Erosional and Depositional Changes Wrought by the Flood of May 1978 in the Channels of Powder River, Southeastern Montana

Scientific Investigations Report 2013–5035

U.S. Department of the Interior
U.S. Geological Survey

Cover. Vertical aerial photograph of Powder River at mouth of Bloom Creek, southeastern Montana, on September 24, 1978, showing effects of May 1978 flood: cutoff of large meander, and newly deposited sediment (white areas) on terraces, flood plains, point bars, and other riparian lands (photo taken by Bill Woodcock).

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Erosional and Depositional Changes Wrought by the Flood of May 1978 in the Channels of Powder River, Southeastern Montana

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Abstract

Powder River's second largest flood of record (1919–2012) moved through northeastern Wyoming and southeastern Montana during May 1978. Within a ninety-kilometer reach of the channel in southeastern Montana, the most prominent planform effects of the flood were the growth of meander bends by bank erosion (this was most intense just downriver of bend apexes, causing 1–2 channel widths of lateral displacement) and the erosion of new cutoff channels through the necks of two large and two small meanders. Surveys of cross sections, made before and after the flood, show the responses of the channel to the flood waters, which ranged from minimal (bedrock control) to large (maximum channel curvature in unconsolidated bank and terrace deposits). Geomorphic work done during two weeks of extreme flooding in May 1978, as measured by cross-channel erosion and new sediment deposition, was approximately equal in magnitude to the work done during the two decades (1978–1998) that followed the flood.

Introduction

On the 20th of May 1978, at about seven o'clock in the evening, a flood crest on Powder River moved north across the Wyoming state line and entered Powder River County, in southeastern Montana. At that moment, the river level at the state line was higher than it had been at any time during the previous 55 years (since the great flood of 1923) and higher than it would be at any time during (at least) the three and a half decades afterwards. Had Powder River County's riparian lands been more densely populated, the flood of May 1978 would have caused considerable havoc. As it was, however, the ranchers along the river took the latest flood more or less in stride, having been taught by the 1923 flood not to build their houses and other permanent structures too close to the River.

It was our great luck, as research hydrologists, to have installed, monumented, and surveyed, during two previous years (1975 and 1977), 20 cross sections along a ninety-kilometer (km) study reach of the river in Powder River County (Moody and Meade, 1990). Our original aim in installing these cross sections was to pursue a long-term (multi-decade), low-intensity program of measuring natural changes in a channel of moderate size that transported a substantial load of sediment in a river that was free of major engineering structures. Our plan was to revisit our cross sections for a couple of weeks every year or two, in order to re-survey their profiles and monitor the rates of year-to-year changes in cross-channel configuration. Our model was the famous long-term monitoring study of Watts Branch, Md., that was instigated by Luna Leopold in 1952 and carried out over many decades (Leopold, 1973; Leopold and others, 2005; see also Leopold, 1962; and Leopold and Emmett, 1965).

The flood of May 1978, however, substantially amended our research plans. During the summer field season that immediately followed the flood, our first task was to relocate our cross sections which had each been marked only by two or three pieces of 13-millimeter (mm) rebar, 1.2 meters (m) long, driven in so that only 10–20 centimeters (cm) protruded visibly above ground. We needed to find only one rebar piece per locality, as we had previously noted the compass bearing of each cross section. At several of the more flood-altered sections, the floodwaters had removed the rebar on one side by bank erosion and had covered the rebar on the other side with new sediment. With the help of a metal detector, however, we were able to relocate 19 (all but one) of the 20 sections we had installed during 1975 and 1977. The resurvey of these 19 cross sections provided the data for the main section of this report on the effects of the flood on channel changes of Powder river.

While we were limiting our efforts to the resurvey of 19 sections in a 90-km reach of the river, however, we soon realized that we were able to develop only a limited picture of the effects of the flood. So we added two sets of observations to our program. First, we contracted with a local aerial photographer to provide us with a strip of new photographs (scale approximately 1:10,000) that showed most of the effects of the flood in Powder River valley. These photographs could be compared with those taken for a similar survey by the same photographer two years earlier, in 1976, and they proved invaluable when we were interviewing local ranchers to help us map the high-water marks and to discuss other effects of the flood on their lands. Second, we spent some weeks making systematic on-the-ground assessments of the distributions, thicknesses, and particle sizes of the new sediment deposited during 1978 on flood plains and terraces, so as to be able to estimate a flood-sediment budget for the entire segment of the river between Moorhead and Broadus, Mont. (Moody and Meade, 2008).

Resurveys have been conducted annually or biennially at all cross sections through 1998 (Moody and others, 1990; 2002) and sporadically at selected cross sections through 2012. Some of our earlier conclusions on the effects of the May 1978 flood are previously published: specifically, the meander cutoffs (Gay and others, 1998) and the deposition of new sediment on the fluvial terraces (Moody and Meade, 2008). Also published are studies of the reconstruction of flood plains during the years that followed the 1978 flood (Pizzuto, 1994; Moody and others, 1999; Pizzuto and others, 2008) and a cartographic assessment of channel changes in Powder River during the four decades preceding the flood (Martinson, 1984; Martinson and Meade, 1983). The present report focuses mainly on channel changes and on providing historical and hydrological contexts for evaluating these effects of the flood.

Powder River and the Flood of May 1978

Geologic Setting

Powder River begins on the eastern slopes of the Bighorn Mountains of Wyoming and flows northward into Montana, where it eventually joins the Yellowstone River, which is the principal tributary to the Upper Missouri River (fig. 1). Powder River's drainage area of 34,700 square kilometers (km^2) lies in the Northern Great Plains at elevations mostly between 700 and 1,500 m above sea level. The climate is semi-arid; mean annual precipitation ranges from 300 to 400 mm per year.

Powder River basin has been an area of active riverine sedimentation and denudation for tens of millions of years. Present-day landscapes of the Powder River drainage basin are formed mostly on sedimentary rocks comprising alluvial materials that were deposited in the foreland basin that developed on the eastern flank of the rising Bighorn Mountains during and after the tectonic upheaval now known as the Laramide Orogeny, some 60–70 million years ago. Sands and finer materials that had been brought in by rivers to this continental fluvial environment were mostly deposited at that time. Between and among the clastic alluvial deposits lay swamplands, remnants of which now remain preserved as substantial layers of coal (Flores, 1981; Johnson and Pierce, 1990; Diemer and Belt, 1991; Brown, 1993).

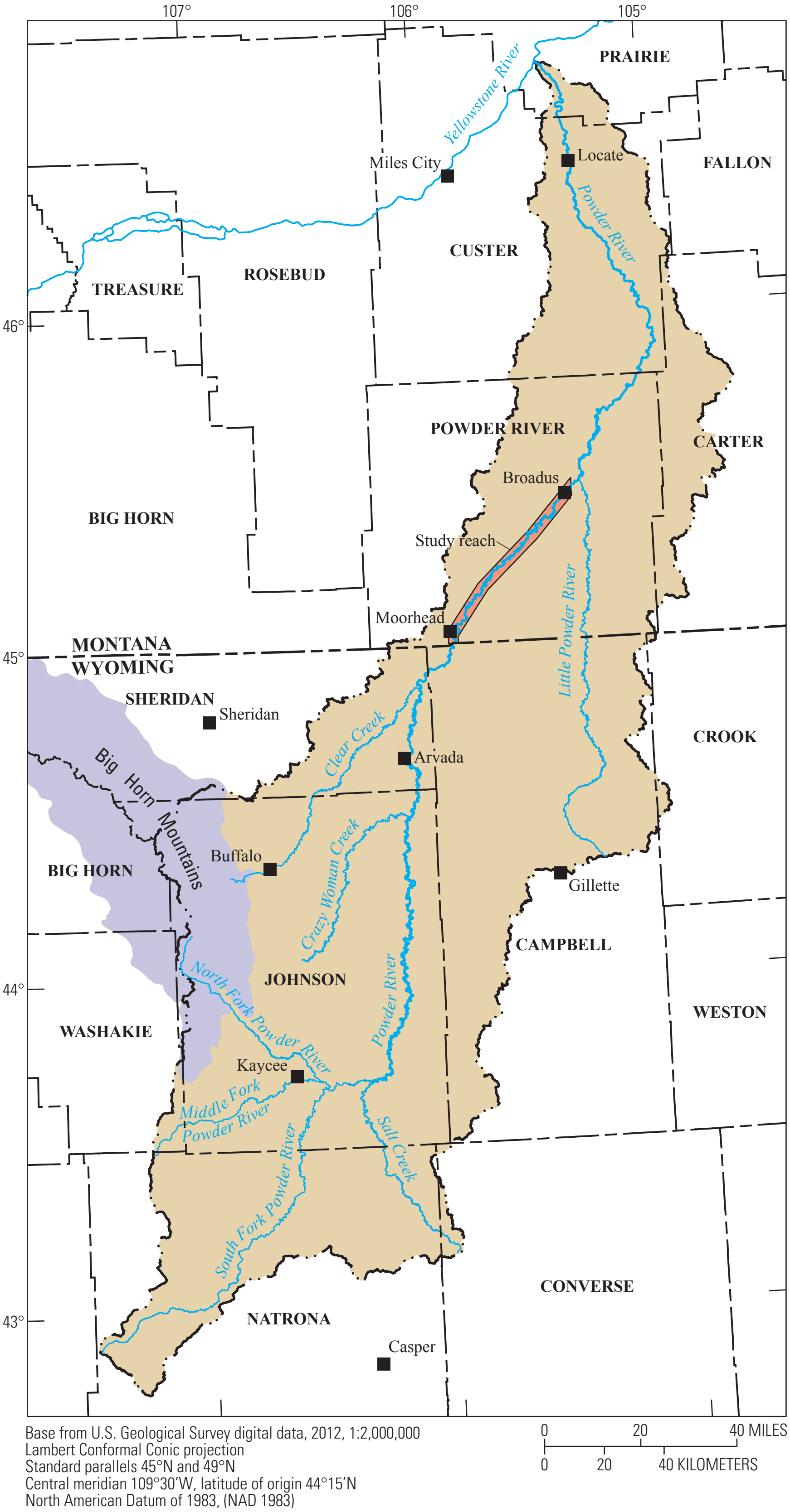
After a period of sediment accumulation that lasted for some millions of years into the Cenozoic Era, the transition was made (most likely quite gradually) from a landscape dominated by sediment deposition to one dominated by erosion. The erosional landscape that characterizes the Powder River drainage basin today (near the Wyoming-Montana border) is dominated by rimrock bluffs of flat-lying sandstone, interlayered with siltstone, shale, and coal (the Paleocene Fort Union Formation and the Paleocene-to-Eocene Wasatch Formation) that overlook a terraced valley of variable width whose thalweg accommodates the northward-flowing Powder River. Estimates based on the dates of natural burning of the outcropping coal beds place the vertical range of erosional downcutting during the last 1.1 million years at 200–400 m (Heffern and others, 2007).

Considered on a million-year time scale, the *ultimate* sources of most of the eroded materials that are being carried today by Powder River in southeastern Montana are the rocks of the Paleocene Fort Union Formation and, to a lesser extent, the Mesozoic sandstones and shales that crop out along its southernmost tributaries in central Wyoming (Hembree and others, 1952). On an annual-to-centennial (or even millennial) time scale, however, the *proximal* sources of most of this eroded material are the banks of Powder River that are actively being cut into the fluvial terraces and older flood plains. At elevations between 2 and 20 m above the present river bed stand three levels of fluvial terraces (Lightning, Moorcroft, and Kaycee) that are believed to have been formed here during the last 4,000 years (Leopold and Miller, 1954). The lower two of these terraces (Moorcroft and Lightning) were among the most active contributors (by erosion) and recipients (by deposition) of sediment that was moved during the flood of May 1978. The uppermost terrace (Kaycee) lay above the level of the 1978 floodwaters and was only eroded.

Powder River Flood of May 1978

Seen in the context of geologic time scales, the flood of May 1978 represents a mere instant in the multimillion-year continuum of movement and storage of sedimentary material in the Powder River drainage basin. It was only one of many thousands of episodes during the post-Laramide era that moved large quantities of sediment significant distances downstream. In the secular time scale of our present generation, however, it represented to us an opportunity to gain insights into the mechanisms and magnitude/frequency relations of the changes in the shape and character of the river and an opportunity to provide a fragment of the connective historical tissue that links our comprehension of past events to our ability to foresee future consequences.

Seen on the decadal-centennial time scale, the flood of May 1978 was an extreme event and was from a different flood population than the annual floods (Moody and Meade, 2008, p. 397). It was the largest on Powder River during the nine decades between 1923 and 2012 (the year this report was completed). The May 1978 flood followed an anomalous pattern of air circulation in which a stationary front was fed by southerly low-level flow that brought moisture from the Gulf of Mexico and resulted in an abnormal period of extended



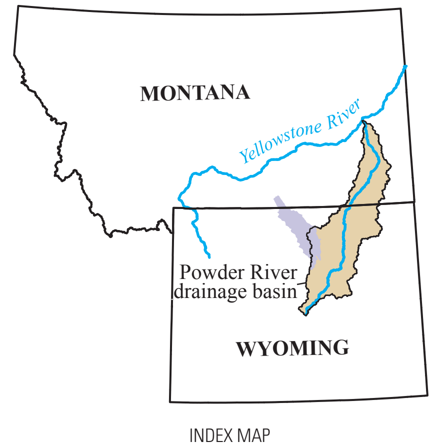


Figure 1. Index map of the Powder River drainage basin showing the locations of towns, tributaries, and the intensively studied reach between Moorhead and Broadus, Mont. For a larger-scale portrayal of the study area, showing the extent of flooding and the locations of the monumented cross sections, see plate 1.

precipitation and runoff that included rain-on-snow at low elevations and snowmelt from higher elevations (Parrett and others, 1984). During May 16–19, intense rain (maximum 128 mm) fell on ground already saturated by previous rain and snow (May 3–8, maximum 100 mm) over northeastern Wyoming and southeastern Montana (fig. 2). Rainfall at Broadus, Mont., during May 1978 totaled 180 mm: three times the long-term average precipitation during the month of May at this station (roughly 60 mm).

The shape of the flood wave was dispersed and attenuated as it moved downriver. The flood crest traveled downriver from Moorhead to Broadus at phase speeds between 3 and 5 km per hour (Moody and Meade, 2008, p. 393). The passage of the flood crest at stages higher than bankfull increased in time from 2.0 days at Arvada, to 3.7 days at Moorhead, to 4.0 days at Broadus. This dispersion and the attenuation of the height of the wave (shown in the successive graphs in fig. 3) were caused by the storage of water on the flood plains and terraces and by the delayed return flow of water back into the River.

About 50 km^2 (nearly half the valley-bottom area) of the Powder River valley between Moorhead and Broadus were inundated by the flood waters of May 1978. The patterns and configurations of high water shown on plate 1 are based on interpretations of aerial photographs taken 4 months after the flood, on discussions with local landowners, and on our own direct observations of high-water marks (such as lines of stranded debris and the upper edges of newly deposited sediment). The highest water levels shown on the map were not reached simultaneously: figure 3 shows that the flood crest was receding at Moorhead while still rising at Broadus.

The most notable changes in the planform channel configuration were: the cutting off of some channel bends; the enlargement of other bends by bank erosion that was most intense just downriver of the bend crests; and the consequent downvalley migration of meander bends, in the style illustrated by Parker and Andrews (1984, their fig. 4). These and other planform changes in the river channel are best seen in plate 1. Criteria for drawing channel boundaries on plate 1 are described by Martinson (1984, p. 8–9) and by Martinson and Meade (1983, sheet 1). The overall channel length of Powder River between Moorhead and Broadus decreased about 2 kilometers (of a total of 110 km) during the 1978 flood, which indicates that the shortening by cutoffs exceeded the lengthening by bend enlargement. This overall shortening during the flood was a reversal of the multidecadal trend recorded before the flood, in which the same reach of channel was lengthened, between 1939 and 1973, by 7 km (Martinson, 1984, p. 13; Martinson and Meade, 1983, sheet 1, table 3).

The sediment budget that we calculated in the Moorhead-to-Broadus reach of Powder River during the flood of May 1978 is shown diagrammatically in figure 4. This budget shows that, in addition to the sediment brought in from upstream by the river (as measured at Moorhead), other sediments were eroded within the reach (from terraces, older flood plains and pointbars, and from the channel itself) and entrained by the flooding waters. Sediment was newly deposited on all features except the highest (Kaycee) terrace, whose surfaces are 10–20 m above the river bed (Moody and Meade, 2008). The quantities of sediment transferred between features, or eroded from one feature and redeposited elsewhere on the same feature, exceeded the quantity transported out of the study reach (as measured at Broadus) during the flood.

Within the Moorhead-to-Broadus reach, the major inputs of freshly mobilized sediment into the flooding river waters were the results of the erosion of the channel banks—either where the channel was being expanded laterally into the riverward edges of the Moorcroft and Lightning terraces or from lower sources (erosion sources labeled as “Channel” in fig. 4). Whether these freshly mobilized sediments (portrayed in the underneath categories of “DEPOSITION” in fig. 4) eventually accumulated atop one of the terraces or in a channel-pointbar-flood-plain environment farther downriver was determined by the levels at which the river was flowing and the quantities of sediment being carried at the time. The accumulations of freshly deposited sediment atop the terraces are described in detail by Moody and Meade (2008). The erosional and depositional changes within the channel-pointbar-flood-plain environment are the subjects of most of the rest of this report. “Workload” is here defined as the transfer of sediment and the augmentation and rearrangement of the riparian riverscape. Direct comparisons are made between the work done during two weeks of May, 1978 (two weeks’ work), and the work accomplished by the river during the 20-year period 1978–1998 (two decades’ work) that followed the flood.

Effects of the Flood of 1978 on River Channels

The most significant effects of the flood of May 1978 on the channels of Powder River were the enlargement of the cross sections and the lateral-and-downvalley shifting of the channel planforms toward the concave banks of meander bends. Our cross-sectional surveys, however, do not permit us to characterize any kind of average response of the river channel to the flood. Although we had originally intended that our monumented sections be fairly randomly spaced, we were heavily influenced during their installation by practical considerations such as access to the section. Consequently, our sections were not only too few, but their spacing and placement were too selective to permit any rigorous statistical analysis of our data. We are confident, however, that our cross-sectional surveys represent the full range of channel responses during the 1978 flood, from minimal changes at bedrock-controlled locations to massive transfers of sediment and large lateral shifts of the cross-channel profile near the apexes of large meander bends that had developed in older alluvial materials. The planform perspective of channel change during the flood is shown in plate 1, onto which have been traced the channel boundaries that were shown on aerial photographs taken in

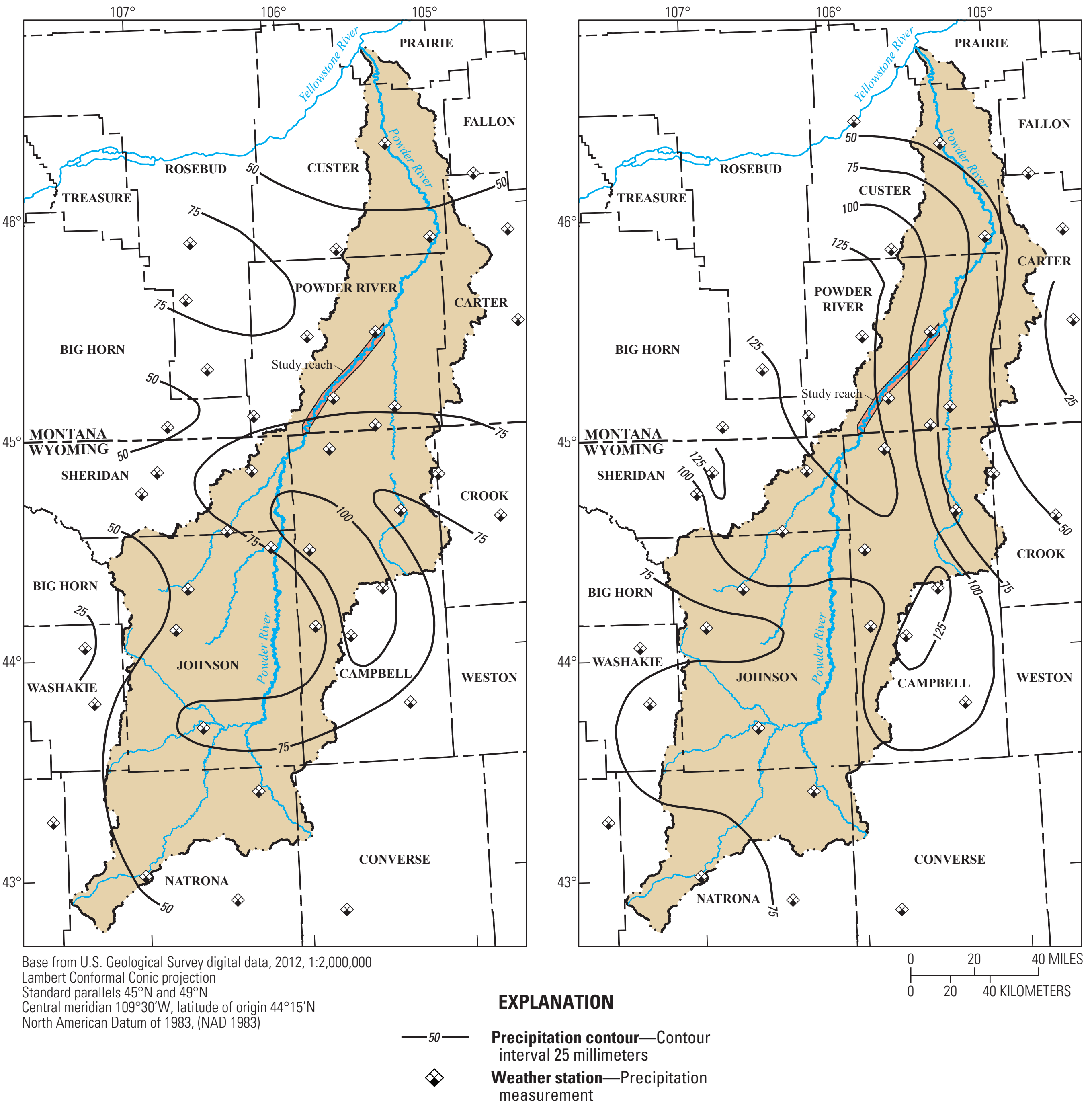


Figure 2. Isohyetal maps showing rainfall in Powder River drainage basin during two periods in May 1978. Contour interval is 25 millimeters, or approximately one inch. Left, Rainfall, May 3–8, 1978. Right, Rainfall, May 16–19, 1978. Dots on maps show locations of National Weather Service rain gages whose periods of records included the year 1978.

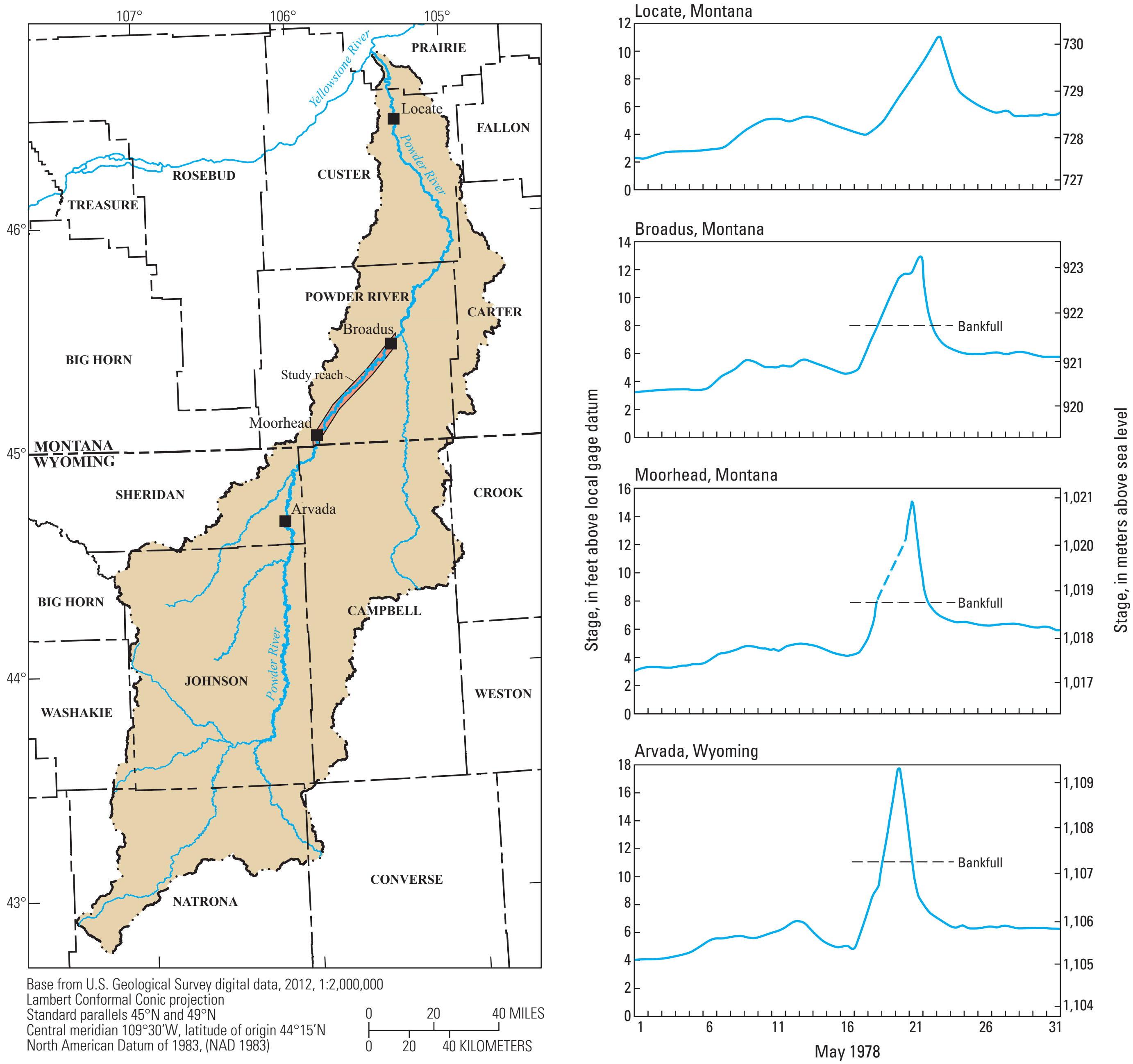


Figure 3. Graphs of stages of Powder River at four gaging stations during May 1978, showing northward (downriver) progression and attenuation of the flood wave between Arvada, Wyo., and Locate, Mont.. Indicated bankfull stages are approximate to plus or minus 0.3 m. Further hydrologic data on the flood of May 1978 are reported by U.S. Geological Survey (1979, 1980) and by Parrett and others (1984).

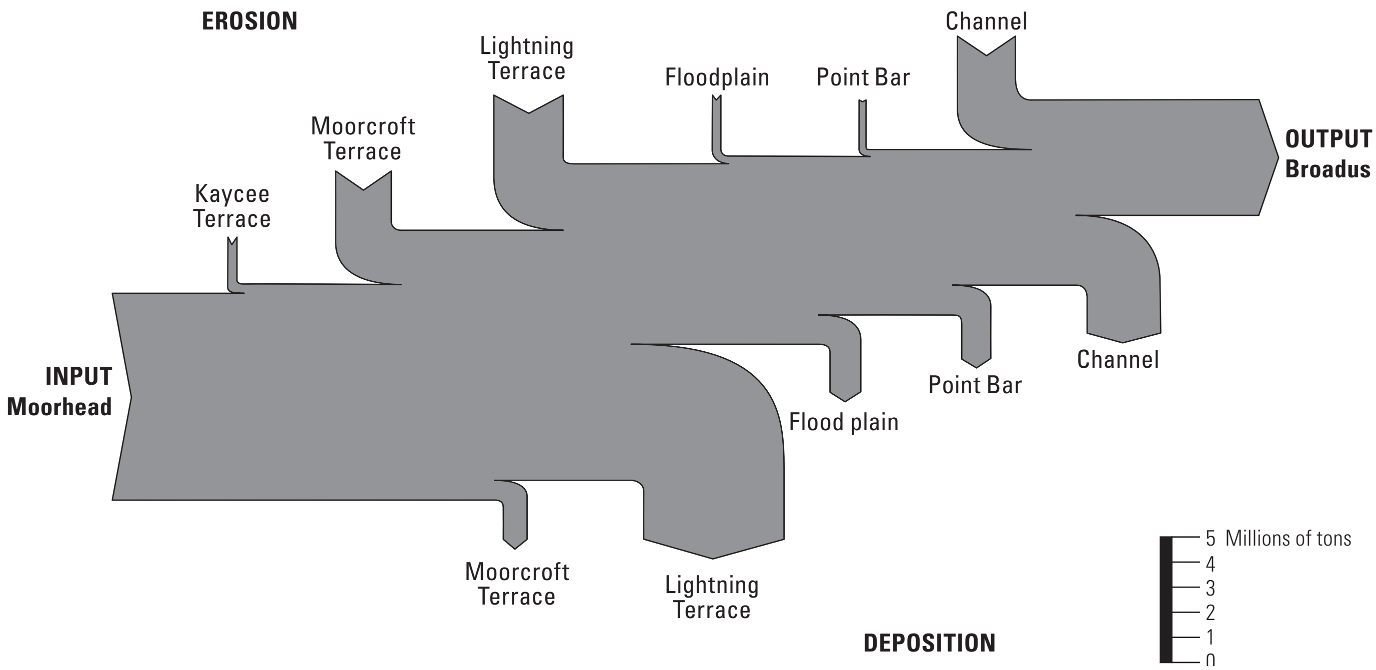


Figure 4. Sediment budget in metric tons for the 58-kilometer reach of the Powder River valley between Moorhead and Broadus, Montana, during the period 16 through May 23, 1978 (Moody and Meade, 2008). Levels of terraces above river bed: Kaycee, 10–20 meters (m); Moorcroft, 3.1–4.2 m; Lightning, 2.1–3.4 m.

1976 and in 1978 (four months after the flood). The discussion that follows in this section portrays and analyzes our data from the cross-sectional perspective.

Considerations of Scale in Portrayals of Cross-Sectional Channel Change

In graphic portrayals of cross-sectional channel change in rivers, we need to address, at the outset, the question of scale distortion. In the smallest streams, the proportions of channel width to channel depth are such that graphic representations can be clearly conveyed without any distortion of the natural scale. See, for example, the frequently cited cross section of Watts Branch, Md., presented by Leopold and others (1964, p. 325; also Leopold, 1994, p. 157), that has become an iconic paradigm in the literature of fluvial channel change. As rivers become larger, however, we must reckon with the fact that they widen faster than they deepen, and that portrayals without some degree of vertical exaggeration become progressively more difficult to interpret. A hydraulic-geometry figure published by Leopold and Maddock (1953, p. 10) shows that, as a river increases from the size of a Watts Branch to the size of (specifically) Powder River at Moorhead, Mont., its mean width can be expected to increase by a factor of ten while its mean depth can be expected to increase only by a factor of two. We take this as a suggestion that, if we are to convey an optimal quantity of useful information in a familiar format, we should exaggerate our vertical scales by a factor of five. (See also the discussion of these aspects of downstream hydraulic geometry given by Emmett, 1975, p. A31–A34.)

The cross-sectional manifestation of erosional processes has an aspect ratio rather different from that of depositional processes. River-bank erosion by nature removes vertical “slices” of sediment whose heights are much greater than the layers of sediment laid down by depositional processes; yet erosional widths are generally much smaller than the depositional widths. If we are interested only in the portrayal of erosional processes in the horizontal dimension, then perhaps the undistorted section (1:1, with no vertical exaggeration) can convey the basic information. If, however, we are interested in the details of the depositional accumulation of smaller thicknesses of sediment over wider areas, then some vertical exaggeration becomes necessary to make them more visible. With these considerations in mind, therefore, we portray all channel cross sections in this report at a consistent vertical exaggeration of 5:1 in order to most optimally represent the manifestations of both erosional and depositional processes.

The cross-sectional data in this report are presented in graphical rather than numerical terms; they are in figures rather than in tables. Comparisons between data sets, therefore, are meant to be made visually, between figures. To assure that these visual comparisons are at least semi-quantitative, all the portrayals of cross-sectional data (figs. 5–7, 10, 12, 14, 16–19) are shown herein at the same scale. Relevant numerical data, including measurements of annual erosion and deposition, are listed elsewhere by Moody and others (2002) and by Moody and Meade (1990).

Channel Enlargement

Widening and deepening of river channels—especially those channels in the straighter reaches of the river—are the most easily anticipated effects of infrequent flooding. Different degrees of channel widening and deepening during the flood of May 1978 are shown in the cross-sectional surveys portrayed in figure 5. Allowing for the 5x vertical scale exaggeration in the figure, we can see that substantially more of the channel change came in the form of widening than came in the form of deepening. In the single exception, PR206 (second panel from the top in fig. 5), the larger increases in channel depth probably were due to the upriver progression (by headcutting during the 1978 flood) of a channel-deepening gully that had first begun to form in 1975 when a large meander was cut off about a mile downstream (see plate 1). At all 19 of our resurveyed cross sections, there was an average decrease of 0.2 m in minimum riverbed elevation (average increase of 0.2 m in maximum depth) during the 1978 flood, but this was followed by a 0.2 m average increase in the minimum riverbed elevation during the 10 years after the flood (Moody and Meade, 1990, p. 11).

Many of the local ranchers whom we interviewed during the months afterwards conveyed their perceptions that the river had deepened significantly during the 1978 flood. Their perceptions were not substantiated by our measurements, but we can think of reasons why they might have come to conclusions different from ours. First, the places where ranchers are most likely to closely observe the river on a day-to-day basis are the pumpsites: where water is pumped out of the river and into irrigation ditches to be transported to hayfields on the terraces. See, for example, the pumpsite that feeds the Randall Ditch, near section PR191, in Section 25 of Township 5 South, Range 50 East (T5S, R50E), shown on plate 1. These places are typically on high terrace banks (so as to be able to lift water high enough to produce enough head for several kilometers of downvalley flow in irrigation ditches) and most often on the concave banks of significant bends in the river. The nature of such locations puts them among the most susceptible during floods to bank erosion, which steepens the view from the banktop to the waterline and increases the perception of deepening. Second, the new sediment deposited by the flood atop the banks of the river (tens of centimeters thick in some places) raises the platform from which the river is observed. Thus, the banks were raised, rather than the river being lowered.

Bank Erosion and Channel Curvature

Bank erosion is most pronounced in the curving reaches of a river. Or, to restate the obvious in another way, river planforms develop the most curvature where the banks have been eroded most heavily. As flood flows move through channel bends, the changing angular relations between the vectors of fluid flow and the alignments of the erodible banks cause marked changes in the intensity of bank erosion. Bank erosion at any point along a bend, therefore, is an accumulative effect of the upstream varying curvature (Furbish, 1988). Bank erosion depends on the spatially varying curvature of a bend, the length of the bend, the channel width, and the actual position of the specific erosive activity within the variable curvature of the bend. It also depends on the cohesive resistance of the bank material that is being eroded.

The close association between channel curvature and bank erosion during the Powder River flood of May, 1978, can be seen best in a general inspection of plate 1. Notice that the erosion during the flood was consistently maximized near the apexes of river bends, or, more commonly, immediately downstream of the bend apexes. This association has been treated in more analytical terms elsewhere (for example, Parker and Andrews, 1986; Furbish, 1988). Our report continues the discussion by adding a third spatial dimension of observational detail where several of our resurveyed cross sections were located in eroding river bends. Next to each section in figure 6, we have included a dimensionless index (C^*) of planform curvature of the river bend (Furbish, 1988). The curvature indexes are roughly correlative with the volumes of concave-bank material eroded (areas of red color) on the graphs, but with enough scatter to suggest the important influences of other factors such as the erosional resistance of bank and bed materials.

The classic pattern of channel change in a river bend is shown in our resurvey of cross section PR167 (second panel of fig. 6): intensive erosion of the concave bank, coupled with the sedimentation of new pointbar deposits and (if the flows are large enough) new flood plain deposits on the convex bank. Or, as Leopold (1994, p. 5) states: “A natural channel migrates laterally by erosion of one bank, maintaining on the average a constant channel cross section by deposition on the opposite bank. In other words, there is an equilibrium between erosion and deposition. The form of the cross section is … more or less constant, but the position of the channel is not.” Had our survey of section PR167 been continued a sufficient distance leftward, it is likely that the cross-sectional area of deposition (shown in blue) would have equaled at least the area of erosion (in red). Our survey of overbank-sediment deposition for cross-valley section V166, which lies just upriver on the same pointbar-flood plain complex (see plate 1), yielded an average thickness of 15 cm (mostly of fine sand and silt) over a horizontal distance of 680 m. The pattern of (1) removal and transport downstream of a certain quantity of material eroded from one side of a river being counterbalanced by (2) deposition of an equivalent quantity of material on the other side exemplifies the episodic nature (in contexts both spatial and temporal) of downstream sediment transport described by L.B. Leopold and others.

This pattern can be demonstrated in rivers of all sizes, from the smallest (Leopold and others, 1964, p. 327–328) to the largest (Dunne and others, 1998; Meade, 2007). In Powder River, during a large flood, the pattern is most evident in channel reaches that have the most curvature. Comparing figures

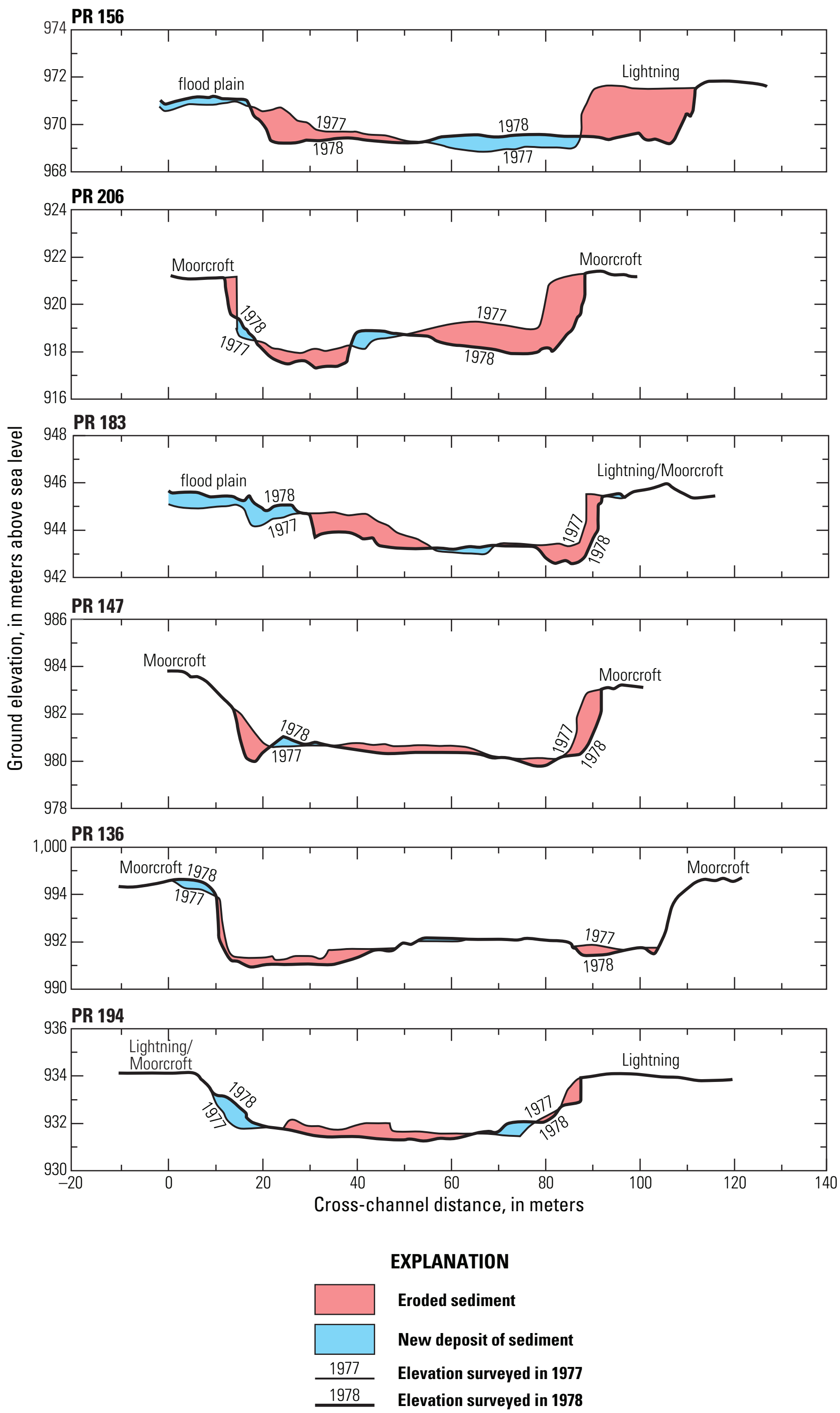
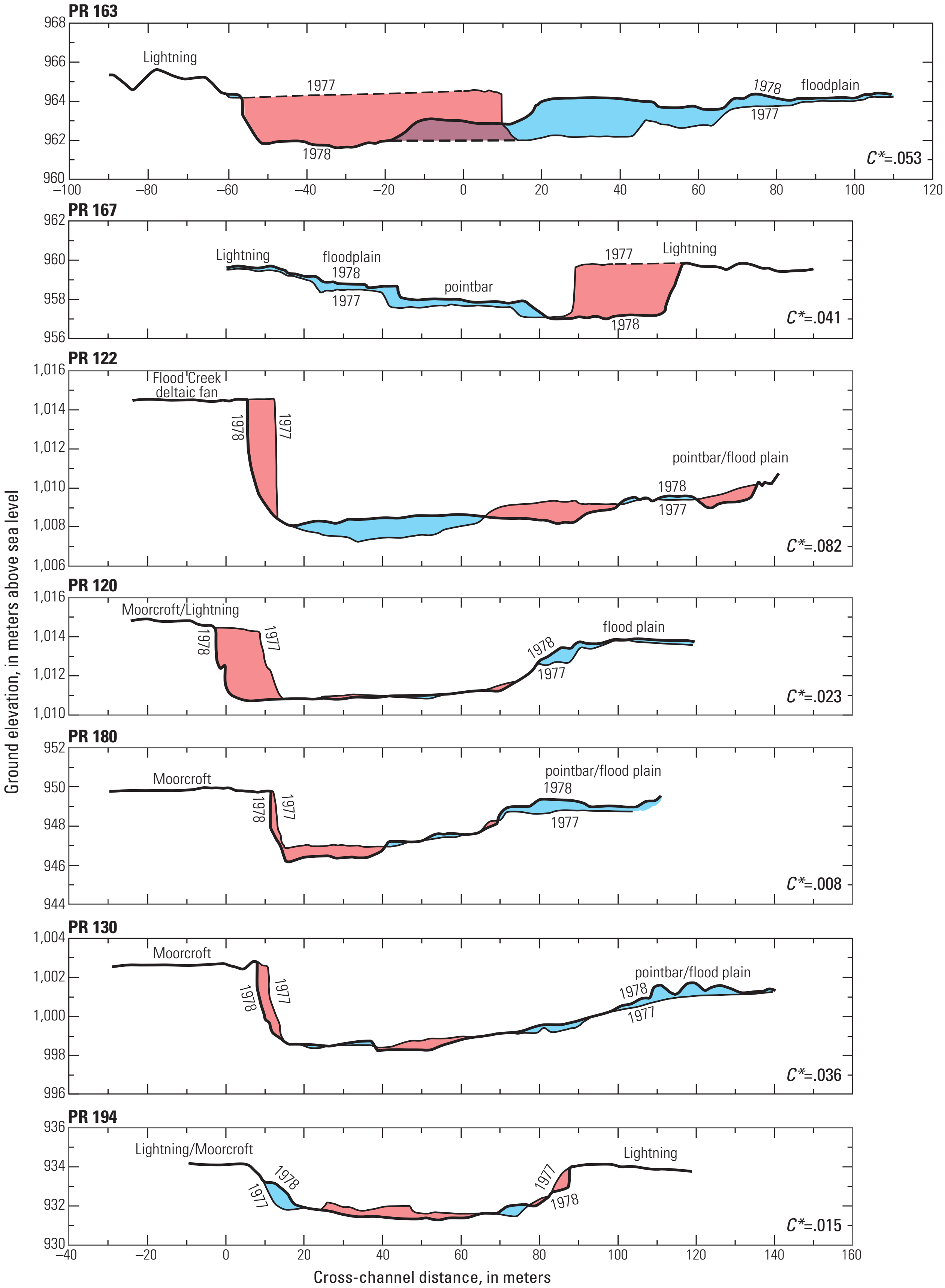


Figure 5. Channel enlargement, as measured by surveys made in cross sections of Powder River before (1977) and after (1978) the flood of May 1978. Sections are arranged, top to bottom in the figure, in approximate decreasing order of quantity of channel change. Vertical scales=5x horizontal scales. All views downriver. Cross-sectional areas of erosion tinted in red; deposition in blue. Locations of sections shown on plate 1. Complete cross-sectional survey data are reported by Moody and Meade (1990). Surfaces are identified at the ends of each section: "Lightning" and "Moorcroft" refer to terrace levels; "Lightning/Moorcroft" designates terraces that are topographically associated but chronologically disjunct (see Cohen and Nanson, 2008), for example, where occasional overbank deposition may have raised a Lightning terrace to the Moorcroft level.


PR 163
Lightning
1977
1978
1978
floodplain
1977
C*=.053
PR 167
Lightning
floodplain
1978
1977
pointbar
1977
Lightning
1978
C*=.041
PR 122
Flood Creek
deltaic fan
1978
1977
pointbar/flood plain
1978
1977
C*=.082
PR 120
Moorcroft/Lightning
1978
1977
flood plain
1978
1977
C*=.023
PR 180
Moorcroft
1978
1977
pointbar/flood plain
1978
1977
C*=.008
PR 130
Moorcroft
1978
1977
pointbar/flood plain
1978
1977
C*=.036
PR 194
Lightning/Moorcroft
1978
1977
1977
1978
Lightning
C*=.015
Ground elevation, in meters above sea level
Cross-channel distance, in meters

EXPLANATION

- **Eroded sediment**
- **New deposit of sediment**
- **Eroded and new deposit of sediment**—Area that was eroded and later filled with new sediment
- 1977 **Elevation surveyed in 1977**—Dashed where inferred
- 1978 **Elevation surveyed in 1978**
- **Elevation inferred**

Figure 6 (facing page). Erosion of banks and deposition of new sediment in curved reaches of the river channel, as measured by surveys made in Powder River before (1977) and after (1978) the flood of May 1978. Sections are arranged, top to bottom in the figure, in approximate decreasing order of channel change, which correlates approximately with the positioning of these cross sections relative to channel curvature. Dimensionless index of curvature, C*, is the reciprocal of the bend radius, multiplied by half the channel width (after Furbish, 1988). Vertical scales =5x horizontal scales. All views downriver. Locations of sections, and their positions relative to channel curvature, are shown on plate 1. Numbers on cross-channel-distance scales in the figure correspond to station numbers listed in the survey data report of Moody and Meade (1990). Further data on the overbank deposition of new sand and mud on the terraces that immediately adjoin the right side of section PR163 are given by Moody and Meade (2008, p. 395).

5 and 6, we can see the prevalence of channel enlargement (more erosion than deposition) in the straighter reaches portrayed in figure 5, and a closer balance between erosion and deposition (approximately equal areas of both red and blue) in the curved reaches portrayed in figure 6. In curved reaches, the compensatory deposition seems to follow the erosive action within days (that is, during the same flood), whereas, in the straighter reaches, the infilling of eroded areas with new sediment is accomplished over periods measurable in years to decades (Moody and others, 1999; Pizzuto, 1994; Pizzuto and others, 2008). For a more rigorous general discussion of some of these issues, see the paper by Lauer and Parker (2008) and, for the consideration of controlling factors other than channel curvature, see the papers by Gaeuman and others (2005) and by Miller and Friedman (2009).

Of the 19 cross sections we were able to survey in 1977 and re-survey in 1978, only one (PR163) was fully representative of river reaches downstream of the bend apexes: the loci of the most intensive erosion in Powder River during the flood of May 1978. The uppermost panel of figure 6 shows section PR163, in which the effects of the flood probably were typical of most of the other locations just downstream of bend apexes between Moorhead and Broadus. The concave bank was eroded back 65 m, or approximately two channel widths. The flood plain on the convex bank was augmented by more than a meter of new sediment vertically accreted over a lateral distance of about 25 m, and by a half meter of new sediment vertically accreted over another lateral distance of 25–30 m. During the later stages of the flood, an entirely new pointbar (nearly 25 m wide) was laid into the area of the section that had been occupied only a week or two earlier by a 2½-m-high terrace.

The lower five panels of figure 6 demonstrate, in the context of channel curvature, the effects of other variables on bank erosion. In sections PR122, PR120, and PR130, the apparent disparities between the observed bank erosion and the amount of erosion that might be expected from the channel curvature can be attributed mostly to differences in the erodibilities of bank and bed material. Section PR122 lies in the apex of a large meander bend where bank erosion was interrupted when the bend was cut off during the later stages of the flood (more about this in the Bend Cutoff near Flood Creek section of this report). The material being eroded in the high bank, formed in the depositional fan of the tributary Flood Creek, was more cohesive and, therefore, more resistant to erosion than bank material elsewhere. Section PR120 was located in the apex area of a broad bend of only moderate curvature in the river, but the bank material consisted of more-easily-erodible sand (mostly overbank deposits laid in by the flood of 1923 and previous flows). Although section PR130 was located in a prominent bend, the small quantity of erosion that was recorded here may have been due to the naturally outcropping ledges of sandstone and coal that form much of the underlying channel bed at this section. Sections PR180 and PR194 were at inflection points between bends, where the existing banks were so nearly parallel to the flood-flow vectors that little lateral erosion was possible.

Cutoffs of Channel Bends

Owing to the placement of our measured cross sections, we were able to record some of the effects of meander-bend cutoffs at four locations between Moorhead and Broadus on Powder River during the flood of May 1978. Two of the cutoffs were of large bends, one near the mouth of tributary Bloom Creek (section PR141) and the other near the mouth of tributary Flood Creek (section PR122). Although these two large bends were similar in size and curvature before the flood (see plate 1), their cutoff histories were different: the cutoff near Bloom Creek was completed during the early stages of the flood, and the cutoff near Flood Creek was completed during the later stages. At two smaller bends (figs 7 & 8), we also were able to observe some of the effects of cutoffs during the flood of May 1978, where we happened to have placed another two of our cross sections (PR175 and PR191).

We begin with the cutoffs of the two smaller bends. At one of these, in which we had located section PR175, we were able to reconstruct the effects of the entire progression of the 1978 cutoff, including the initial erosion and then abandonment and filling of the old bend, and the scouring of the new channel that crossed the neck of the old bend. (See plate 1 and

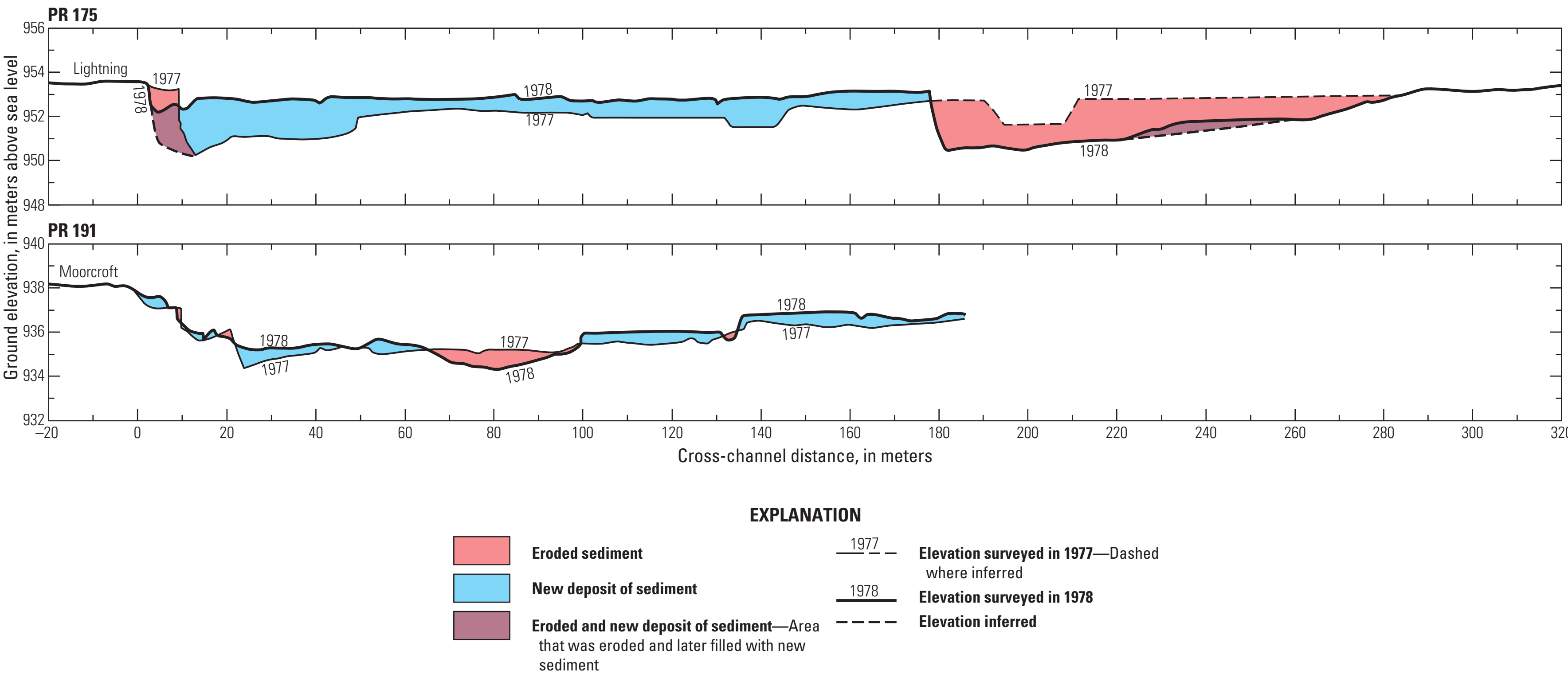


Figure 7. Two cross sections of Powder River that were at or near the apexes of smaller bends where cutoff channels were formed, and in which channel curvature was decreased, during the flood of May 1978. Both views downriver. Vertical scales exaggerated 5x. Numbers on cross-channel distance scale in the figure correspond to station numbers listed in the data report of Moody and Meade (1990). Locations of sections, and plan views of channel change during the flood, are shown on plate 1. Upper, Section PR175. Elevations of 1978 surface (post-flood) are based on a complete survey between stations -20 and +320. Surveyed elevations are complete for 1977 only between stations -2 and +149. Elevations of 1977 surface between stations +150 and +179 were determined in repeated surveys during the two decades following the flood, as the section was progressively eroded (Moody and others, 2002, p. 238–243) and the thicknesses of the 1978 sediment layer could be measured in the retreating cutbank. Elevations of the 1977 surface between stations +180 and +320 are estimated from examinations of pre-1978 aerial photographs and inferred from our visual inspections of the ground while we were conducting the 1978 survey. Lower, Section PR191, showing rightward shift of active channel thalweg by some 55 meters, and filling of the previous channel with new sediment. Further information on the overbank deposition of new sand and mud on the terraces that immediately adjoin the right side of section PR191 (to cross-channel distance of 578 m) is given by Moody and Meade (2008, p. 396).

Figure 8. Powder River at section PR175 during the falling stages of the flood, on May 25,1978. View upriver. Note that the upriver perspective on section PR175 in this photograph is the reverse of the downriver perspective shown in the cross section in figure 7. Center of photo shows the main flow of Powder River coming toward the viewer (along the left margin of the photograph) and through the new cutoff channel formed only days earlier, while newly deposited sediment on the old pointbar (right center of photograph) and in the old channel (narrow channel along the bend apex, far right center of photograph) is being exposed to view by the falling waters. The now-abandoned arcuate older channel in the farther center of the figure was for some decades the main channel of Powder River until, at some time during the late 1940s or early 1950s, it was cut off artificially (Martinson and Meade, 1983, Sheet 2). Rice ranch house near the right margin of the picture. For further assistance in orientation, compare the photograph (view south-southwest) with plate 1 at Section 15 of T6S, R50E.

the upper panel of fig. 7.) During the rising stages, the flood waters eroded the old cutbank at the meander apex (between stations 0 and +10) laterally for a distance of about 7 m. When the river rose high enough to pass through a low swale (inferred to have been near station +200) across the neck of the bend, most of the force of the flow was diverted into it, in response to the local increase in downriver gradient. This began the further excavation of the new channel. Meanwhile, the older, outer sections of the bend (stations +2 to roughly 180) were receiving deposits of new sand that averaged about 1 m in thickness on the old pointbar and eventually reached 2 m in the old channel. A photograph of section PR175, taken during the falling stages of the flood, is shown in figure 8.

At the other small bend (section PR191: lower panel in fig. 7), some of the same cutoff processes were demonstrated, but to a much lesser degree than those from section PR175. It may be worth mentioning that both these reaches of Powder River had been subjected to artificial modification during the decades preceding the May 1978 flood: section PR175 crosses the path of an artificial cutoff that was made during the late 1940s or early 1950s (Martinson and Meade, 1983, Sheet 2), and section PR191 is a short distance upriver of a failed experiment at erosion control by lining the concave river bank with automobile bodies. These artificial activities may have destabilized these river reaches sufficiently to render them more susceptible to change during the flood.

Bend Cutoff near Bloom Creek

The most spectacular cutoff of a bend along Powder River between Moorhead and Broadus during 1978 was that of the large bend at the mouth of Bloom Creek (see Section 29 of T7S, R49E on plate 1). It breached the meander neck early in the flood, so that the rising flood waters were able to scour out a fairly wide new channel before they subsided. Local rancher Hubert Gay had pointed out to us during initial conversations in 1975 that the normal flow of the river in this large bend over the years had become "boggy and slow." Across the neck of the meander, furthermore, there had already formed a head-cutting gully—of the type described by Gay and others (1998) and by Smith and Pearce (2002)—that was within a few meters of breaching the upstream bank of the neck. During the flood of May 1978, members of the Gay family were able to observe the rising water as it went slack in the old meander loop and began to flow rapidly across the meander neck (Gay and others, 1998, p. 657). Aerial views of this meander before and after the breach of 1978 are given in figure 9.

Powder River appears to have first deposited substantial sediment before the completion of the main erosion process that formed the cutoff across the neck of the Bloom Creek bend. The old channel filled with more than 1 m of new sediment (fig. 10, upper left), most of which probably was laid in before the cutoff had diverted the main flood flow. We are uncertain as to whether this accumulation of sediment at section PR141, in the bend that was about to be cut off, was an essential cause or a secondary consequence of the cutting-off process.

Erosion began as scouring of the new cutoff channel in the pre-existing headcut gully near cross-channel distance +180 (fig. 10, middle right) and spread leftward some 150 m, eroding a new cutbank as it went. New pointbar deposits were laid in, probably during the falling stages of the flood, between stations +30 and +80. More sediment was removed during the flood than was removed from section PR141A during the two decades that followed the flood (fig. 10, lower right). However, the post-flood erosion was accompanied by much more new deposition of sediment on the flood plain and pointbars of section PR141A.

Bend Cutoff near Flood Creek

The flood of May 1978 cut off another bend, at the mouth of tributary Flood Creek, that was nearly as large as the bend at Bloom Creek (see Section 28 of T8S, R48E on plate1). The planform of this meander bend had been shifting steadily downvalley; it had shifted by half a kilometer in the four decades since 1939 (Martinson and Meade, 1983, sheet 1). Unlike that of the meander bend near Bloom Creek, however, the neck of this meander did not include any previously gullied depressions that could facilitate a cutoff by the overflowing flood waters. At least four of these headcutting

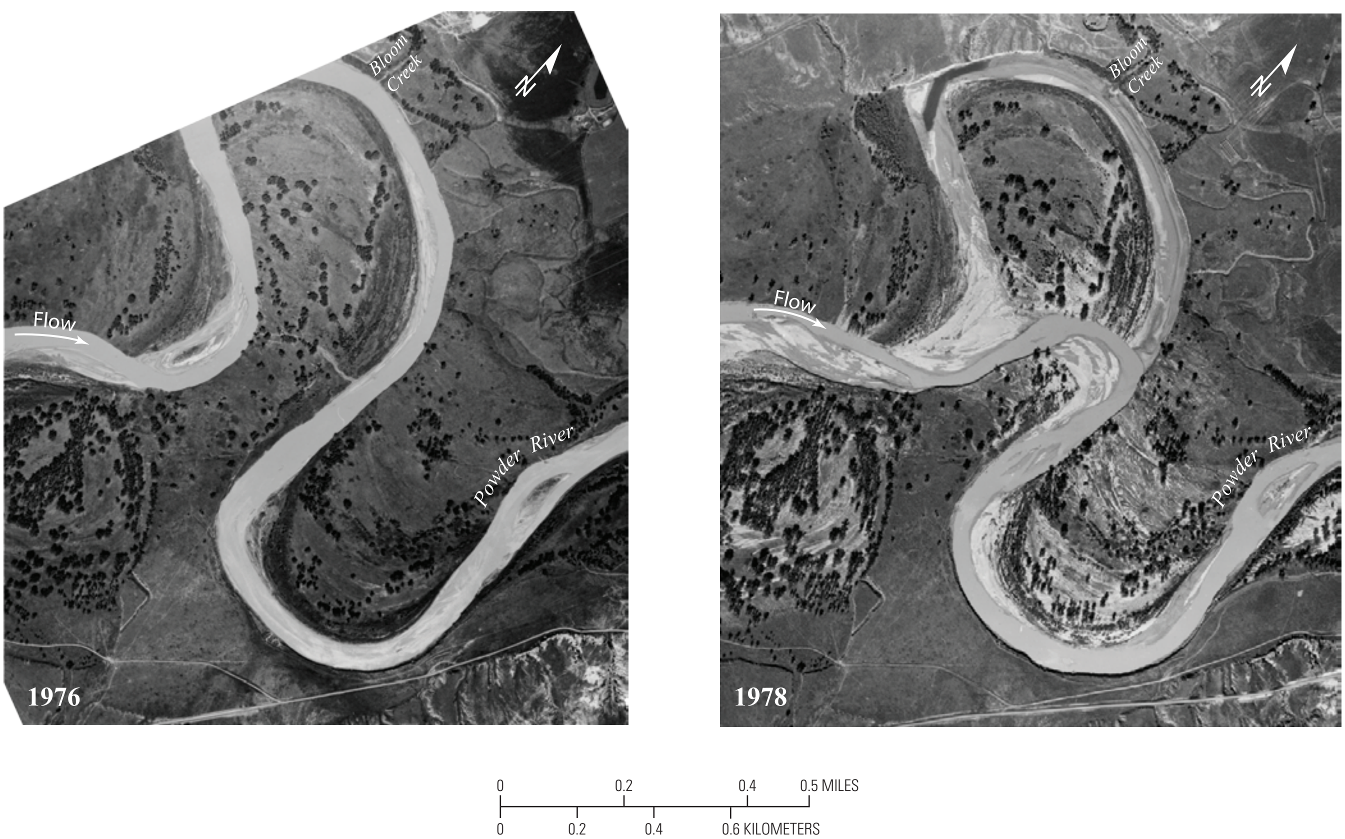
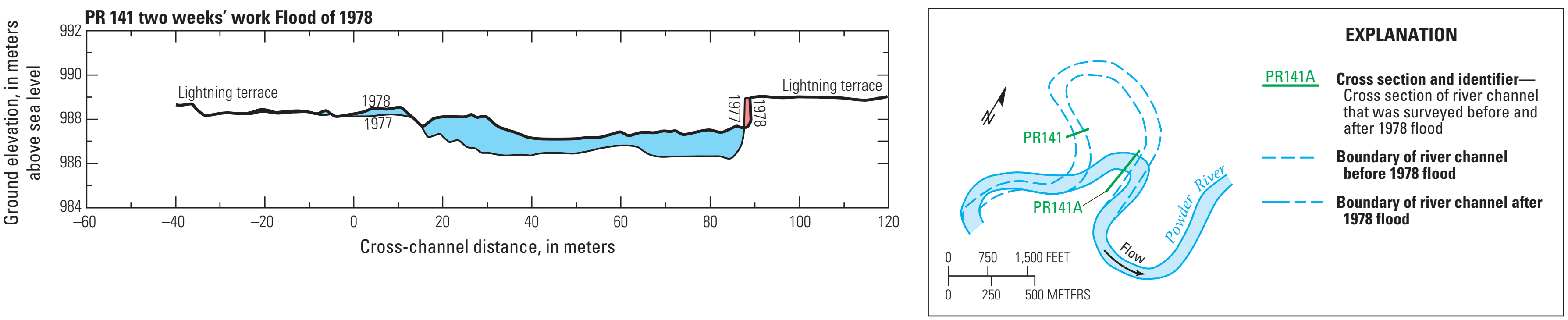


Figure 9. Aerial photographs of Powder River near Bloom Creek taken before (1976) and after (September 1978) the flood of May 1978. Photos by Bill Woodcock of Miles City, Mont. River flow is from left to right. Note, in center of 1976 photo (left), the headcut gully that was to initiate the breach and become the new main channel when the meander bend was cut off in 1978 (right).



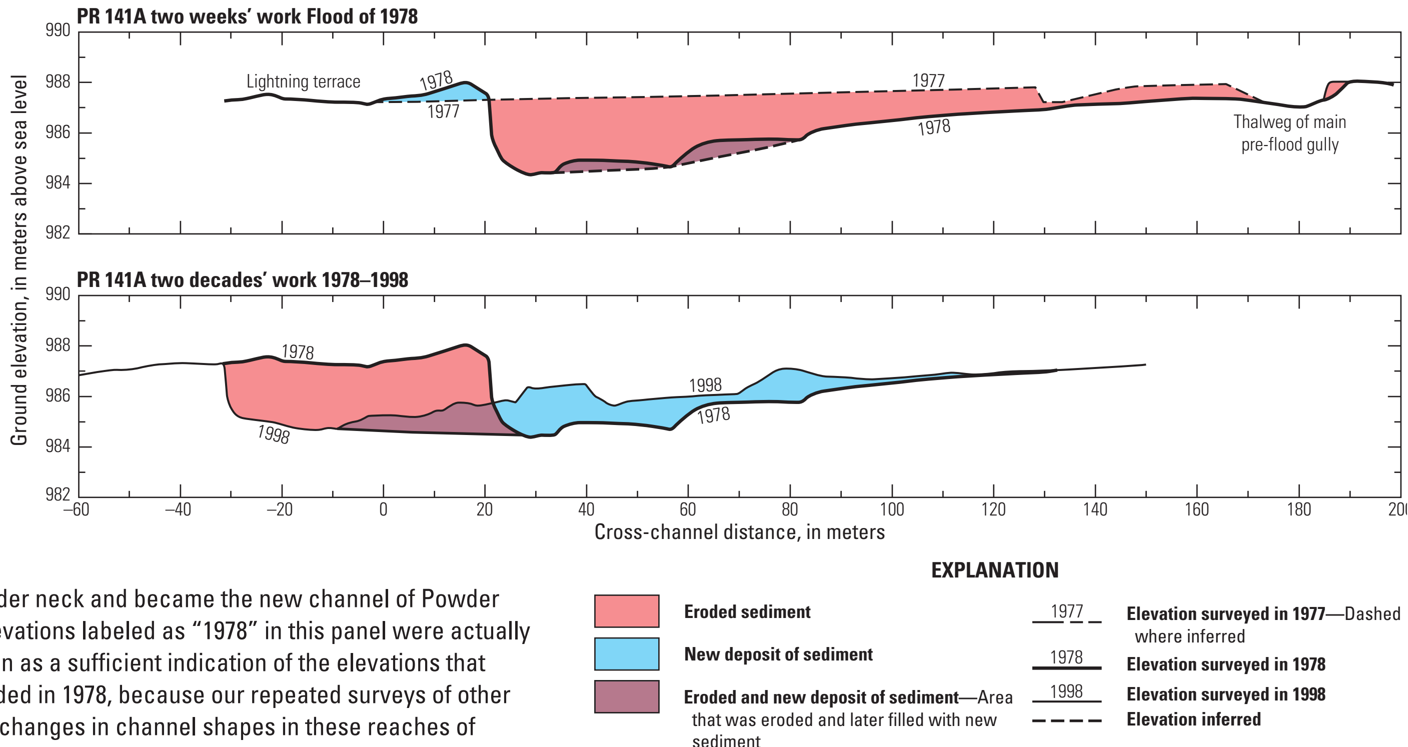


Figure 10. Cross sections of Powder River near Bloom Creek, showing changes during and after a major channel cutoff caused by the flood of May 1978. Vertical scales are 5x horizontal scales. All views downriver. Numbers on cross-channel distance scales correspond to station numbers in the data reports by Moody and others (1990, 2002). Upper Left, Section PR141, across the upriver end of the 1.7-km segment of channel that was isolated during the early stages of the flood. Middle Right, Section PR141A, across the chute channel that formed across the meander neck and became the new channel of Powder River during the flood of May 1978. Elevations labeled as "1978" in this panel were actually surveyed in 1979, but they can be taken as a sufficient indication of the elevations that prevailed after the flood waters subsided in 1978, because our repeated surveys of other cross sections showed no significant changes in channel shapes in these reaches of Powder River between 1978 and 1979 (Moody and Meade, 1990). Elevations labeled "1977" were inferred from aerial photos (such as fig. 9) and USGS topographic maps (Bloom Creek and Huckins School quadrangles, both 1969). Note the prominent gully that crosses the section near cross-channel station 180. Lower Right, Section PR141A, showing changes in the newly formed channel during the two decades following the flood of May 1978.

gullies were initiated here during the early stages of the flood of 1978 – in much the same manner as those observed to have formed on the neck of another meander on Powder River during an ice-jam flood in March 1989 (Gay and others, 1998, p. 653–656; see also the graphic portrayal of Ghinassi, 2011, his fig. 12). The first of these gullies to breach the upriver bank of the neck of the meander bend near Flood Creek became the new main channel of Powder River. Aerial views of the new cutoff channel, only a few days old, are shown in figure 11.

In the apex of the meander bend at Flood Creek, the rising flood waters of Powder River appear to have first eroded its concave bank and then deposited new sediment during the cutoff process (fig. 12, upper left). During the earlier stages of the flood, before the new chute channel had cut off the meander at its neck, the high left bank at the bend apex (in the fanlike subaerial delta of Flood Creek) was cut laterally about 7 m, scour holes formed near the (floated-in?) remains of large cottonwood trees on the old pointbar, and as much as a meter of new sediment was deposited in the old channel thalweg. As the rising waters flowed across the meander neck, they began scouring several gullies whose headcuts progressed rapidly upriver. The first of these headcutting gullies to breach the upriver edge of the meander neck became the new main channel of Powder River. The new cutoff channel was scoured down to a substrate of coarse gravel, upon which no pointbars or other sandy deposits had accumulated before the flood waters subsided (fig. 12, middle right). By way of comparison, the amount of erosion accomplished in the cutoff channel during two weeks of extreme flooding in May 1978 was substantially greater than the total amount of erosion accomplished here during two decades of regular annual flooding (fig. 12, lower right). In the years since 1978, the cutoff channel has widened, and a substantial pointbar has been constructed.

Changes in the old channel, abandoned since 1978, can be seen in the series of photographs shown in figure 13. Only during a few years since 1978 have the annual floodwaters been high enough to inundate the old channel, and only a few centimeters of new sand have been deposited on section PR122 (Moody and others, 2002, p. 66).

Other Channel Changes

In addition to the effects we have discussed so far—the channel widening, the massive erosion of channel bends, and the cutoffs—other geomorphic changes were made to the channel of Powder River during the flood of May 1978. Two of our cross sections, PR113 and PR125, showed drastic shifts, from one side of the channel to the other, of the thalweg and the main focus of bank erosion (fig. 14). In both instances, during the lateral shifts of the thalwegs, new sediment was deposited in the parts of the channel from which old pointbar sediment had been eroded only a few days earlier.

In both instances, much of this new sediment was cobble-sized gravel. At cross section PR113, the modal size of the gravel was 3–5 cm, but many of the larger pieces were blocks and slabs of sandstone mostly 25–35 cm across (in their *b*-axis dimensions). The entire cross-sectional area of newly deposited sediment (tinted blue in the upper panel of fig. 14) consisted mostly of these gravels, with only a 10–20–cm thickness of fine sand covering the top of the newly deposited gravel bar between stations +50 and +65. At cross section PR125, the material newly deposited in the old channel (tinted blue in the lower panel of fig. 14) was part of a continuous large gravel bar that could be seen to emerge from the right bank of the river some 200 m upstream and to have moved across the river and into the left side of section PR125. Prominent among the cobble-sized gravels were blocks and slabs of sandstone (see fig. 15), of much the same sizes as those we saw at section PR113. These cobbles represent the largest sizes that we know to have been transported significant distances in Powder River during the flood of May 1978. The angularity (lack of rounding of the sharp edges) of the large sandstone slabs shown in figure 15 suggests that their source was not far upstream—a few hundred meters at most. The 35-year post-flood history (1978–2012) of cross section PR125 has followed almost exactly the stages portrayed in the depositional model of Dean and others (2011, their fig. 14).

Some reaches of Powder River were changed only slightly, if at all, by the flood of May 1978. The most obvious of these minimally-changed reaches were those in which outcrops of bedrock (especially the sandstone layers of the Fort Union Formation) control the configuration of the channel. Our section PR116 was installed at such a location. In 1975, we purposely placed the section directly underneath the cableway for the USGS gaging station at Moorhead, in hopes of being able to eventually correlate our studies with the long-term records that had been collected there. We installed the section with full understanding that gaging-station locations are selected specifically for their stability, so that engineers may develop a consistent long-term relation between river stage and water discharge. The very small quantity of channel change wrought at section PR116 by the flood of 1978 is shown in the upper panel of figure 16. We hope that the contrast between these data and those from other segments of the river—especially those from the nearest sections up- and downriver (PR113 in fig. 14 and PR120 in fig. 6)—will serve as a cautionary note to geomorphologists who attempt to extrapolate gaging-station data to large reaches of rivers.

Other reaches in which the channel was changed only slightly during the flood of May 1978 are those in which the vectors of flood flow were mostly parallel to the banks of the river. Sections PR151 and PR136 (center panels in fig. 16) lie across fairly straight reaches of Powder River. Section PR194 (lowermost panel) crosses the river at the inflection point of zero curvature between two bends.

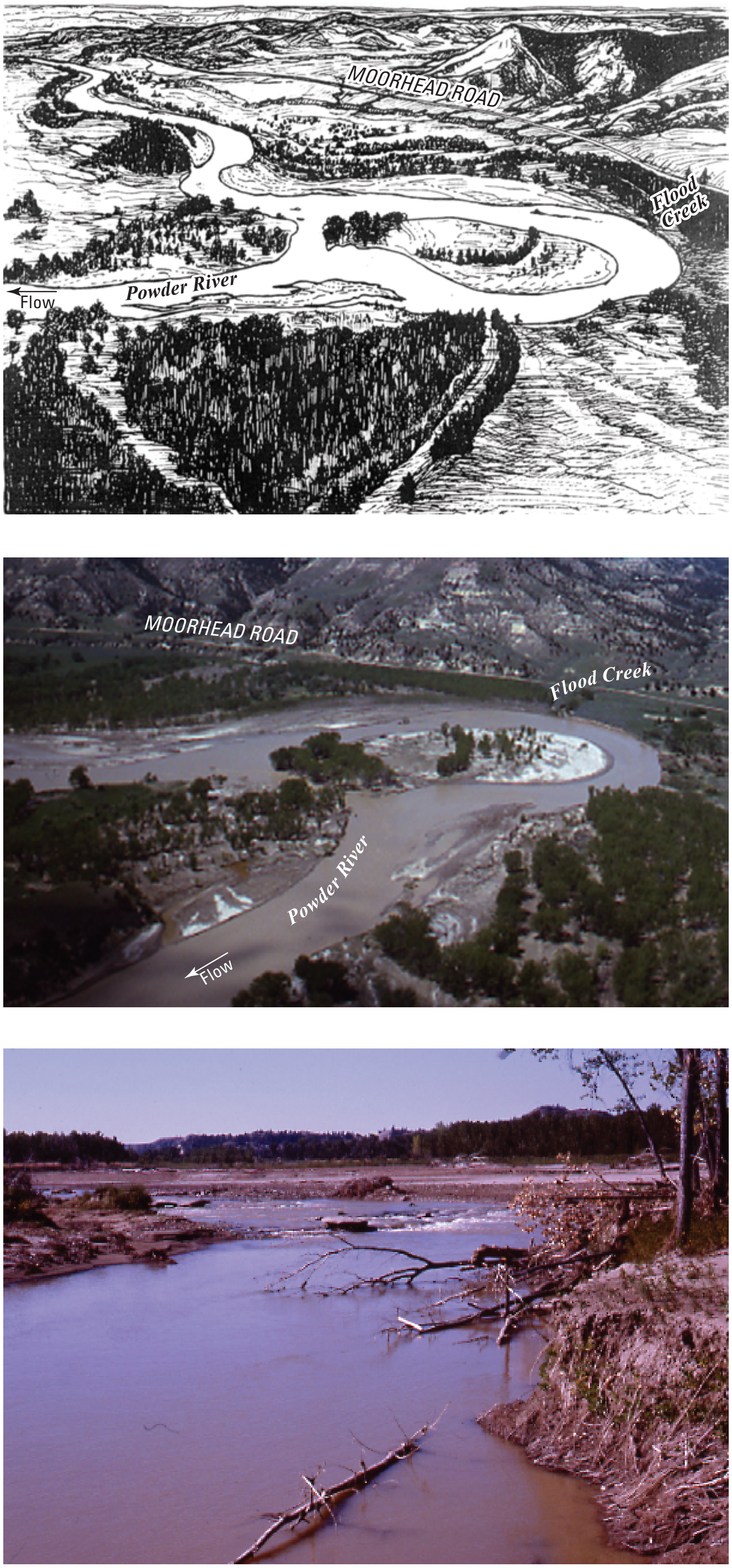
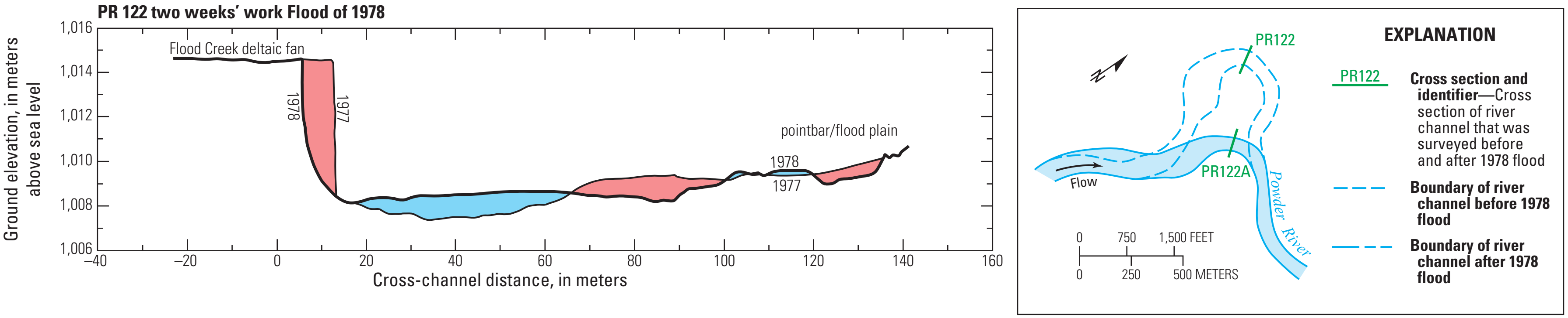
A
B
C


Figure 11. Upriver views of Powder River near Flood Creek, showing meander bend cutoff during and after flood of May 1978. *A*, sketch by Bobbie Myers, from oblique aerial photo taken by R.H. Meade during the falling stages of the flood, on May 25, 1978. Flood waters still high in old meander bend and in new cutoff channel. *B*, closer view of Powder River at same locality. Photo taken May 25, 1978. New cutoff channel is partly obscured by large cottonwood trees. Flood Creek is the small channel crossing under Moorhead road and entering Powder River on the left bank near the bend apex. *C*, view upriver through new cutoff channel, September 4, 1978. Bedrock ledges form the channel bottom at the upriver edge of the new channel. For comparison, see the photograph taken on same day of the dry channel of the abandoned meander (fig. 13, *A*).



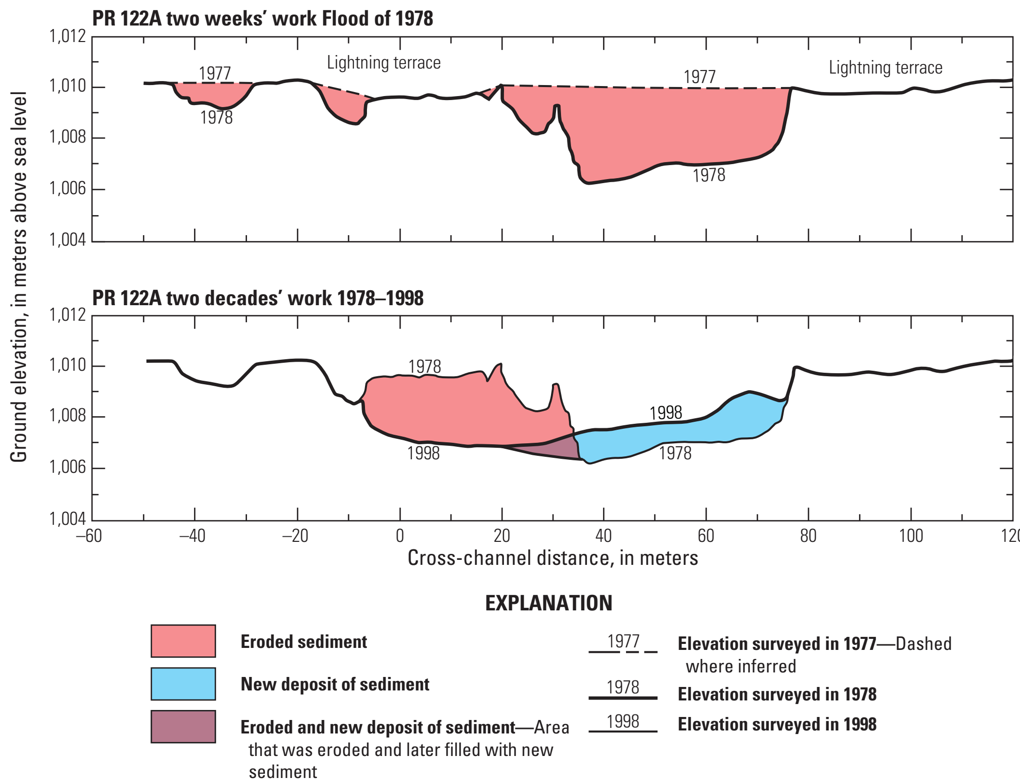
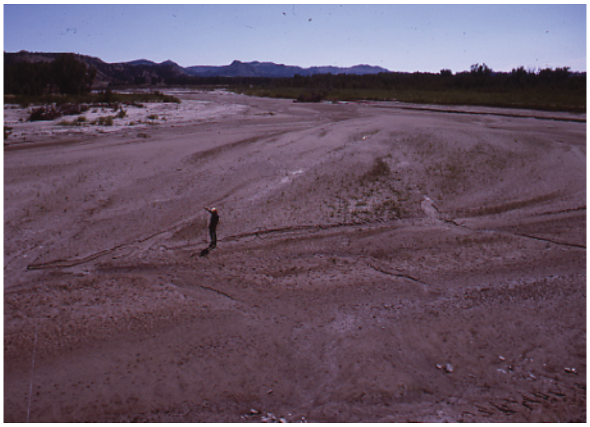


Figure 12. Cross sections of Powder River near Flood Creek, showing changes during and after a major channel cutoff caused by the flood of May 1978. Vertical scales are 5x horizontal scales. All views downriver. Numbers on cross-channel distance scales correspond to station numbers in the data reports by Moody and others (1990, 2002). Upper Left, Section PR122, at the apex of the meander bend that was cut off from the main channel of Powder River during the later stages of the flood. Middle Right, Section PR122A, in the chute channel that formed across the meander neck and became the new channel of Powder River during the flood of May 1978. Elevations labeled as "1978" in this panel were actually surveyed in 1979, but they can be taken as sufficiently accurate indications of the elevations that prevailed after the flood waters subsided in 1978, because our repeated surveys of other cross sections showed no significant changes in channel shapes in these reaches of Powder River between 1978 and 1979 (Moody and Meade, 1990). Elevations labeled "1977" were inferred from aerial photos and from inspection of the site after the flood. Note the three smaller floodwater-cut gullies that cross the section near stations -35, -10, and +25. Lower Right, Section PR122A, showing changes in the newly-formed channel during the two decades following the flood of May 1978.

A



B

C

D

Figure 13. Photographs showing repeated upriver views of abandoned channel of Powder River at section PR122, and three-decades-worth of plant succession, following the cutoff of the Flood Creek bend by the flood of May 1978. Standing person (approximately 2 m tall) is in approximately the same ground location in each photo. Near-vertical line faintly visible in left side of top three photos is a cable that marks the line of section PR122. *A*, three to four months after flood, on September 4, 1978. Seedlings of willow (*Salix exigua*) and cottonwood (*Populus sargenti*), growing from seeds transported in by the flood of May 1978, are barely visible as sprouts in flood-deposited sand. *B,* fifteen months after flood, on August 17, 1979. Large clump of willows dwarfs smaller sprouts of cottonwood. *C*, six years after flood, on September 3, 1984. Cottonwood trees, now 2–3 m high, are taller than willow bushes. Grasses becoming established. *D*, thirty-two years after flood, on November 2, 2010. Person stands in grove of cottonwood trees, 7–10 m high. Grasses are well established.

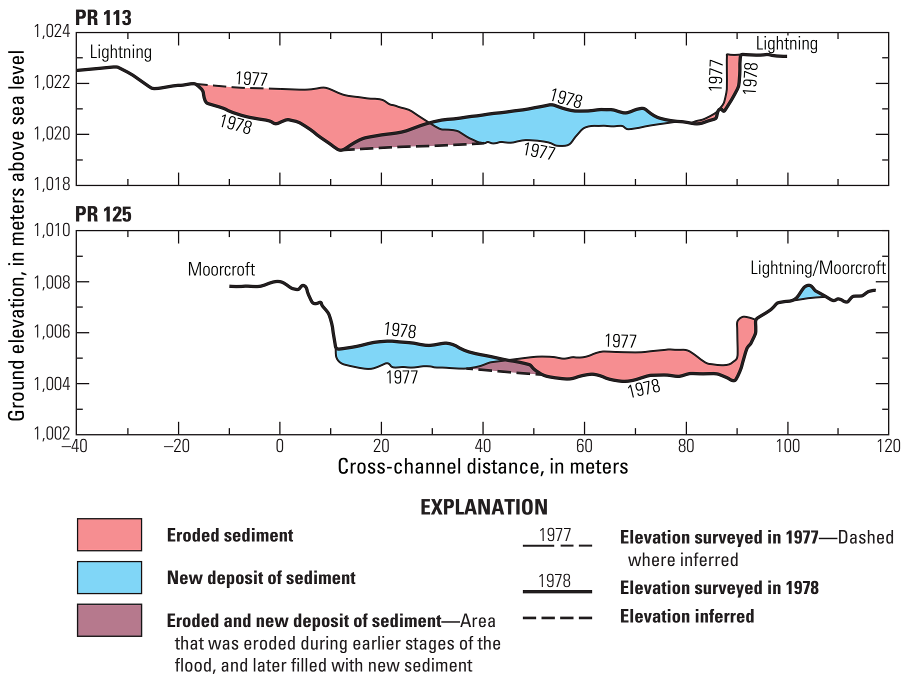


Figure 14. Two cross sections of Powder River in which the thalweg and the locus of most active erosion (including cutbank erosion) was shifted from one side of the channel to the opposite side during the flood of May 1978, based on surveys made before (1977) and after (1978) the flood. Both views downriver. Vertical scales exaggerated 5x. Cross-sectional areas in midchannel that we infer to have been first eroded (red) and then to have received deposits of new sediment (blue) later in the flood are marked with both colors. Numbers on cross-channel distance scale in the figure correspond to station numbers listed in the data report of Moody and Meade (1990).

Effects of the Flood of 1978 Compared with the Cumulative Effects of Subsequent Flows of Lesser Magnitude

What proportion of the total workload of Powder River is accomplished during infrequent events such as the extreme flood of May 1978? “Workload” is here defined as the transfer of sediment and the augmentation and rearrangement of the riparian riverscape. From our data on cross-sectional changes recorded mostly annually between 1977 and 1998 (Moody and others , 1990, 2002), we can estimate, overall, that the magnitude of channel changes wrought during two weeks of flooding in May 1978 is roughly equivalent to that wrought by the more average flows of the following 20 (plus or minus 5) years.

We began this line of inquiry earlier in this report in the discussions of figures 10 and 12. The segment that follows makes several more direct comparisons (figures 17, 18, and 19) between the work done during two weeks of May 1978, and the work accomplished by the river during the two decades (1978–1998) that followed the flood. Owing to the nonrandom spatial distribution of our 19 cross sections and to our conviction that the flood of May 1978 belongs to a population of floods different from the annual floods during 1979–1998, our data probably do not permit more quantitative analysis of magnitude and frequency of the sort given by Wolman and Miller (1960) and by Emmett and Wolman (2001).

The nature and magnitude of the difference between two weeks’ work (May 1978) and two decades’ work (1978–1998) depend heavily on the location of the measured section where the comparison is being carried out. Cross section PR113 was one of the more actively changing locations, both during the flood (when the thalweg and actively-eroding cutbank were shifted from the right side to the left side of the channel) and after the flood (when the destabilizing changes made during the flood were being sorted out [equilibrated?] progressively from one year to the next). At section PR113, the volumes of newly deposited sediment were roughly equivalent during the two periods, and the left bank was eroded somewhat more during the decades following the flood than during the flood itself (fig. 17).

The placement of the cross sections relative to planform channel curvature is the major factor that determines the magnitudes of the local responses, such as cutbank erosion and pointbar deposition, to river flows of sufficient force to move sediment. The channel curvature at any fixed section might change with time (as a meander bend translates downriver, for example), causing marked changes in the rates of bank erosion and other processes in the active channel. Cross section PR180 showed only a small amount of channel change during the flood of May 1978 (when the section was near the inflection point between two meander bends), but a much larger amount of change during the following two decades (when a more active segment of river bend moved into the location where the cross section had been fixed and monumented). This difference is shown in figure 18.

In other sections on other parts of meander curves, the channel displacement during the May 1978 flood was more than double the amount of displacement during the subsequent two decades. This is likely to have been true in most of the river reaches immediately downriver of meander apexes, which plate 1 shows to have been the loci of maximum bank erosion during the flood. The two portrayals of cross section PR163 shown in figure 19 demonstrate that the entire cross

A

B

Figure 15. Photographs showing cobble-size gravels transported by the flood of May 1978, and deposited in section PR125. Length of shovel about 1.0 m. Both photos taken September 2, 1978. *A,* view downriver of edge of new gravel bar, about 10 m upriver of cross-channel station 50, section PR 125. *B,* cross-channel view (toward left bank) of new gravel bar that filled the previous year's thalweg channel. Note the imbricate arrangement of the large cobble-size slabs of sandstone. Centerline of photo is about 10 m upriver of line of section PR125.

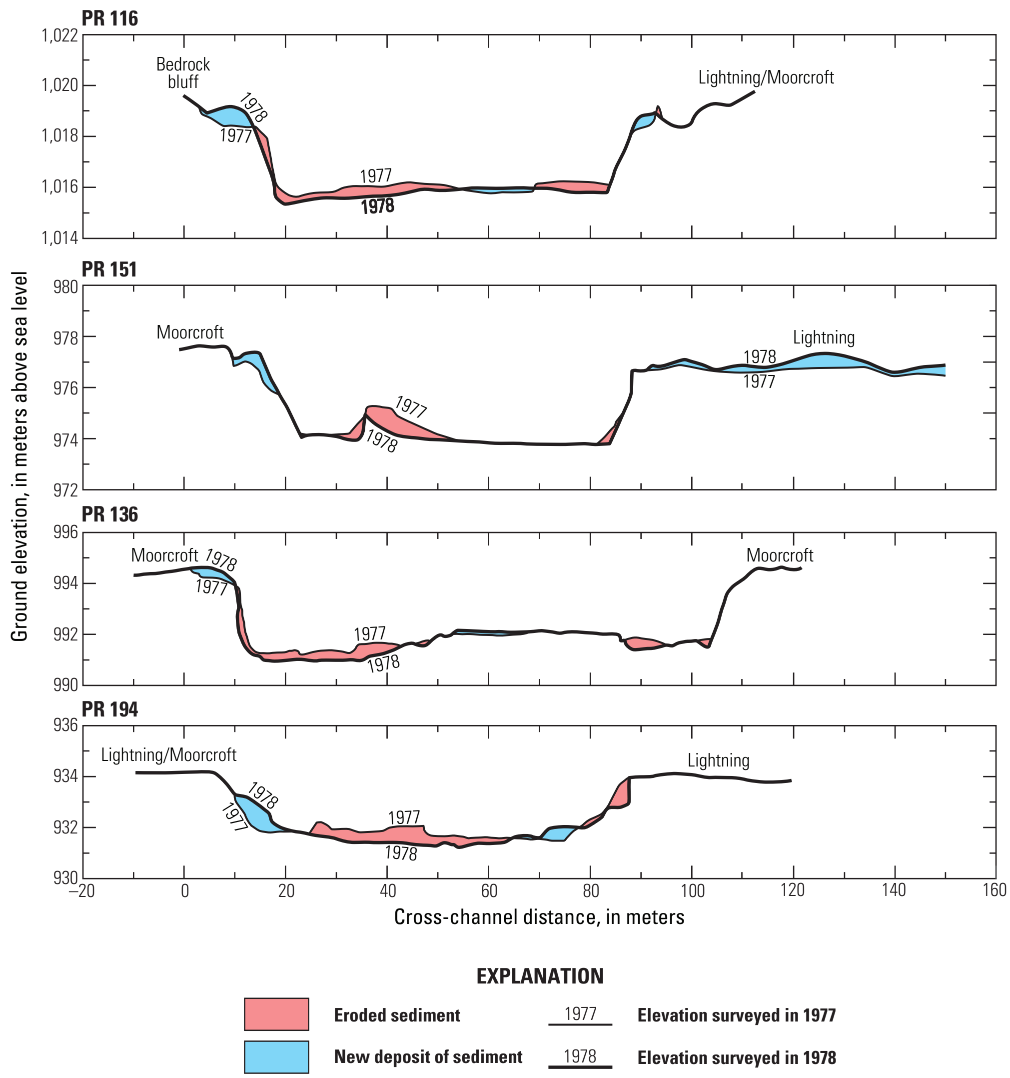


Figure 16. Cross sections of Powder River in which flood-induced channel changes were minimal, based on surveys made before (1977) and after (1978) the flood of May 1978. Views downriver. Vertical scales exaggerated 5x. Locations of sections shown on plate 1. Complete cross-sectional survey data reported by Moody and Meade (1990). Our survey of the overbank deposition of new sediment on the terraces that immediately adjoin the right side of section PR151 yielded an average thickness of 14 cm of newly deposited sand and mud between stations +105 and +520.

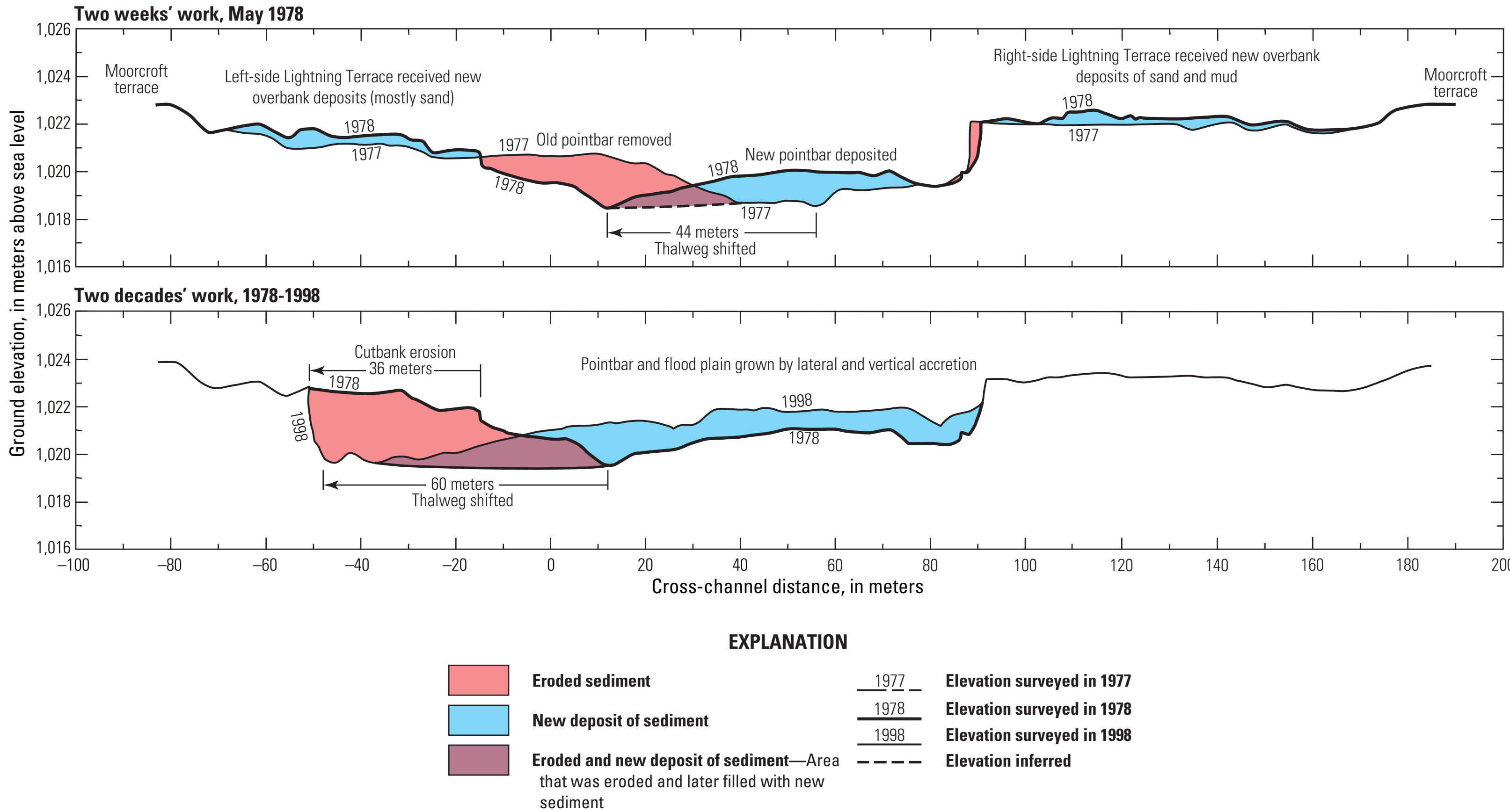


Figure 17. Powder River cross section PR113, comparing channel changes during two weeks of the flood of May 1978 with channel changes during the two decades (1978–1998) of more average flows that followed the flood. Views downriver. Vertical scales exaggerated 5x. Cross-sectional areas of erosion tinted in red; deposition in blue. Cross-sectional areas that were first eroded (red) and which later received deposits of new sediment (blue) are marked with both colors. Complete cross-sectional data reported by Moody and others (1990, 2002).

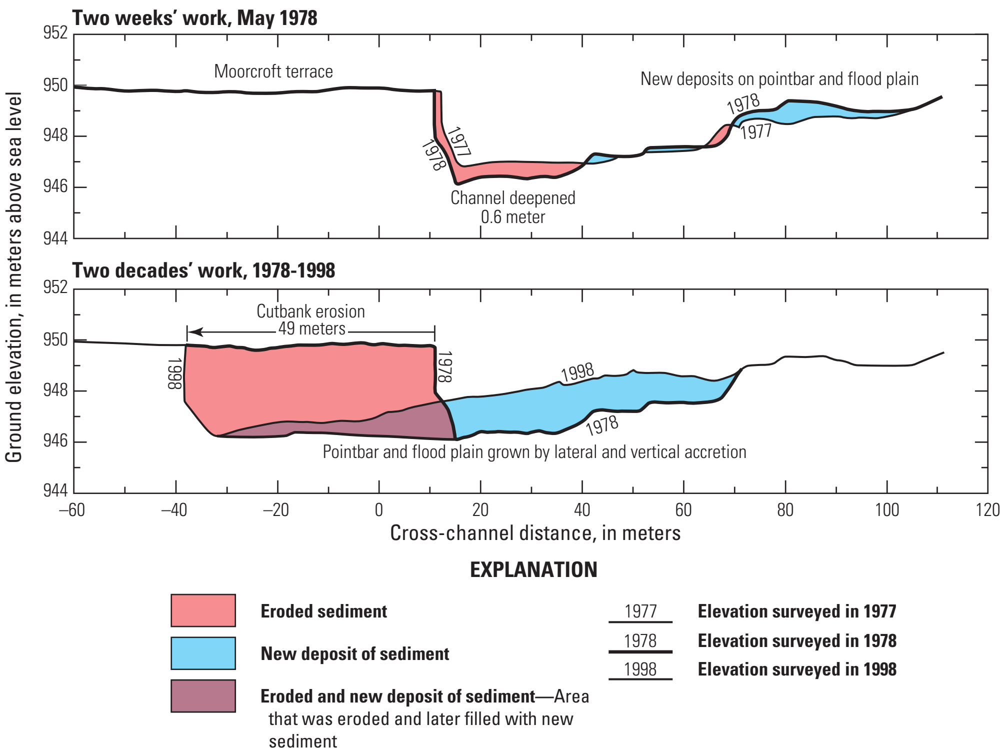


Figure 18. Powder River cross section PR180, in which channel changes during the flood of May 1978 were small, compared with subsequent changes during the two decades (1978–1998) that followed the flood. Views downriver. Vertical scales exaggerated 5x. Complete cross-sectional data reported by Moody and others (1990, 2002).

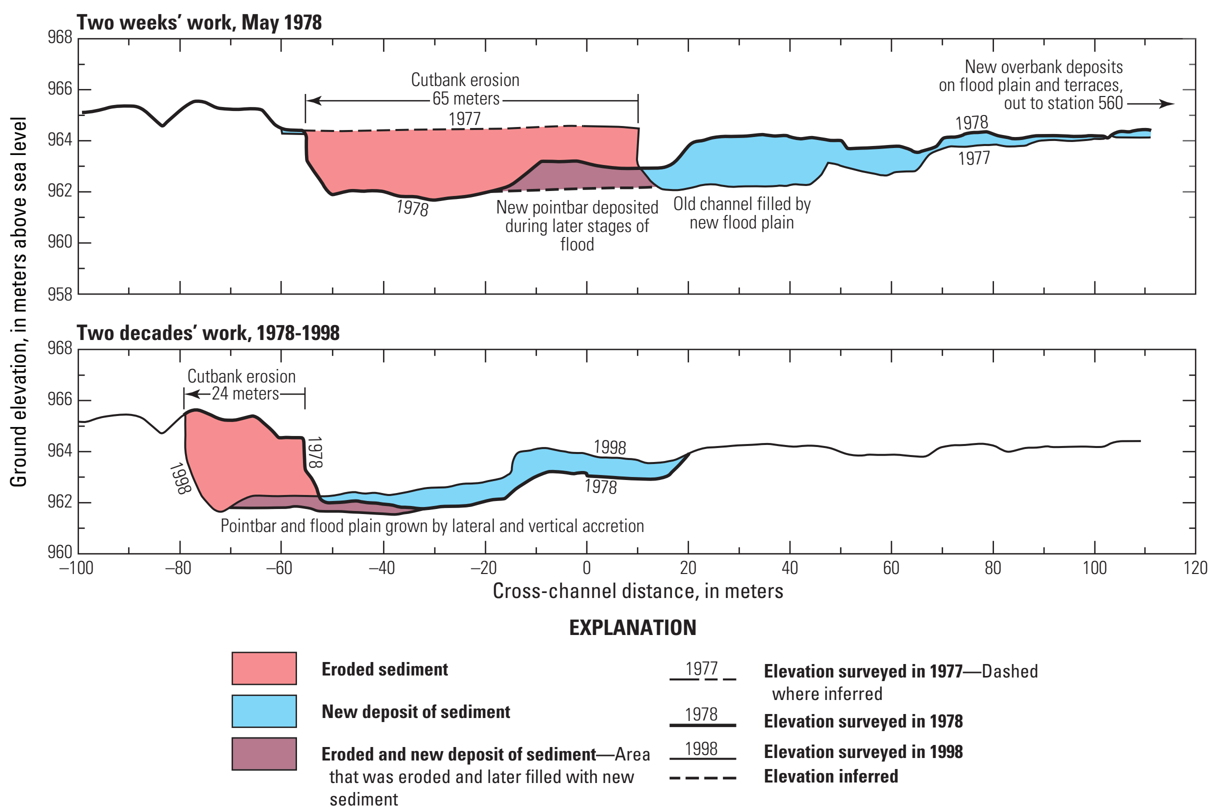


Figure 19. Powder River cross section PR163, in which channel changes during the flood of May 1978 greatly exceeded the subsequent changes during the two decades (1978–1998) of more average flows that followed the flood. Views downriver. Vertical scales exaggerated 5x. Complete cross-sectional data are listed by Moody and others (1990, 2002). Further data on overbank deposits (out to station +660) at this section are given by Moody and Meade (2008, p. 395).

section in such a location was shifted laterally by two channel widths during the flood but by less than one full channel width during the two decades following the flood.

Recollections of the Flood of 1923

The only other record of an extreme flood of a magnitude equal to or greater than that of May 1978 in Powder River was that of September–October, 1923. A heavy fall of wet snow that began in the Bighorn Mountains on September 24, "was later followed by rain, which melted the snow and caused all the streams that flow eastward from the mountains to reach severe flood stages." (Follansbee and Hodges, 1925, p. 119) During the last four days (27–30) of September 1923, rainfall totaled 100 mm or more (reaching 150 mm at several rain gages) over the entire Powder River drainage basin. Peak discharge at Arvada, Wyo., during the 1923 flood was 2,700 cubic meters per second (m^3/s) (Follansbee and Hodges, 1925), or about three times the peak discharge at Arvada (920 m^3/s) during 1978. Stories concerning the flood of 1923 in the Moorhead-Broadus reach were recorded extensively at the time in the local weekly newspaper, *Powder River Examiner*, microfilm copies of which are available in Malley Library in Broadus. Later recollections of the 1923 flood are included in locally produced memorabilia volumes (Toman and others, 1967, p. xxii–xxiii, 589, 595–596, 641, 673; Beach and Thaden, 1989, p. 64, 189). In our interviews with local residents of the Powder River valley following the flood of 1978, we were occasionally treated to memories of 1923, from either the older residents themselves or (mostly) from their recollections of what their forebears had told them. Several of these recollections were of sufficient hydrological interest to be recorded on plate 1.

High water levels of the 1923 flood at Gay Ranch and at Randall Ranch (Sections 20–21 of T7S, R49E, and Sections 17–18 of T5S, R51E), as described by Hubert Gay and J.L. Wilson (oral communs., 1978), are shown as isolated dashed blue lines on plate 1. Wilson recalled how his father (who in 1923 lived in the dwelling that is labeled as "Randall ranch house" on plate 1) rigged a block-and-tackle from the interior house rafters to hoist a cast-iron kitchen stove out of reach of the flood waters. In the young town of Broadus, the 1923 flood waters extended approximately to the 3,040-foot elevation contour. A much-repeated story in the several accounts of the 1923 flood (Toman and others, 1967, p. xxii–xxiii; Beach and Thaden, 1989, p. 189) tells of a crude rowboat being launched (during the peak of the 1923 flood in Broadus) from the steps of the old hotel that then stood on the northwest corner of the mid-town intersection where US Highway 212 now makes its right-angled turn. At all three locations, high-water levels of 1923 were 2–3 m higher than those of 1978.

The concave bank of the large bend of Powder River in Section 21, T6S, R50E was eroded so rapidly during the flood of 1923 that it completely undermined (and destroyed) a substantial dwelling that had been built on the middle (Moorcroft) terrace near the river. An artesian well that had been drilled on the left-side terrace is now on the point bar on the right side of the river. That is, the river has shifted laterally, during and after the flood of 1923, to such an extent that the present left-side terrace bank is now about 100 m to the left of the location of the well that formerly flowed atop the terrace. As of our latest visit in 1998, the artesian well, decapitated and on the pointbar, was still flowing at a rate of a few liters per minute. Location of the flowing artesian well on the pointbar, as of 1978, is shown on plate 1. Progressive development of the large bend during the years 1939–1978 is shown in the maps of Martinson and Meade (1983, sheet 2) and in the report by Gay and others (1998, their fig. 9).

Massive bank erosion was recorded at Huckins Ranch during the 1923 flood's falling stages:

" 'Old Powder' had only begun to do her dirty work to us. As she dropped, her banks started sluffing [*sic*] off foot by foot and here she came right towards our nice big barn. …. It was a two-story structure, measuring about 35' x 50'. Our neighbors … began to arrive to see what they could do to help us. …. We probably salvaged about 500 or 600 bushels of grain but lost about 1000 bushels of oats that we didn't have time to get out. …. 'Old Powder' quit chewing at us about 100 feet from the house and as it turned cold right after that, we figured it would be safe to stay there that winter. She was soon to return and finish her work as we had to get out to higher land the next March." (Huckins, 1967)

Similar instances of massive rapid bank erosion have been described along the Mississippi River by Mary Hamilton, (1992, p. 60–61) and along the River Trent by William Shakespeare (*Henry IV, Part 1, Act III, Scene 1*):

"HOTSPUR. See how this river comes me cranking in,
And cuts me from the best of all my land
A huge half- moon, a monstrous cantle out."

The cuspate-in-planform area that was eroded out at Huckins Ranch during 1923–24 was re-flooded (but not re-eroded) during 1978, as shown by the blue-shaded area on Plate 1 on the right bank of Powder River in the NW corner of Section 22, T7S, R49E.

Given the general sinuosity of Powder River and the magnitude of the flood, it is likely that several river bends were cut off between Moorhead and Broadus during 1923. For only one of these bends, however, do we have any certainty that it might have been cut off by the flood of 1923. We refer to the bend in Section 14 of T8S R48E (see plate 1). Data from the 1890 cadastral survey and the first series of aerial photographs taken here (Martinson and Meade, 1983, Sheet 1) show that the bend was cut off at some time between 1890 and 1938. The late Hubert Gay, although he had been only four years old at the time, was fairly certain that this bend had been cut off during the 1923 flood. We are even less certain of the other bends of Powder River that might have been cut off during 1923. Much of this uncertainty lies in the reliability of the surveys of the river channel made during the years 1890–1911, which appears to be rather more sketchy near Broadus than near Moorhead, judging from the disparities between the remnant topography observable on the present riparian lands and the traces of some of the older "surveyed" channels (Martinson and Meade, 1983, sheets 1 and 2).

With its water levels reaching higher stages than those of 1978, the flood of 1923 certainly deposited large quantities of new sediment on the terraces that rise alongside Powder River. On the site of the Cheyenne and Sioux Indian encampment that was attacked in March, 1876, by a contingent of the US Army ("Reynolds Battlefield", at the mouth of Thompson Creek, in Sections 32-33 of T8S, R48E), cartridge cases and other remnants of the battle were reportedly easier to find before they were covered up by 2 feet or more of overbank sediment that was deposited there by the flood of 1923 (Vaughn, 1961, p. 89). At Gay Ranch, the area inundated by the flood of 1923 (Sections 20–21 of T7S, R49E) still shows topographic evidence such as lee dunes and other features of the extensive accumulation of sand on the terraces.

One event did not happen on Powder River during the flood of 1923. Among those who promote the lore of western rivers, there lingers a persistent story of a steam locomotive that was parked on a railroad bridge to stabilize the bridge during a flood, but the train was swept away when the bridge collapsed, and now lies buried in the river sands a short distance downriver of the old washed-out bridge crossing (for example, Cussler and Dirgo, 1996; see also Darling, 2011). We first heard this story near the beginning of our study when we were told by a former colleague that the place and time of this famous "happening" was actually the railroad bridge over Powder River at Arvada, Wyo., during the flood of 1923 (E.V. Richardson, oral commun., 1975). However, when we inquired of the storekeeper in Arvada—who previously had been in the employ of the railroad there—he assured us that the railroad would not have risked so expensive a piece of essential equipment (Ray Smith, oral commun., 1975). The five-span steel-girder railroad bridge at Arvada was indeed washed out by the flood of 1923, as its concrete piers were "undermined and overthrown" by the flooding waters (Follansbee and Hodges, 1925, p. 118). But no locomotive lies buried in the sands of Powder River.

Summary

The timely establishment of a series of monumented cross sections has permitted a detailed quantitative evaluation of the erosional and depositional effects of a major flood on a geomorphically active river of the Northern Great Plains. The channel changes in a segment of Powder River in southeastern Montana during a two-week episode of flooding in May 1978 were approximately equivalent in magnitude to the total changes incurred during the next twenty years of more average flows. The changes that took place in the channels during the flood were both accretionary and avulsive in nature.

Accretionary changes spanned a wide spectrum in magnitude. At the low end were slight enlargements of the cross-channel dimensions. At the high end were wide expansions caused by lateral erosion of concave banks that was compensated by the deposition of new sediment on opposing convex banks as point bars and flood plains. The magnitude of accretionary channel change varied directly with planform curvature, and it ranged from near zero in straight reaches (including the inflection points of zero curvature between consecutive meander bends) to lateral shifts of 1 to 2 channel widths on the downriver extensions of the apexes of meander bends. Accretionary changes also were greater where the river banks consisted of previously deposited alluvial material (such as fluvial terraces) rather than bedrock.

Avulsive changes were mostly confined to channel bends. In some of the smaller bends of Powder River, the channel curvatures decreased as thalwegs shifted toward the convex banks. The necks of some larger bends were cut off by growing gullies that began (or had already begun) on the downriver edges of meanders, and worked their ways upstream across the flooded meander necks by headcutting. A net effect of the flood of May 1978 on the channel between Moorhead and Broadus was a decrease in length of about 2 km (of a total of 110 km), which tells us that, in this reach of Powder River, the avulsive shortening by cutoffs during this flood exceeded the accretionary lengthening by bend enlargement.

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