Channel adjustments to changing discharges, Powder River, Montana

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ABSTRACT

Sixteen years of annual surveys reveal how Powder River responds to varying discharges. During 1978, the second largest recorded daily mean discharge occurred. Cutbank migration, bed degradation, net bank erosion, and overbank deposition all contributed to increase the channel area at 12 cross sections by an average of 62%. During the ensuing years, the channel area decreased as sediment was stored in low-lying benches adjacent to the active bed of the channel.

The survey data indicate that the balance between bank erosion and deposition varies with discharge. In years when the annual maximum daily mean discharge is <60 m^3/s (a flow of 60 m^3/s has a recurrence interval of ~1.1 yr), bank erosion and deposition are approximately equal. In years when the annual maximum daily mean discharge is between 60 and ~150 m^3/s (a discharge of 150 m^3/s has a recurrence interval of ~2.7 yr), bank deposition exceeds bank erosion, and the channel contracts, often by developing benches. In years with higher discharges, the channel expands through net bank erosion. These results demonstrate that the channel of Powder River is influenced by a wide variety of formative discharges. Powder River's recent history of expansion and contraction and the development of prominent benches cannot be explained by equilibrium models based on a single, channel-forming discharge.

INTRODUCTION

River channels adjust their morphologies to transport the fluid and sediment supplied by the watershed, within the constraints provided by additional factors such as bank erodibility and channel roughness (Leopold and Maddock, 1953; Wolman, 1955; and many others recently summarized by Ferguson, 1986). However, the supply of fluid and sediment is continuously influenced by the passage of storms, changes in land use or other anthropogenic activities, the intrinsic behavior of the system itself, ongoing tectonic activity, and fluctuations in climate. As a result, river channels are in a constant state of flux, and a true equilibrium is never reached (Leopold and Maddock, 1953; Wolman, 1955). Furthermore, the characteristic time scales of channel change are typically long when compared to human life spans. Natural processes such as climatic change and tectonism occur slowly, and even rapid anthropogenic changes, such as dam construction, produce changes in river morphology that may take many decades to be fully realized (Andrews, 1986).

Because rivers evolve slowly, long periods of observation are needed to clearly establish causal relationships between controlling variables and morphologic change. However, long-term monitoring studies of river morphology are rare, though the ongoing Vigil Network program may help to alleviate this shortage (Leopold, 1962; Osterkamp and others, 1991). As a result, our ability to develop and test detailed models of fluvial processes is limited.

In this paper, 16 yr of annual surveys are analyzed to describe the evolution of the channel of Powder River in southeastern Montana. Because rates of geomorphic evolution are rapid along Powder River, and also because a large flood occurred early in the monitoring program, the data clearly illustrate how the channel of Powder River responds to flows of widely varying magnitudes.

STUDY AREA

A 95 km reach of Powder River between Moorhead and Broadus, Montana, provides the setting for this study (Fig. 1). In this area, Powder River is a meandering river with a mean annual discharge (at Moorhead) of 13 m^3/s and a mean annual flood of 159 m^3/s. The river's banks are composed of stratified sand with varying amounts of silt and clay (Martinson and Meade, 1983; Martinson, 1984; Leopold and Miller, 1954), and the bed is composed of sand and gravel. The valley of the study reach is used primarily for grazing and alfalfa production (Martinson, 1984; Martinson and Meade, 1983). The valley is not heavily irrigated, and the vegetation growing on the valley bottomlands consists primarily of cottonwood trees and small shrubs and grasses.

The Powder River is a tributary of the Yellowstone River (Fig. 1). Its headwaters lie on the eastern flanks of the Bighorn Mountains, where most of the runoff originates (Martinson and Meade, 1983) in areas underlain by Precambrian crystalline rocks and Paleozoic sandstones and limestones. Most of the sediment carried by Powder River is derived from areas of lower elevation that are underlain by sedimentary rocks of Mesozoic and younger ages (Hembree and others, 1952; Martinson, 1984; Martinson and Meade, 1983). These rocks provide Powder River with a very high suspended sediment load, averaging 2–3 million metric tons (t) of suspended sediment per year, equivalent to a sediment yield of ~400 t/km^2/yr (Moody and Meade, 1990).

Annual precipitation in the watershed of Powder River varied from <300 to >500 mm during 1939–1991 (National Oceanic and Atmospheric Administration, 1939–1991) (calculated by averaging data obtained at Casper Airport, Gillette, and Sheridan Airport in Wyoming) (Fig. 1). Most of the runoff and most annual peak discharges are related to snowmelt events between May and July. The flow of Powder River at Moorhead is weakly influenced by three small reservoirs in Wyoming with a combined maximum capacity of 4.4×10^7 m^3 and also by small diversions for irrigating 24 400 ha (U.S. Geol. Survey, 1991).

Values of the maximum daily mean discharge for each water year between 1939 and 1991 for the gaging station at Moorhead are

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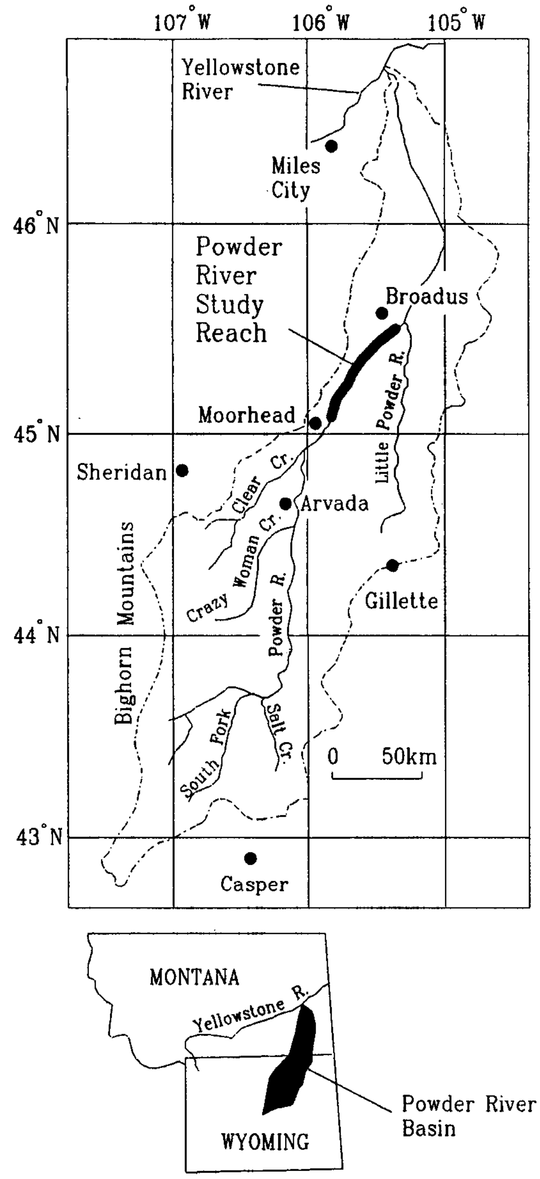

Figure 1. Locations of Powder River basin and the study reach (after Moody and Meade, 1990).

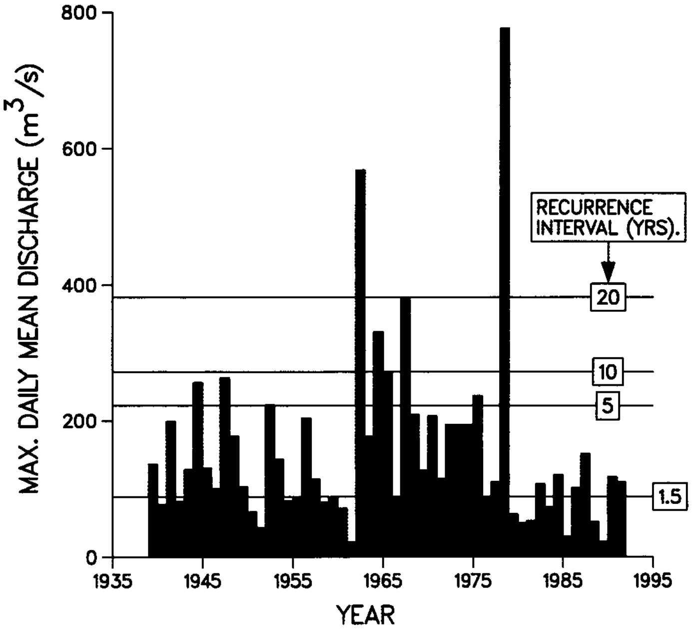

Figure 2. The annual maximum daily mean discharge at Moorhead, Montana, for water years 1939–1991.

illustrated in Figure 2. Discharges with selected recurrence intervals are also indicated for reference. Recurrence intervals are calculated using the Weibull formula $(n + 1)/m$ (Singh, 1992), where n is the 63 yr of record between 1939 and 1991 at Moorhead and m is the rank of a particular annual maximum daily mean discharge. The Weibull formula was selected because of its simplicity and also because the data deviate systematically from theoretical distributions such as the Log-Pearson Type III commonly used to estimate recurrence intervals (U.S. Water Resources Council, 1981).

Figure 2 indicates that the highest daily mean discharge (778 m^3/s) occurred during 1978 (a larger discharge occurred in 1923, before the gaging station at Moorhead was established in 1929). Discharges with recurrence intervals of 2.7 yr or less occurred from 1979 to 1991. The survey data described below were obtained from 1975 to 1991; thus the surveys document the effects of relatively large and relatively small maximum daily mean discharges during these years.

METHODS

The first cross sections at the study reach were surveyed in 1975 and 1977 by R. H. Meade and his associates at the U.S. Geological Survey. Since then, nearly all cross sections have been surveyed annually by R. H. Meade, J. A. Moody, and other U.S. Geological Survey personnel, except in 1981 and 1983. Data were obtained using an optical level, tag line, and stadia rod. The accuracy of the surveys was discussed in detail by Moody and Meade (1990), who also presented detailed maps locating the cross sections and the raw survey data for 1975–1988.

The goal of this study is to describe changes in cross sections of Powder River, which are correlated with changes in discharge. However, the magnitude of geomorphic change along a river is not only related to discharge, but also to local factors. For example, rates of geomorphic change at meandering reaches may be different from rates observed at braided reaches. Similarly, cross sections located at or near cutoffs should evolve at different rates from cross sections which are not influenced by cutoffs.

To reduce the potentially overwhelming influence of these local effects, only 12 of the 23 cross sections listed by Moody and Meade (1990) were included in the present analysis (Table 1) (an overview of patterns of erosion and deposition at all 23 sites through 1988 is provided by Moody and Meade [1990]). These 12 sections are located at single-thread, straight or meandering reaches that have not been abandoned by cutoffs and that have been observed throughout the full duration of the study. Of the sites that were not selected, five are located at or near cutoffs, two are located at islands, one is located within 100 m of another site which was selected, and three are no longer normal to the primary orientation of the channel

TABLE 1. PLANFORM CLASSIFICATION OF STUDY REACHES*

Site no.[†]	Classification
116	Straight
120	Straight
125	Crossover
130	Bend
147	Straight
151	Straight
156	Straight
163	Bend
167	Bend
180	Crossover
183	Bend[§]
194	Crossover

*After Moody and Meade, 1990.
[†]River distance in kilometers downstream from the mouth of Crazy Woman Creek near Arvada, Wyoming, as shown in U.S. Geological Survey maps of 1946 (Martinson and Meade, 1983).
[§]River pattern influenced by bedrock valley wall just downstream.

because the channel has migrated obliquely to the plane of the cross section.

To document the temporal evolution of the channel, the following fluvial landforms were defined at each cross section: the active bed, right and left banks, bench, and valley flat (Fig. 3). Generally, the active bed and the banks were defined by inflections in the cross sections (Fig. 3). Benches are "actively accreting flat-topped bodies of sediment occurring along the banks of a stream channel" (Woodyer and others, 1979); their occurrence and evolution will be discussed in greater detail below. The valley flat is defined here as a strip of relatively smooth land bordering a stream without regard to how frequently this surface is inundated or to how this surface is formed. The term *valley flat* is adopted here in preference to the term *flood plain* to avoid difficulties in distinguishing between the "active" flood plain of Powder River and terraces which have been defined in the area by Leopold and Miller (1954).

The valley flat was located by defining inflection points between the sloping channel banks and the relatively flat surface bordering the river. Two inflection points, one for each bank, are defined in this manner; the lower of these was used to define the bankfull elevation of the channel (relative to the datum of the surveys, which is given by Moody and Meade [1990] in meters above sea level). The term *bankfull elevation* is adopted here for convenience without implying any specific recurrence interval for flows reaching the bankfull stage.

The bankfull elevation was defined primarily to provide a vertical datum for calculating the extent of overbank deposition caused by the flood of 1978. Where the inflection points described above were difficult to locate precisely, the location of the boundary between the bank and the valley flat (as defined by the horizontal distance from the local reference pin) was simply carried over from the previous survey. This method provided an unambiguous, objective, and precise means of calculating changes in the bankfull elevation between surveys. Furthermore, because changes in the bankfull elevation only occurred between the 1977 and 1978 surveys, the definition of the bankfull elevation adopted here only influences the results for those years.

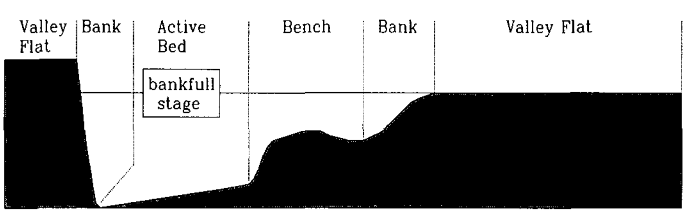

Figure 3. Definitions of fluvial landforms at a typical cross section of Powder River and the adjacent valley flat.

Areas of erosion and deposition were calculated between successive surveys by "linearly interpolating the elevations between horizontal locations at every 0.1 m for both surveys and then summing separately the positive (deposition) and negative (erosion) differences in elevation. This method approximates the area as a sum of narrow (0.1 m wide) rectangular strips" (Moody and Meade, 1990, p. 17). These calculations were completed for the entire surveyed cross section, as well as for each landform (that is, the banks, bed, benches, and flood plain). Occasionally, the cross section had migrated beyond the previously surveyed endpoints, and in these instances, the previous cross section was extrapolated to estimate areas of erosion and deposition.

The surveys represent annual observations of fluvial landforms of Powder River. To explain the changes observed between successive surveys, the magnitude of the annual maximum daily mean discharge is used to represent the intensity of fluvial processes. This approach ignores the possibility of multiple channel-forming events occurring during the same year. For example, more than one hydrograph with a peak daily mean discharge larger than that of the 1.5 yr flood occurred in 1978, 1982, 1984, and 1987. Using a single discharge to represent the intensity of fluvial processes during these years of multiple high flows undoubtedly introduces some errors into the results. However, because no observations are available to define the effects of these individual flows, they are not explicitly accounted for here.

To characterize sediments deposited in the benches, samples were obtained from the bench sediments at site 120. The sediments were soaked in hydrogen peroxide to remove organic material, and then they were wet sieved on a 4 phi sieve to separate sand from mud. The sand was sieved at 0.5 phi intervals and pipette analysis was used to determine the percentages of silt and clay. Methods of Folk (1974) were used throughout.

CHANNEL CHANGES, 1977–1978

Above-average rainfall combined with snowmelt runoff produced higher than average streamflows in early May 1978. Heavy precipitation during May 16–19, combined with runoff from earlier rains, produced high flows during May 16–22. On May 20, the highest daily mean discharge recorded by the Moorhead gaging station occurred. At many other gaging stations in Wyoming and Montana, flows exceeded the inferred 100 yr peak discharge (Parrett and others, 1978) during this storm.

The actual recurrence interval of the 1978 flood at Moorhead is difficult to estimate due to the relatively short length of record available at this gaging station. According to the Weibull equation applied to 1929–1991 data series, the recurrence interval is 64 yr. Plotting the Weibull statistic on log-log, semilog, and probability graph paper and fitting smooth curves through the data yield return periods of 64–105 yr. However, if the Moorhead gaging station had existed in 1923, the year of an even larger flood along Powder River, a recurrence interval of only 35 yr would have been obtained for the 1978 flood. Thus the recurrence interval of the 1978 flood at Moorhead is clearly <100 yr, and it is probably <50 yr.

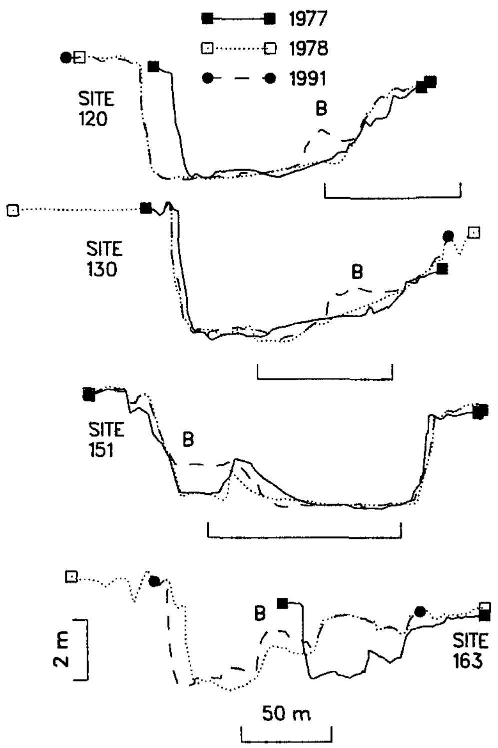

Figure 4. Cross sections of sites 120, 130, 151, and 163 in 1977, 1978, and 1991. The letter B indicates the locations of benches.

The channel of Powder River was considerably modified during the 1978 flood (Fig. 4, Table 2). The outer banks at the 12 sites migrated a mean distance of 11 m, equivalent to 30% of the active bed width of the channel (Table 2). Bank erosion averaged 36.4 m^2, or 35% of the 1977 bankfull channel area, and some bank erosion occurred at all of the sites. Bank deposition occurred at 9 of the 12 sites. Generally, magnitudes of bank erosion exceeded magnitudes of deposition. Changes in bed width were not significantly different from 0, though large changes (both positive and negative) occurred at some sites. The minimum bed elevation decreased at 10 of the 12 sites, with an average change of −0.18 m. At all of the sites, sediment was deposited on the valley flat at the margins of the channel, raising the bankfull elevation by an average of 0.3 m. (Because the surveys do not extend far beyond the channel margins, this figure should not be interpreted as an average value of accumulation for the entire valley flat.) Thus the average changes caused by the 1978 flood include channel widening by net bank erosion, scour of the bed, and deposition on the valley flat. All of these processes contributed to increase the average bankfull area of the channel by 57 m^2, an increase of 62% over the average bankfull area of the channel in 1977 (Table 2).

The statistical significance of the results of Table 2 was assessed using t-tests in addition to nonparametric Wilcoxon signed rank tests and sign tests (Ryan and others, 1985). The t-tests and Wilcoxon signed rank tests indicate that all of the results presented above are significant at the 0.05 level, except for changes in the active bed width, which are not significantly different from 0 (Table 2). The sign test provides a similar evaluation of statistical significance, except for paired observations of bank erosion and deposition at each site. According to the sign test, there is only a 0.85 probability that bank erosion exceeded bank deposition during the 1978 flood. These results differ from those obtained using the other tests, because the sign test does not account for the magnitude of the difference between bank erosion and bank deposition; it only accounts for the sign of the difference. Table 2 indicates that bank erosion exceeded bank deposition at 9 of the 12 sites and that erosion typically exceeded deposition by a wide margin at these sites. At the 3 remaining sites, bank deposition exceeded bank erosion by a relatively small margin.

CHANNEL CHANGES, 1978–1991

In the 13 yr following the 1978 flood, the channel changes along Powder River were considerably less dramatic than those revealed

TABLE 2. MORPHOLOGIC CHANGES OF POWDER RIVER, 1977–1978

Site	Outer bank migration*		Bank erosion		Bank† deposition		Change in bed width		Change in minimum bed elevation	Bankfull elevation	Change in area	
	(m)	(%)§	(m^2)	(%)**	(m^2)	(%)**	(m)	(%)	(m)	(m)	(m^2)	(%)**
116	1.0	2	−2.6	−1	1.2	1	−2.1	−3	−0.29	0.6	60	34
120	8.0	14	−43.2	−22	5.8	3	−2.9	5	−0.02	0.1	43	22
125	−0.3	0	−5.2	−3	23.1	12	−37.3	−50	−0.24	0.0	37	20
130	0.0	0	−10.1	−7	6.6	5	−14.1	−22	−0.06	0.4	39	28
147	4.0	7	−17.2	−11	0.0	0	0.0	0	−0.19	0.1	29	18
151	1.5	3	−3.5	−2	3.8	2	0.9	2	+0.10	0.2	21	12
156	21.0	39	−69.0	−78	0.0	0	28.7	53	+0.31	0.4	65	74
163	65.0	224	−172.1	−174	35.8	36	7.5	26	−0.37	0.1	44	44
167	25.0	57	−65.6	−54	12.1	10	−18.0	−41	−0.17	0.2	51	42
180	0.5	1	−17.9	−21	15.0	17	0.5	1	−0.70	0.7	57	66
183	1.0	3	−26.4	−45	0.0	0	22.0	71	−0.35	0.6	221	375
194	4.7	8	−3.5	−2	6.3	4	0.7	1	−0.18	0.2	22	14
Mean	11.0	30	−36.4	−35	9.1	8	−0.7	4	−0.18	0.30	57	62
σ††	19.0	64	−48.8	−50	10.9	10	17.3	34	0.25	0.23	53	100
Median	2.8	5	−17.7	−16	6.1	4	0.6	1	−0.19	0.20	44	31
p§§	0.00	NA***	NA	NA	NA	NA	0.79	NA	0.03	0.00	0.00	NA

*Defined by the translation of the lowest point of the outer bank.
†Includes deposition on benches.
§(Outer bank migration/1977 active bed width) × 100.
**Percent of 1977 bankfull area.
††Standard deviation.
§§Probability that the data are equivalent to a column of zeros (measured by the Wilcoxon signed rank test).
***Not applicable.

TABLE 3. MORPHOLOGIC CHANGES OF POWDER RIVER, 1978–1991

Site	Outer bank migration		Change in bed width		Change in minimum bed elevation	Bankfull area		Bank erosion		Bank deposition*	
	(m)	(%)†	(m)	(%)	(m)	(m^2)	(%)§	(m^2)	(%)§	(m^2)	(%)§
116	1.3	2	−0.3	−1	+0.10	−11.0	−5	−3.3	−1	1.8	1
120	0	0	−8.2	−14	−0.03	−15.0	−6	0.0	0	2.5	1
125	2.4	7	2.4	7	+0.26	−13.0	−7	−6.1	−3	23.5	12
130	0.1	0	−3.1	−6	+0.05	−7.0	−4	−0.5	0	17.1	10
147	4.0	7	−9.7	−6	+0.37	−4.0	−2	−1.3	−1	9.0	4
151	−0.6	−1	−27.6	−45	−0.01	−18.0	−9	0.0	0	8.7	4
156	−14.0**	−17	−11.8	−14	−0.08	−2.0	−1	−3.1	−2	21.6	14
163	10.0	27	40.5	111	+0.13	−18.0	−13	−39.4	−28	26.0	18
167	3.3	13	17.3	67	+0.07	−9.0	−5	−41.5	−24	44.7	26
180	31.4	70	37.4	83	+0.29	40.2	+28	−103.8	−72	45.3	32
183	1.0	2	−22.0	−42	+0.32	−155.0	−55	−2.8	−1	11.1	4
194	−1.4	−2	−13.4	−23	+0.03	−9.0	−5	−6.4	−3	17.3	10
Mean	3.1	9	0.13	10	0.13	−18.4	−7	−17.4	−11	19.1	11
σ††	10.5	22	21.49	50	0.15	45.7	18	31.0	21	14.4	10
Median	1.2	2	−5.65	−6	0.09	−10.0	−5	−3.2	−1.5	17.2	10
p§§	0.16	—	0.64	—	0.02	0.03	—	NA***	NA	NA	NA

*Includes deposition on benches.
†(Outer bank migration/1978 active bed width) × 100.
§Percent of 1978 bankfull area.
**Thalweg shifted across the channel.
§§Probability that the data are equivalent to a column of zeros (measured by the Wilcoxon signed rank test).
††Standard deviation.
***Not applicable.

by the 1977–1978 surveys (Table 3, Fig. 4). The mean distance of outer bank migration was only 3.1 m (9% of the active bed width); at three sites, deposition occurred along the outer bank, producing a population of positive and negative distances of outer bank migration that is not significantly different from 0. The amount of bank erosion was highly variable, with high amounts of bank erosion at sites 180, 167, and 163, and lower values elsewhere. When averaged over all the sites, values of bank erosion observed from 1978 to 1991 are slightly lower than those caused by the 1978 flood. This is confirmed by the Wilcoxon signed rank test and the sign test, which suggest probabilities of 0.92 and 0.61, respectively, that bank erosion from 1977 to 1978 exceeded bank erosion from 1978 to 1991. The mean value of bank deposition for 1978–1991, however, greatly exceeds the mean value of bank deposition for 1977–1978. The Wilcoxon signed rank test and sign test, when used to compare volumes of deposition listed in Tables 2 and 3, both indicate probabilities of 0.98 that the values for 1978–1991 exceed those of 1977–1978. Furthermore, the mean value of bank deposition for 1978–1991 exceeds the mean value of bank erosion for this period; statistical tests, however, suggest that the difference is not very significant (very significant results will be reported below, however, after grouping the results according to varying annual maximum daily mean discharges). Changes in bed width were variable; as a group, they are not significantly different from 0. The average minimum bed elevation recovered 0.13 m from the scour of the bed caused by the 1978 flood. This overall bed recovery represents the cumulative effects of increases in minimum bed elevation during 6 yr and decreases in minimum bed elevation during 5 yr (Fig. 5). No flows inundated the valley flat between 1978 and 1991; therefore, the bankfull elevations of the sites did not change. Net bank deposition and recovery of the bed caused the bankfull area to decrease at 11 of the 13 sites, for an average decrease of 7% of the 1978 bankfull area (Table 3).

BANK EROSION AND DEPOSITION

The size of a migrating alluvial channel is partly controlled by the balance between rates of erosion on the outer bank and rates of deposition on the inner bank. A similar balance may also be important in straight reaches that do not migrate. Below, the survey data are used to determine how this balance varies in response to changes in discharge.

Rates of bank erosion and deposition are partly controlled by local variables such as planform curvature that change rapidly over short distances. As a result, rates of bank processes may vary widely from site to site. Such local variability, however, is not relevant when considering variations controlled by discharge, which is essentially constant for all sites. To remove the effects of local variability, areas of bank erosion (E) and deposition (D) calculated between two successive annual surveys for a particular site were scaled by the maximum value of erosion, E_m, observed at that site during the entire monitoring period. The resulting values were then multiplied by 100 to produce dimensionless variables that quantify bank deposition and erosion between two successive annual surveys at a particular site expressed as *percentages of the largest area of bank erosion*

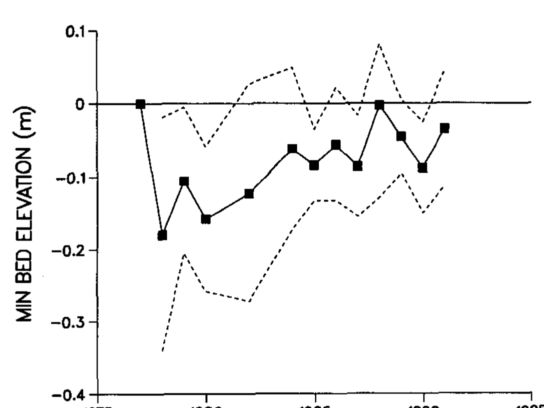

Figure 5. Cumulative changes in mean minimum bed elevation at the study sites for 1977–1991. The 95% confidence interval about the mean is also illustrated.

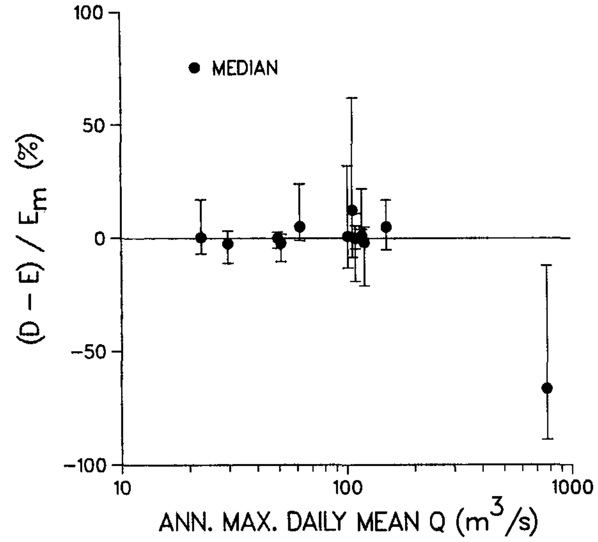

Figure 6. Median contraction-expansion factor plotted as a function of the annual maximum daily mean discharge. Error bars are standard deviations about the mean.

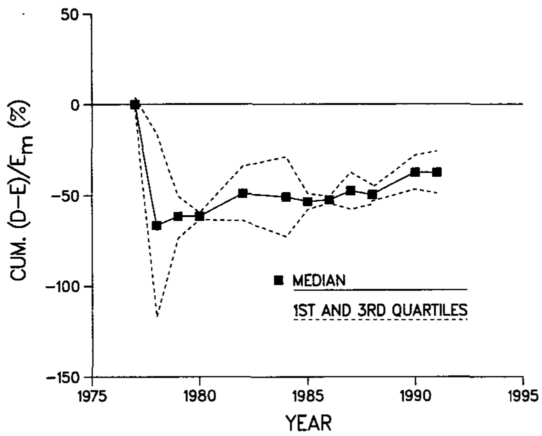

Figure 7. Cumulative changes in the median contraction-expansion factor for 1977–1991.

observed at that site during the study. This method allows very active sites, perhaps located at tight bends, to be compared with less active sites, perhaps located at straight reaches.

To more precisely determine the balance between bank erosion and deposition as a function of discharge, the *contraction-expansion factor* (CEF) is defined as $[(D - E)/E_m] \times 100$. The CEF represents the net bank deposition or erosion between two successive annual surveys at a particular site expressed as a percentage of the maximum area of erosion observed at that site. The CEF is positive when bank deposition exceeds bank erosion, and it is negative when bank erosion exceeds bank deposition.

The relationship between the CEF and the maximum daily mean discharge between successive annual surveys is illustrated in Figure 6. The plotted points indicate the median values of the CEF for all 12 sites; the error bars indicate the standard deviations about the mean. Extensive net bank erosion caused by the 1978 flood is represented by the large negative value of the CEF at a discharge of 778 m^3/s. At discharges below ~60 m^3/s, the CEF is not significantly different from 0, suggesting that neither expansion nor contraction of the channel occurs at these low discharges (the recurrence interval for an annual maximum daily mean discharge of 60 m^3/s is ~1.2 yr). CEF values between 60 and 150 m^3/s are relatively noisy. However, statistical analyses demonstrate that the data from all the sites within this range of discharge are significantly greater than 0. For example, the probabilities that the values of the CEF are greater than 0 within this range are 0.981, 1.00, and 0.993 according to a t-test, a sign test, and a Wilcoxon signed rank test (although it is not explicitly proven here, the CEF values within this range are normally distributed, so a t-test is a reasonable statistical procedure to use).

The results of Figure 6 indicate that at annual maximum daily mean discharges below ~60 m^3/s, the channel neither expands nor contracts. At intermediate discharges from 60 to ~150 m^3/s (recurrence intervals of ~1.2–2.7 yr), the channel contracts slowly, as is indicated by the median value of 0.03 for the CEF within this range of discharge. At the highest flows, such as the 1978 flood, the channel expands through net bank erosion. Unfortunately, the boundary between flows that cause net bank deposition and flows that cause net bank erosion is very poorly defined, as only one flow with a recurrence interval >2.7 yr (the 1978 flood) occurred during the study.

Time series of cumulative median values of the CEF are illustrated in Figure 7 for 1977–1991. The dominantly erosive nature of the 1978 flood is once again evident, as is the gradual channel recovery throughout the ensuing years. Figure 7 suggests that the channel of Powder River follows an asymmetrical temporal pattern of expansion and contraction, with periods of rapid channel expansion during rare high discharges followed by long periods of gradual channel contraction and recovery. Figure 7 implies that many decades will be needed for Powder River to fully recover from the 1978 flood.

BENCH FORMATION AND CHANNEL CONTRACTION

In 1991, prominent benches (Figs. 3 and 4) were present at 10 of the 12 sites (Table 4). The term *bench* is applied to these landforms following the definition of Woodyer and others (1979), who further defined *point benches* as "arcuate benches which form . . . on the insides of bends . . . primarily by suspended load sedimentation." Woodyer and others' (1979) definition of *point benches* is

TABLE 4. BED WIDTH DATA AND THE OCCURRENCE AND CLASSIFICATION OF BENCHES IN THE STUDY AREA

Site	Bench development 1977	Bench development 1991	Bed width, 1977 (m)	Change in bed width, 1977–1991 (m)	Bench type in 1991
116	N	N	58.0	4.7	N.A.*
120	N	Y	60.0	−8.2	point
125	N	Y†	70.2	−31.2	other
130	N	Y	74.0	−27.0	point
147	N	N	81.0	−9.7	other
151	N	Y	33.0	7.0	other
156	N	Y	54.3	16.9	other
163	Y	Y†	29.0	48.0	point
167	Y	Y	44.0	0.1	point
180	Y	Y	44.5	37.9	point
183	Y	Y	31.0	0.0	other
194	N	Y	58.8	−12.7	other

†Bench developed during the May 1978 flood.
*N.A. = not applicable; no bench is present.

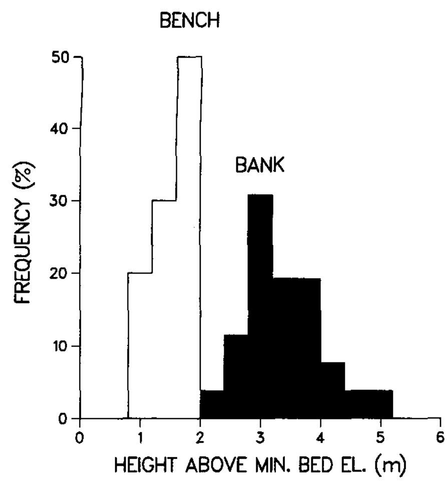

Figure 8. Histograms of bench and bank heights relative to the minimum bed elevation.

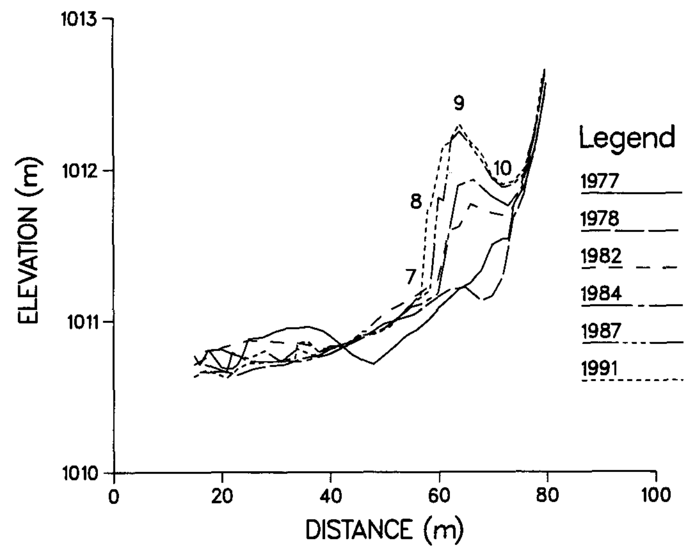

Figure 9. Successive stages in the growth of the bench at site 120. The approximate locations of sediment samples 7–10 are also illustrated.

similar to the definition of *scroll bars* in the *Glossary of Geology* (Bates and Jackson, 1987), although the basal sediments of scroll bars may not be deposited from suspension (Nanson, 1980, 1981). Benches that are not located on the insides of bends are simply classified here as *other* (Table 4). Several benches of the *other* category may actually be *concave bank benches* (Woodyer, 1975; Page and Nanson, 1982; Hickin, 1979).

Benches surveyed in 1991 vary considerably in height, with crests ranging from 0.9 m to 2.0 m above the minimum bed elevation of the adjacent channel (Fig. 8). The modal height for 17 benches at the 13 study sites is 1.7 m, considerably lower than the modal bank height of 3.0 m.

The survey data suggest that bench formation is an important process of channel contraction. For example, several of the sites with the largest active bed widths in 1977 (sites 120, 125, and 130) did not have benches (Table 4). By 1991, benches had formed at all of these sites, and the width of the active bed had decreased significantly. At two sites (151 and 156), bench formation was associated with increases in bed width; the width of the bed at these sites, however, was relatively small in 1977. Thus bench formation is a prominent mechanism for reducing the width of many relatively wide reaches of Powder River.

The spatial and temporal patterns of point bench evolution are clearly illustrated by data from site 120 (Fig. 9). Following the 1978 flood, the bed on the inside (right) bank was a gently sloping surface composed of sand and gravel (R. H. Meade, 1992, personal commun.). Between 1978 and 1991, a distinctive bench formed, with most sedimentation documented by surveys in 1982, 1984, 1987, and 1991. Although it is uncertain precisely which flows deposited the layers illustrated in Figure 9, the largest daily mean discharges during these periods had recurrence intervals of 1.1–2.7 yr. Sediment deposited by these flows consists of fine to very fine sand and silt and clay (Table 5). Trenches excavated in August 1992 revealed beds of laminated sand several decimeters thick with interbeds of massive silt and clay 5–15 cm thick (similar deposits have also been described by Hereford [1984], Taylor and Woodyer [1978], and others). The very small Rouse numbers (the Rouse number is defined in Table 5 and was discussed by Middleton and Southard [1984, p. 219]) associated with these sediments (Table 5) indicate that the benches were built by deposition from suspension. Taylor and Woodyer (1978), Woodyer and others (1979), and Woodyer (1975) also suggested that benches are built primarily by deposition from suspension.

DISCUSSION AND CONCLUSIONS

The data presented above demonstrate that Powder River expands and contracts its channel in response to variations in discharge. High discharges such as those of the 1978 flood expand the channel through net bank erosion, scour of the bed, and by raising the elevations of the channel margins during overbank flows. Lower, more frequent flows cause slow channel contraction through aggradation and, at many sites, bench formation. The relatively infrequent occurrence of rapid channel expansion, followed by slow channel recovery, results in the asymmetric pattern of channel expansion and contraction illustrated in Figure 7.

Similar processes have been described in studies of rivers in arid, semiarid, and temperate climates. Hereford (1984), Schumm

TABLE 5. PERCENTAGES OF SAND, SILT, AND CLAY IN BENCH SAMPLES FROM SITE 120

Sample no.*	Sand (%)	Silt (%)	Clay (%)	Mean (ϕ)	Rouse no. of mean†
120-1	77.2	18.9	3.9	3.3	0.10
120-2	71.8	23.3	4.9	3.4	0.07
120-3	73.6	20.2	6.2	3.4	0.07
120-4	85.2	11.8	3.0	3.1	0.12
120-5	87.3	10.0	2.7	3.0	0.13
120-6	68.2	26.7	5.1	3.6	0.06
120-7	34.5	57.4	8.1	..§	very small
120-8	94.2	4.3	1.5	2.9	0.13
120-9	64.4	30.4	5.2	3.6	0.07
120-10	12.7	28.3	59.0	..§	very small

*Samples 1–6 were collected from the crest of the bench at distances of −70 m, 110 m, 220 m, 330 m, 400 m, and −200 m from the PR120 Survey Section (positive values are upstream). Samples 7–10 are located in Figure 11.

†The Rouse number is calculated as (the settling velocity of a sphere at 10 °C) ÷ $0.4(gDS)^{1/2}$ where $g = 9.8$ m/s^2, $D = 2.0$ m, and $S = .0013$. Values ~2 indicate transport in suspension.

§Mean within the silt fraction.

and Lichty (1963), Everitt (1968), Burkham (1972), Webb (1987), Osterkamp and Costa (1987), Stevens and others (1975), and many others describe rapid channel expansion in arid and semiarid regions during large floods. Processes of channel contraction that typically require decades for completion have also been widely described (Graf, 1978; Hadley, 1961; and others cited above). Similar processes have also been described in humid temperate regions (Costa, 1974; Gupta and Fox, 1974; Williams and Guy, 1973; Wolman and Gerson, 1978), though rates of channel recovery are typically much higher in temperate regions than in semiarid and arid regions (Wolman and Gerson, 1978).

The results of this study should provide some guidance for those developing "process-based" models of river channel cross sections and planforms. Recently, several models of "equilibrium" channel morphology have been developed by (1) quantifying processes of erosion and deposition and (2) setting the rates of these processes equal at a dominant discharge (usually considered to be bankfull flow) (Parker, 1978; Pizzuto, 1984). However, models that adopt a dominant, channel-forming discharge would fail to explain the occurrence of the benches of Powder River as well as Powder River's history of expansion and contraction. A satisfactory model of fluvial processes for Powder River should consider the cumulative effects of a wide variety of flows operating over many decades. The existence of a quasi-equilibrium condition could then be demonstrated by (1) averaging rates of erosion and deposition over appropriate spatial and temporal scales and (2) demonstrating that the two are equal "to within a consensual degree" (Howard, 1982). Simpler definitions of equilibrium processes, no matter how convenient analytically, would misrepresent fluvial processes at Powder River and provide misleading answers.

These considerations are not solely of academic interest. Discharge variations caused by the operation of dams and withdrawal schemes are common in the American West. Managers are increasingly being required to operate such schemes to minimize impacts to the fluvial environment. However, if the balance between erosion and deposition varies over a wide range of discharges, and if the morphologies created over this range of discharges are significant (as they are at Powder River), then simple operating rules based on the return period of a single dominant discharge will not provide satisfactory results.

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