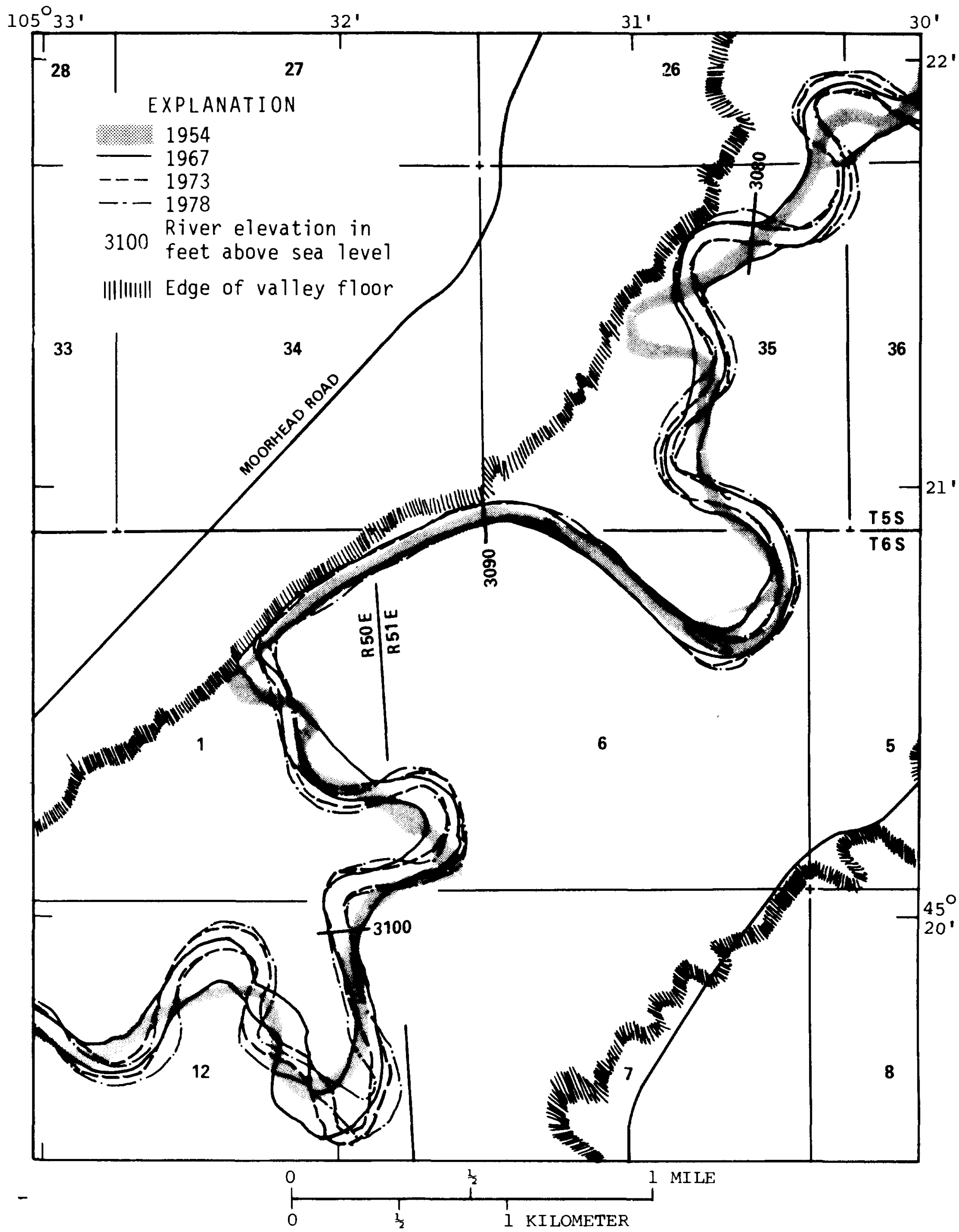

FIGURE 19.--Powder River, Montana, between about 3,110- and 3,080-foot elevation, with locations and configurations of the bankfull channel between 1954 and 1978. The channel had consistently lengthened by lateral migration and development of meander bends, with negligible downstream translations of the meanders. The reach typifies changes along the Powder River between the 3,110- and 3,070-foot valley-bottom contours.

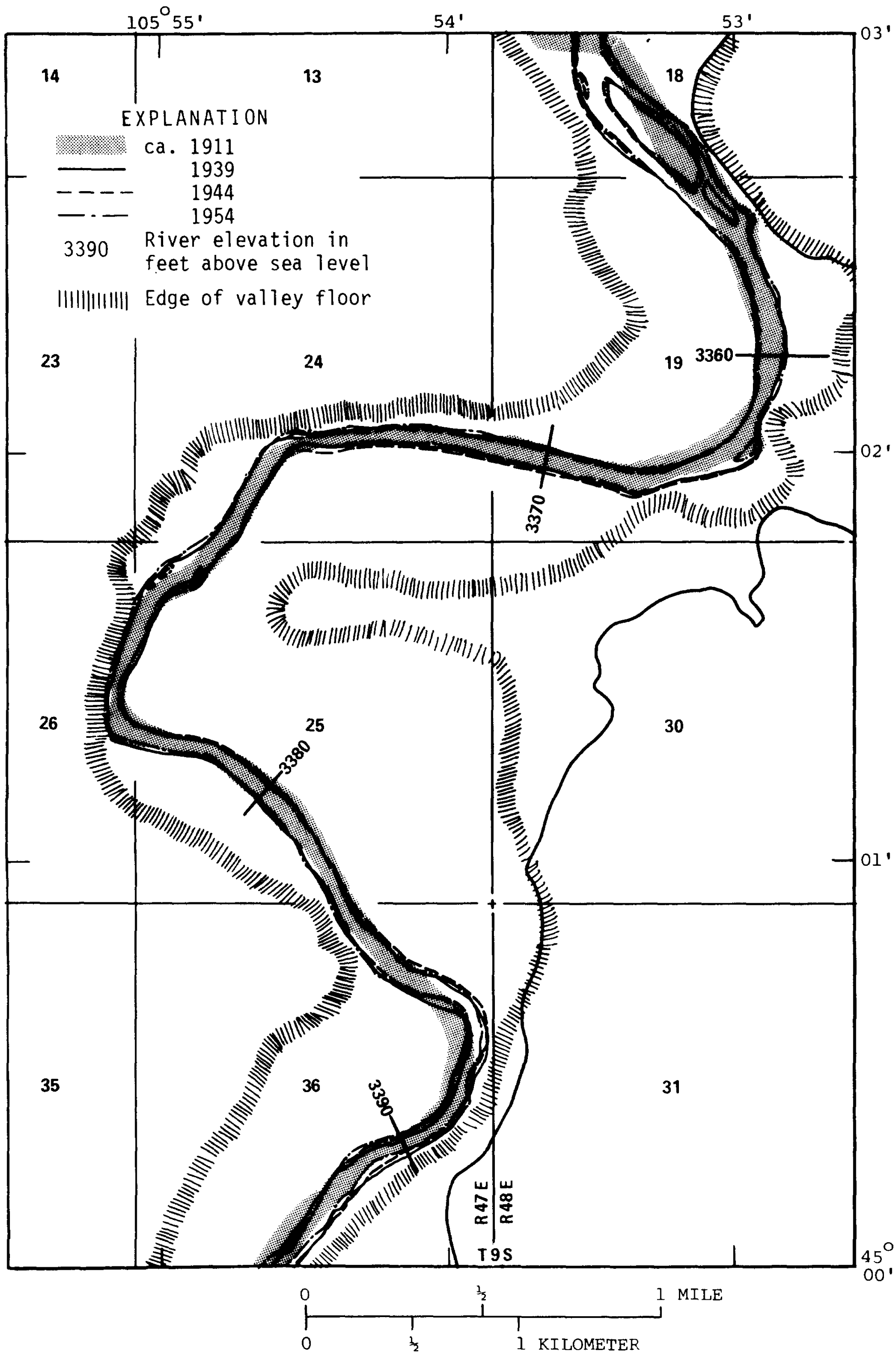

FIGURE 20.--Powder River, Montana, between about 3,390- and 3,360-foot elevation, with locations and configurations of the bankfull channel between about 1911 and 1954. Bedrock control in the channel had minimized changes in channel size, configuration, and length.

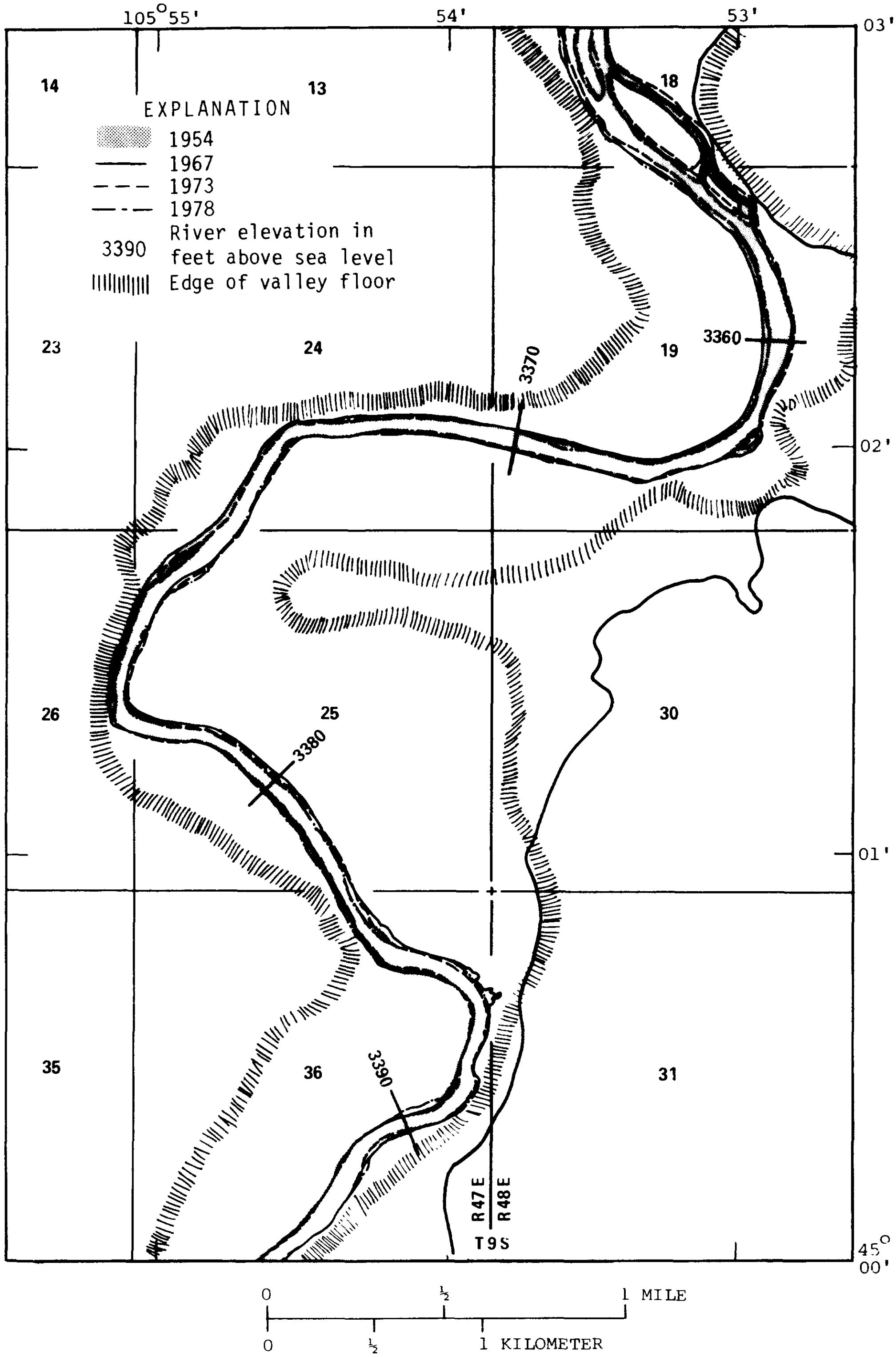

FIGURE 21.--Powder River, Montana, between about 3,390- and 3,360-foot elevation, with locations and configurations of the bankfull channel between 1954 and 1978. Bedrock control in the channel had minimized changes in channel size, configuration, and length.

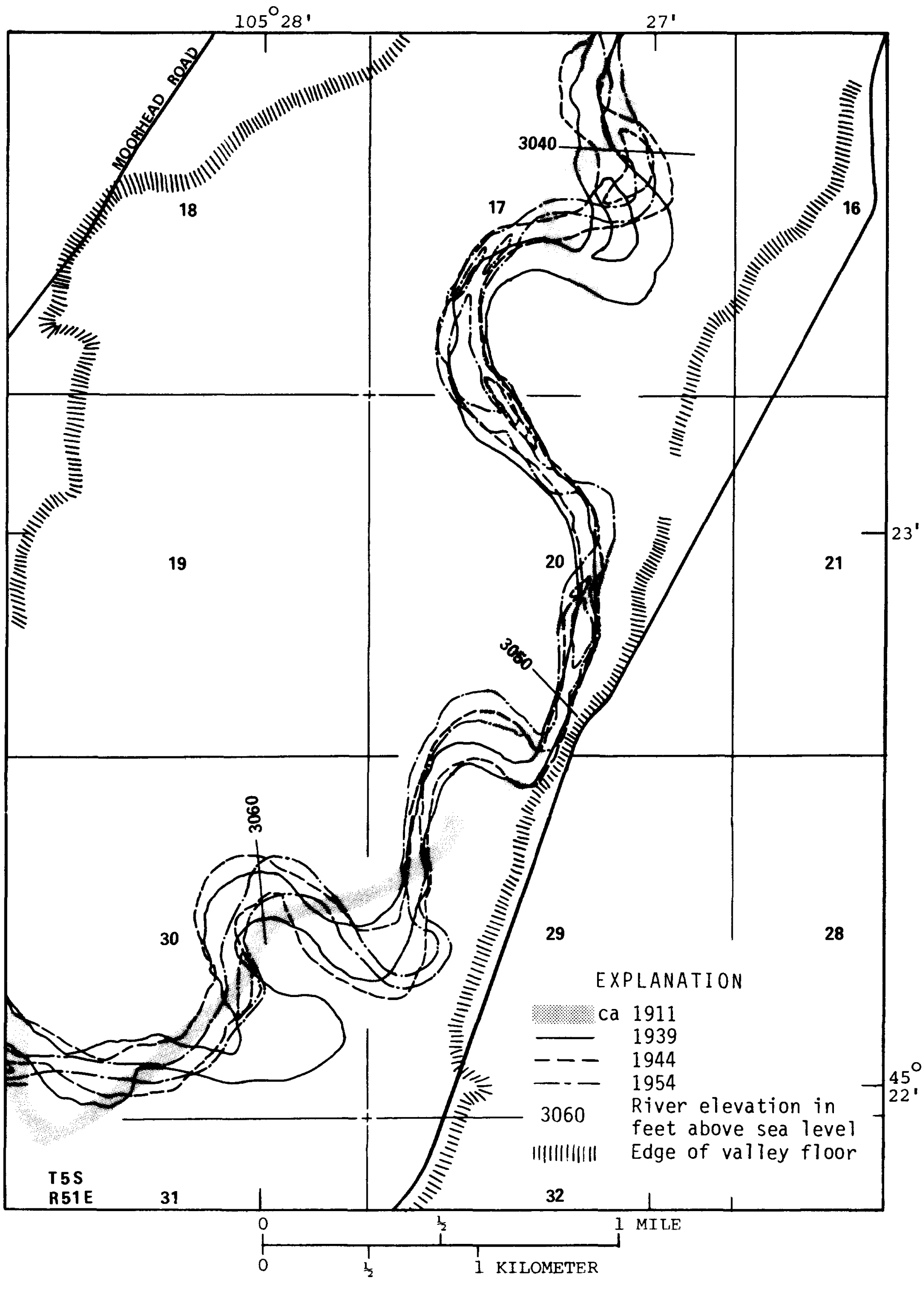

FIGURE 22.--Powder River, Montana, between about 3,070- and 3,040-foot elevation, with locations and configurations of the bankfull channel between about 1911 and 1954. The channel had shifted primarily by downstream translation rather than lateral migration of the meander bends.

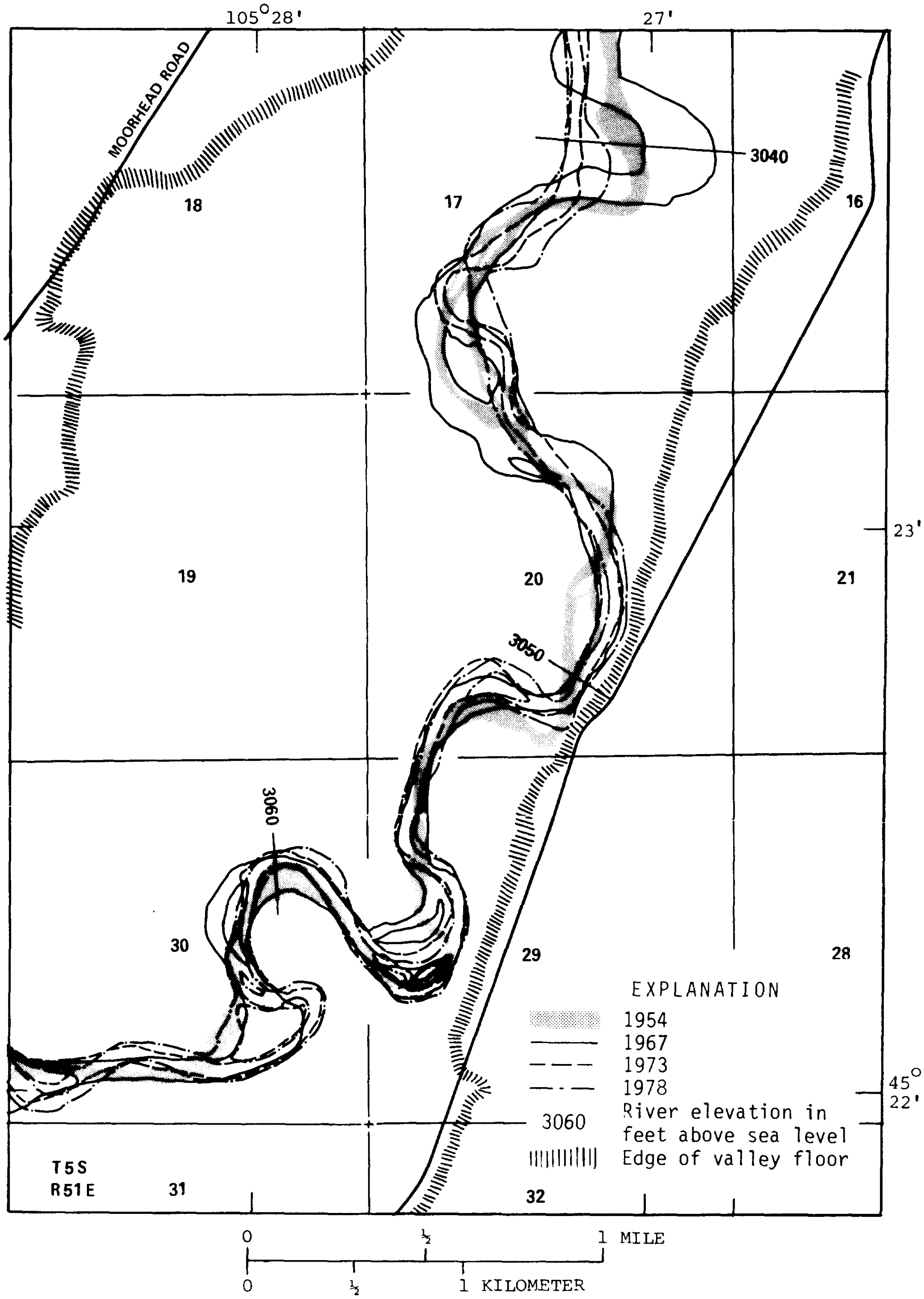

FIGURE 23.--Powder River, Montana, between about 3,070- and 3,040-foot elevation, with locations and configurations of the bankfull channel between 1954 and 1978. The channel had shifted primarily by downstream translation rather than lateral migration of the meander bends.

Changes in Island Area

Islands occupied between 5 percent (1973) and 11 percent (1944) of the bank-to-bank area of the channel (table 2). Presence of vegetation was used to distinguish "islands" from "mid-channel bars" which also divided the flow in a number of reaches. Although net island area decreased by 50 percent between 1939 and 1978, it increased during periods of higher peak flows and increased bank erosion (fig. 4, table 3). Conversely, island areas decreased during periods of relatively lower peak flows.

This variability in island area may reflect temporary changes of material in storage in the channel. During periods of higher peak flows and accelerated bank erosion, the increase of sediment supplied to the channel resulted in the expansion of islands. During periods of low flow, with a decrease in sediment introduced to the channel by tributary input or bank erosion, material from the channel was removed from storage. An alternative interpretation is that the islands may be part of the chaotic disarray left in the channel during high flows and that they disappear during periods of low flow when the smaller channels between the islands and the banks fill in (F. J. Heimes, U.S. Geological Survey, written commun., 1981).

Change in Meander Wavelength and Amplitude

Meander wavelengths and amplitudes remained fairly constant during the 40 yr for which photographs were available. However, meander size and spacing varied within the study reach (figs. 18-25). Generally, the meander wavelengths varied between 4 and 10 channel widths, and meander amplitudes varied from 4 to 20 channel widths (Martinson and Meade, 1983). Maximum increase in meander amplitude during the 40 yr was only 2.5 to 3 channel widths (figs. 18 and 19). Amplitude of many bends commonly increased by only 1 to 2 channel widths during the same period.

Changes in Channel Patterns

Straight, meandering, and braided reaches of channel can be identified in the reach between Moorhead and Broadus. During the 40 yr delimited by aerial photographs, channel patterns of discrete channel reaches changed through the development and breaching of meander bends, which resulted in the lengthening or straightening and shortening of the reach. Variations in channel length and sinuosity were studied to assess changes in channel pattern and channel stability.

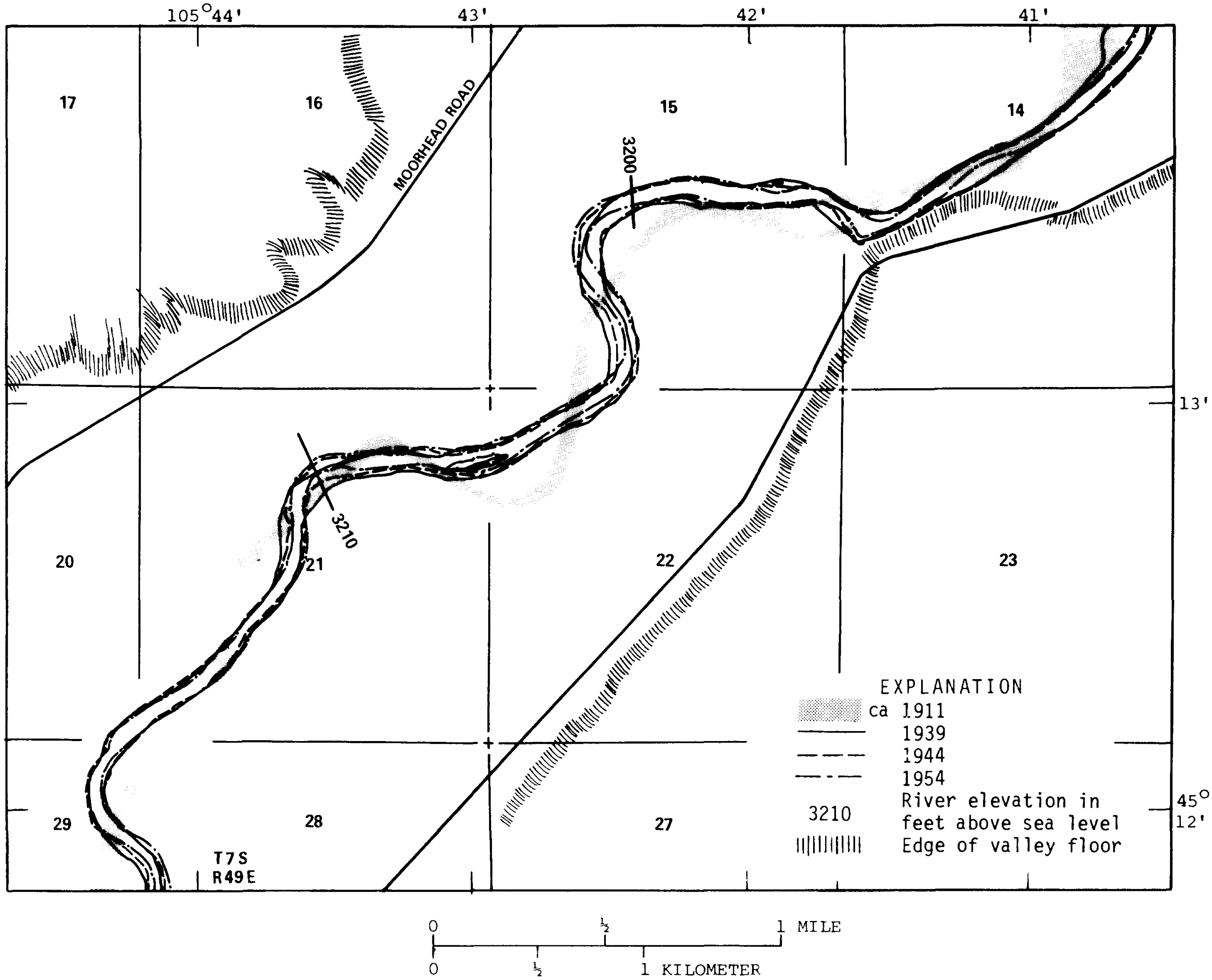

FIGURE 24.--Powder River, Montana, between about 3,220- and 3,190-foot elevation, with locations and configurations of the bankfull channel between about 1911 and 1954. Neck cutoffs and chute cutoffs of meander bends have compensated for the slight increases in length that have been due to the development of meander bends. Therefore, channel length through this reach had remained more or less constant.

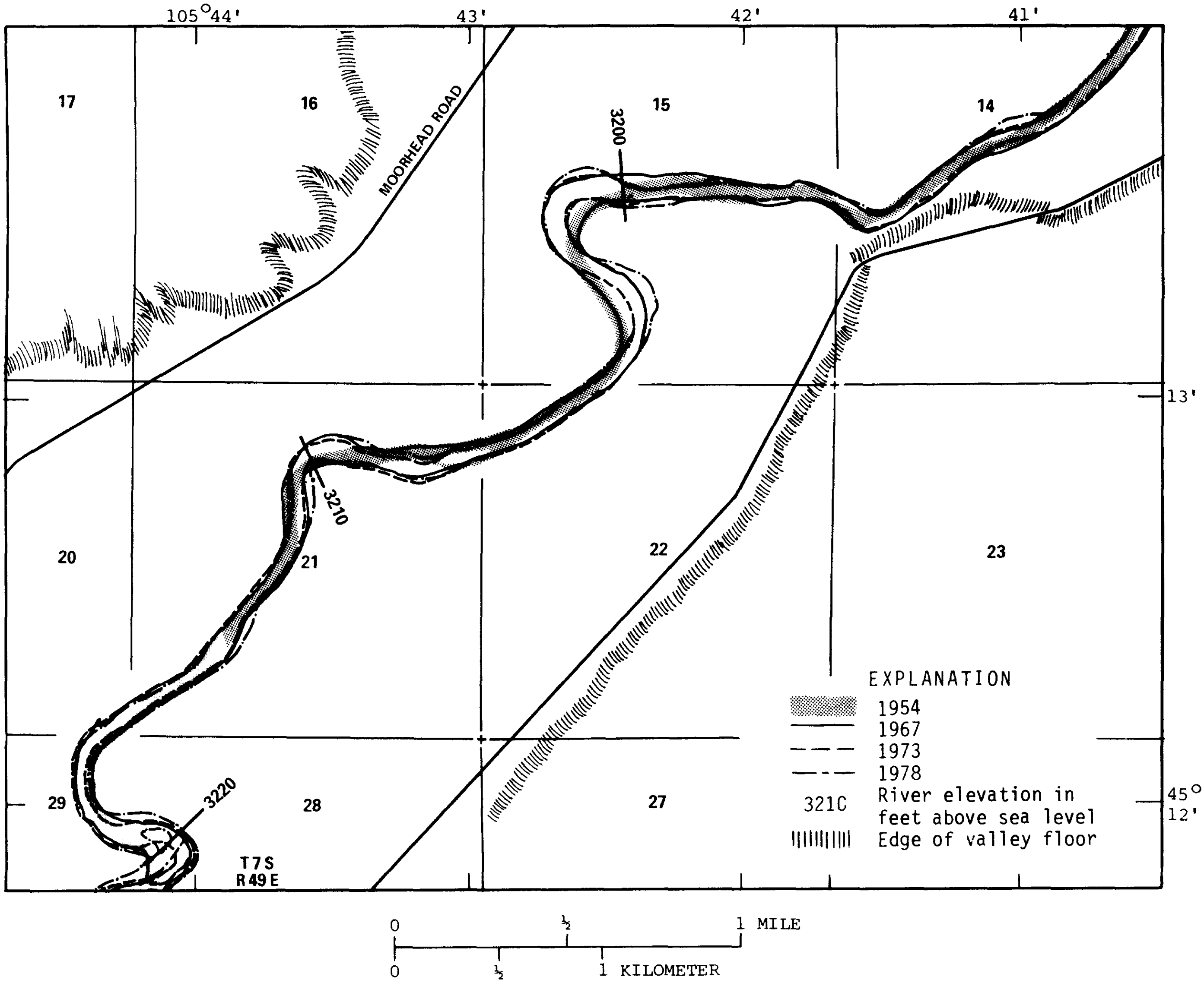

FIGURE 25.--Powder River, Montana, between about 3,220- and 3,190-foot elevation, with locations and configurations of the bankfull channel between 1954 and 1978. Neck cutoffs and chute cutoffs of meander bends have compensated for the slight increases in length that have been due to the development of meander bends. Therefore, channel length through this reach had remained more or less constant.

Changes in Channel Length

Between 1939 and 1973, channel length increased by 7 percent between Moorhead and Broadus (table 2). Although meander-bend cutoffs eliminated several miles of channel, development of existing meander bends and the beginning of new bends resulted in net elongation of the channel. This process of meander growth continued between 1973 and 1978, but the breaching of several large meander bends during 1975 and 1978 resulted in net shortening of the channel by 1.4 mi (table 2).

Changes in channel length were not distributed equally along the reach. For each set of maps, the length of channel between topographic contours was measured (table 4). A plot of the cumulative downstream distance corresponding to valley-floor elevation for each set of maps (fig. 26) shows that the river upstream of about the 3,190-ft valley-floor elevation has remained relatively constant in length; decrease in length due to meander-bend cutoffs has been compensated by channel elongation. Practically all net elongation has occurred at elevations between 3,190 and 3,070 ft, as indicated by the divergence and change in slope of lines representing cumulative channel lengths for 1939, 1954, 1967, and 1978 (fig. 26). Between the 3,070-ft elevation and Broadus, channel length has remained almost constant (fig. 26).

The variable rates of lengthening correspond to channel pattern modifications. Upstream from about 3,330 ft there has been no lengthening. The valley bottom is narrow (approximately 10 channel widths), and deformation of the channel within this reach has been negligible, probably because of bedrock constraints imposed by the valley (figs. 20 and 21). Between 3,330 and 3,190 ft, the channel also has maintained a constant length. Meander cutoffs or chute cutoffs have balanced slight increases in length due to lateral migration of the meander bends in this reach of channel. Meander bends are linked by straight, stable reaches of channel, indicating the probability of bedrock control in this reach (figs. 24 and 25). Between 3,190 and 3,070 ft, the channel has consistently lengthened, primarily through lateral migration of meander bends with negligible downstream translation of the meanders. The channel impinges against the valley wall periodically along the reach (figs. 18 and 19). Between the 3,070-ft elevation and Broadus, the channel is migrating through the valley primarily by downstream translation, with negligible lateral migration of the meander bends (figs. 22 and 23). That the meanders can translate so freely downstream indicates differences in bedrock constraints and control on the channel from those that exist upstream. Data from a geologic map of the area between Moorhead and Broadus indicate a change in the geology underlying the valley-bottom alluvium at about valley elevation 3,070 ft from massive to thick-bedded sandstones and siltstones containing numerous thick coal beds upstream to thin-bedded sandstones, shales, and coal downstream (Miller, 1979); between Moorhead and Broadus, rate of meander development and mode of meander deformation reflect the transition from bedrock to alluvial channel, and the degree of bedrock control is responsible for at least some of the variability in channel pattern and characteristics.

Table 4.--Length of segments of valley and channel measured between 10-foot topographic contours, Powder River between Moorhead and Broadus, Montana, 1939 to 1978

Contour interval (elevation in feet)	Length of valley segment (feet)	Approximate centerline length of channel (feet)					
		1939	1944	1954	1967	1973	1978
3,390-3,380	6,183	6,625	6,781	6,812	6,875	6,875	6,875
3,380-3,370	9,969	11,062	11,000	10,938	10,875	10,812	11,000
3,370-3,360	3,490	5,125	5,031	5,188	5,125	5,188	5,312
3,360-3,350	6,334	8,688	8,875	8,312	8,250	8,438	8,312
3,350-3,340	5,016	6,812	6,688	7,188	7,000	7,000	6,844
3,340-3,330	5,475	7,312	7,312	7,375	7,438	7,438	7,500
3,330-3,320	5,853	6,812	7,312	7,312	7,688	8,000	7,938
3,320-3,310	7,442	8,000	8,250	7,438	7,562	7,625	7,750
3,310-3,300	2,712	6,250	6,188	4,500	4,625	4,875	2,500
3,300-3,290	10,429	15,375	15,594	15,625	16,104	16,469	16,781
3,290-3,280	6,315	7,500	7,562	7,688	8,250	8,344	8,438
3,280-3,270	6,046	8,000	8,344	8,375	8,750	8,969	9,250
3,270-3,260	7,138	10,500	10,625	10,750	9,438	9,562	9,469
3,260-3,250	3,980	5,312	5,625	5,500	6,188	6,312	6,500
3,250-3,240	3,390	6,000	6,719	6,938	8,125	8,562	8,938
3,240-3,230	4,977	7,188	7,312	7,688	8,188	8,250	6,812
3,230-3,220	3,451	9,312	9,344	9,625	10,125	10,375	6,812
3,220-3,210	5,808	7,500	7,750	7,875	8,062	8,375	8,250
3,210-3,200	6,145	7,938	8,000	8,250	8,875	9,125	9,375
3,200-3,190	8,676	8,875	9,125	9,062	9,000	9,000	9,125
3,190-3,180	4,729	7,687	7,469	8,000	8,187	9,000	9,062
3,180-3,170	4,729	7,687	7,469	8,000	8,187	9,000	9,062
3,170-3,160	7,335	9,250	10,500	10,250	9,750	10,312	11,062
3,160-3,150	6,873	10,375	11,125	11,812	12,562	13,312	13,438
3,150-3,140	6,701	8,000	8,375	9,062	9,250	9,562	9,438
3,140-3,130	6,417	7,438	8,875	10,062	9,062	9,625	9,688
3,130-3,120	5,072	12,750	13,625	8,438	9,062	9,562	8,938
3,120-3,110	5,770	9,562	10,438	9,688	10,875	11,938	12,125
3,110-3,100	4,747	6,500	7,188	8,312	10,062	11,468	12,000
3,100-3,090	5,365	9,750	10,000	11,187	10,750	11,469	11,688
3,090-3,080	5,852	11,125	11,875	12,438	11,750	12,563	13,188
3,080-3,070	5,936	7,125	7,438	8,062	7,750	10,188	10,438
3,070-3,060	5,521	9,188	8,000	8,000	9,562	9,938	9,000
3,060-3,050	4,572	7,688	9,000	9,688	10,312	10,031	10,062
3,050-3,040	7,040	11,062	10,750	11,000	12,562	10,312	9,375
3,040-3,030	9,681	9,438	9,688	9,500	9,125	9,688	9,875
3,030-3,020	9,045	10,875	10,562	9,125	9,125	9,281	9,188
3,020-3,010	5,955	8,250	7,812	7,938	8,312	8,312	8,750
3,010-3,000	3,214	9,000	10,500	9,750	11,438	11,250	4,063
3,000-2,990	7,867	11,812	12,250	11,750	12,500	13,375	-----

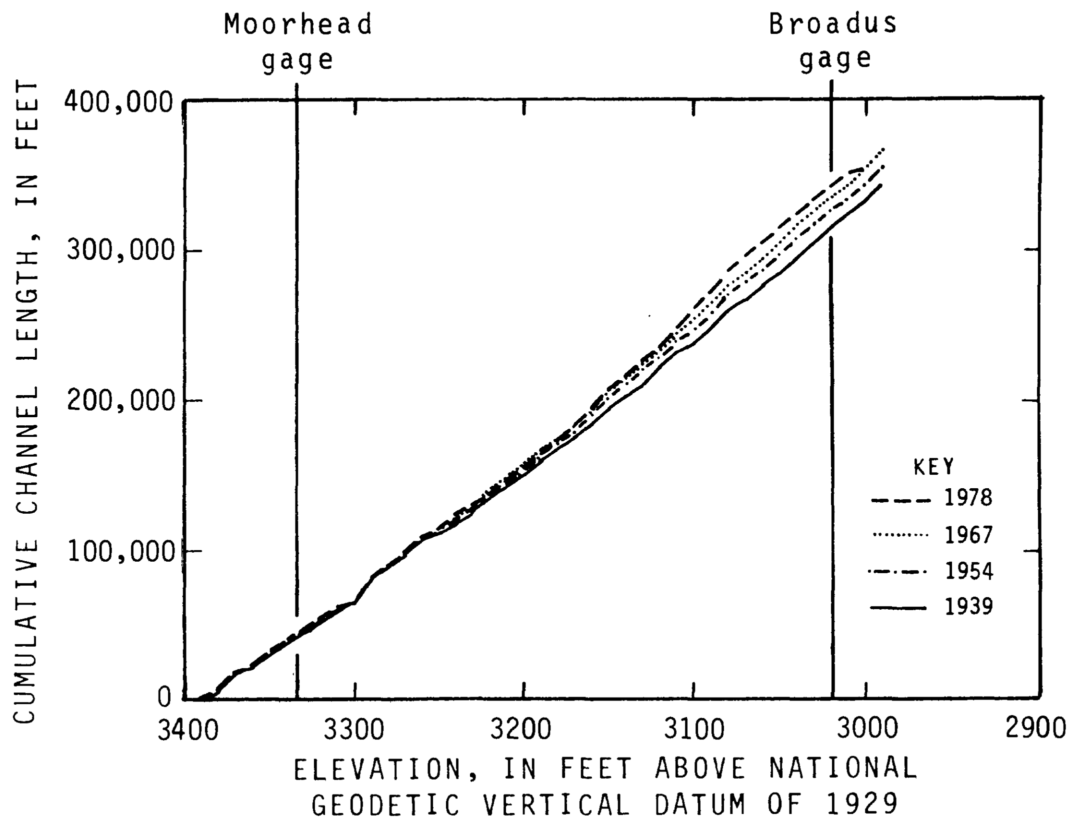

FIGURE 26.--Cumulative channel length downstream from the 3,390-foot contour, Powder River between Moorhead and Broadus, Montana, 1939, 1954, 1967, 1978.

Channel-Pattern Stability

Variability in channel pattern and characteristics of the Powder River also can be attributed to local variations in valley slope. Experimental data (Schumm and Khan, 1972) and data from the Mississippi River (Schumm and others, 1972) were first used to demonstrate this relation and identify thresholds of pattern stability (fig. 27). Valley slope and sinuosity measurements for the Powder River between Moorhead and Broadus from the 1939, 1944, 1954, 1967, 1973 and 1978 channel maps as plotted in figure 28 demonstrate the variability in sinuosity within a reach through time for a given valley slope. Those data from figure 28 that pertain only to channel reaches that have been shortened by meander or chute cutoffs are shown in figure 29. Initial sinuosity, maximum sinuosity, and sinuosity following shortening are plotted. The dashed lines in figures 28 and 29 generalize the trend to channel sinuosity subsequent to a cutoff for reaches of the Powder River between Moorhead and Broadus. Most cutoffs occurred in reaches where sinuosity had exceeded the hypothetical optimum. Notable are the breaches of several large meander bends during 1975 and 1978 which resulted in large decreases of sinuosity. These cutoffs occurred in sinuous reaches of channel developed in steep reaches of the valley (table 5, fig. 29) and probably resulted from high water discharges and sediment loads associated with the peak flows of 1975 and 1978. The channel presently flowing through these valley segments has been steepened relative to the channel upstream and downstream of the cutoff (table 5), and sinuosity of these reaches can be expected to increase as the channel erodes its bed and banks to adjust channel slope.

The relation between channel pattern stability and valley slope first determined experimentally by Schumm and Khan (1972) and verified by data from the Powder River provides a useful tool for land management and prediction purposes. The relationship indicates what may be an optimum sinuosity with a range of sinuosities that a channel reach may have, dependent on the valley slope of the reach. These minimum, maximum, and optimum sinuosities for a given reach may be identified by studying previous locations and configurations of the channel on old maps and aerial photographs. Meanders that have cut off during the past 40 yr all had abnormally large sinuosities prior to breaching. Reaches of channel very likely to breach are those that plot far above the optimum curve (figs. 28 and 29); therefore, one reach likely to cut off is that between elevations 3,110 and 3,080 ft (figs. 18 and 19), a reach of moderate valley slope in which channel length has increased by about 33 percent during the past 40 yr (table 4). Sinuosity of all segments in the reach is much greater than the optimum (fig. 30).

This type of analysis lends insight into why some meander bends breach and others that appear equally or even more sinuous do not. This method identifies reaches that have been more active or susceptible to changes than others, and as a management tool, it identifies not only the most stable or efficient configuration of the channel, but also the probable limit to pattern changes which man can induce on the channel.

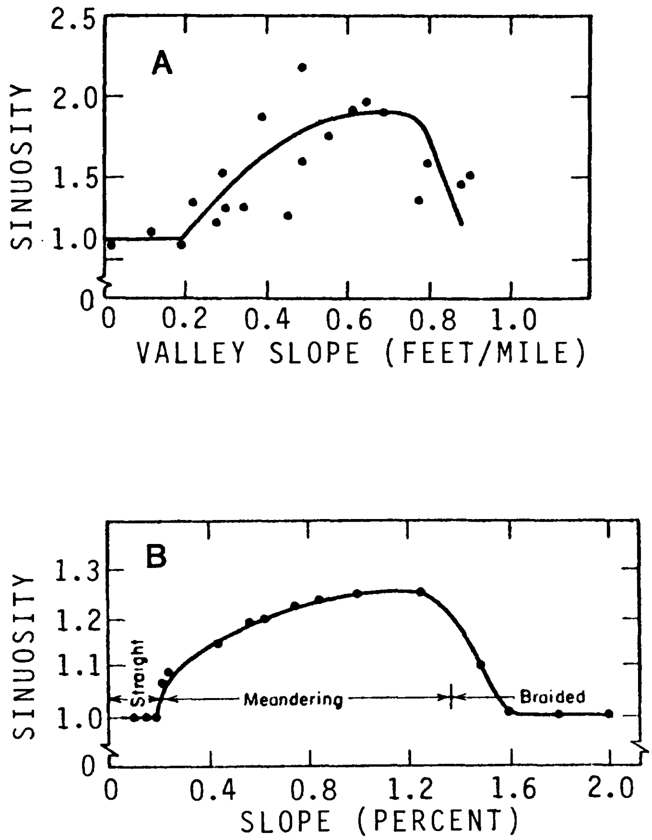

FIGURE 27.--Relation between channel sinuosity and valley (or flume) slope. A. Mississippi River between Cairo, Illinois, and Head of Passes, Louisiana (modified from Schumm and others, 1972, published by permission from Nature: Physical Sciences, v. 237, no. 74, p. 76, copyright (c) 1972, Macmillan Journals Limited); B, Flume data (modified from Schumm and Khan, 1972, published by permission from Geological Society of America Bulletin, v. 83, no. 6, p. 1761, copyright (c) 1972, The Geological Society of America, Inc.).

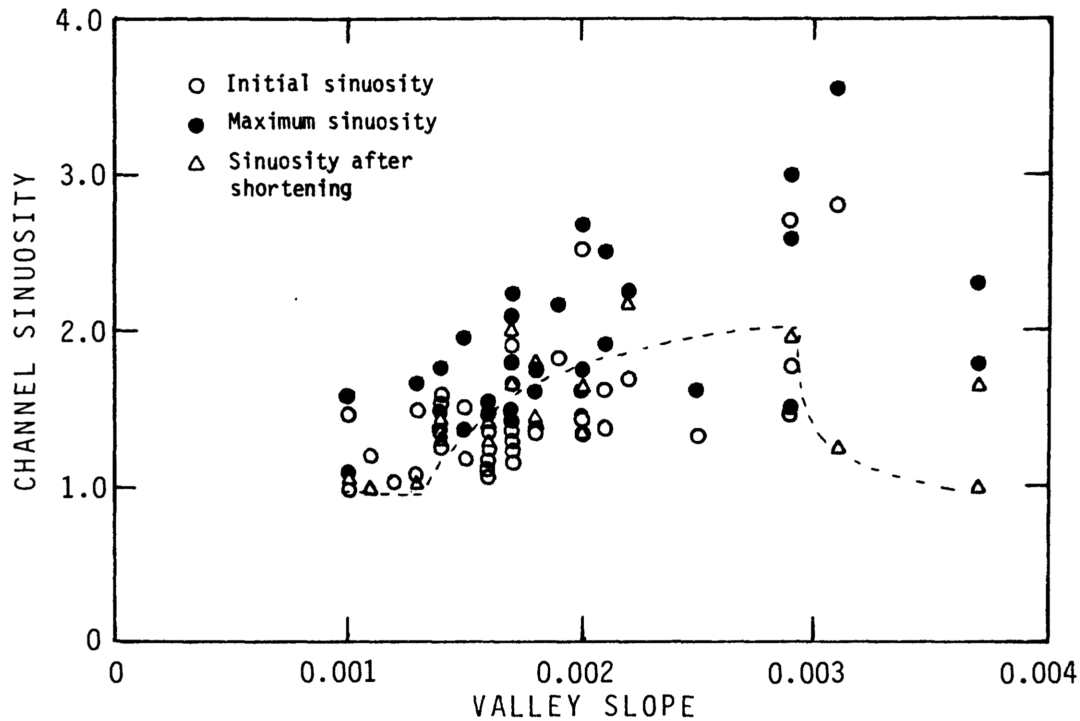

FIGURE 28.--Relation between channel sinuosity and valley slope for segments of channel between 10-foot topographic contours with initial sinuosity, maximum sinuosity, and sinuosity after shortening for all channel segments in the study reach, Powder River between Moorhead and Broadus, Montana, 1939-78. Dashed line indicates optimum sinuosity for a given valley slope.

Table 5.--Valley slope and channel sinuosity, measured between 10-foot topographic contours, Powder River between Moorhead and Broadus, Montana, 1939 to 1978

Contour interval (elevation in feet)	Valley slope	Channel sinuosity					
		1939	1944	1954	1967	1973	1978
3,390-3,380	0.0016	1.07	1.10	1.11	1.11	1.11	1.11
3,380-3,370	.0010	1.11	1.10	1.10	1.09	1.08	1.10
3,370-3,360	.0029	1.47	1.44	1.49	1.47	1.49	1.52
3,360-3,350	.0016	1.37	1.40	1.31	1.30	1.33	1.31
3,350-3,340	.0020	1.36	1.33	1.43	1.40	1.40	1.36
3,340-3,330	.0018	1.34	1.34	1.35	1.36	1.36	1.37
3,330-3,320	.0017	1.16	1.25	1.25	1.31	1.37	1.36
3,320-3,310	.0013	1.08	1.11	1.00	1.02	1.02	1.04
3,310-3,300	.0037	2.30	2.28	1.66	1.71	1.80	1.00
3,300-3,290	.0010	1.47	1.50	1.50	1.54	1.58	1.61
3,290-3,280	.0016	1.19	1.20	1.22	1.31	1.32	1.34
3,280-3,270	.0017	1.32	1.38	1.39	1.45	1.48	1.53
3,270-3,260	.0014	1.47	1.49	1.50	1.32	1.34	1.33
3,260-3,250	.0025	1.33	1.41	1.38	1.55	1.59	1.63
3,250-3,240	.0029	1.77	1.98	2.05	2.40	2.52	2.64
3,240-3,230	.0020	1.44	1.47	1.54	1.65	1.66	1.37
3,230-3,220	.0029	2.70	2.71	2.79	2.93	3.01	1.97
3,220-3,210	.0017	1.29	1.33	1.36	1.39	1.44	1.42
3,210-3,200	.0016	1.29	1.30	1.34	1.44	1.48	1.53
3,200-3,190	.0012	1.03	1.05	1.04	1.04	1.04	1.05
3,190-3,180	.0021	1.63	1.58	1.69	1.73	1.90	1.92
3,180-3,170	.0021	1.63	1.58	1.69	1.73	1.90	1.92
3,170-3,160	.0014	1.26	1.43	1.40	1.33	1.41	1.51
3,160-3,150	.0015	1.51	1.62	1.72	1.83	1.94	1.96
3,150-3,140	.0015	1.19	1.25	1.35	1.38	1.43	1.41
3,140-3,130	.0016	1.16	1.38	1.57	1.41	1.50	1.51
3,130-3,120	.0020	2.51	2.69	1.66	1.79	1.89	1.76
3,120-3,110	.0017	1.66	1.81	1.68	1.88	2.07	2.10
3,110-3,100	.0021	1.37	1.51	1.75	2.12	2.42	2.53
3,100-3,090	.0019	1.82	1.86	2.08	2.00	2.14	2.18
3,090-3,080	.0017	1.90	2.03	2.12	2.01	2.15	2.25
3,080-3,070	.0017	1.20	1.25	1.36	1.31	1.72	1.76
3,070-3,060	.0018	1.66	1.45	1.45	1.73	1.80	1.63
3,060-3,050	.0022	1.69	1.97	2.12	2.26	2.19	2.20
3,050-3,040	.0014	1.57	1.53	1.56	1.78	1.46	1.33
3,040-3,030	.0010	1.00	1.00	1.00	1.00	1.00	1.00
3,030-3,020	.0011	1.20	1.17	1.00	1.00	1.00	1.00
3,020-3,010	.0017	1.39	1.31	1.33	1.40	1.40	1.47
3,010-3,000	.0031	2.80	3.27	3.03	3.56	3.50	1.26
3,000-2,990	.0013	1.50	1.56	1.49	1.59	1.70	----

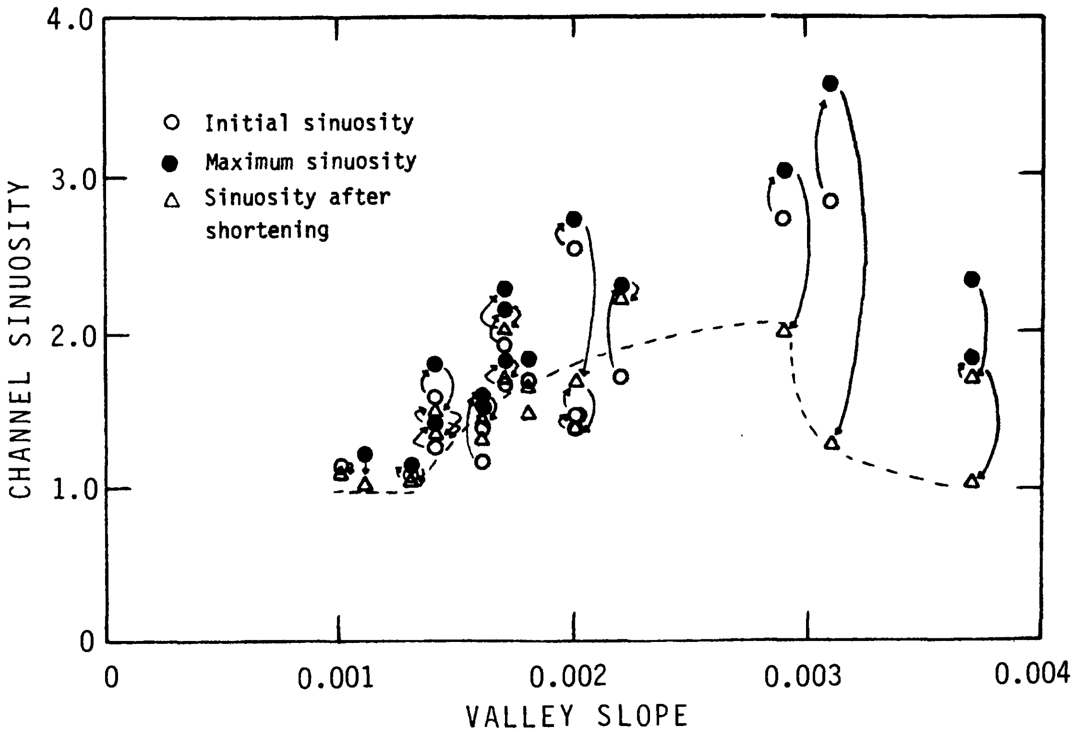

FIGURE 29.--Variation in channel sinuosity for those reaches of channel that shortened, usually through cutoff, between 1939 and 1978, Powder River between Moorhead and Broadus, Montana.

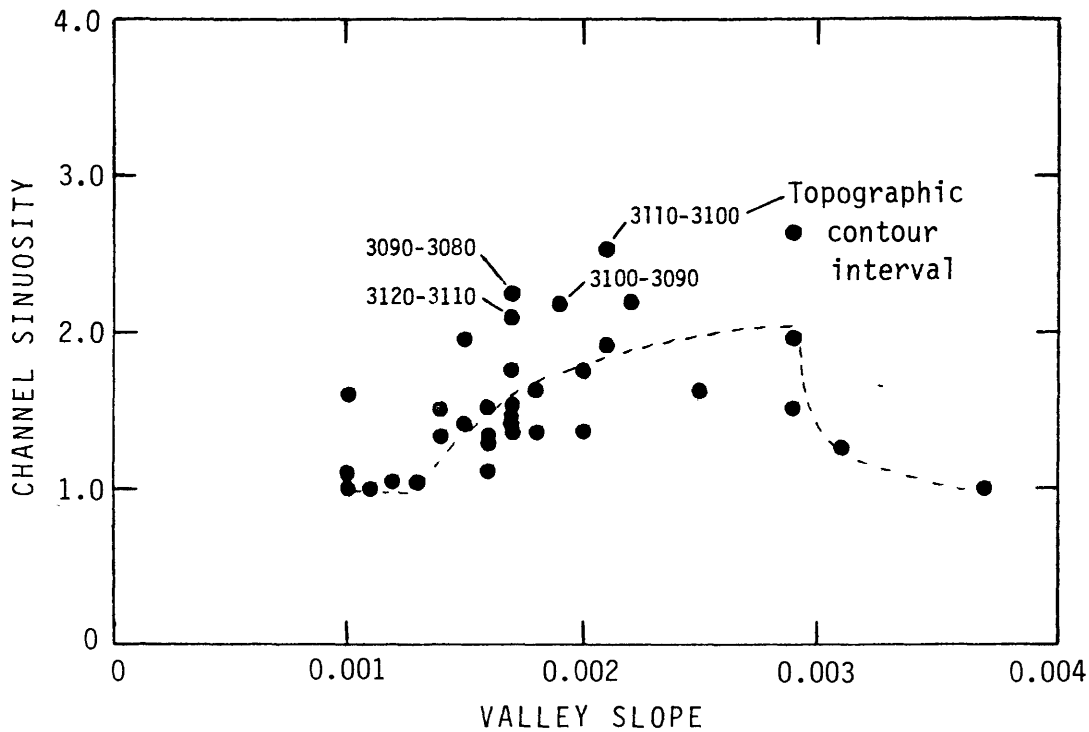

FIGURE 30.--Sinuosity of channel segments, Powder River between Moorhead and Broadus, Montana, 1978.

SUMMARY AND CONCLUSIONS

Maps constructed from aerial photographs taken during 1938-39, 1944, 1954, 1967, 1972-73, and 1978 show previous locations of the Powder River between Moorhead and Powderville, Montana. Mapped channels were adjusted to bankfull stage based on topography and the distribution of vegetation. A photogrammetric stereoplotter and scale-stable basemap and map materials were used to maximize horizontal control and accuracy of the mapped channels.

For the reach between Moorhead and Broadus, Montana, relations between bank erosion measured from historic channel maps and water discharge for the 40 yr of concurrent photographic coverage and daily mean discharge and peak-flow data were examined. Relations between the area of bank erosion during periods of time delimited by the maps and the number of days that mean discharge equaled or exceeded about 5,600 ft^3/s, and between area of bank erosion and the number of times peak discharge equaled or exceeded 9,400 ft^3/s were identified.

Values of bankfull discharge and effective discharge were computed for the Powder River from water and sediment records for Moorhead and Broadus. Flow-recurrence frequency and flow-equation techniques produced similar values for bankfull discharge. A value for bankfull discharge of 5,600 ft^3/s determined by the flow-frequency technique was used in this study. The effective discharge for total-load transport was 2,200 ft^3/s.

Comparison of computed values for bankfull discharge (5,600 ft^3/s) and effective discharge (2,200 ft^3/s) with the values of discharge associated with measurable bank erosion shows that area of bank erosion is related to the number of days that mean discharge equals or exceeds bankfull discharge. There is no apparent relation between the effective discharge and bank erosion.

Several years of recent onsite measurements of bank erosion at a number of monumentned sections and the corresponding discharge record for the Powder River study reach were evaluated for threshold values of discharge. Sections surveyed after sustained flow above bankfull discharge showed significant bank erosion. Little or no bank erosion occurred at flows less than bankfull discharge (5,600 ft^3/s). The channel of the Powder River is adjusted to the bankfull discharge.

The five periods of time defined by aerial photographic coverage were characterized by annual peak flows of different magnitudes and recurrence intervals. Measurements from the maps show that channel width, number and size of islands and bars, and rate of bank erosion varied through time. Following periods characterized by relatively higher annual peak flows (1967, 1978), average channel width appeared to have increased. Conversely, following periods characterized by lower annual peak flows (1954, 1973), average channel width appeared to have decreased. The widest measured channel (1967) did not coincide with the highest peak flow (1978). Changes and variability in channel width were less for upstream (near Moorhead) than for downstream (towards Broadus) reaches, probably reflecting a greater degree of bedrock control in the upstream reaches.

Changes in channel length were not distributed equally along the study reach. The variable rates of lengthening correspond to the pattern of channel deformation or lack thereof within the valley. The degree of bedrock control and local variations in valley slope are responsible for at least some of the variability in channel pattern and characteristics. Channel sinuosity and valley slope data from the Powder River between Moorhead and Broadus were used to test the concept of thresholds of channel pattern stability demonstrated experimentally by Schumm and Khan (1972). The data support the experimental results, indicating an optimum sinuosity for the Powder River and a range of sinuosities dependent on valley slope, that a channel segment can assume. Historically, most meanders that have cut off have been in reaches where channel sinuosity has been far greater that the indicated optimum.

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APPENDIX A.--Summary of correlation coefficients (r) and corresponding F statistics (F) for regressions determining the relation between the occurrence or exceedence of a given discharge, Q (measured at the Moorhead gaging station), and the area of bank erosion (measured between Moorhead and Broadus, Montana, from channel maps). Regressions are based on five observations. Leaders indicate that no statistics were computed

Discharge, in cubic feet per second	Number of days mean discharge equaled or exceeded given discharge, Q		Number of times peak discharge equaled or exceeded given discharge, Q		Sediment transported at daily mean discharge equal to or greater than given discharge, Q	
(Q)	r	F	r	F	r	F
10,000	---	---	0.98	64.0	---	---
9,900	---	---	.99	166.0	---	---
9,700	---	---	.97	53.3	---	---
9,600	---	---	.97	51.8	---	---
9,500	---	---	.98	62.6	---	---
9,400	---	---	.98	62.1	---	---
9,300	---	---	.88	10.09	---	---
9,000	0.90	12.63	---	---	0.71	7.4
8,900	---	---	.88	9.80	---	---
8,800	---	---	.88	10.40	---	---
8,500	---	---	.82	6.17	.74	8.4
8,400	---	---	.80	5.36	---	---
8,300	---	---	.78	4.52	---	---
8,000	.93	18.82	---	---	.74	8.4
7,800	---	---	.73	3.38	---	---
7,700	---	---	.71	3.07	---	---
7,600	---	---	.68	2.61	---	---
7,500	.95	25.99	---	---	.81	12.9
7,000	.94	24.64	---	---	.90	26.1
6,800	.95	27.07	---	---	.91	32.0
6,600	.94	23.55	---	---	.95	62.5
6,400	.94	24.15	---	---	.96	68.4
6,200	.93	20.35	---	---	.97	97.1
6,000	.95	30.75	---	---	.98	125.6
5,800	.97	54.7	---	---	.97	99.1
5,600	.96	35.4	---	---	.99	210.1
5,400	1.00	409.9	---	---	.94	47.1
5,200	.97	55.6	---	---	.95	55.7
5,000	.97	56.3	---	---	.91	29.7
4,800	.98	73.9	---	---	.93	44.2
4,600	.93	17.9	---	---	---	---
4,400	.93	18.1	---	---	---	---
4,200	.87	9.7	---	---	---	---
4,000	.91	13.6	---	---	---	---
3,900	.92	16.3	---	---	---	---
3,800	.92	17.1	---	---	---	---
3,700	.92	17.6	---	---	.97	30.3
3,600	.89	11.8	---	---	---	---
3,500	.89	11.0	---	---	---	---
3,400	.88	10.3	---	---	---	---
3,300	---	---	---	---	.88	22.2
3,200	.72	7.9	---	---	.86	18.5
3,100	.85	16.4	---	---	.88	22.7
3,000	.91	32.3	---	---	---	---
2,800	.96	63.0	---	---	---	---
2,600	.89	24.2	---	---	---	---
2,300	.90	28.2	---	---	.89	24.2