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Decadal Changes in Channel Morphology of a Freely Meandering River—Powder River, Montana, 1975–2016

By John A. Moody and Robert H. Meade

Open-File Report 2018–1012

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

Cover. Photograph showing a downstream view of the Powder River valley. Powder River flows northward (away from the camera) through uplands consisting of the coal-bearing Fort Union Formation of Paleocene age. The photograph was taken in October 2012 about 20 kilometers north of the Wyoming-Montana State line and about 4 kilometers downriver from the streamgaging station at Moorhead, Montana (U.S. Geological Survey station 06324500).

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Deputy Director
exercising the authority of the Director

U.S. Geological Survey, Reston, Virginia: 2018

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1929 (NGVD 29).
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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Abstract

Few studies exist on the long-term geomorphic effects of floods. However, the U.S. Geological Survey (USGS) was able to begin such a study after a 50-year recurrence interval flood in 1978 because 20 channel cross sections along a 100-kilometer reach of river were established in 1975 and 1977 as part of a study for a proposed dam on Powder River in southeastern Montana. These cross-section measurements (data for each channel cross section are available at the USGS ScienceBase website) have been repeated about 30 times during four decades (1975–2016) and provide a unique dataset for understanding long-term changes in channel morphology caused by an extreme flood and a spectrum of annual floods.

Changes in channel morphology of a 100-kilometer reach of Powder River are documented in a series of narratives for each channel cross section that include a time series of photographs as a record of these changes. The primary change during the first decade (1975–85) was the rapid vertical growth of a new inset flood plain within the flood-widened channel. Changes during the second decade (1985–95) were characterized by slower growth of the flood plain, and the effects of ice-jam floods typical of a northward-flowing river. Changes during the third decade (1995–2005) showed little vertical growth of the inset flood plain, which had reached a height that limited overbank deposition. And changes during the final decade (2005–16) covered in this report showed that, because the new inset flood plain had reached a limiting height, the effects of the large annual flood of 2008 (largest flood since 1978) were relatively small compared to smaller floods in previous decades. Throughout these four decades, the riparian vegetation, which interacts with the river, has undergone a gradual but substantial change that may have lasting effects on the channel morphology.

Introduction

Powder River is a special river. In geomorphologic terms, it can be considered a reference standard for moderately large tributaries of the Missouri River in the Great Plains, because (1) its natural fluvial processes are unperturbed by any large engineering modifications, either structural or operational; (2) it, like all rivers, interacts with the vegetation, (3) it is itself a visibly active modifier of the landscape through which it flows; and, consequently, (4) it is a significant transporter of fluvial sediment. For the foregoing reasons, in 1975, Powder River was selected by the U.S. Geological Survey (USGS) for long-term geomorphologic study. And by now (2016), four decades later, the systematically collected data have chronicled significant

changes in the fluvial system during a period markedly longer than those in more usual geomorphologic studies that are constrained by the few years allowed to a graduate student to complete a thesis, or by the expected completion time required of the recipient of a conventional research grant.

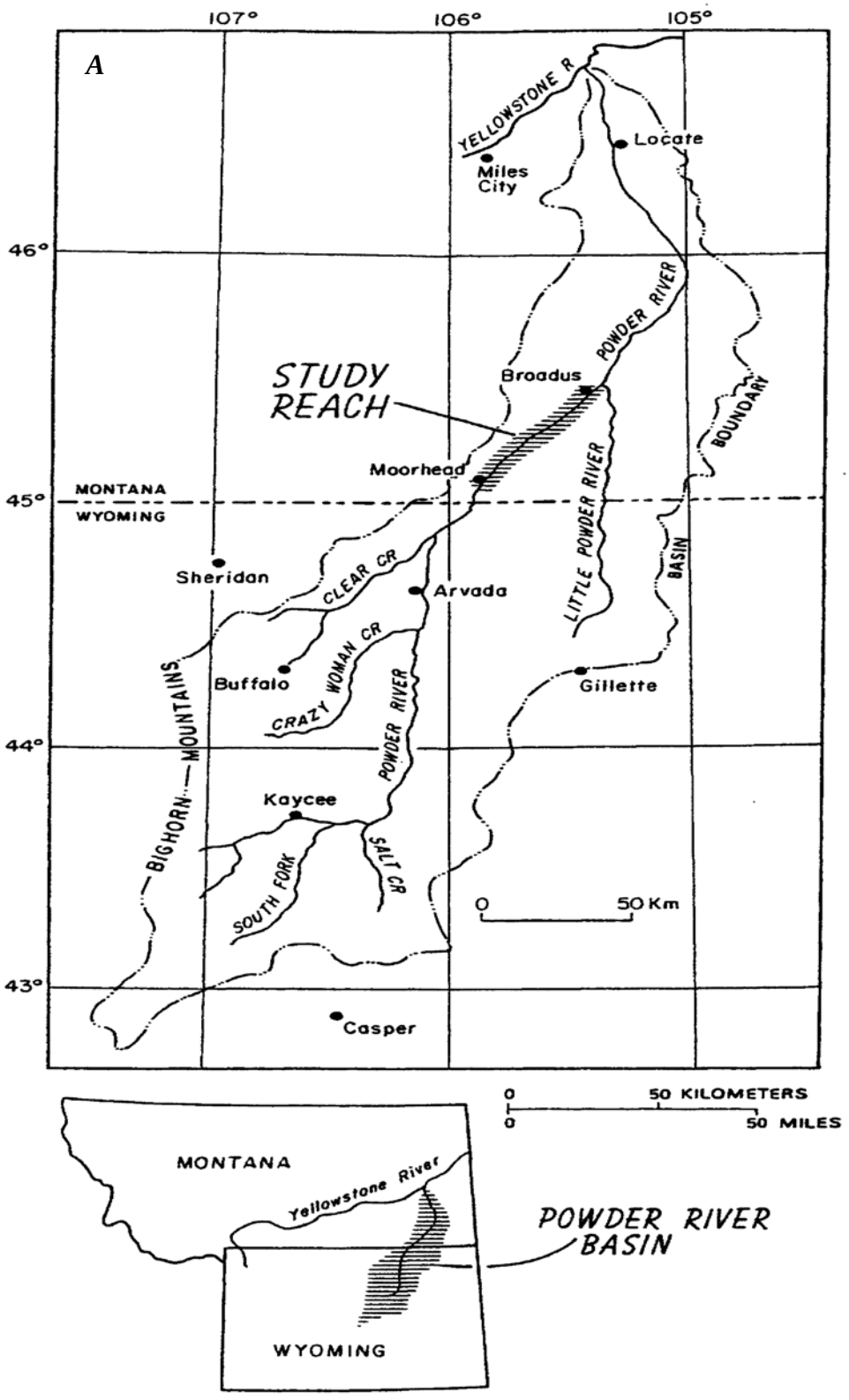
The data in this report are concerned entirely with the configurations and annual geomorphic changes of river cross sections. During 1975 and 1977, 20 cross sections were established at more or less equidistant intervals along an approximately 100-kilometer reach of the meandering channel of Powder River in southeastern Montana. A major (about 50-year recurrence interval) snowmelt flood in 1978 caused significant geomorphic changes such that the number of cross sections was increased to 23. Powder River flows northward such that ice-jam floods in early spring also are agents of geomorphic change; therefore, another cross section was installed in 1994 to monitor future changes of ice-related sediment.

Purpose and Scope

The purpose of this report is to describe and illustrate the decadal changes in channel morphology for the 24 cross sections of the freely flowing Powder River (fig. 1) using a narrative format of a series of photographs taken at each cross section that spans 41 years. Vegetative changes on the flood plain also are described. In total, 22 sections were resurveyed every year (except 1981 and 1983) through 1998, and 6 sections through 2002, which resulted in a near-continuous 20-year and 24-year record of annual channel change with few parallels in the published geomorphological literature. Two other long-term programs come to mind. The annual cross-sectional surveys (20 years) begun in 1952 by Luna Leopold on the Watts Branch in Maryland (Leopold, 1973; Leopold and others, 2005), and monitoring of the sediment response to large floods on Redwood Creek (1973–1991) using similar cross-sectional surveys (Madej, 1992; Madej and Ozaki, 1996). The Watts Branch program was, in fact, a major inspiration for the initial design of our study of Powder River.

Background

Powder River rises in the Bighorn Mountains of Wyoming and flows northward through a semiarid landscape in Wyoming and Montana to the Yellowstone River. The river drains an area of 34,700 square kilometers (km^2) and has an average daily discharge of 12.2 cubic meters per second (m^3/s) at the Moorhead streamgaging station (fig. 1) for the 41-year period (1975–2016) (data from USGS National Water Information System; USGS, 2017). Powder River has no dams or other large-scale human modifications, which, combined with its substantial suspended-sediment load (2–3 million metric tons per year), makes it an optimal outdoor laboratory for studying natural fluvial processes (Moody and Meade, 1990; Hubert, 1993; Moody and others 2002). The river valley (see cover photograph) emerges from a narrowly confined reach near Moorhead, Montana, and widens northward, bordered by hills of the coal-bearing Fort Union Formation of Paleocene age.


A
107°
106°
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45°
44°
43°
YELLOWSTONE R
Miles City
Locate
POWDER RIVER
STUDY REACH
Broadus
BOUNDARY
Moorhead
MONTANA
WYOMING
LITTLE POWDER RIVER
BASIN
Sheridan
CLEAR CR
Arvada
CRAZY WOMAN CR
Buffalo
POWDER RIVER
Gillette
BIGHORN MOUNTAINS
Kaycee
SALT CR
SOUTH FORK
0
50 Km
Casper
0
50 KILOMETERS
0
50 MILES
MONTANA
Yellowstone River
POWDER RIVER BASIN
WYOMING

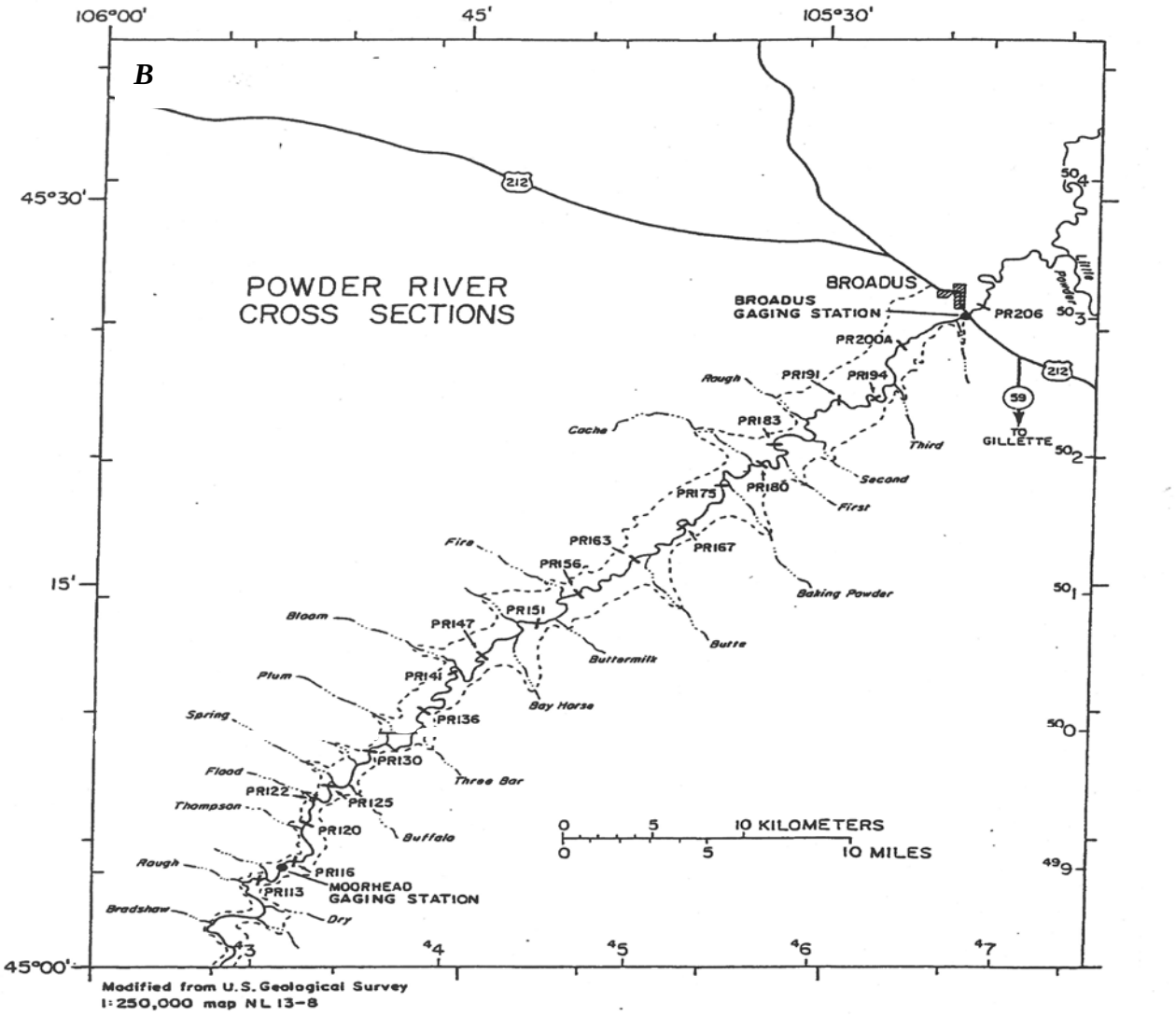

Figure 1. The study reach of Powder River and some of the tributaries. *A*, Powder River Basin and the study reach, which is enlarged in figure 1B. *B*, The original 20 channel cross-sections are labeled by PR (Powder River) followed by the distance downstream in kilometers (km) from Crazy Woman Creek in Wyoming. Additional cross sections were added near some of the original 20 cross sections after the flood of 1978 (PR122A, PR141A, PR141.7, and PR156A). The streamgaging station at Moorhead, Montana (U.S. Geological Survey [USGS] station 06324500) is about 80 river km upstream from a discontinued streamgaging station at Broadus, Montana (USGS station 06324710). The streamgaging station at Moorhead is shown where it was located in 1978. It has moved twice since 1978, and as of 2017 the station is at the Moorhead Bridge about 400 meters downriver from PR113.

Vegetation

Vegetation along Powder River tends to grow in bands. In general, a narrow band (about 2–4 meters [m] wide) of reddish sedge (*Scirpus* spp.) that borders the channel bed (see cover photograph) and grows at about the water level that just covers the channel bed (bed-full flow =12 m^3/s, Moody and others, 1999) with a wider band of mixed grasses (*Agropyron repens, A. pauciflorum, Bromus inermis, Elymus canadensis, Spartina pectinata, and S. cynosoroids*). Willows (*Salix exigua*) and small cottonwood seedlings and trees (*Populus sargentii*) have always grown on the point bars and flood plains, whereas tamarisk (*Tamirix ramosissima*) and Russian olives (*Elaeagnus angustifolia*) were introduced after human settlement of the valley and also populate the flood plain. Three Holocene terrace surfaces have been identified along Powder River (Leopold and Miller, 1954; Moody and Meade, 2008). The first and lowest is the Lightning terrace with small cottonwood trees adjacent to the flood plain in the right- and left center of the cover photograph. The second is the Moorcroft terrace that forms the left bank (downriver from the ranch buildings on the left) and extends as a flat surface to the left (west) with a few large cottonwood trees still retaining their green leaves. The Moorcroft terrace is often cleared and releveled by ranchers into a series of smaller stepped terraces to facilitate irrigation of hay or alfalfa fields. Sagebrush (*Artemisia tridentate* or *Artemisia cana*) commonly grows on the Moorcroft terrace where it has not been plowed. The third and highest is the colluvial Kaycee terrace with no trees, which grades slowly upwards to meet the hills of the Fort Union Formation. This terrace can be seen in the cover photograph on the right side at the base of the hills and in the far distance on the left side.

Floods

Four types of floods are common on Powder River (Moody and others, 2002; Moody and Meade, 2014; Schook and others, 2017). Ice break-up floods are usually in February, March, and April; snowmelt floods are usually in May and June; flash-floods from convective storms are usually in June, July, and August; and fall floods are usually in September or October. The largest flood of record was a fall flood in 1923 (approximately 2,830 m^3/s), and the second largest was a snowmelt flood in 1978 (779 m^3/s) (fig. 2). Maximum total suspended sediment concentration for snowmelt floods is 52,200 milligrams per liter (mg/L), 49,700 mg/L for flash floods, and 26,000 mg/L for ice break-up floods (Moody and others, 2002). Based on hydrographs at the Moorhead and Broadus streamgages (fig. 1), which are about 58 kilometers (km) apart along a straight line rather than following the river channel, the peak for the 1978 flood wave flowing down valley encountering substantial vegetative drag had a phase speed of about 3.3 kilometers per hour (km/h) (Meade and Moody, 2013), whereas the mean phase speed for smaller flood peaks (25–160 m^3/s) confined to the channel was 6.3 km/h.

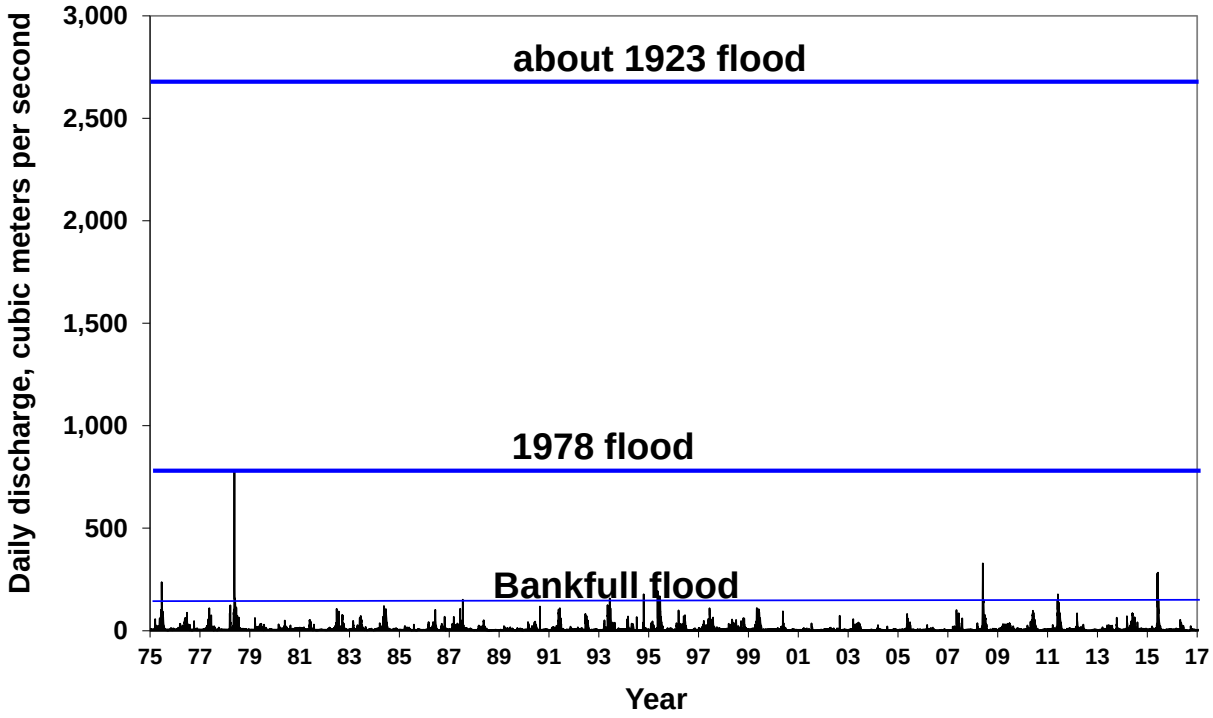

Figure 2. Daily discharge of Powder River at Moorhead, Montana, from 1975 through 2016. The streamgage, Powder River at Moorhead, Montana (U.S. Geological Survey [USGS] station 06324500; USGS, 2017) has been in operation since May 1, 1929. Bankfull discharge (170 cubic meters per second) corresponds to channel conditions at Moorhead. See the appendix for hydrographs of each year from 1975 through 2016.

Cross Sections

Each cross section was assigned a permanent identification number (for example, PR136) where PR stands for Powder River and the number corresponds to the approximate distance, in kilometers, along Powder River from the mouth of the tributary Crazy Woman Creek in Wyoming. These assigned distances were converted to kilometers from the river miles indicated on a series of larger scale maps made in 1944 for the assessment by the Bureau of Reclamation of the proposed dam site at Moorhead, Montana. Because Powder River has substantially changed its planimetric configuration since 1944 (Martinson, 1984; Martinson and Meade, 1983), the distances or identification numbers should not be used in any precisely analytical sense. They are to identify the cross section and to provide approximate distances between cross sections.

Elevations at the cross sections were established, surveyed, and resurveyed by traditional means, usually involving a two-person crew consisting of a rodman and a level operator (table 1). Horizontal distances in meters (referred to as “stations” in this report) were taken from a beaded wire tagline that was stretched between permanent markers (1.2-m lengths of 13-millimeter [mm] diameter steel rod [commonly referred to as rebar] that had been driven into the ground so that only 10–15 centimeters [cm] remained exposed) placed near the ends of the

section. Horizontal station numbers always increased toward the right descending bank or right bank (determined by facing downriver), beginning with a zero station that was initially atop the left descending bank or left bank. Annual resurveys usually were made in late summer or early autumn when the river was low and shallow enough to be waded comfortably by the rodman (Moody and Meade, 1990; Moody and others, 2002).

Elevations were measured in meters above the National Geodetic Vertical Datum of 1929 (NGVD 29). A permanent bench mark was established at each cross section, and its elevation was determined by leveling in from the nearest roadside bench mark of the U.S. Coast and Geodetic Survey. The study was begun in 1975 before the North American Vertical Datum of 1988 (NAVD 88) existed, so elevations mentioned or shown in figures in this report are relative to NGVD 29. Conversions are given for NAVD 88 in a data release (Moody and Meade, 2017, https://doi.org/10.5066/F7TQ5ZRN). From 1999 to 2013, systematically repeated annual surveys were not done at more than one-half of the 24 cross sections (table 1). Therefore, 1999 marked the transition of time scales in our long-term study—from annual change to decadal change. Of the sections, 16 were resurveyed systematically during 2014, 2015, and 2016. Most complete are the records (31 of 38 consecutive years) of channel change at cross sections PR122A and PR141A, both of which were formed as chute cutoffs during the flood of 1978.

Table 1. Annual leveling surveys carried out at cross sections of the channel of Powder River in southeastern, Montana, 1975–2016.

[Cross section IDs are **PR** follwed by the distance, in kilometers, downriver from the confluence of Crazy Woman Creek and Powder River in Wyoming; black cells, cross section was surveyed; blank cells, cross section was not surveyed]

Cross section ID	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
PR113	■		■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■										■		■	■	■
PR116	■		■	■	■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■																				
PR120	■		■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■											■	■	■	■	■
PR122	■		■	■	■	■		■		■		■		■	■	■	■	■		■		■	■	■	■	■	■													■		
PR122A				■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■			■	■	■	■	■	■	■	■
PR125	■		■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■											■	■	■	■	■	■
PR130	■		■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■										■	■	■	■	■
PR136	■		■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■													■		■	■	■
PR141	■		■	■	■	■		■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■															■		
PR141A					■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■			■	■	■	■	■	■	■	■
PR141.7																		■	■	■	■	■	■	■															■		■	■	■
PR147	■		■	■	■	■				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																■		■	■	■
PR151	■		■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■														■	■	■	■	■
PR156A				■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■													■	■	■	■	■
PR156			■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																		
PR163			■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■										■	■	■	■	■
PR167			■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■													■		■	■	■
PR175			■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																		
PR180			■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												■	■	■
PR183			■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															■	■	■
PR191			■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															■	■	■
PR194			■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															■	■	■
PR200A			■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																		
PR206			■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															■	■	■

The year-to-year data that we obtained at most cross sections (1977–98 and 2014–16) probably are sufficient to define the scales of annual change under moderate flow conditions. Furthermore, we did manage to obtain “year-before” and “year-of” data to show the effects of three of the four largest annual floods—those of 1978, 1995, and 2015. As table 1 shows, we missed the opportunity to record directly the effects of the large 2008 annual flood.

Cross-Section Narratives

This report consists of detailed narratives of observations made over four decades at 24 cross sections. Included in these narratives are photographs taken over the years. Each of the narratives includes a link to the complete cross-sectional survey data collected at that section during the years 1975 through 2016, which are available on USGS ScienceBase (Moody and Meade, 2017; https://doi.org/10.5066/F7TQ5ZRN). The cross-sectional data have so far provided the basis for detailed analyses of the effects of a large flood on channel morphology (Meade and Moody, 2013), on the recovery of flood plains after a major flood (Pizzuto, 1994; Moody and others, 1999; Moody and Troutman, 2000; Pizzuto and others, 2008), the incremental growth of point bars (Moody and Meade, 2014), flow reconstruction (Schook and others, 2016), and channel bank migration rates (Schook and others, 2017).

PR113 Narrative

Cross section PR113 was first established and surveyed in 1975 (fig. 3). It was resurveyed annually during the 4 consecutive years 1977–80, resurveyed in 1982, resurveyed annually during the 19 consecutive years 1984–2002, and, after a 9-year hiatus, resurveyed in 2012 and from 2014 to 2016 (Moody and Meade, 2017, PR113_SciBase2.xlsx for survey data).

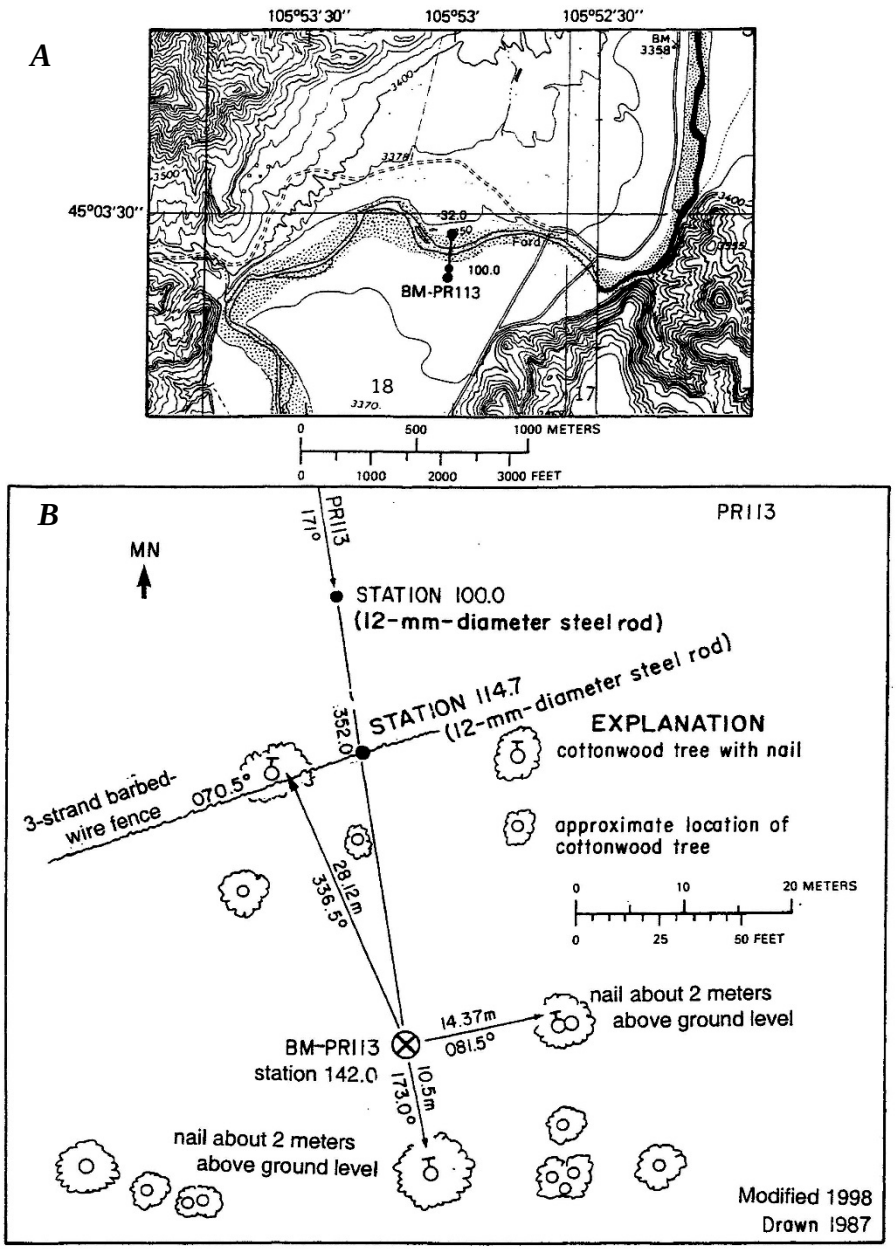

Figure 3. Location maps for cross section PR113. *A*, Location of cross section PR113, bench mark BM–PR113, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Bradshaw Creek quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and some reference pins on the right bank. MN is magnetic north.

Cross section PR113 is 1.5 km downvalley and 2.5 km downriver from the narrows at the proposed dam site at Moorhead, Montana. At the cross section, the valley is sufficiently wide to allow the river channel to make a nearly orthogonal 1.5-km-long cross-valley excursion from the valley's left-side bedrock wall to the right-side bedrock wall. Section PR113 was placed near the midpoint of this 1.5-km-long segment, about 0.4 km upriver of the Moorhead Bridge (fig. 4). The right bank of Powder River at this section is formed by the lower flood plain surface developed after the flood of 1978 (Moody and others, 1999), and the left bank is a Lightning-level terrace (Leopold and Miller, 1954; Moody and Meade, 2008).

Figure 4. Aerial view of cross section PR113. The view is nearly due west, looking up the Powder River from just below the Moorhead Bridge. The approximate location of cross section PR113 is shown by the red line. Photograph was taken on September 22, 1989.

In section PR113, the flood of 1978 caused substantial changes, which we were able to record by comparing our survey data for 1977 and 1978 (figs. 5 and 6). The principal change was a complete shift in the lateral arrangement of the section from a cut bank on the right side and point bar on the left side to the opposite, a cut bank on the left side and point bar on the right side. The thalweg of the river channel here shifted, during 2 weeks of flood flows in May 1978, about 44 m leftward (downvalley). Our surveys indicated that the flood waters had removed most of the preflood point bar from the left bank and had deposited a large new point bar, 0.5–1.5 m in thickness, across a lateral distance of about 40 m on the right bank. Data showing the effects of the flood of 1978 on section PR113 have been portrayed and discussed by Meade and Moody (2013, see especially their figs. 14 and 17). These flood effects may not be typical of all sections of Powder River because the channel at PR113 is at near right angles to the main valley axis and, therefore, at near right angles to the direction of the flow of the highest (overbank) flood waters.

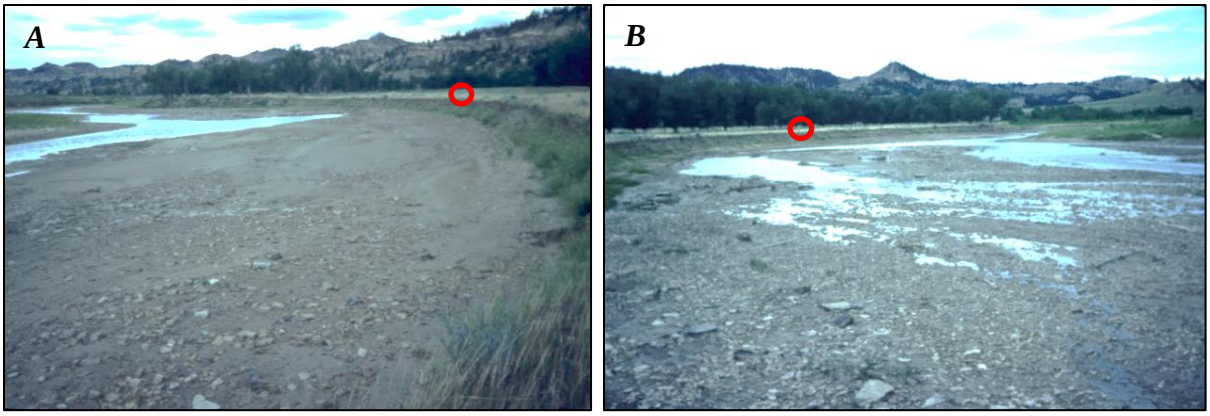

Figure 5. Views of cross section PR113 before the flood of 1978. Photographs were taken on July 20, 1977.*A*, View is downriver, and E. Meade (about 1.6 meters tall) in red circle is on the section. *B*, View is upriver, and E. Meade in red circle is on the section.

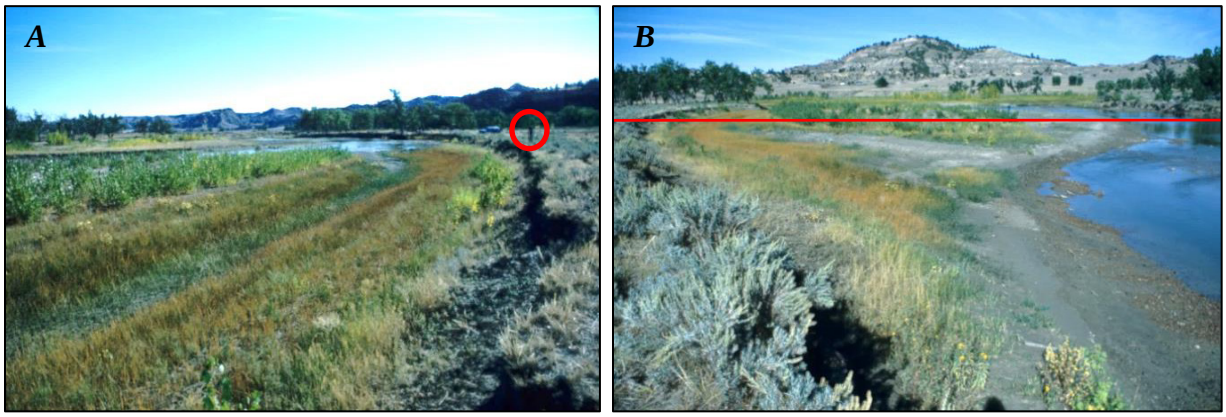

Figure 6. Views of cross section PR113 taken on September 19, 1978. *A*, View is downriver. J. Moody (~1.9 m tall) in red circle is on the section. A band of small cottonwood trees with green leaves starts at the center left of the photograph and parallels the old channel with some water in it. *B*, View is upriver. Red line indicates the approximate line of section. Sagebrush with bluish-gray foliage is along the edge on the Moorcroft-level terrace.

The leftward shift continued during the decades following the flood of 1978. The channel thalweg shifted leftward another 56 m in the 17 years between 1978 and 1995 (fig. 7). The left-side cut bank was eroded back about 40 m during the same period; more than one-half of this bank recession (a total of some 30 m) took place during only 4 of the 17 years (1987, 1991, 1993, 1995). By 1995, the right-bank point bar had grown leftward about 40 m and upward by an average of about 1 meter, and most of the growth happened during 1987, 1993, and 1995.

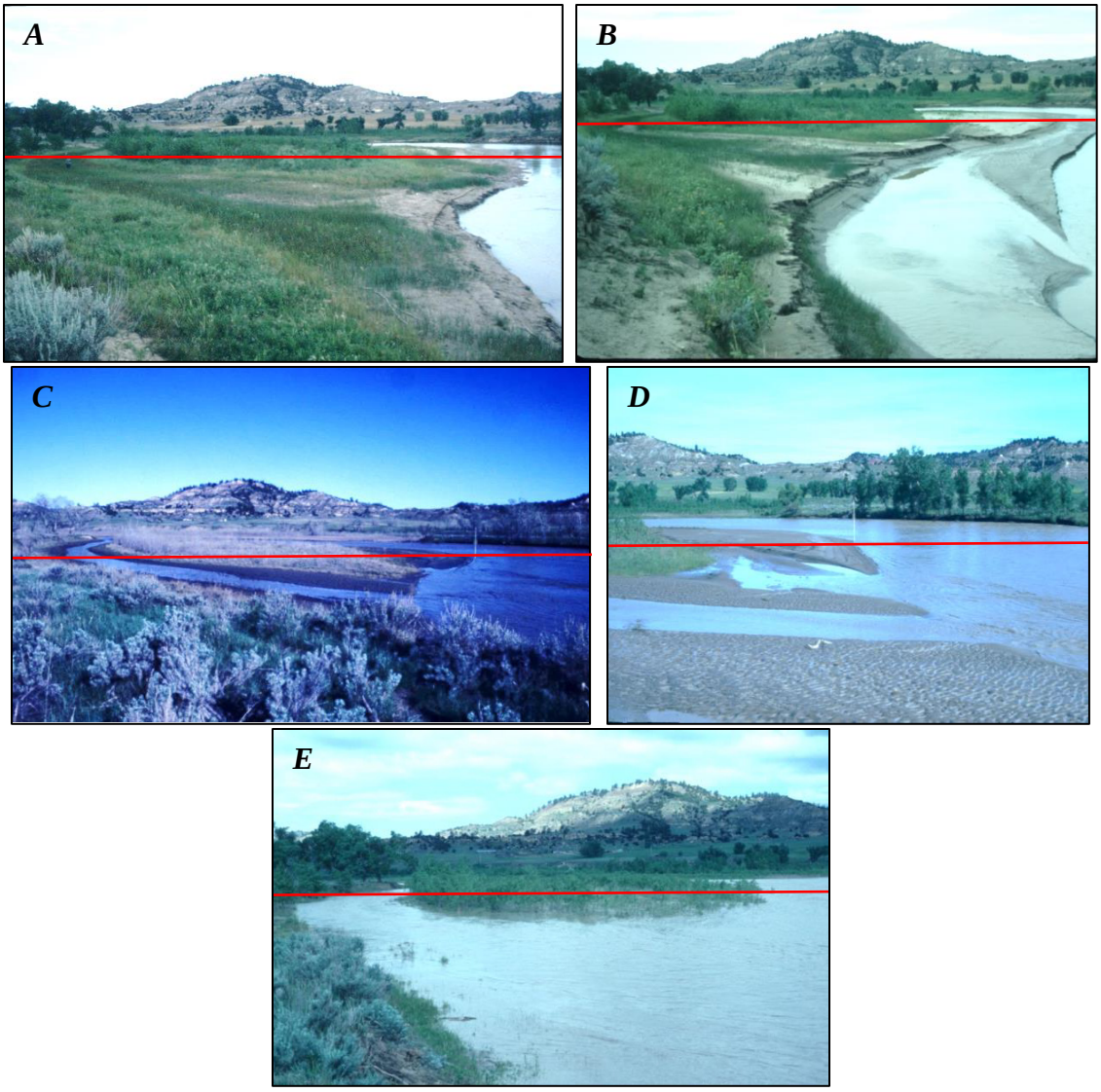

Figure 7. Series of upriver views of cross section PR113 taken at different water discharges in 1992 and 1993. The old channel is in the left center of the photographs and curves into the center of each photograph. Bands of cottonwood trees on the point bar are in the center of the photographs. Red lines indicate approximate line of section. *A*, Discharge of 3.14 cubic meters per second (m^3/s) on August 25, 1992. *B*, Discharge of 11.0 m^3/s on August 25, 1993. *C*, Discharge of 82 m^3/s on May 10, 1993. White vertical survey rod is on the section. *D*, Discharge of 93 m^3/s on June 10, 1993. White vertical survey rod is on the section. *E*, Discharge of 176 m^3/s on June 19, 1993.

After 1995, the rate of change in section PR113 was reduced substantially. The left-side cut bank shifted leftward only another 5 m (with no appreciable lateral shift in channel thalweg) in the 17-year period 1996–2012. Only a few decimeters of new sand (no more than 0.6 m at most stations) were deposited during the period atop most of the right-side point bar and flood plain. We speculate that this slowdown marked the restabilization, by about 1995, of the configuration of the segment of Powder River represented by section PR113, after nearly two decades (1978–1995) of active adjustment to the disruptive changes wrought by the flood of 1978. This apparently stable configuration shows in the 1995 cross section: a 40-m-wide main channel,

adjoined to the right by a 40-m-wide point bar, which is adjoined to the farther right by a 40-to-50-m-wide flood plain (fig. 8). The total post-1995 history so far shows no more change in the 20-year period 1996–2015 than the change that took place in the single year of either 1993 or 1995.

Vegetation has become well established on the right-side point bar. By 2012, cottonwood trees 8–10 m high were growing in the parts of the cross section (that is near cross-channel station 45) that had been the unvegetated bottom of the active channel in 1977 and which had subsequently received repeated deposits of (mostly) sand whose aggregate thickness has totaled, by now (2016), as much as 2 m.

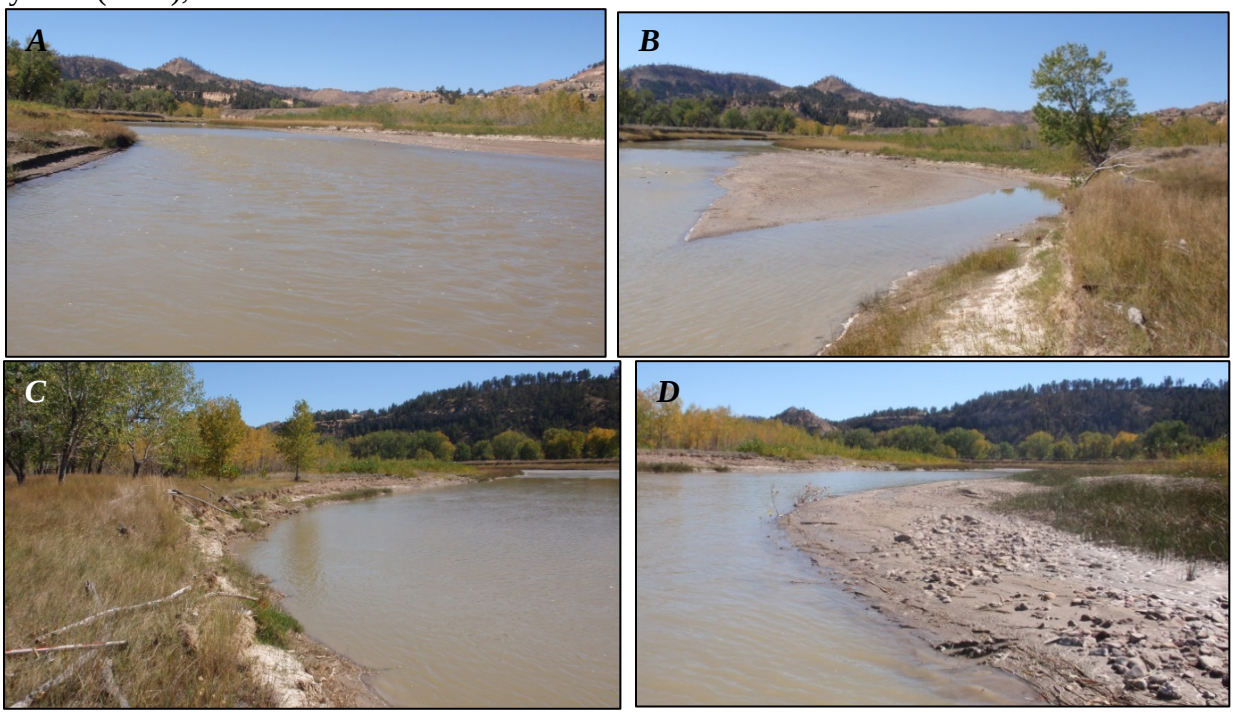

Figure 8. Photographs of cross section PR113 taken on September 26, 2014. All views were taken standing on the line of section. *A*, Upriver view of the edge of the point bar on the right bank. *B*, Upriver on the left bank. *C*, Downriver of the left bank. *D*, Downriver view of the edge of the point bar on the right bank.

In 2015, the snowmelt flood on Powder River had two peaks greater than 200 m^3/s on May 28 (280 m^3/s) and June 6 (283 m^3/s). This was the fourth annual flood greater than 200 m^3/s since the first flood in 1975 (see hydrographs in the appendix). At most stations, the 2015 floods deposited 0.2–0.5 m of sediment on the flood plain surface, which has grown to 1.5–2.5 m above the thalweg, and thus was inundated barely. The most common depositional features were lee dunes (Moody and Meade, 2008) downstream from trees and shrubs (fig. 9).

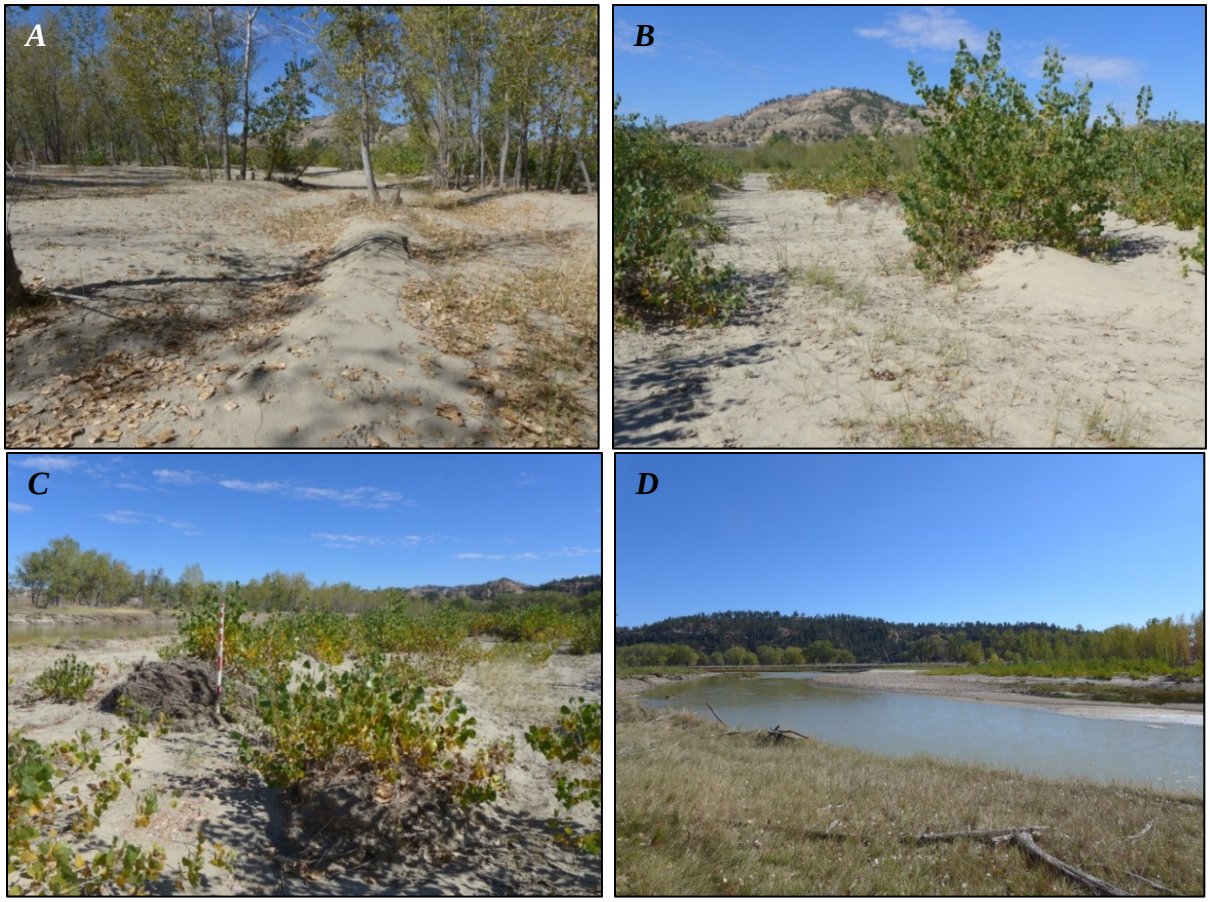

Figure 9. Photographs of lee dunes on the right-bank point bar of cross section PR113 on September 30, 2015. Photographs *A*, *B*, and *C* were taken on the right bank point bar between stations 0 to 40. *A*, Upriver view of lee dunes extending downriver from a single cottonwood tree in the center and a row of cottonwood trees in the upper right. Closest tree on center of lee dune is about 10 meters upriver of the line of section. *B*, Upriver view of lee dune downriver from shrubby cottonwood trees. *C*, View is downriver showing the common debris of roots and branches on the upriver side of a lee dune. Leveling rod is about 3 meters downriver of the line of section. *D*, View of the right bank point bar taken from the left bank. The tagline, in the lower right corner of the photograph, marks the line of section.

PR116 Narrative

Cross section PR116 was established in 1975 at the exact location of a cross-channel cableway (fig. 10) that had been built earlier by the USGS Montana District for measuring water discharge at the streamgaging station, Powder River at Moorhead, Montana (Moody and Meade, 2017, PR116_SciBase2.xlsx for survey data).

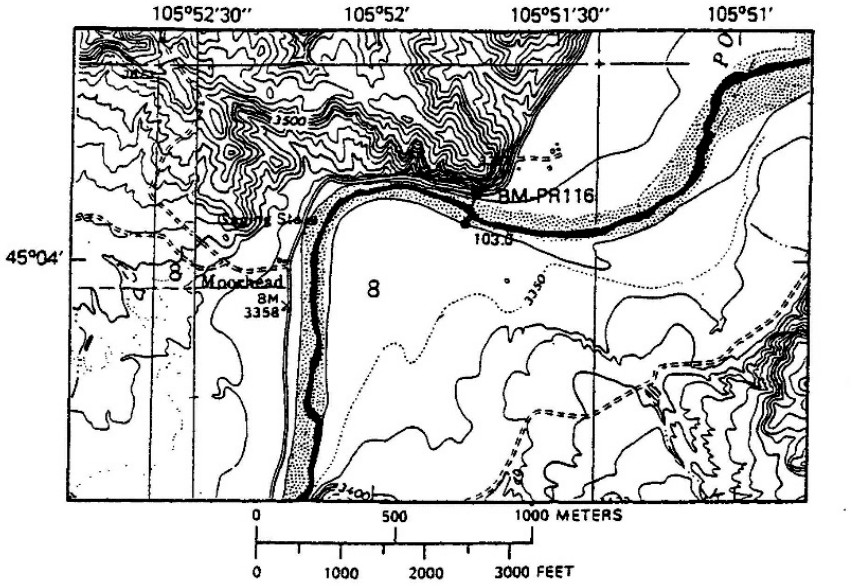

Figure 10. Location map for cross section PR116. Maps show the bench mark BM-PR116, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Moorhead quadrangle. Planform configuration was taken from 1969 aerial photos. The bench mark was a bolt in the upriver footing for the cable car A-frame. The footing and bolt were removed when this site was modified by a local rancher after 1998. Station 109.1 was at the end of an iron hoop anchored in the right-bank deadman. It is unknown, as of 2015, whether or not the deadman is still in place on the right bank.

Our intention in this 1975 installation was to be able to include previous measurements made here with those we intended to make ourselves in the coming years. Like many such USGS cableways installed on U.S. rivers, this one's location was selected for its stability so as to be able to develop, over the long term, a permanently stable relation between river stage and water discharge and thereby produce a useful discharge rating curve. Section PR116 is controlled partially by bedrock and shows the least channel change with time (fig. 11).

In addition to its usefulness to USGS hydrologists during periods when river flows were swift and deep enough to preclude wading measurements of the velocity and depth of the water, the cableway (fig. 12) also served at least one ranch lad (Hugh Fulton) when he wanted to visit a friend on the opposite bank of Powder River. The overhead cableway was dismantled in September 1988, but the concrete foundations for the cableway's pylons are still visible (and usable as section bench marks) on both sides of the river. Hugh Fulton and his father, George Fulton, participated in our studies by collecting daily samples of suspended sediment during 1974–96, using the USGS sediment sampler that was installed on the upriver railing of the Moorhead Bridge (sediment data available at https://waterdata.usgs.gov/usa/nwis/uv?site_no=06324500). Earlier measurements (1938–46) of suspended sediment at the Moorhead gaging station were reported by Hembree and others (1952).

Figure 11. Downriver view of cross section PR116 taken on July 21, 1977. This was the site of the streamgaging station in 1977 and 1978 and shows the bedrock control of this exceptionally stable reach of Powder River.

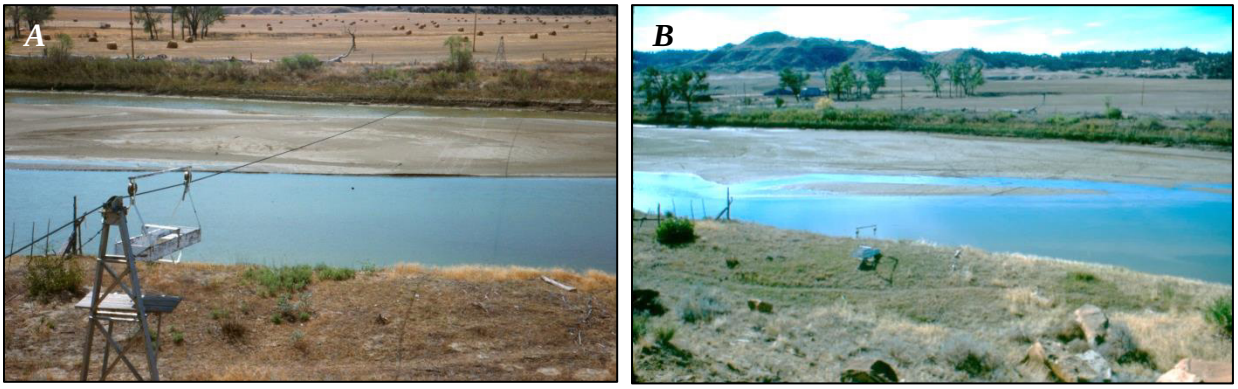

Figure 12. Views of the site of the cable car used to measure the water discharge at cross section PR116 until 1988. The U.S. Geological Survey gaging station at PR116 was abandoned some time in the 1990s, and as of 2017 the gaging station is 2.5 kilometers upriver at the Moorhead Bridge. *A*, View is from the left bank and cableway is on section. Flow is from right to left. Photograph was taken on August 16, 1986. *B*, View is from above the left bank taken on September 19, 1988, about 10 days after removal of cableway. Cable car is approximately on section, and flow is towards the upper left.

Leveling surveys remeasured the elevations every year from 1975 through 1998, with the exception of 1976, 1981, 1982, and 1983. During the flood of 1978, the left-side terrace bank was eroded laterally 1.8 m, while a 0.2–0.7 m thickness of new sand was deposited over a 6–7-m width atop the left-side terrace, and a 0.3–0.4 m thickness of new sand was deposited atop the riverward edge of the right-side terrace (fig. 16 of Meade and Moody, 2013). The flood deepened the channel by 0.1–0.3 m, but these deepened spaces were refilled soon with sands during subsequent years.

During the two decades following the flood of 1978, annual resurveys showed how the active river bed varied between net deposition one year and net erosion the next, at rates of only a few decimeters of vertical change, either up or down, from year to year. During the same two decades, the left terrace bank was eroded back at an average rate of 0.1 meter per year (m/yr), but the sediment was deposited as narrow benches (about 8 m wide) along each bank (fig. 13).

After 2010, the site for this cross section was converted to an irrigation pump site by the local rancher and is no longer monitored.

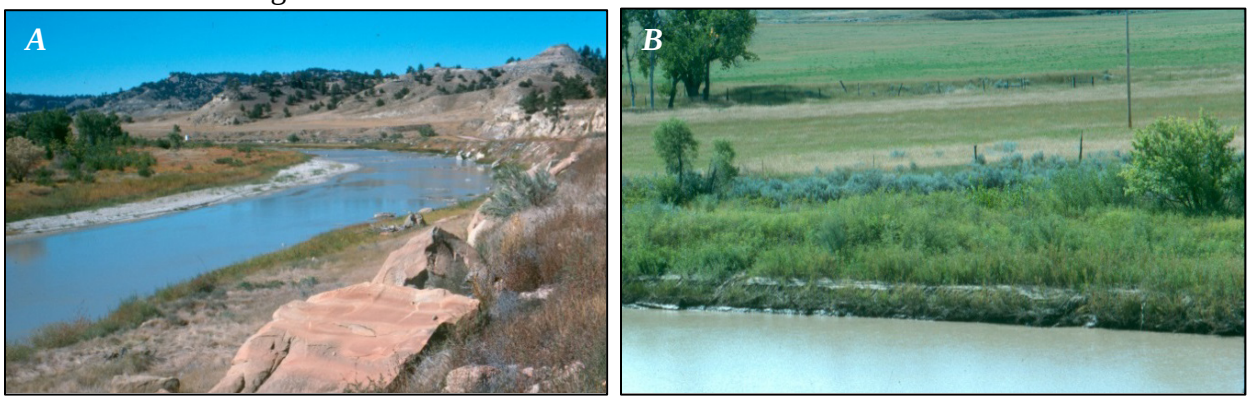

Figure 13. Views of cross section PR116 in 1989 and 1993. *A*, Photograph was taken on September 19, 1989 from the left bank looking upriver (camera man is standing on the line of section PR116). The white cylindrical structure on the left bank upriver, left of the center of the photograph, is the interim gage house for Powder River at Moorhead, Montana. Current gage house is now at Moorhead Bridge (fig. 4), about 1.8 kilometers upriver from the interim gage house. *B*, Newly deposited sand bench along the right bank just downriver from PR116. Flow is from right to left. Photograph was taken on August 25, 1993.

PR120 Narrative

Cross section PR120 was first established and surveyed in 1975 (fig. 14). It was resurveyed annually during the 4 consecutive years 1977–1980, resurveyed in 1982, resurveyed annually during the 18 consecutive years 1984–2001, and, after a 10-year hiatus, resurveyed in 2012 through 2016. Additional surveys were made during 1993, 1994, and 1998, and a complete cross valley cross section (1,600 m long) was surveyed in 2006 and is included in the data file for PR120 (Moody and Meade, 2017, PR120_SciBase2.xlsx for survey data).

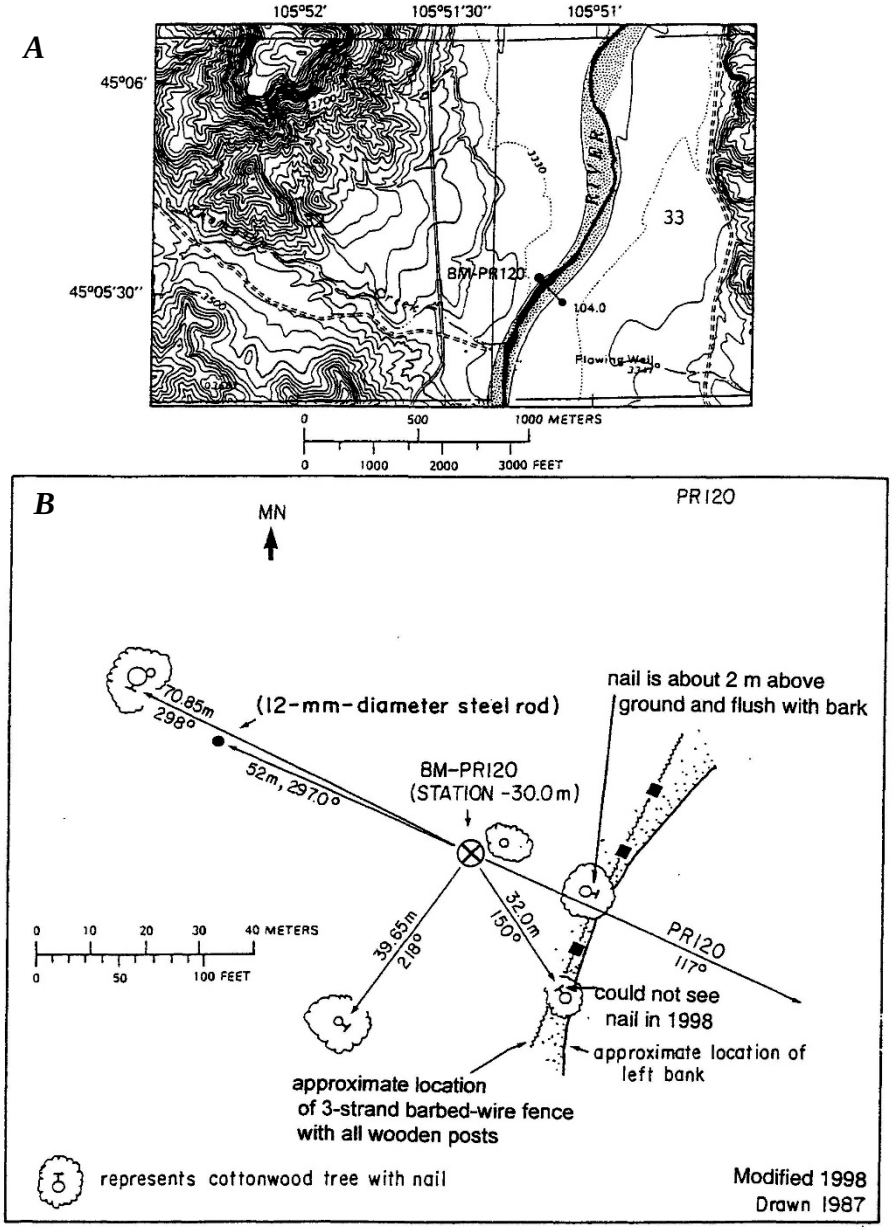

Figure 14. Location maps for cross section PR120. *A*, Location of cross section PR120, bench mark BM–PR120, and left- and right-bank reference pins (12-millimeter-diameter steel rod) on the Moorhead quadrangle. Planform configuration was taken from 1969 aerial photos. *B,* Location of bench mark and some reference pins on the left bank. MN is magnetic north.

Section PR120 crosses a gently curving reach of Powder River, about 0.3 km downriver of the mouth of Thompson Creek (fig. 1). The left bank of Powder River is developed on a Moorcroft-level terrace (Leopold and Miller, 1954) that covers most of the area locally known as "Reynolds Battlefield" (Moody and Meade, 2008; Vaughn, 1961; Hedren, 2016, p. 145–182) (fig. 15).

Figure 15. View downriver of cross section PR120 before the 1978 flood. Photograph was taken on July 21, 1977, with E. Meade (about 1.6 meters tall) standing on the line of section (inside the red circle).

The right bank of the low-water channel is formed by a flood plain developed after the flood of 1978 (Moody and others, 1999), which grades laterally onto the Lightning-level terrace (Leopold and Miller, 1954) (fig. 16).

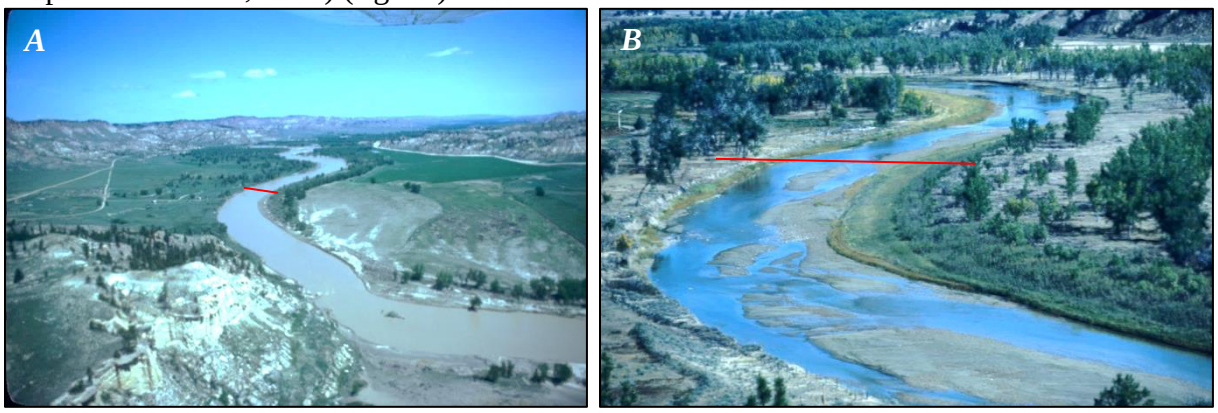

Figure 16. Two views of cross section PR120 in 1978 and 1988. Red lines indicate approximate line of section. *A*, The aerial view looks downriver during the waning stage of the flood of 1978 and was taken on May 25, 1978, by B. Ringen. "Hospital Bluff" is in the bottom left of the photograph. New sediment (mud and sand) can be seen deposited on the right bank starting just upriver from the cross section. *B*, Zoom lens view is looking downriver from Hospital Bluff taken on September 19, 1988.

In section PR120, the principal effect of the flood of 1978 was an increase in the area of the channel cross section. The cross section was enlarged mainly by 11 m of lateral erosion of the 3.5-meter-high left bank on the Moorcroft-level terrace (fig. 2; Leopold and Miller, 1954; Moody and Meade, 2008; fig. 6 of Meade and Moody, 2013). This channel enlargement was not compensated during the flood by the deposition of new sediment on the right-bank flood plain, although the flood did leave some new sediment (averaging 0.5-m thickness between stations 80 and 100) on the right-side Lightning-level terrace.

A new inset flood plain (figs. 17 and 18) was constructed by the river at section PR120 during the two decades following the flood of 1978—mostly during the years 1982, 1987, 1993, and 1995 (Moody and others, 1999). By 1995, new sediment had accumulated to thicknesses mostly between 1.0 and 1.5 m from station 56 to about station 80. A 23-m-long trench dug through these deposits in 1998 revealed their stratigraphic relations and their correspondence (or lack of it) with the annual survey data (Pizzuto and others, 2008).

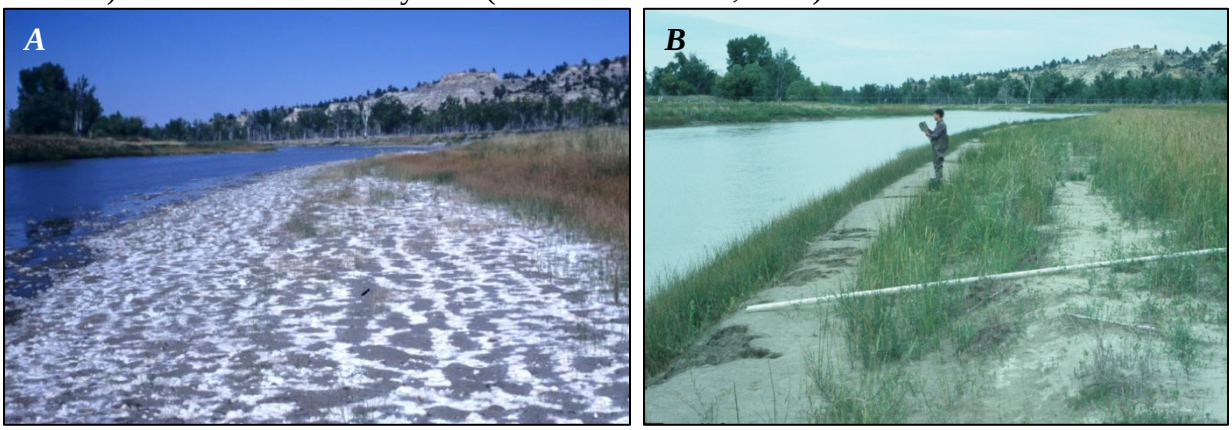

Figure 17. Two views of the new inset flood plain at cross section PR120. *A*, View is downriver from station 53. New emerging right-bank flood plain is on the right of photograph. Photograph was taken on September 16, 1989. *B*, Photograph shows deposition of additional sand on the right-bank flood plain as a levee and sand bench (fig. 13*B*). J. Pizzuto is about 1.7 meters tall, and the white survey rod lies on the line of section. Photograph was taken on August 25, 1993.

Powder River generally flows northward so that frequently the snow and ice melt out in the southern reaches of the river in Wyoming before they melt out in Montana. Thus, there are often ice-break-up floods on Powder River, which are a geomorphic agent that can locally erode and deposit sediment (fig. 19).

Figure 18. Views of cross section PR120 at different discharges. Red lines indicate the approximate line of section. *A*, Discharge is 170 cubic meters per second (m^3/s) on June 9, 1993. Note the water in the trough between the new inset flood plain and the old bank (Lightning-level terrace) above and below the section. *B*, Discharge is 34 m^3/s on May 13,1993. *C*, Discharge is 17 m^3/s on May 9, 1994. *D,* Discharge is 3.1 m^3/s on March 10, 1995. *E*, Discharge is about 1.5 m^3/s on September 24, 1994. *F*, Discharge is 0.23 m^3/s on 23 August 23, 1994.

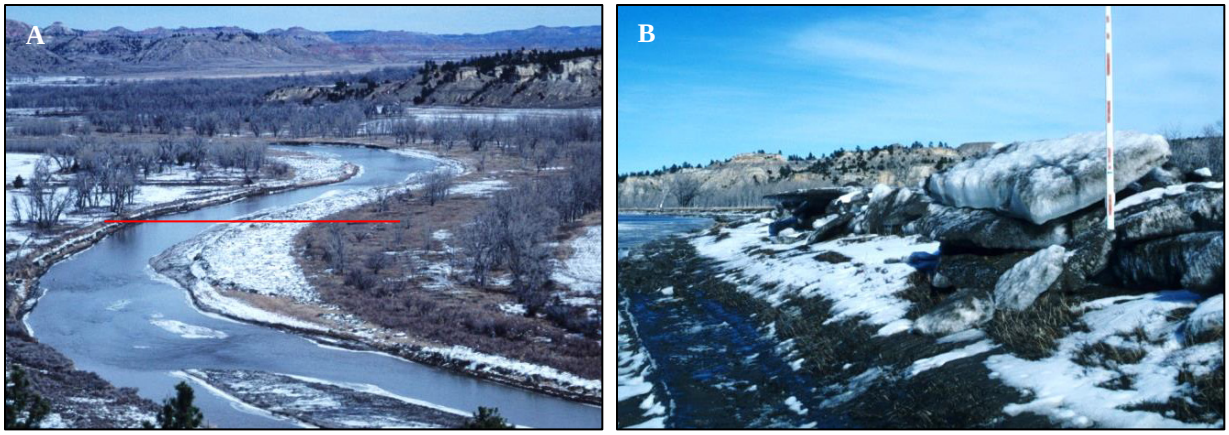

Figure 19. Ice effects at cross section PR120. *A*, View is downriver of ice covering the new inset flood plain along the right bank. Discharge is 3.1 cubic meters per second on March 10, 1995. *B*, View is downriver along the right bank. Close-up view of ice blocks with sediment. White survey rod with red bars stands on the line of section at about station 60.

During the last decade (judging from surveys done in 2001, and 2012 through 2015) the width of the low-water channel has decreased. The right-side flood plain has expanded leftward by another 6 m as a bench, and an additional bench (approximately 2 m wide) has been built along the base of the cut bank (Page and Nanson, 1982; fig. 41) further decreasing the width of the low-water channel at section PR120 (figs. 20 and 21). The low-water channel width in 2016 was less, by some 10–15 m, than it was in 1977, the year before the flood of 1978.

Figure 20. Downriver view of cross section PR120 was taken on September 27, 2006.

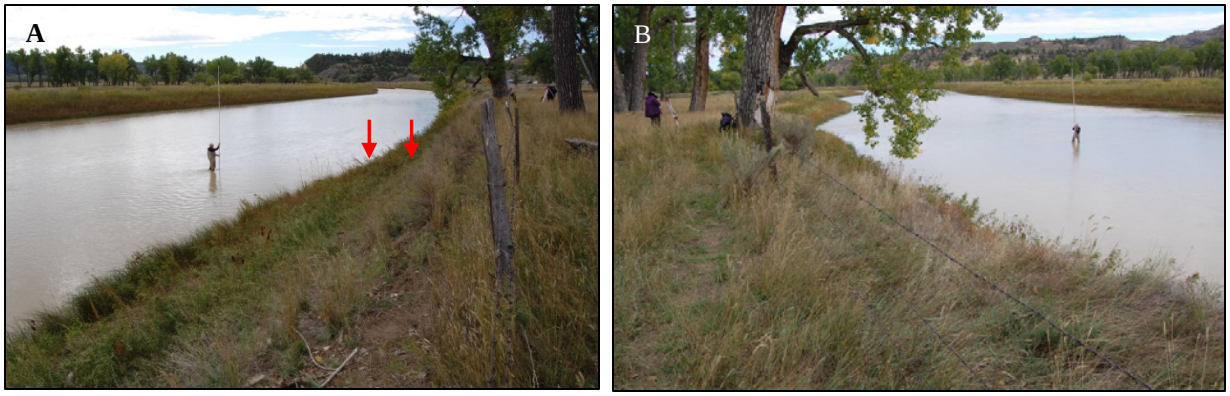

Figure 21. Upriver and downriver views of cross section PR120 on September 28, 2013. *A*, View is upriver. A narrow bench (approximately 2 meters [m] wide) below the top of the left bank is shown by the red arrows (also see fig. 41). J. Moody (1.9 m tall) is standing on the line of section in Powder River. The edge of the 2-m high flood plain along the right bank is now at about station 50, whereas in 2001 it was about at station 58. *B*, View is downriver and J. Moody (1.9 m tall) is standing on the line of section in Powder River.

Beginning in 2013, sediment cores were collected for dating of sediment by optical stimulated luminescence (OSL). Cores for OSL analysis are generally 20 cm in length and collected horizontally from the bank. In 2013, one core, at 1,014.12 m above sea level, was taken in sediment presumed to have been deposited during the flood of 1923 raising the Lightning-level terrace up to the level of a low-level Moorcroft-level terrace (Cohen and Nanson, 2008) (figs. 22 and 23). Another core was collected at an elevation of 1,012.68 m and is presumed to represent sediment from the Lightning-level terrace. Two cores were collected from the Kaycee-level terrace that is on the extended line of section (fig. 23*A*). In 2014, two additional cores were collected at 1,013.57 and 1,013.22 m above sea level to help determine rates of sediment deposition.

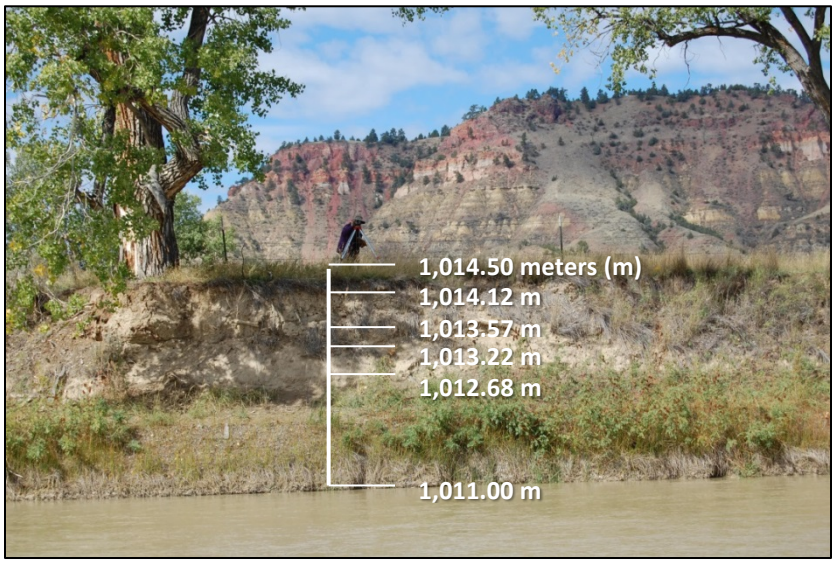

Figure 22. View of the left bank of cross section PR120 showing the location of sediment cores collected for optical stimulated luminescence dating. River flows from left to right in photograph (the tripod and D. Martin are 15 meters upriver from station -7.0).

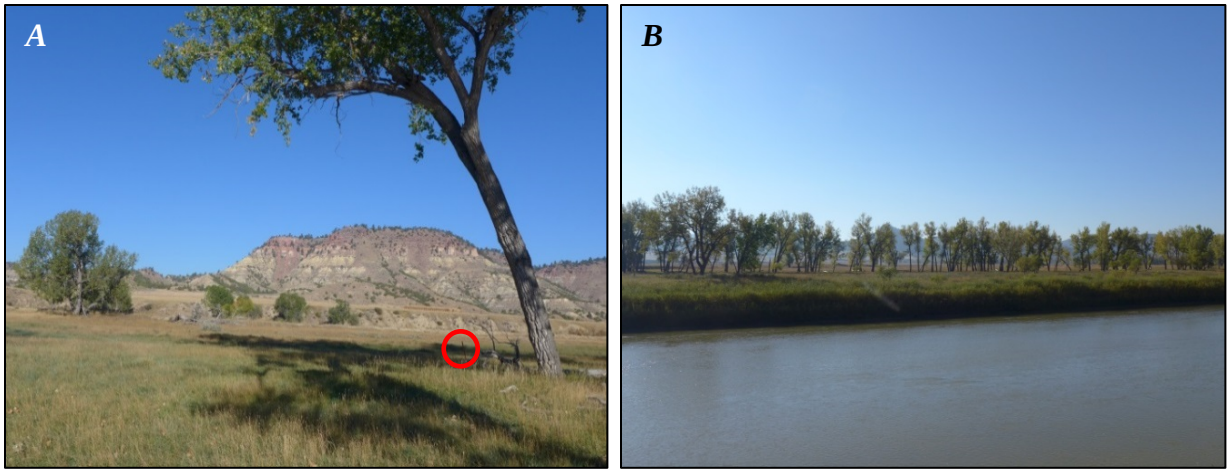

Figure 23. Views of cross section PR120 on September 30, 2015. *A*, View is across a Moorcroft-level terrace with the higher Kaycee-level terrace in the background behind a row of cottonwood trees growing at the base of the terrace. The higher hills behind the Kaycee-level terrace are the Fort Union Formation. Optical stimulated luminescence (OSL) cores were collected from the Kaycee-level terrace in 2013. They were approximately on the line of section at elevations of 1,018.8 and 1,023.2 meters (m) above sea level (NGVD 29). The red circle encloses an orange, metal fence post that is on the line of section and next to the brass bench mark set in concrete. *B*, View of the approximately 2-m high inset flood plain, which has developed along the right bank since the flood of 1978 (compare with fig. 15). An OSL core was collected 2 m downstream from station 57 and 0.2 m below the 2015 surface in sediment (elevation 1,012.71 m) recently deposited by the snowmelt floods.

PR122 Narrative

Cross section PR122 was established in 1975 in the crest of a large meander bend of Powder River just downriver from the mouth of Flood Creek (figs. 1 and 24).

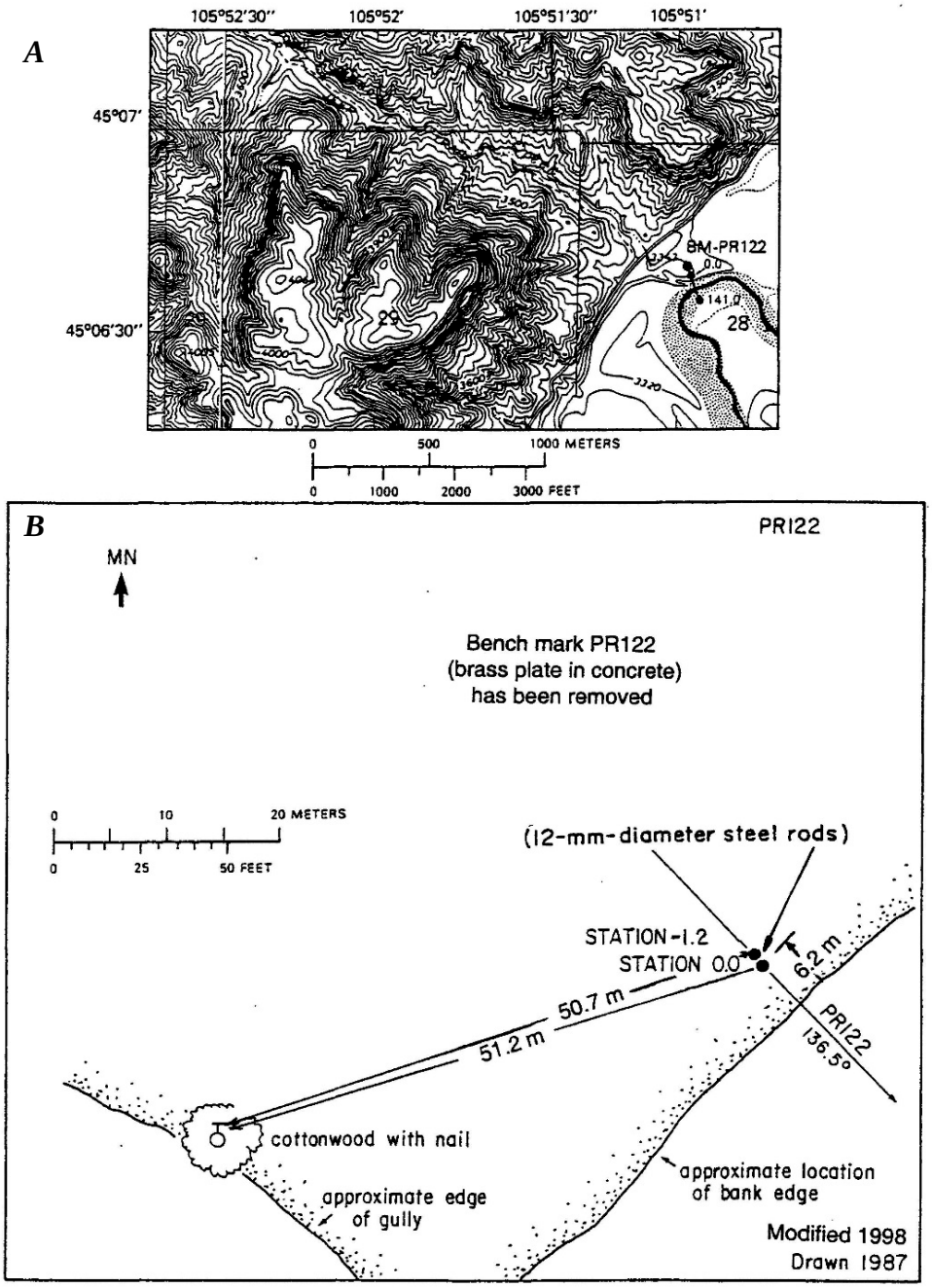

Figure 24. Location maps for cross section PR122. *A*, Location of cross section PR122, original bench mark BM-PR122, and left- and right-bank reference pins (12-millimeter-diameter steel rod) on the Moorhead quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Bench mark was inadvertently removed when a new fence line was constructed. A pin was put in at station -20.6 in 1993 on the left bank and the other reference pins on the left bank are still present as of 2014. MN is magnetic north.

The bend had been migrating steadily down valley, having shifted at least 0.5 km in 80 years (sheet 1 of Martinson and Meade, 1983; fig. 8 of Gay and others, 1998). The 6–7-m-high left bank of the section cuts into a large deltaic fan that has formed at the mouth of Flood Creek (figs. 1 and 25).

Figure 25. View of cross section PR122 just downriver from the mouth of Flood Creek on September 5, 1975. E. Andrews (about 1.7 meters [m] tall) is standing beneath the line of section (red line), and the flow is from left to right. The 7-m-high bluff behind E. Andrews is the deltaic fan that was deposited by Flood Creek.

The meander bend that includes section PR122 was cut off at its neck by the flood of 1978 (figs. 11 and 12 of Meade and Moody, 2013). But before the neck of the bend was breached, the flowing flood waters had already eroded the bend crest, removing a 7-m width of deltaic fan material from the left bank at section PR122, and adding a thickness of 0.5–1.0 m of new sand across a 40-m width (stations 20 to 60) of the river channel (fig. 26).

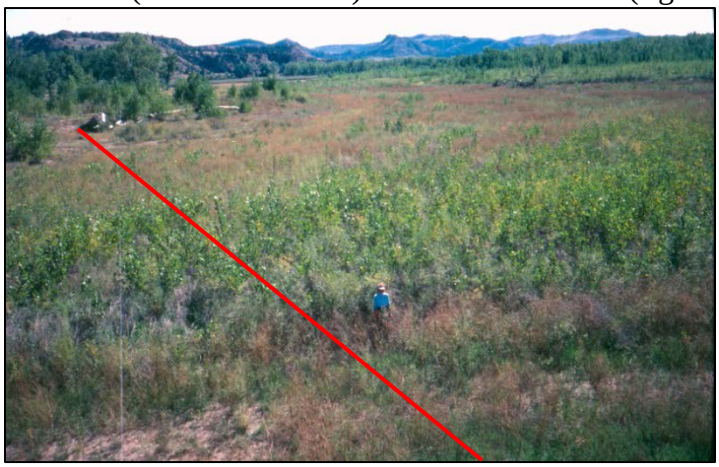

Figure 26. New vegetation growing in the cutoff at cross section PR122 on September 17, 1982. The taller vegetation is a band of cottonwood trees about 4 years old. S. Stewart (about 1.7 meters [m] tall) is 6 m upriver from station 30. Red line shows the approximate line of section.

After the 1978 cutoff, cross section PR122 was resurveyed in 1979, 1980, 1982, 1984, 1987, 1993, and 1995 (Moody and Meade, 2017, PR122_SciBase2.xlsx for survey data). None of these resurveys showed any significant change in the cross-sectional profile.

Vegetation of the abandoned channel at section PR122 has changed markedly, as shown by repeated photographs (fig. 27; see also fig. 13 of Meade and Moody, 2013). Seeds of willow and cottonwood trees brought in during or after the flood of 1978 soon sprouted in the abandoned river channel. Willows grew more rapidly during the first few years. Then cottonwoods gradually supplanted the willows. As of year 2013, cottonwood trees have grown 10 m tall in what was, before the flood of 1978, the unvegetated active channel of Powder River (fig. 25).

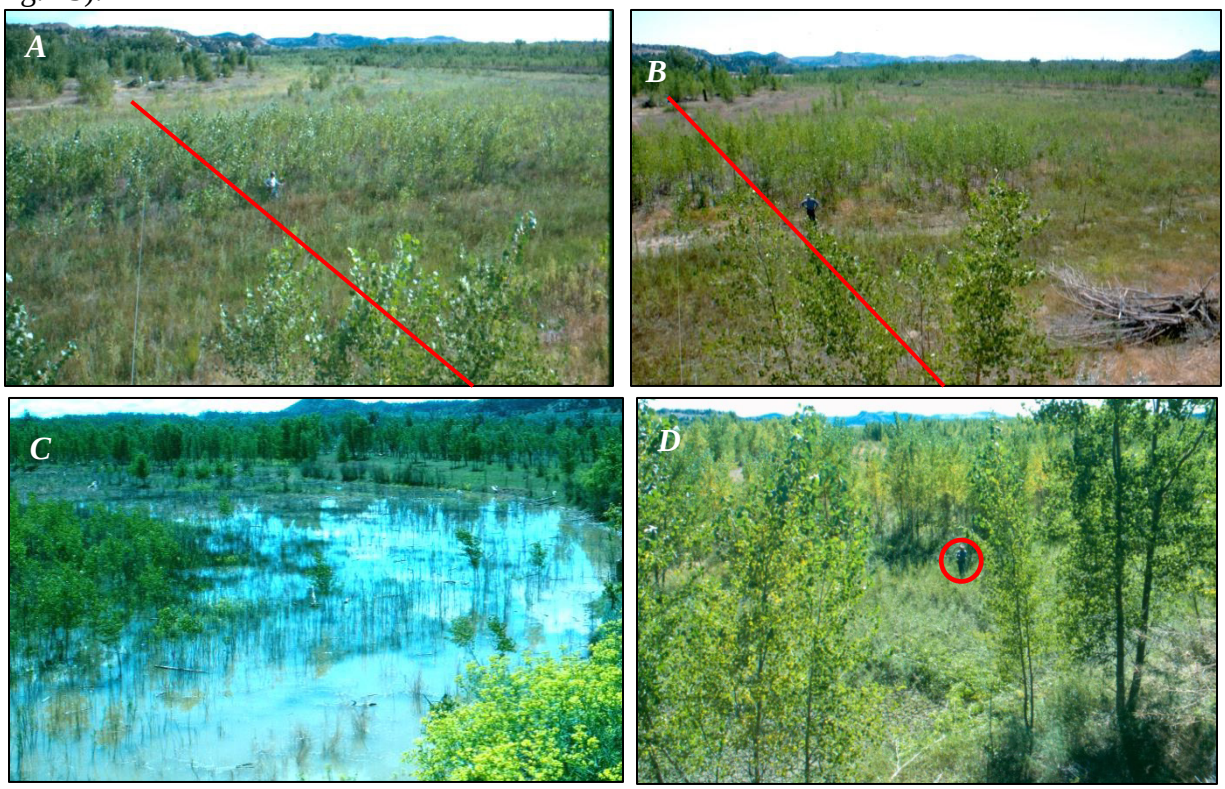

Figure 27. Changes in vegetation at cross section PR122. Red lines indicate the approximate line of section. *A*, View is from the top of the left-bank bluff showing vegetation in the cutoff on September 3, 1984. J. Moody (about 1.9 meters [m] tall) is 6 m upriver from station 30. *B*, August 17, 1986. *C,* View shows the reach upriver from PR122 on June 9, 1993. Water discharge was about 170 cubic meters per second (m^3/s) (fig. 18) so that water could fill the abandoned channel. *D*, View is from the left bank along the line of section on September 26, 1995. J. Moody (inside red circle) is standing between stations 20 and 30.

The cross section was resurveyed in 2014, and 0.15–0.40 m of sediment has been deposited along the line of section in the cutoff channel since 1978. The density of cottonwood trees has decreased with time (fig. 28).

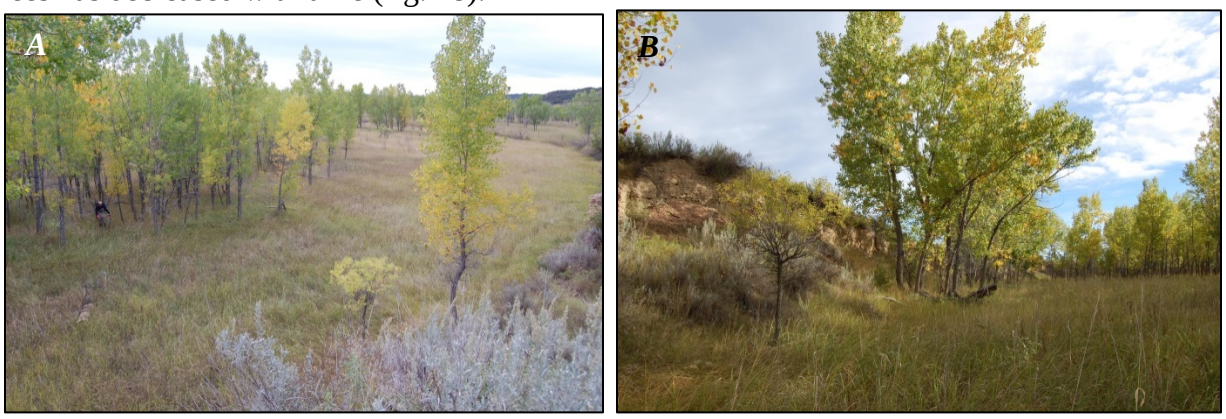

Figure 28. Views of the abandoned channel at cross section PR122 on September 29, 2013. *A*, View is upriver from PR122 showing channel abandoned during the flood of 1978. J. Moody is standing between stations 20 and 30. Distant skyline is no longer clearly visible because of the height of the cottonwood trees. *B*, View is downriver through section PR122, showing the left bank of the pre-flood channel (cut into the alluvial fan of Flood Creek) that was eroded back 7 meters during the flood of 1978 (fig. 25; see also fig. 6 of Meade and Moody, 2013). The clump of cottonwood trees in center of photograph grew since the flood of 1978 at approximately the same location where E. Andrews was standing in figure 25.

PR122A Narrative

Cross section PR122A was established in 1979 across a new cutoff channel that had formed as the flood of 1978 cut across the neck of a meander bend in Powder River at the mouth of Flood Creek (fig. 29).

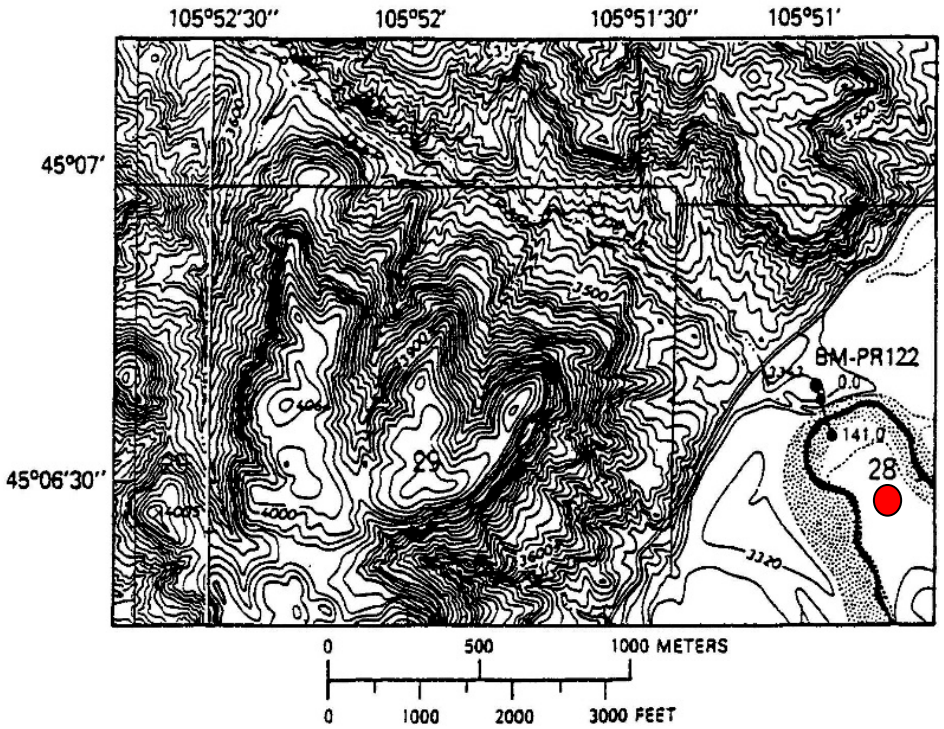

Figure 29. Location map for cross section PR122A.The location of cross section PR122, the original bench mark BM–PR122, and the left and right bank reference pins (12-millimeter-diameter steel rod) are shown on the Moorhead quadrangle. Planform configuration was taken from 1969 aerial photos. This bend was cut off by the flood of 1978 and cross section PR122A was established near the red dot on the map.

PR122A is one of two cross sections (the other is PR141A) in which we have been able to document the "birth," "adolescence," and "maturity" of a point bar of Powder River. The section was surveyed annually from 1979 through 2002 (except in 1981 and 1983), again in 2006, and annually from 2009 through 2016 (see Moody and Meade, 2017, PR122A_SciBase2.xlsx for survey data).

As the flood of 1978 flowed across the neck of the bend, several gullies formed on the downstream bank of the meander neck (fig. 30) and began cutting their way headward across the neck. One of these eventually succeeded in breaching the neck and in diverting the main flow of the flood waters (fig. 8 of Gay and others, 1998; figs. 11 and 12 of Meade and Moody, 2013). Because the cutoff was completed late in the flood, the width of the new channel remained fairly narrow—45 m on the line of section (fig. 31).

Figure 30. Headcut at cross section PR122A on September 21, 1982. View is down valley through the headcut that crosses section PR122A near station -35. S. Stewart (about 1.7 meters [m] tall), in the middle ground, is standing on the line of section and M. Karlinger (about 1.8 m tall) is standing downriver of the section.

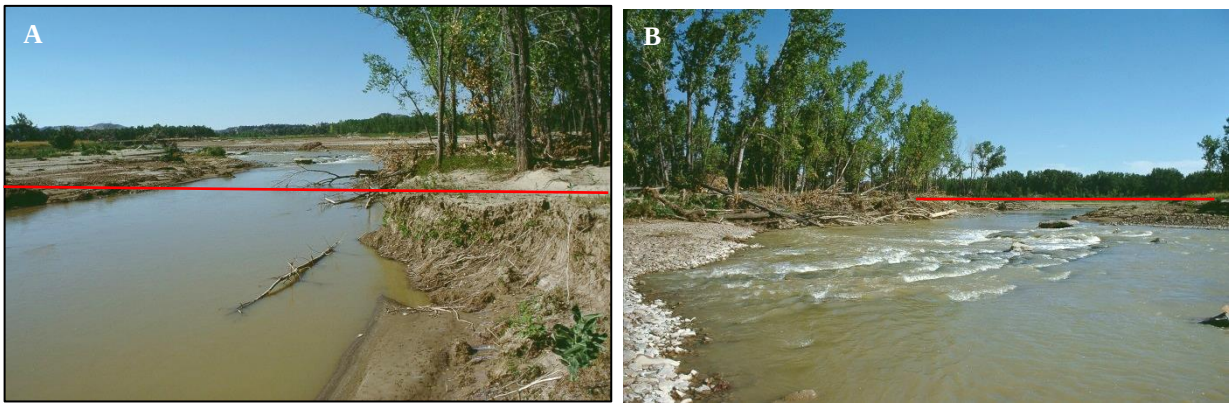

Figure 31. Views through the cutoff at cross section PR122A on September 4, 1978. Red lines show the approximate location of cross section PR122A. *A*, View is upriver through the cutoff showing the bedrock rapids in the new channel formed during the flood of 1978. *B*, View is downriver of the bedrock (coal) rapids.

Along the right side of the new channel, extending from the thalweg at station 38 to the right bank at station 75 (destined to become a point bar, fig. 32), the initial bed sediment was primarily gravel, plus some sand. The channel was bedrock controlled and had a downstream slope of 0.0043 (several times steeper than the average slope of about 0.0011 for Powder River; Moody and Meade, 2008).

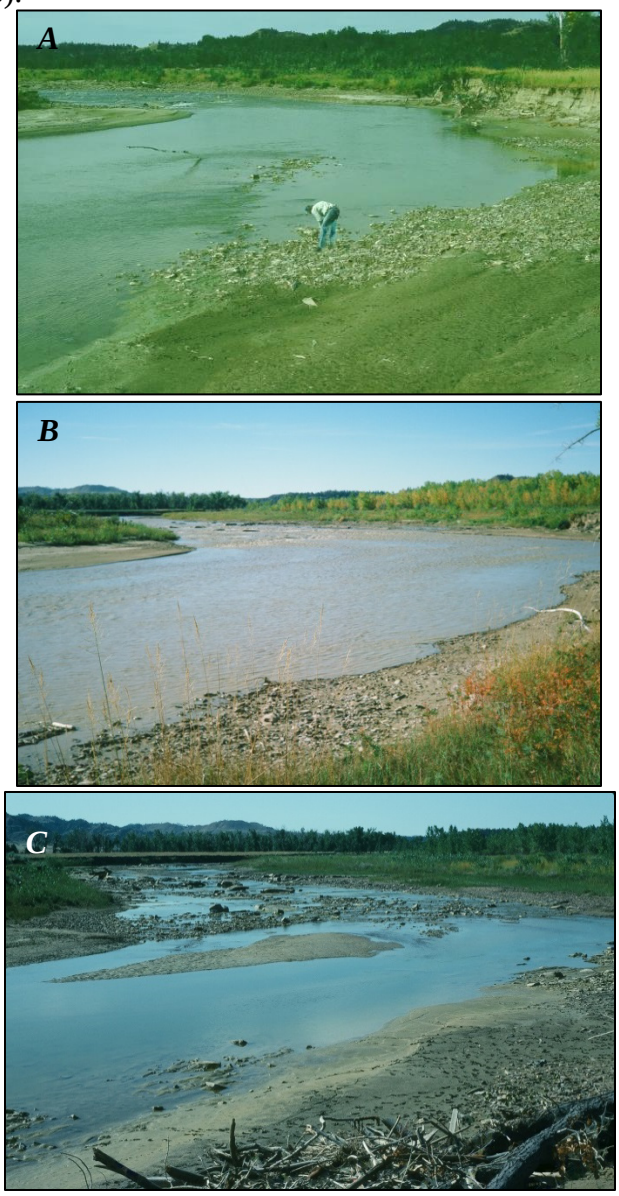

Figure 32. Repeated upriver views of a developing point bar at cross section PR122A. *A*, Photograph was taken on September 5, 1984. J. Moody is standing on the line of section, and the bedrock rapids can be seen at the top of the photograph. Early stages of future right-bank point bar can be seen in the upper left of the photograph. *B*, Photograph was taken on September 22, 1987, about 20 meters below cross section PR122A showing the bedrock rapids and the developing point bar on the right bank. *C*, Exposed bedrock outcrop on August 29, 1991.

Between 1979 and 1985 the bank-to-bank width of cross section PR122A increased from 45 to 62 m without much consistent deposition of sediment. In 1985 and again in 1987, layers of sand (0.1–0.6 m thick) were deposited between stations 43 and 76 (fig. 33); and then in 1989, an ice break-up flood deposited additional sand and gravel between stations 50 and 75, and this became the foundation of the point bar (Moody and Meade, 2014). More sediment was added to the point bar in 1990, 1993, and 1995, while the channel continued to widen to 90 m (double its initial postflood width) by 1999 (fig. 33).

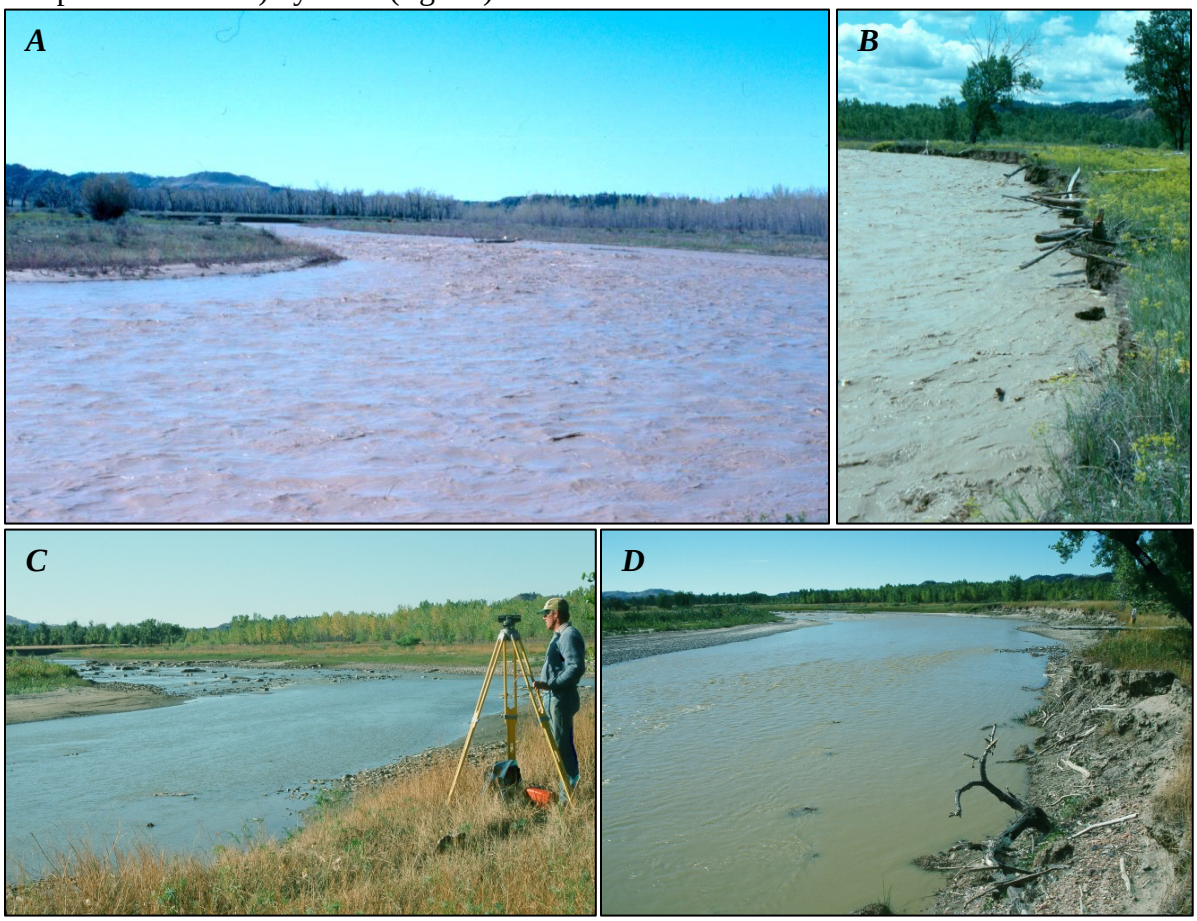

Figure 33. Upriver views of the location of cross section PR122A. *A*, Photograph was taken on May 10, 1993, about 30 meters (m) upriver from the location of cross section PR122A to show the bedrock rapids at higher flow (daily mean discharge was 76.2 cubic meters per second [m^3/s] at Moorhead Bridge upriver) than in figure 32. *B*, Photograph was taken on June 9, 1993. Tripod was on the line of section, water level was 1008.9 m above sea level (NGVD 29), and the daily mean discharge at the Moorhead Bridge was 157 m^3/s. *C*, Photograph was taken on September 25, 1994. J. Moody and tripod are near the line of section. Right edge of water is at station 45.5 and top of berm is at about station 65. *D*, Photograph was taken on September 26, 1995, and J. Moody is on the line of section.

The width of the channel has remained stable from 1999 to 2013 with only about 2 m of widening in 2011, while substantial amounts of sediment were added to the point bar in 2002, between 2003 and 2006, in 2008 (0.2–0.5 m thick), and by another ice break-up flood deposit in 2012, creating irregular topography. The 2013 and 2014 surveys indicated that this ice-related, irregular topography on the point bar had begun to smooth out, and the 2014 survey showed a small "bench-like" feature between stations 39 and 42 near the right edge of water in figure 34*A*.

The snowmelt floods in 2015 (May 28, 2015, 280 m^3/s; June 6, 2015, 283 m^3/s) further smoothed out the irregular topography on top of the point bar, deposited a substantial amount of gravel on the riverward side of the point bar (fig. 34*B*), and further widened the channel by eroding about 4 m of the left bank (fig. 34*C*).

Figure 34. Views of cross section PR122A in 2013 and 2015. *A*, Photograph was taken on September 29, 2013, looking upriver. J. Moody with the leveling rod is on the line of section near station 15, which is where the edge of the left bank stood in 1984. In 1979, the edge of the left bank stood at station 31, which is now the approximate right edge of water in the photograph indicating nearly 50 meters of lateral bank erosion during 1979–2013. *B*, Photograph was taken on September 28, 2015, looking downriver from the left bank near the line of section. *A* substantial amount of gravel was deposited by the snowmelt floods in 2015 riverward of the point bar along the right bank. *C*, Photograph was taken on September 28, 2015, looking along the line of section toward the left bank (tripod is on the line of section).

PR125 Narrative

Cross section PR125 was first established and surveyed in 1975 (fig. 35). It was resurveyed annually during the 4 consecutive years 1977–1980, resurveyed in 1982, resurveyed annually during the 18 consecutive years 1984–2001, and, after a 9-year hiatus, resurveyed in 2011 through 2016 (see Moody and Meade, 2017, PR125_SciBase2.xlsx for survey data).

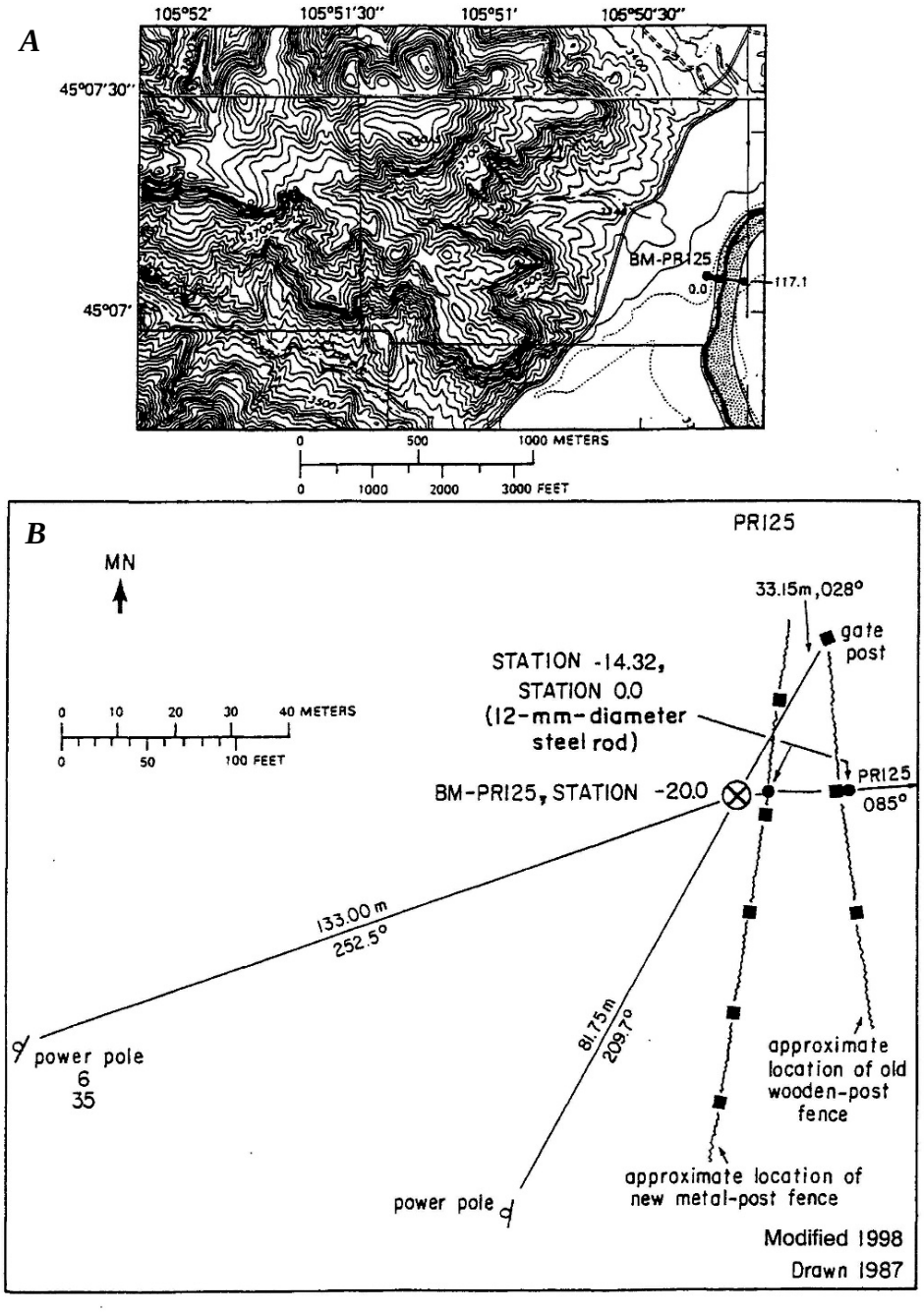

Figure 35. Location maps for cross section PR125. *A*, Location of cross section PR125, bench mark BM–PR125, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Moorhead quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and some reference pins on the left bank. MN is magnetic north.

Cross section PR125 is about 1.5 km down Powder River valley from the point where the channel of Flood Creek enters the left side of the valley (fig. 1). The section is near the crossover point of a large bend in Powder River (fig. 36). The left bank of the channel is formed by the flood plain surface developed after the flood of 1978 (Moody and others, 1999), which steps upward onto a piece of the Moorcroft-level terrace. The right bank is a Lightning-Moorcroft-level terrace (Moody and Meade, 2008).

Figure 36. Elevated view of cross section PR125 in May 1996. View is eastward across Powder River valley, and Powder River is flowing from right to left in the channel in the foreground. Approximate location of PR125 is shown by the red line. The surface with grazing cattle is the top of the Moorcroft-level terrace.

The flood of 1978 produced one massive change in section PR125: a shift in the lateral arrangement of the channel from cut bank on the left side and point bar on the right (fig. 37) to cut bank on the right and pointbar on the leftside. The thalweg of the river channel here shifted, during 2 weeks of flood flows in May 1978, some 70 m toward the right bank. This lateral shift seems to have been produced by the downriver transport of a large gravel bar (some 40 m wide and about 1 m in thickness; figs. 14 and 15 of Meade and Moody, 2013) toward the left bank. Bank erosion during the flood of 1978 amounted only to 3 m of cutback of the right bank. The combination of large (70 m) thalweg shift and small (3 m) cut bank erosion was probably a result of section PR125 being near the inflection point (or, more likely, in the inflection zone) between the downriver limb of one meander bend and the upriver limb of the next meander bend downstream.

Figure 37. Upriver view of cross section PR125 on July 22, 1977. The cut bank is on the left side, and E. Meade (about 1.6 meters tall) is standing on the section in the red circle.

During the decades following the flood of 1978, the left-side gravel bar at section PR125 has become a new vegetated inset flood plain (figs. 38 and 39) by the incremental addition of new sand (Moody and others, 1999; Pizzuto and others, 2008). A total thickness of 1–2 m of new sand has accumulated between stations 20 and 50 (figs. 38*B* and 39), mostly during years 1982, 1987, 1993, 1995, and, probably, 2008 (peak daily discharge of 329 m^3/s was on May 27, 2008) and 2011 (peak daily discharge of 178 m^3/s was on June 1, 2011). The right-side cut bank meanwhile has eroded some 8 m laterally, mostly during the same 5 years.

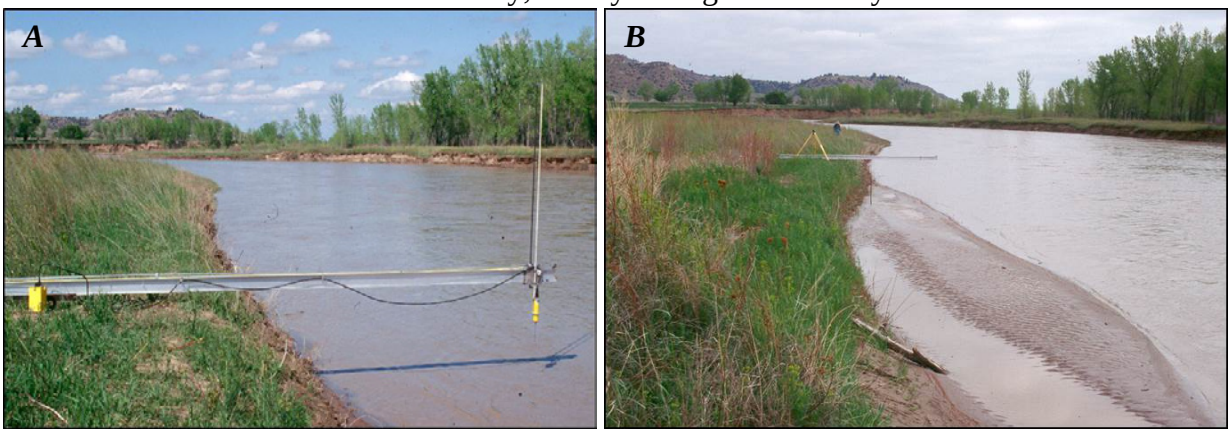

Figure 38. Downriver photographs taken on May 28 and May 30, 1996, of the left-bank flood plain containing cross section PR125. *A*, An acoustic Doppler velocimeter (yellow object) is mounted on a carriage that moves on an I-beam cantilevered over the edge of the left bank of the new inset flood plain built since the flood of 1978. The I-beam is 42 meters (m) upriver from cross section PR125. Water discharge is about 71 cubic meters per second (m^3/s). *B*, Water discharge is about 62 m^3/s on May 30, 1996. View is downriver showing the tripod, I-beam, and D. Martin (about 1.6 m tall) who is standing approximately on the line of section at about station 40. The exposed sediment along the left bank was deposited between May 28 and 30, 1996.

Measurements of Reynolds stress were made in 1996 at the edge of the new vegetated inset flood plain (fig. 38). An acoustic Doppler velocimeter (ADV) was mounted on a carriage (fig. 38*A*), which could move the velocimeter horizontally out over the channel and vertically in the water (Moody and Smith, 2002). Measurements were made on May 28, 1996, at six verticals between the edge of the water and 3.2 m into the water. Water depths ranged from 0.1 to 0.6 m at a quasisteady discharge of 71 m^3/s.

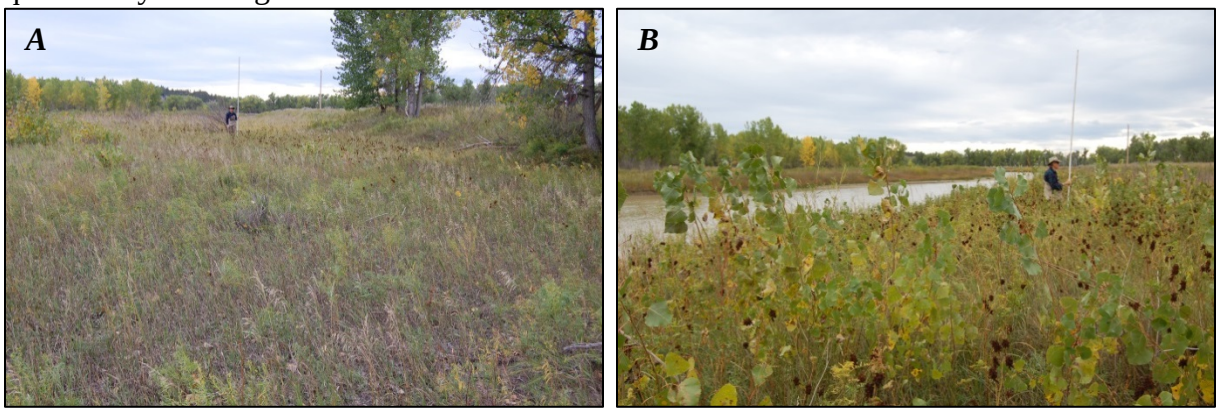

Figure 39. Views of the new inset flood plain at cross section PR125 on September 29, 2013. *A*, View is upriver. The tripod and D. Martin (about 1.5 meters [m] tall at the right edge of the photograph and behind the trees) are about 7 m downriver from station 4. J. Moody (about 1.9 m tall) is standing, with the survey rod, on the section at station 38, which is the top of a natural levee representing about 1.5 m of sediment deposited since 1978. Compare this view with the right-side photo in figure 37, which was taken, 36 years earlier, from a similar location. *B*, View is upriver. J. Moody is standing at station 38.

Additional sediment (0.1–0.2 m) was deposited landward (between stations 13 and 40; fig. 40) of the levee (at station 38, fig. 39) on the left-bank, inset flood plain during the snowmelt flood in 2015. This flood plain surface in 2015 was about 3 m above the thalweg.

Figure 40. Photograph of the newly deposited sediment in 2015 on the inset flood plain at cross section PR125. Photograph was taken on September 27, 2015, and shows sediment deposited during the snowmelt floods in May 2015. Most of the sediment is in the form of lee dunes deposited downstream from clumps of vegetation. The view (looking toward the right bank, which is at about station 104) encompasses the inset flood plain starting at about station 12 in the foreground.

A small bench (Page and Nanson, 1982) was first noted at the base of the right bank in our survey of 2011 (fig. 41). Because we did not survey section PR125 between 2001 and 2011, we can only surmise that the bench may have begun to form as early as 2008 or 2006. This bench has continued to accrete and is now (2015) about 2 m wide. The riverward edge is vegetated by sedges (fig. 41).

Figure 41. Photograph of a developing bench along the right bank of cross section PR125. The view is downriver and was taken on September 27, 2015. It shows the most recent (2015) sediment deposit that forms the top of the bench at the base of the right bank. The bench is about 2 meters wide. Green sedges have red tops at this time of year and usually colonize the banks starting at the level of the bed-full discharge (12 cubic meters per second; Moody and others,1999).

PR130 Narrative

Cross section PR130 was established in 1975 on a curved reach of Powder River that is controlled by bedrock (fig. 42).

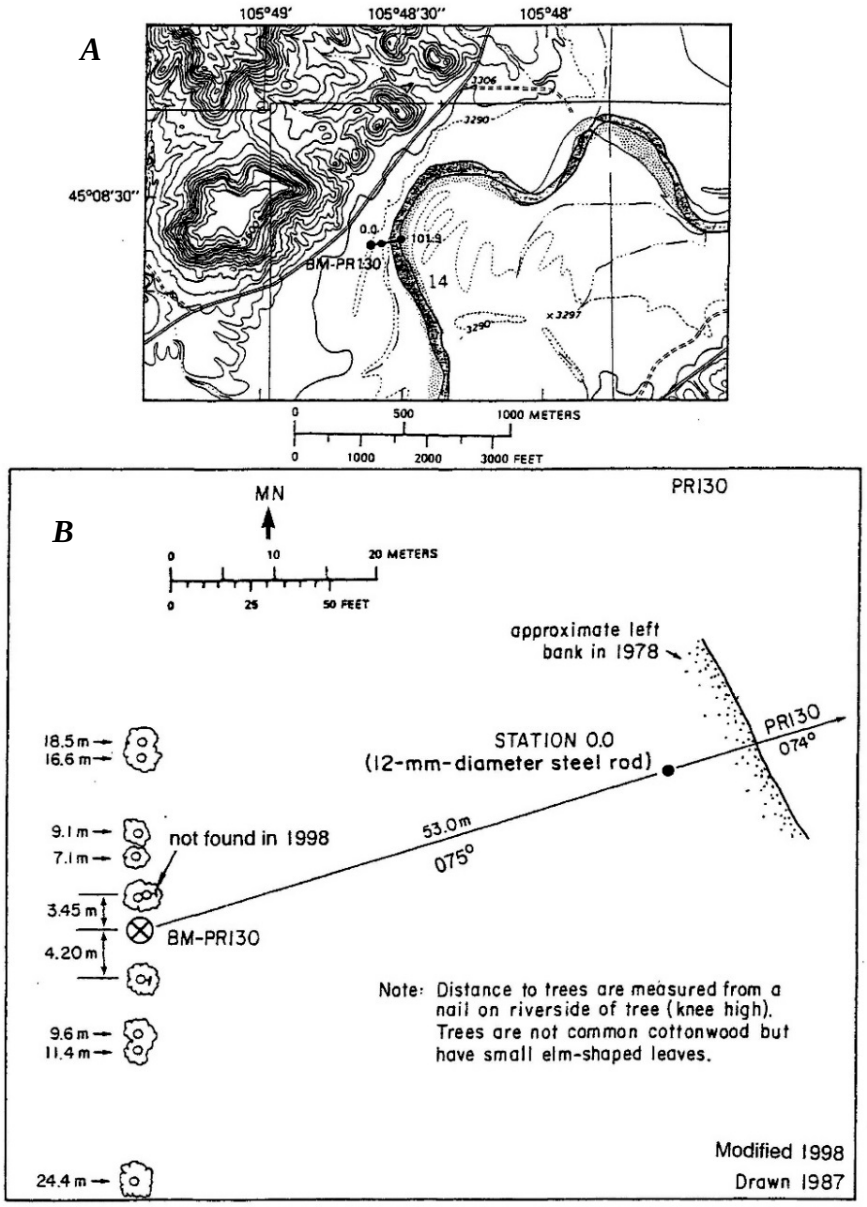

Figure 42. Location maps for cross section PR130. *A*, Location of cross section PR130, bench mark BM–PR130, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Bloom Creek quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and some reference pins on the left bank. MN is magnetic north.

The stability of the cross section is evidenced by the small amount of lateral erosion of the concave left-side cut bank (left bank): only 3.8 m in 38 years (1977–2015). A coal seam outcrops at the level of the riverbed on the left bank (fig. 43), which can be seen when waters are low and clear. The seam dips slightly across the river as it has never been seen along the right

bank. This cross section was established in 1975, resurveyed annually during the 4 consecutive years 1977–80, resurveyed in 1982, and resurveyed annually during the 18 consecutive years 1984–2001. After a 11-year hiatus, it was resurveyed in 2012 through 2016 (see Moody and Meade, 2017, PR130_SciBase2.xlsx for survey data). In 2000, the cross section survey was extended across the valley to station 334.7 at a fence line.

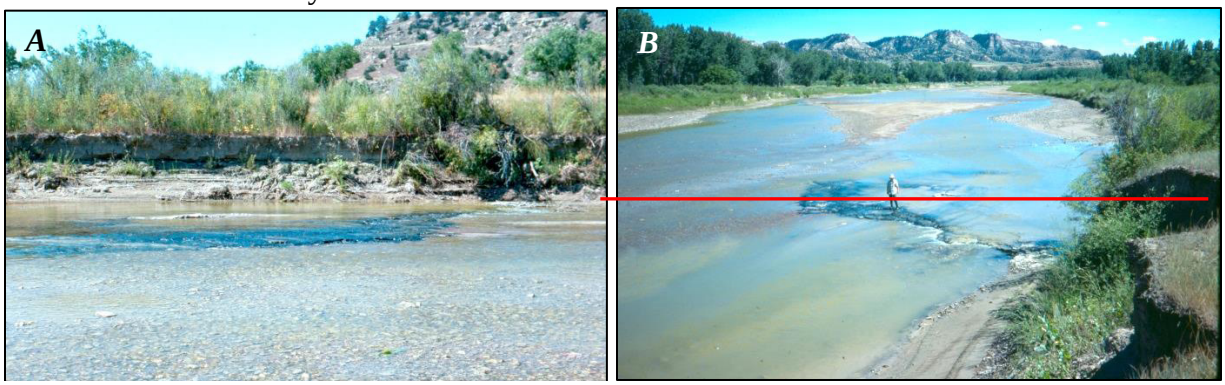

Figure 43. Photographs of cross section PR130 taken before the extreme flood of 1978 showing the bedrock control. *A*, Photograph was taken on September 9, 1975, from the right bank looking at the left bank about 25 meters (m) upriver from cross section PR130. The river is flowing from left to right, and coal outcrop is visible along the left bank. *B*, The upriver view was taken on July 21, 1977, and shows E. Meade (about 1.6 m tall) standing on the coal outcrop—about 25 m upriver from section PR130. Red line is the approximate location of the cross section, drawn at the elevation of the top of the left bank.

The flood of 1978 eroded 2.4 m from the left bank and left some lee-dune-type deposits of new sand (Moody and Meade, 2008) on the right-bank flood plain (fig. 6 of Meade and Moody, 2013). No significant changes were measured in two surveys done during the next 3 years. A levee began to develop in the cross-sectional profile along the right bank in 1982 and was the first evidence of the beginnings of a new inset flood plain similar to those described by Moody and others (1999) at cross sections PR120, PR125, PR136, PR151, and PR156A. This flood plain was built in three stages in 1982–84, 1990–94, and 1995. Initially, the flood plain was narrow and only about 10 m wide in 1984, but additional sediment deposited in 1987 widened the flood plain to about 20 m and added about 0.30 m of height (fig. 44).

In 1990, a small bench (about 4 m wide) was added on the riverward side of the nascent flood plain (fig. 45), and then in succeeding years (1991 and 1993) additional sediment was added on top of this bench until it was higher than the original flood plain deposited in 1982–84. This new inset flood plain (Moody and others, 1999) was about 28 m wide in 1994. During the last stage, a large and long snowmelt flood lasting from May through July 1995 deposited a wedge of sediment, which was about 0.5 m thick nearest to the river and tapered to about 0.05 m in the flood plain trough about 30 m from the river.

After 1995, virtually no change was measured in the cross section of PR130 until a new bench (about 2 m wide) was evident in the 2012 cross sectional profile (see also PR120 and PR125 narratives) (Page and Nanson, 1982). Unfortunately, the 11-year hiatus in our survey record leaves us without the certainty of knowing the exact years of the creation of the bench (fig. 46); however, the most likely year for this creation was 2008 (peak daily discharge was 329 m^3/s) or perhaps 2011(snowmelt flood, peak daily discharge was 178 m^3/s).

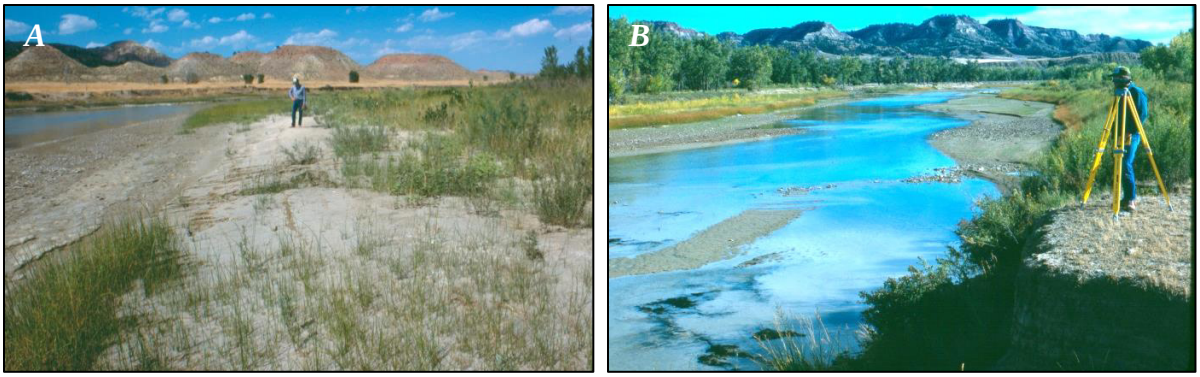

Figure 44. Views of cross section PR130 in 1986 and 1988. *A*, Downriver view was taken on August 18, 1986, showing the new sand (0.1–0.3 meter [m]) on the upriver end of the point bar. J. Moody (about 1.9 m tall) is standing at station 72. *B*, Upriver view was taken on September 19, 1988. J. Moody and tripod with level are just upriver from section PR130.

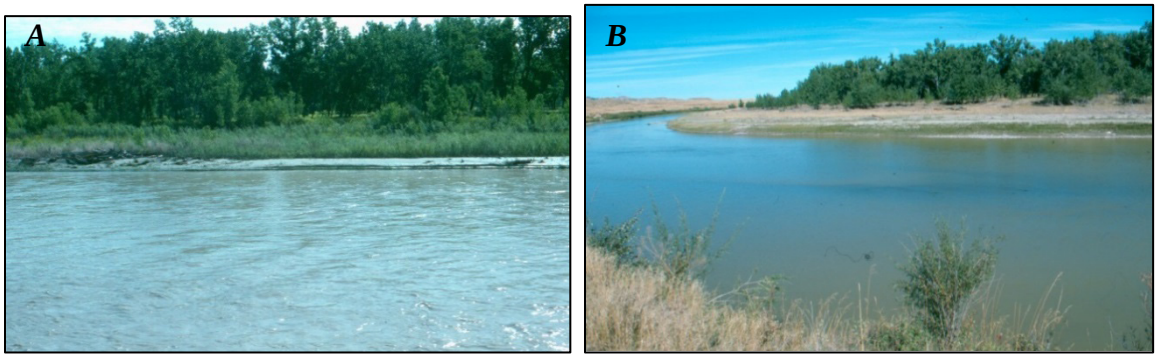

Figure 45. Photographs of newly deposited sand along the right bank of cross section PR130 in 1993 and 1995. *A*, Newly deposited sand along the right bank. Photograph was taken on June 11, 1993. *B*, View is downriver, showing newly deposited sand behind the berm crest and about 0.5 meter thick on the upper end of the point bar downriver from section PR130. Photograph was taken on September 24, 1995.

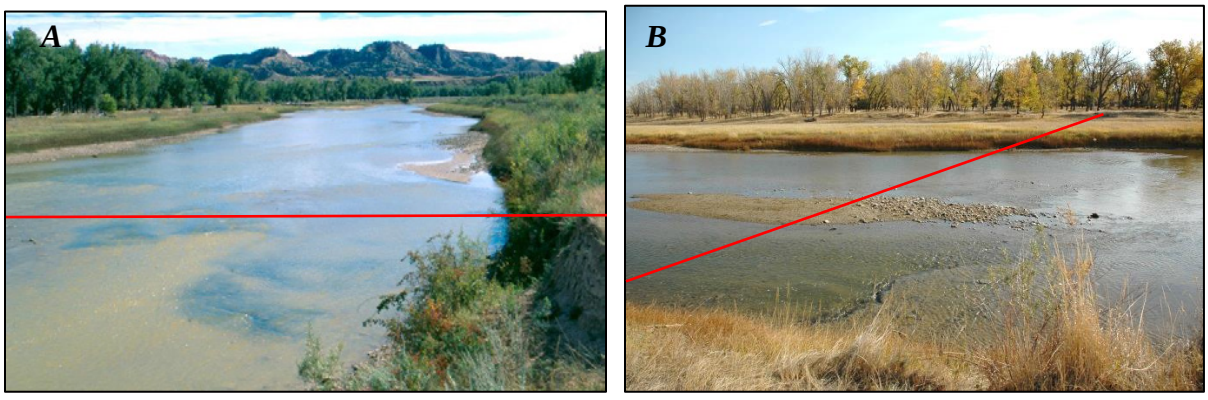

Figure 46. Photographs of cross section PR130 in 1997 and 2012. Red lines show the approximate location of the cross section, drawn at the elevation of the top of the left bank. *A*, View is upriver, showing the coal outcrop in the river bed on September 19, 1997. *B*, View is downriver showing the coal outcrop on October 20, 2012, between the left bank and the mid-channel gravel bar and just upriver from cross section PR130. A bench (in front of the inset flood plain with yellow-colored grasses) along the right bank is highlighted by the red-colored sedge growing on it.

The left bank has been stable and top of the bank has only retreated 4.4 m in 40 years (1975–2015) (fig. 47). On the original sloping post-1978 flood surface, Powder River has built an inset flood plain that stands about 1.7 m higher than in 1975 (figs. 46, 47, and 48). The snowmelt floods in 2015 raised most of the 27-m wide surface about 0.15 m.

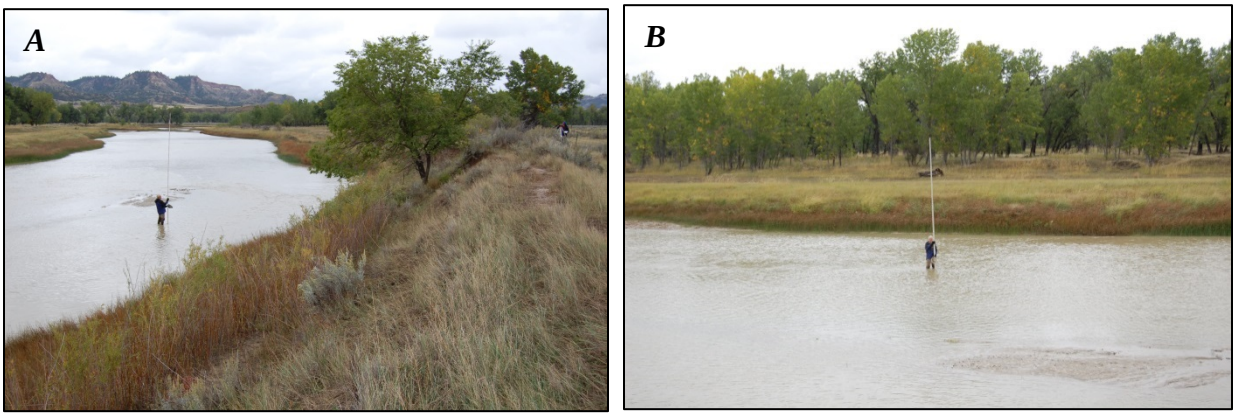

Figure 47. Views of cross section PR130 on September 27, 2013. *A*, View is upriver and J. Moody (about 1.9 meters [m] tall) is standing on the line of section. D. Martin (about 1.6 m tall) is standing at the tripod on the left bank. *B*, View is from the left bank, and J. Moody with the white surveying rod is at station 45. The inset flood plain extends across the entire photograph behind J. Moody. This surface transitions into a point bar downriver of section PR130 (fig. 45*B*).

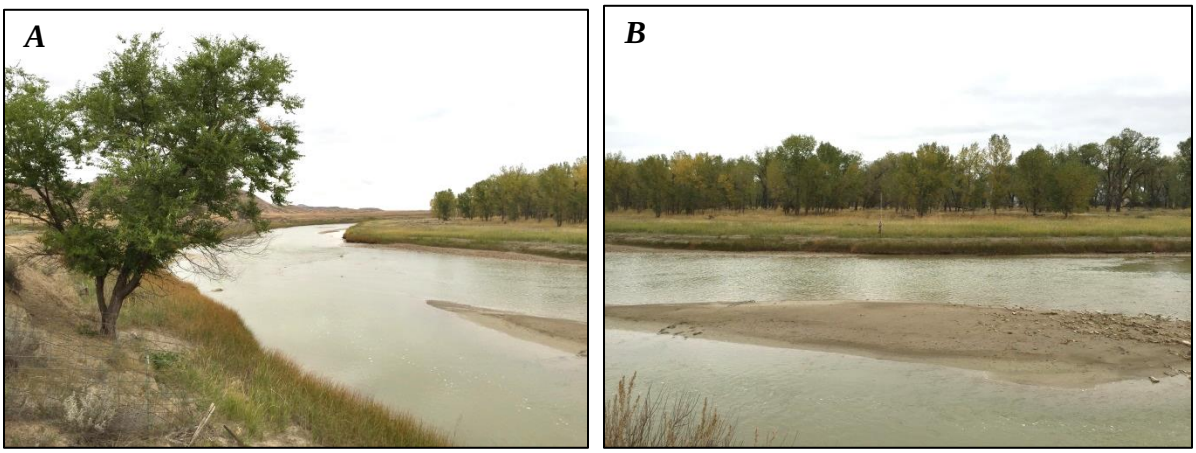

Figure 48. Views of cross section PR130 on October 2, 2015. *A*, View is downriver and the cross section passes through the branch of the tree on the upriver side. *B*, Photograph was taken standing on the left bank facing the right bank and J. Moody (about 1.9 meters tall) is standing on the line of section at about station 67 just behind bench that started to form in 2012, but in front of the inset flood plain with yellow-colored grass.

PR136 Narrative

Cross section PR136 was a symmetrical cross section with a central bar in the middle of the channel when it was established in 1975 (fig. 49).

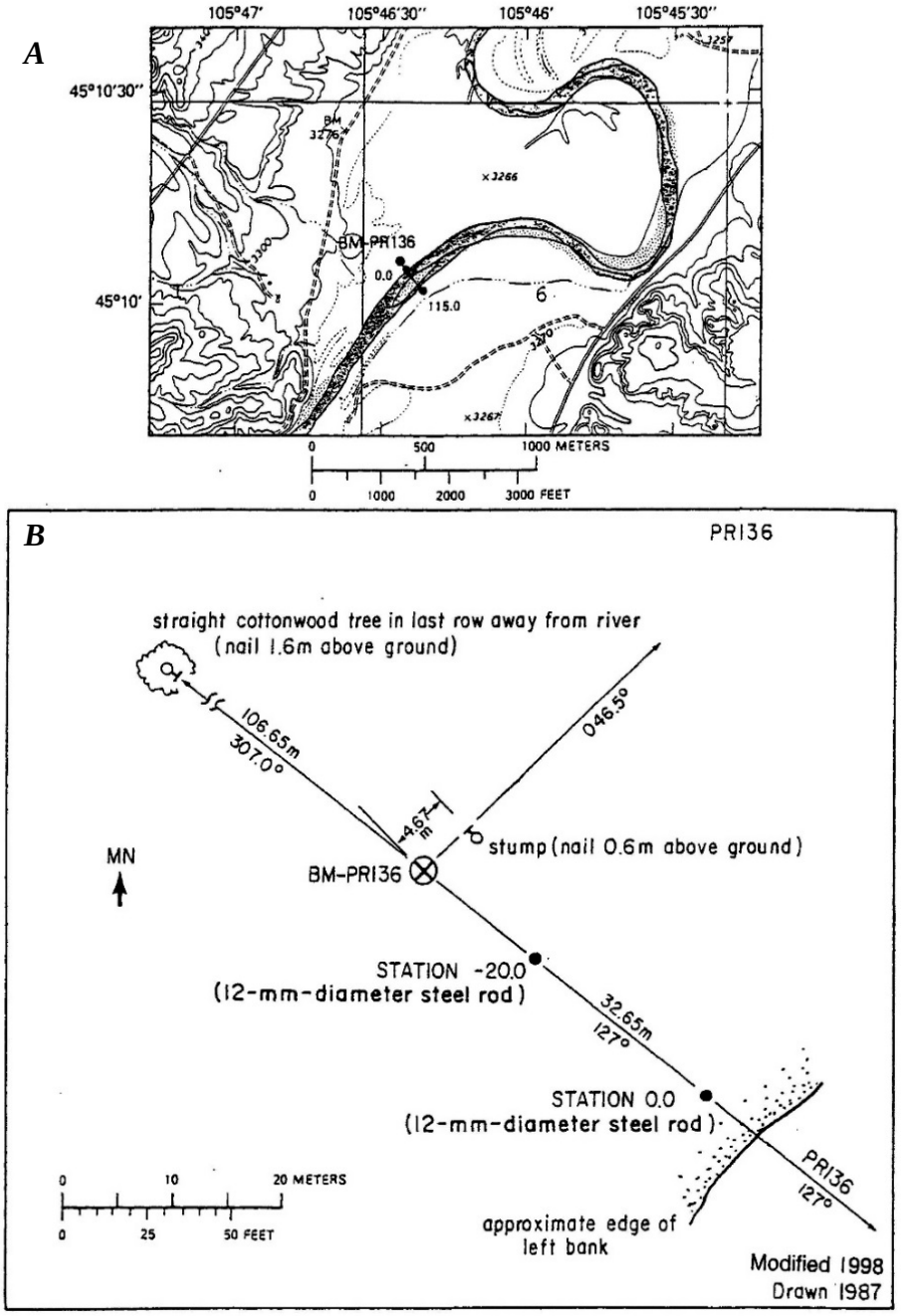

Figure 49. Location maps for cross section PR136. *A*, Location of cross section PR136, bench mark BM–PR136, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Bloom Creek quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and some reference pins on the left bank. MN is magnetic north.

Both banks (fig. 50) are on Moorcroft-level terraces (Leopold and Miller, 1954). The cross section was resurveyed annually during the 4 consecutive years 1977–80, resurveyed in 1982, resurveyed annually during the 15 consecutive years 1984–98, and, after a 13-year hiatus, was surveyed in 2012, 2014, 2015, and 2016 (see Moody and Meade, 2017, PR136_SciBase2.xlsx for survey data).

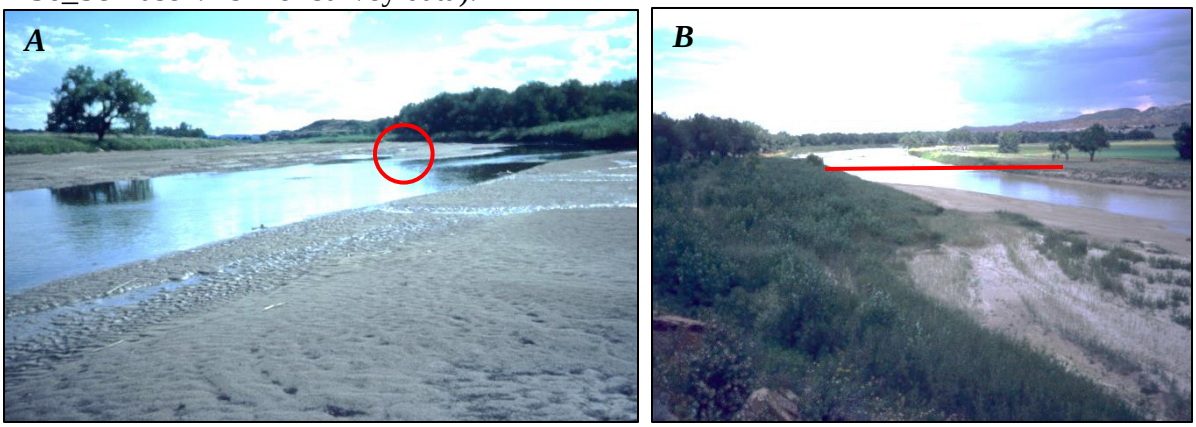

Figure 50. Views of cross section PR136 in 1977 and 1979. *A*, Upriver view was taken on July 22, 1977. The cottonwood tree on the right bank is on the Moorcroft-level terrace. E. Meade (about 1.6 meters tall) in red circle is standing on central bar on the line of section. *B*, Downriver view was taken on August 16, 1979. Red line, shown at the elevation of the tops of the terrace banks, indicates the approximate line of section.

The flood of 1978 caused no erosion of the approximately 3.5-m high banks or of the central bar, and thus had little effect on the shape and size of the channel cross section. The secondary channel along the right bank was deepened by about 0.50 m during 1979. The greatest change came between 1980 and 1982 when the elevation of the central bar was raised 0.2–0.3 m, and again by about 0.1 m during the spring runoff in 1987. Photographs taken in 1987 show the central bar was vegetated so that it could be designated as an island (fig. 51).

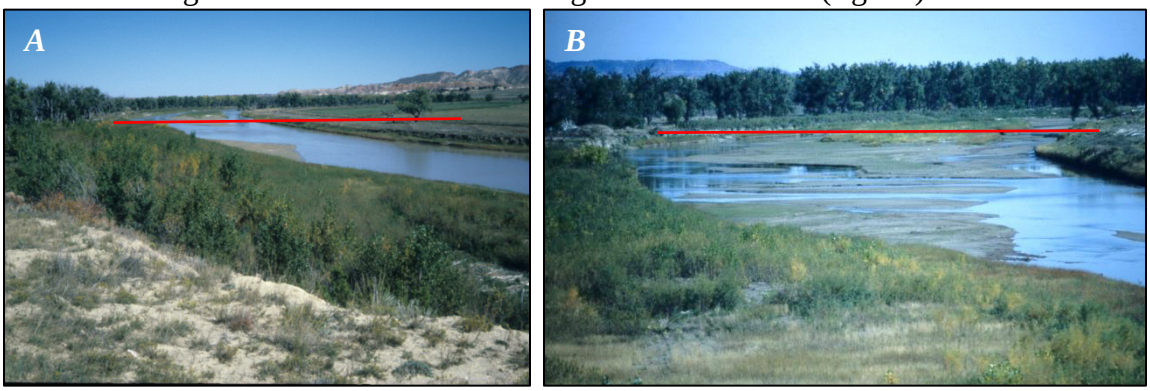

Figure 51. Views of cross section PR136 in 1987 and 1988. Red lines, shown at the elevation of the tops of the terrace banks, indicate the approximate line of section. *A*, Downriver view was taken on September 26, 1987. *B*, Close-up view taken on September 21, 1988, where the vegetated island is easier to see.

This island was mainly new flood plain that was raised again in 1993 (fig. 52) along both edges as levees increased in height by 0.1–0.2 m. During the annual snowmelt flood of 1995 sediment was deposited and raised the entire island an additional 0.2–0.4 m (Moody and others, 1999). Some sediment deposition was the result of local ice jams leaving blocks of ice on the flood plain and sediment filling in around the blocks (fig. 53*A*).

Figure 52. Downriver view of cross section PR136 on August 27, 1993. A secondary channel exists between the tree on the right bank just downriver from the line of section (shown by the red line drawn at the elevation of the top of the island) and the vegetated island seen in the upper center of the photograph.

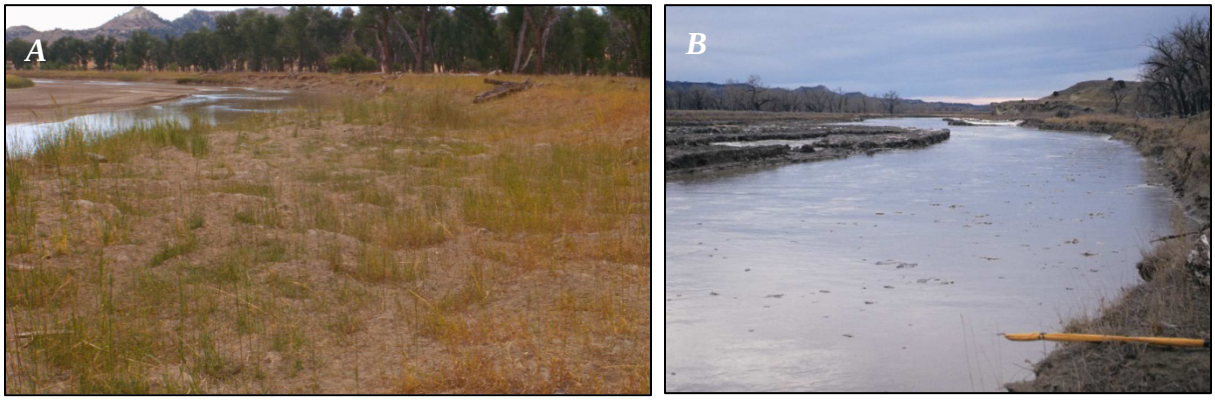

Figure 53. Upriver views of cross section PR136 in 1994 and 1995. *A*, Photograph showing mounds of sediment, which were deposited around ice blocks about 500 meters downriver from PR136 on the left bank. Photograph was taken on September 3, 1994. *B*, Photograph taken on March 11, 1995, shows ice on the upriver end of the vegetated island. Survey rod in orange cover lies on the line of section for PR136.

During the entire time from 1978 to 1995, there was virtually no erosion of either bank. Between 1995 and 2012, the left bank was eroded laterally about 3.5 m near the top of the bank, and benches (Page and Nanson, 1982; see also PR120, PR125, and PR130 narratives) have been deposited at the base of both sides of the island. The secondary channel along the right bank of the cross section degraded by about 1.0 m during this period.

Three sediment cores were collected in 2015 for dating using optical stimulated luminescence (OSL). The cores were taken in what is thought to be a Lightning-level terrace (Leopold and Miller, 1954) and 22 m upriver from station 1.0 of cross section PR136 on the left bank (fig. 54). Earlier in 2013 and 2014, OSL cores were collected from a nearby Kaycee-level terrace on the left side of Powder River.

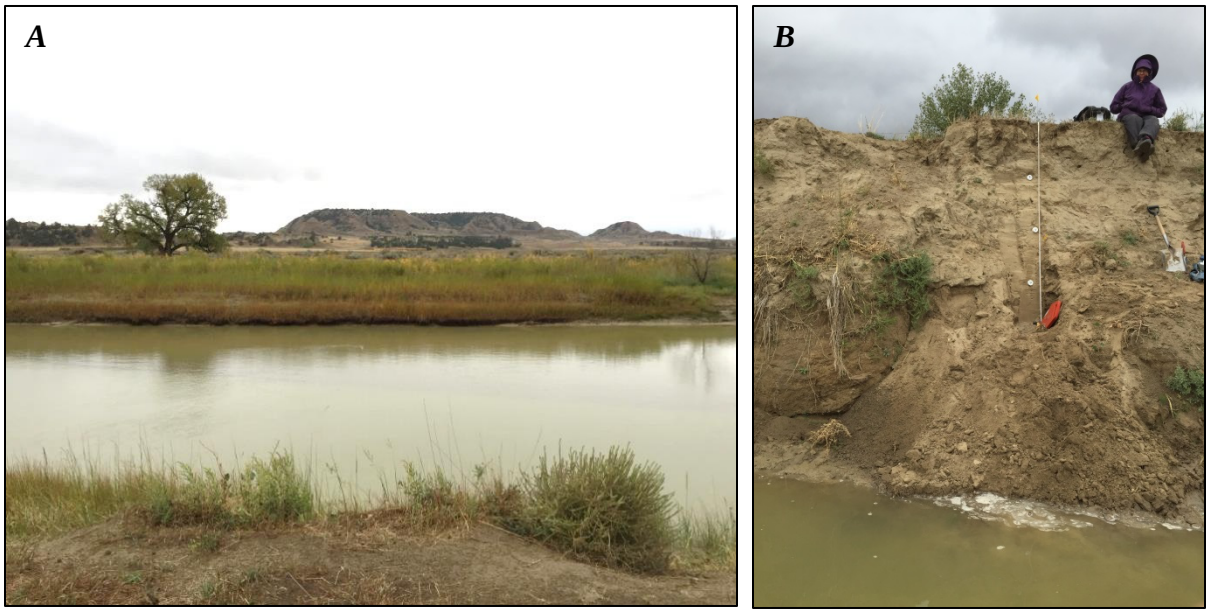

Figure 54. Views of cross section PR136 on October 2, 2015. *A*, View is across the main channel of Powder River from the left bank with the bank of the vegetated island in the center of the photograph. Flow is from right to left in the photo. Cottonwood trees on the island have yellow leaves and sandbar willows still have green leaves. *B*, View is of the left bank (Lightning-level terrace) about 22 meters (m) upriver from station 1.0 of cross section PR136. The top of the bank is at an elevation of about 994.5 m above the National Geodetic Vertical Datum of 1929 (NGVD 29). The elevations of the sediment cores (white dots) from top to bottom are 992.15, 991.52, and 990.92 m, respectively. The water level is at about 989.7 m above NGVD 29.

PR141 Narrative

Cross section PR141 was established in 1975 in the upriver limb of a large meander bend in Powder River at the mouth of tributary Bloom Creek (figs. 1 and 55). Leveling surveys of section PR141 were repeated in 1977, 1978, 1979, 1980, 1984, 1998, and 2014 (see Moody and Meade, 2017, PR141_SciBase2.xlsx for survey data).

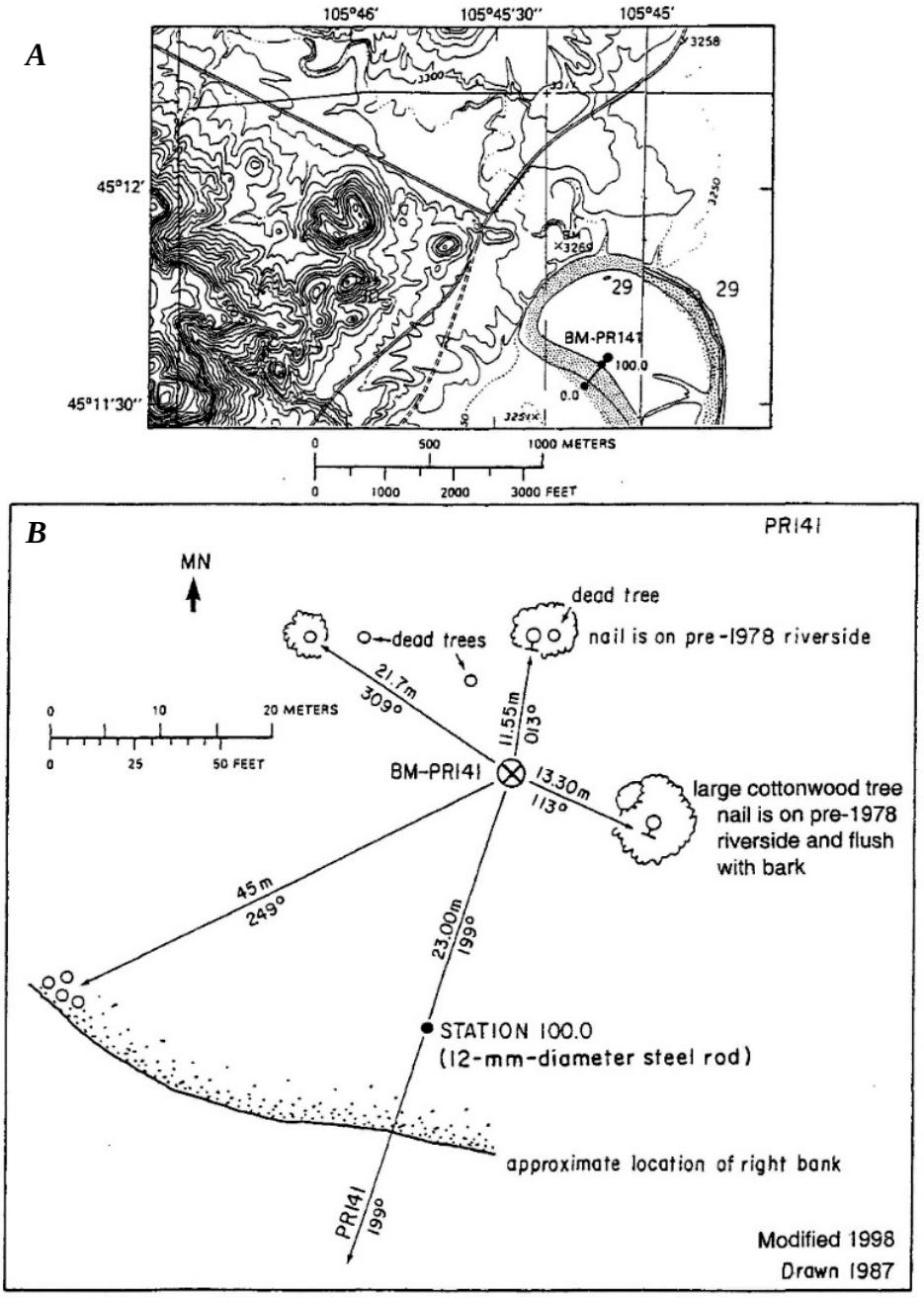

Figure 55. Location maps for cross section PR141. *A*, Location of cross section PR141, bench mark BM–PR141, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Bloom Creek-Huckins School quadrangles. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and some reference pins on the left bank. MN is magnetic north.

During the flood of 1978, the meander bend was cut off at the neck (figs. 56 and 57), and section PR141 was left high and dry (figs. 9 and 10 of Meade and Moody, 2013; fig. 7 of Gay and others, 1998). Re-leveling of the cross section after the flood of 1978 showed that the section had accumulated new sediment to depths of 0.5 to 1.5 m across a channel width of some 70 m (stations 17 to 87). We are uncertain as to whether the new sediment was deposited before or after the bend neck was cut off.

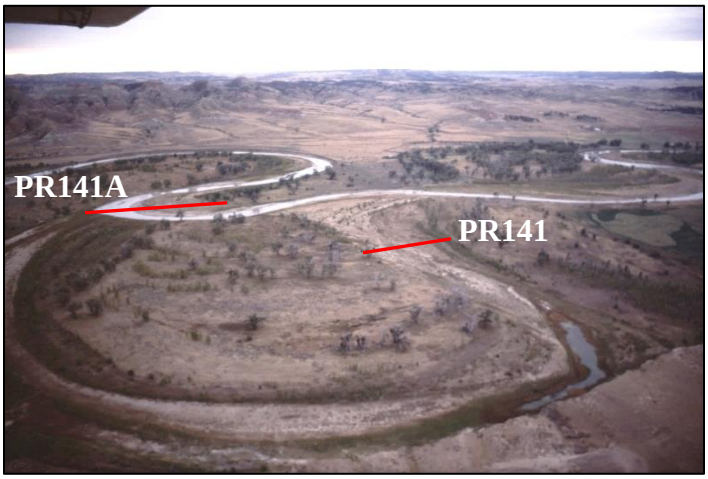

Figure 56. Aerial view of cross section PR141 on September 22, 1989. View is southeastward of the large meander bend cut off by the flood of 1978 on Powder River, which is flowing from right to left. An oxbow lake was left in the old channel downstream from PR141. Red lines indicate the approximate location of the cross sections.

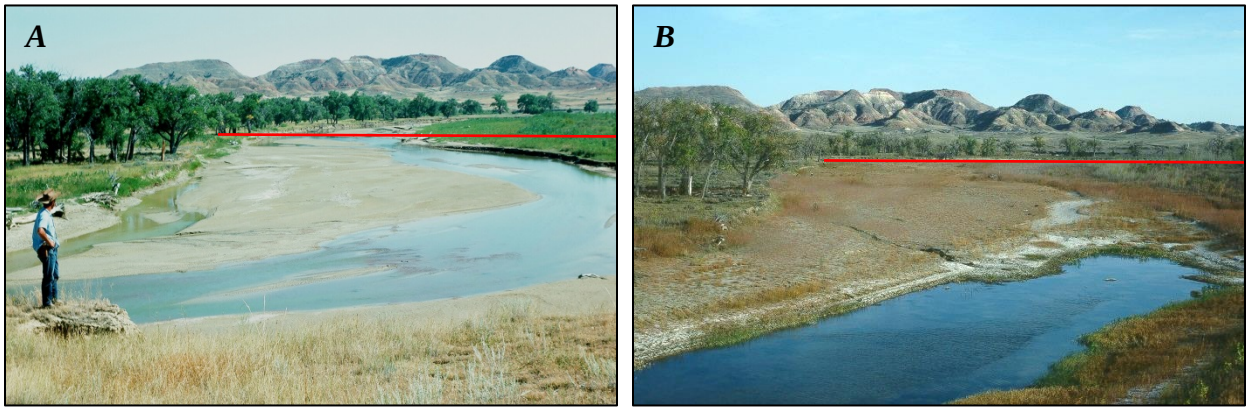

Figure 57. Pre- and post-1978 views of the channel downriver from cross section PR141. *A*, Photograph was taken on September 9, 1975, before the flood of 1978 looking upriver toward the southeast from top of bluff near old saw mill site near the mouth of Bloom Creek (fig. 1). *B*, Photograph was taken on October 12, 1980, after the flood of 1978 looking upriver as in *A*. This channel is now partially occupied by an oxbow lake.

Little geomorphic change has been recorded in the large oxbow channel of Powder River that was cut off here by the flood of 1978. Repeated upriver-looking photographs (taken from a point about 300 m downriver from section PR141 in the abandoned channel) show little change over the years (fig. 58). Some annual floods have refilled the channel and presumably deposited some fine suspended sediment (fig. 59).

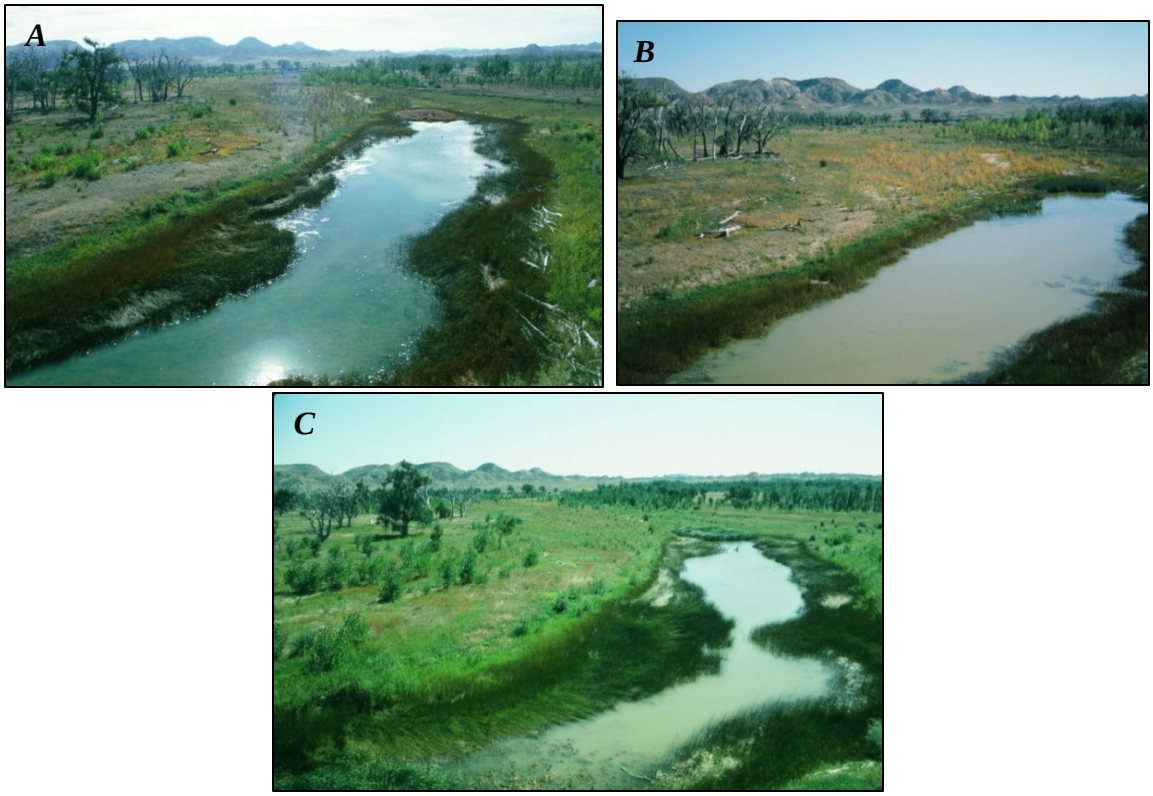

Figure 58. Photographs showing the changes in the oxbow lake formed by the cutoff during the flood of 1978 at PR141. See figure 56 for approximate location of cross section PR141 and the oxbow lake. All views are upriver toward the southeast from top of the bluff near the old sawmill site near the mouth of Bloom Creek (fig. 1). *A*, September 24, 1987. *B*, September 18, 1989. *C*, August 28, 1993.

Figure 59. Downriver view of the oxbow lake near cross section PR141 on June 9, 1993. Photograph was taken northeastward from the same bluff-top locality as the southeastward-looking photos in figures 57–59.The view is 0.5–1.0 kilometer downriver from cross section PR141, which is not visible. The channel of Bloom Creek enters the abandoned Powder River channel in the group of cottonwood trees at the left edge of the photograph. Water filled and connected the oxbow lake to the main channel during high flow in 1993.

New vegetation in the form of groves of willow (*Salix* spp.) and cottonwood trees (*Populus sargentii*) (such as those that have grown in the abandoned meander channel at cross section PR122) is not as dense at section PR141 as it is in the abandoned channel at PR122 (fig. 27). When section PR141was resurveyed in 2014 (16 years after the survey in 1998) the bed of the abandoned channel generally had a covering of sparse grass growing under a few scattered cottonwood trees that have grown here since 1978 (fig. 60).

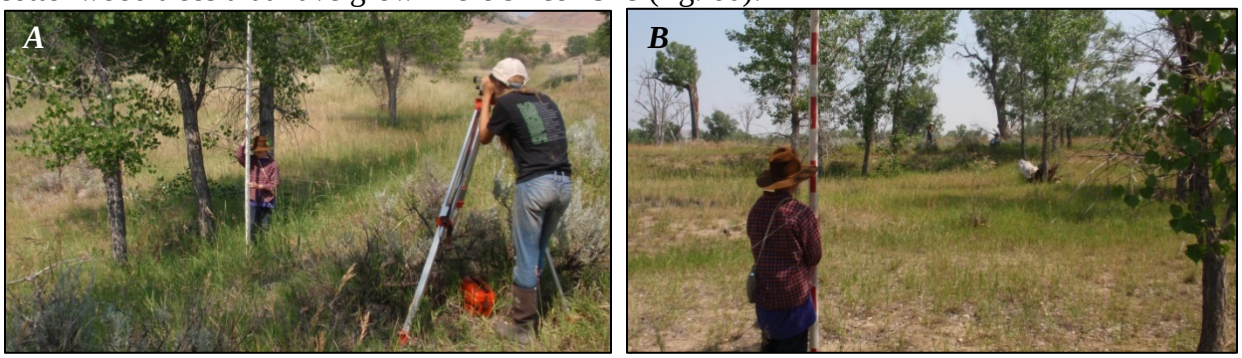

Figure 60. Views of cross section PR141 on July 20, 2014. *A*. View is from the old right bank of Powder River in the downstream direction. R. Held (about 1.8 meters [m] tall) is standing behind the tripod, which is about 4 m to the right of the line of section. Trees behind J. Held (about 1.7 m tall) standing at station +50.0 are cottonwood trees growing in the abandoned channel. *B*. J. Held holds the survey rod in the foreground. View is along the line of section, toward the right bank where R. Held in the white hat stands behind the tripod, and R. Meade sits in a chair to her right in the photograph. The whitish log at the right center of the photograph is lying on top of about a meter-thick layer of sand that was deposited by the flood of 1978 before the channel was abandoned.

PR141A Narrative

Cross section PR141A was established in 1979 in a cutoff channel that had formed during the flood of 1978 across the neck of a large meander bend in Powder River near the mouth of Bloom Creek (figs. 1, 61, and 62).

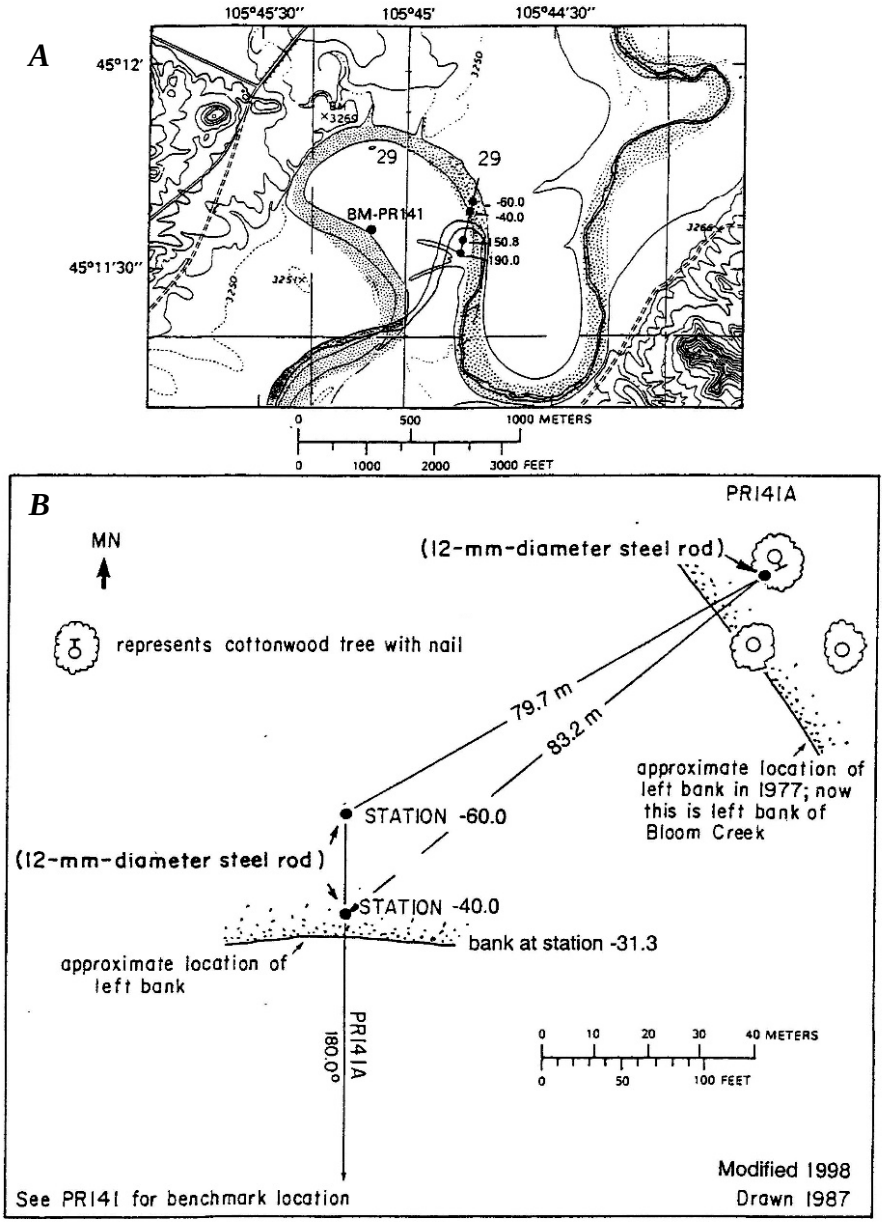

Figure 61. Location maps for cross section PR141A. *A*, Location of cross section PR141A, bench mark BM–PR141, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Bloom Creek-Huckins School quadrangles. Planform configuration was taken from 1969 aerial photos. *B*, Location of some reference pins on the left bank. Reference pins at stations -40.0 and -60.0 have been removed by erosion. Reference pins have been put in on the left bank at stations -100.0, -100.8, and -105.0 in 2010, 2013, and 2015, respectively. MN is magnetic north. The cottonwood tree closest to the bank is gone but the tree with the nail is still standing.

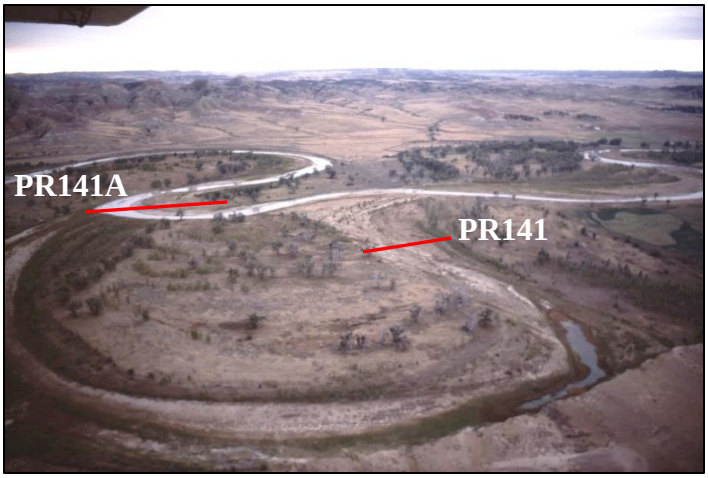

Figure 62. Aerial view of cross section PR141A on September 22, 1989. View is southeastward of the large meander bend cut off by the flood of 1978 on Powder River, which is flowing from right to left. An oxbow lake was left in the old channel downstream from PR141. Red lines indicate the approximate locations of the cross sections.

The 1978 cutoff channel (fig. 62) began by following the course of a preflood headcut gully that had been sporadically active for decades, and had nearly cut through the neck of the bend by early 1978 (fig. 7 of Gay and others, 1998; figs. 9 and 10 of Meade and Moody, 2013). Because the actual cutoff at PR141A happened during the early stages of the flood of 1978, we infer that this left enough time for the floodwaters to erode the adjacent flood plain across the neck, and to widen the new cutoff channel sufficiently so that new sand could be deposited therein. This new channel had a gentle downstream slope (0.00061, as compared with Powder River's average overall slope of 0.001) and a nominal radius of channel curvature of 125 m.

The record at PR141A provides the most complete narrative, so far, of any cross section of Powder River. Early aerial photographs show the preflood gully that was to become the initial course of the cutoff channel. Local ranchers actually observed the moment of transition in May 1978 when waters went slack in the old meander channel (see foreground of fig. 62 above) and began to flow rapidly across the meander neck (Gay and others, 1998, p. 657). During the years since the birth of this cutoff channel, we have been able to observe the deposition and maturation of a large point bar (fig. 63) and the formation of three scroll bars (Moody and Meade, 2014). Also recorded are the first 34 years (1979–2012) of concave-left-bank erosion, which has removed a width of 80 m (approximately 160 m^3 per meter of bank) of old sand and gravel from the Lightning-level terrace. Leveling surveys of cross section PR141A were made in 1979, 1980, and 1982, annually during the 19-year period 1984–2002, in 2006, and annually during the 8-year period 2009–16 (see Moody and Meade, 2017, PR141A_SciBase2.xlsx for survey data). Annual surveys of cross section PR141A for the years 1999–2002 are portrayed graphically in figure 3 of Moody and Meade (2014).

Early large changes at cross section PR141A were erosion of about 14 m of the left bank recorded in 1984, and the erosion of the right bank in 1986. Between 1987 and 1995 there were a series of overbank deposits on top of the right bank landward of station 80 (fig. 63). Evidence of the first scroll bar in section PR141A is in the cross-channel profile surveyed in 1992 between stations 70 and 90. Successive higher deposition after 1992 built up the first scroll bar, which consisted of mostly very fine sand and silt. Sometime during these depositional and erosional events, a cottonwood tree sprouted and grew on the crest (near station 80) of this scroll bar

within 1 m of the line of section, and thus the scroll bar has slowly evolved into what Nanson (1980, p. 6) defined as a flood-plain ridge, which "is vegetated and flooded only near bankfull flow."

Figure 63. Upriver view of the point bar at cross section PR141A on October 1, 2013. This point bar has formed since the flood of 1978. J. Moody (about 1.9 meters tall) is standing on the line of section at station 20, which was the location of the left-side cut bank in 1979 and is now the location of the third scroll bar. The second scroll bar is centered at about station 38, and the first scroll bar is at station 80 where the cottonwood tree with yellow leaves is growing (left side of photograph).

Figure 64. Upriver view of the left bank at cross section PR141A on August 28, 1993. The yellow tripod is a few meters upriver from the line of section. The new mouth of Bloom Creek is indicated by the red arrow.

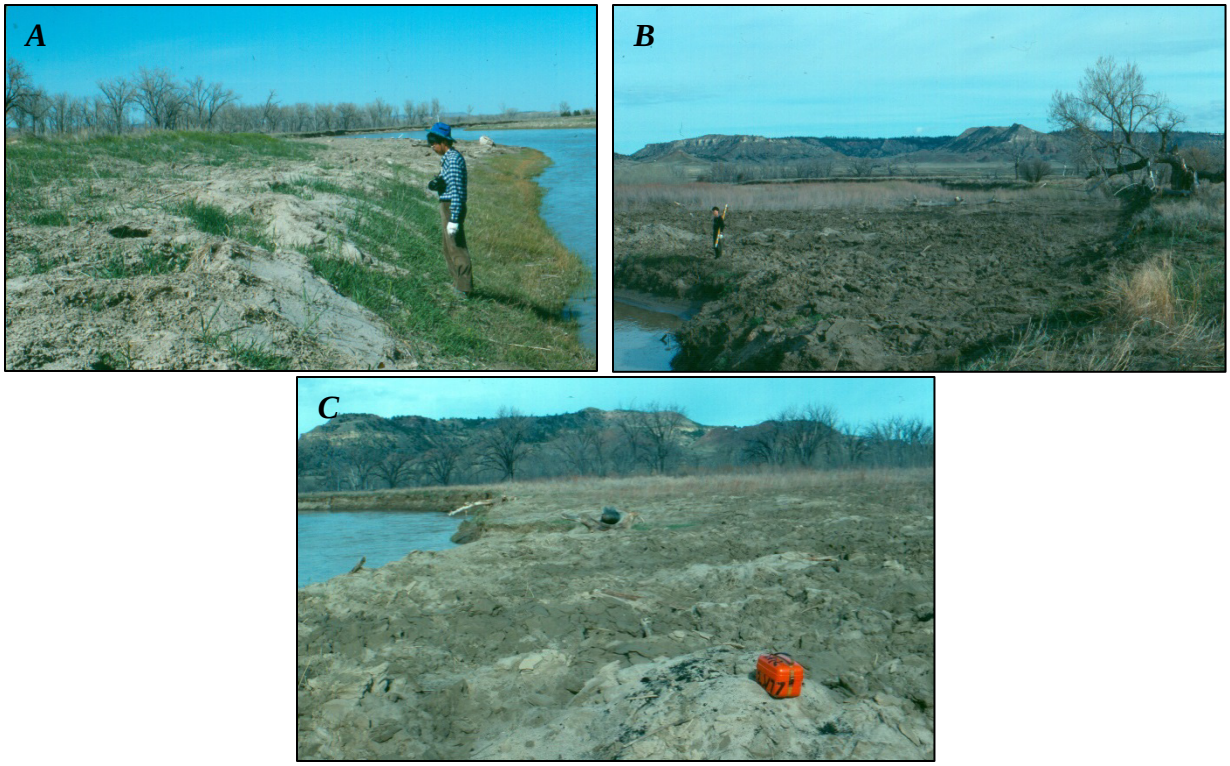

Figure 65. Photographs of ice-deposited sediment near cross section PR141A in May 1994. *A*, Downriver view of ice-deposited sediments atop the left bank about 300 meters (m) upriver from PR141A. K. Fujita is about 1.8 m tall. Water discharge was about 17 m^3/s. *B*, View is upriver showing ice-deposited sand piles in the mouth of Bloom Creek and on PR141A, for which only a short segment near the person shows in the photograph. *C*, View is upriver showing a close up of the ice-deposited sediment (see data file PR141AComposite_Jan2016.xlsx [Moody and Meade, 2017] for detailed survey).

The foundation of the second scroll bar was laid down in 1994 between stations 26 and 46 (fig. 63). In 1995, an approximately 14-m width of old Lightning-level terrace was eroded from the left bank (39.6 m^3 per meter of bank), which was nearly balanced by 10.5 m^3 per meter of new flood plain deposition and 26.9 m^3 per meter of new point-bar deposition between stations 18 and 48 (Moody and others, 2002; fig. 3 of Moody and Meade, 2014). The scroll bar may have formed by the process of rapid channel expansion and subsequent deposition of sediment near a separation zone along the opposite bank (a process described by Nanson, 1980). The scroll bar was further increased in height by sediment deposition in 1996.

The base for the third scroll bar (between stations 0 and 20) was deposited by floods in 1995, 1996, and 1997, but did not become discernible in the cross-channel profile until after the 1999 flood (fig. 3 of Moody and Meade, 2014). Later, in year 2000, pebbles, coal particles, and coarse sand were added atop the third scroll bar and also filled the gap between the second and third scroll bar. This third scroll bar increased in height in three stages: (1) medium-fine suspended sand was deposited by a small flash flood in August 2002 (73 m^3/s), (2) coarse sediment was deposited during the snowmelt flood in June 2005 (82 m^3/s), and (3) silt and fine sand were probably deposited during the flood of June 2008 (329 m^3/s; the largest since May 1978). Accompanying the scroll-bar deposition in 2008 was a corresponding lateral erosion of approximately 12 m of the left bank, again suggesting the rapid bank erosion-point bar deposition process proposed by Nanson (1980). A secondary chute channel was started during

the 2008 flood as a headcut gully along the joint interface (stations 24–30) between the second and third scroll bars. Thus, by 2009, three distinct scroll bars had developed on the point bar at PR141A.

An extensive topographic survey was done around this bend in 2009 and 2010. The survey started about 450 m upstream along the left bank from PR141A and extended downstream along the left bank about 350 m (fig. 66). The survey along the left bank was limited to 2–4 m landward from the cut bank but included the entire point bar formed by the right bank. The data are in Moody and Meade (2017), file PR141ATopog.xlsx.

In 2013, there was a substantial flood in the tributary Bloom Creek (fig. 1) probably as a consequence of wildfires in 2011 and 2012 along Bloom Creek in the hills to the west of Powder River. This flood cut through the left bank of Powder River along the cross section from station -86 to -58 (fig. 67) such that the end of the section PR141A on the left bank in 2014 was an embayment. The large snowmelt floods in 2015 (280 m^3/s, May 28, 2015, and 283 m^3/s, June 6, 2015) deposited sediment in part of the embayment created by the Bloom Creek flood in 2013 and began to "rebuild" the left bank. Sedimentation in 2015 raised the floor of the embayment by about 1.1 m.

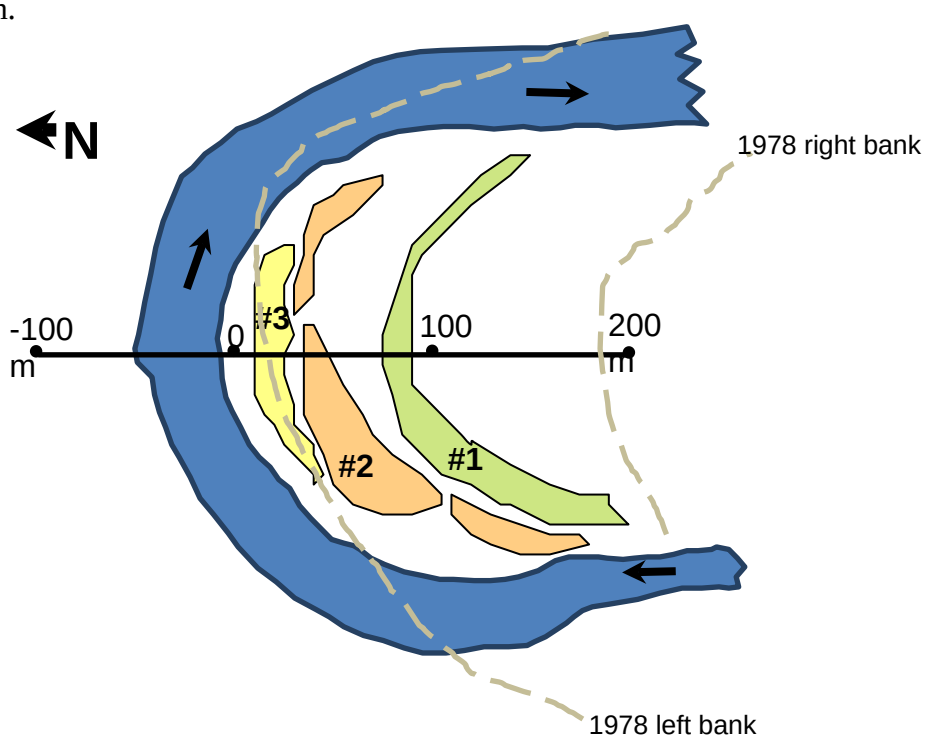

Figure 66. Diagram showing the relative locations of the three scroll bars along cross section PR141A.

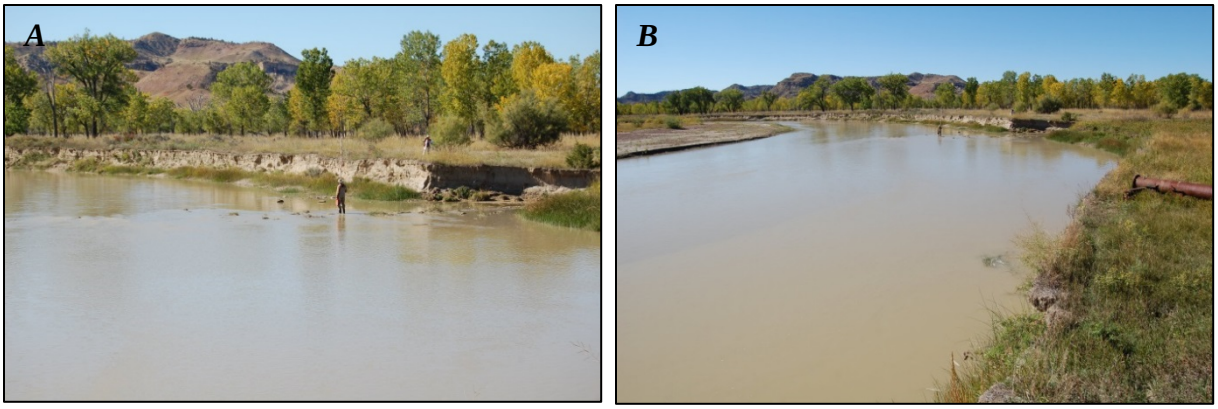

Figure 67. Views of cross section PR141A on October 1, 2013. *A*, View is upriver. Level, tripod, and D. Martin (about 1.5 meters [m] tall) are about 12 m upriver from station -60. J. Moody (about 1.9 m tall) is standing on the line of section at station -47. Washout gully at the mouth of Bloom Creek is to the right of J. Moody. *B*, Same view as in the photograph *A* but farther downriver with J. Moody standing at station -41.

In 2015, an exploratory trench was dug by hand across part of the point bar on the right bank. It was 2 m downriver from cross section PR141A and between stations 18 and 40 (fig. 68). This trench cut through sediments forming the third scroll bar at about station 20 and through a channel (between the second and third scroll bar), which was partially filled by sediment deposited in 2011 (178 m^3/s, June 1, 2011). Accretionary surfaces in this short trench were fragmented rather than being continuous (Torres, 2016). In 2016, a second, longer trench was dug using a backhoe between station 0 and 80. Comparison of the accretionary bodies indicates the some corresponded to chronostratigraphic units defined by the annual resurveys of the cross section, whereas others represented the accretion from several floods within 1 year or from several years (Warwick and others, 2016).

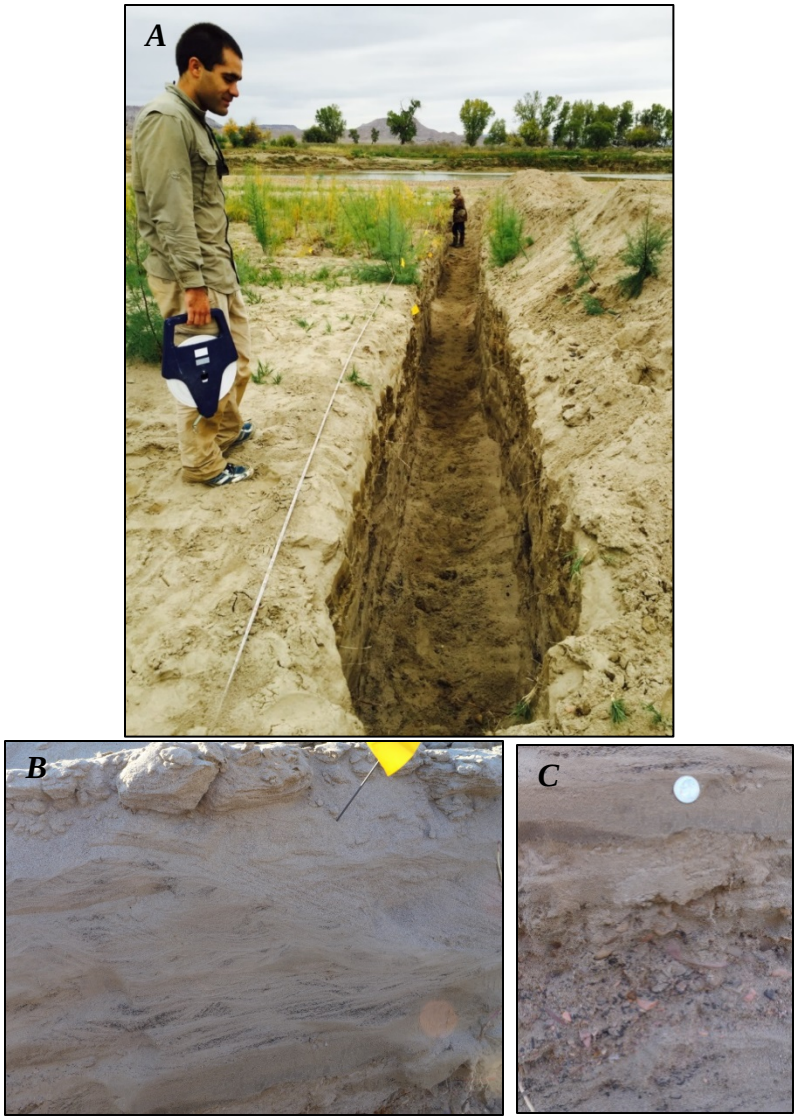

Figure 68. Photographs of a trench dug at cross section PR141A on October 3, 2015. Trench was dug along a cross-channel line 2 meters (m) downriver from the line of section for PR141A. *A*, View is from the right bank towards the left bank. A. Torres (about 1.7 m tall) is standing at about station 36, and J. Held (about 1.7 m tall) is standing in the distance near station 20. *B* and *C*, These two close-up photographs indicate some of the sedimentary structures and the range of particle sizes. Diameter of the wire holding the yellow flag in *B* is about 2 mm, and the coin in *C* is a quarter.

PR141.7 Narrative

Cross section PR141.7 was established in 1994 after an ice-breakup flood caused a jam in the channel of Powder below cross section PR141A. The location of cross section PR141.7 is in a backwater area from the ice jam and where ice floes deposited sediment along the left bank (fig. 69).

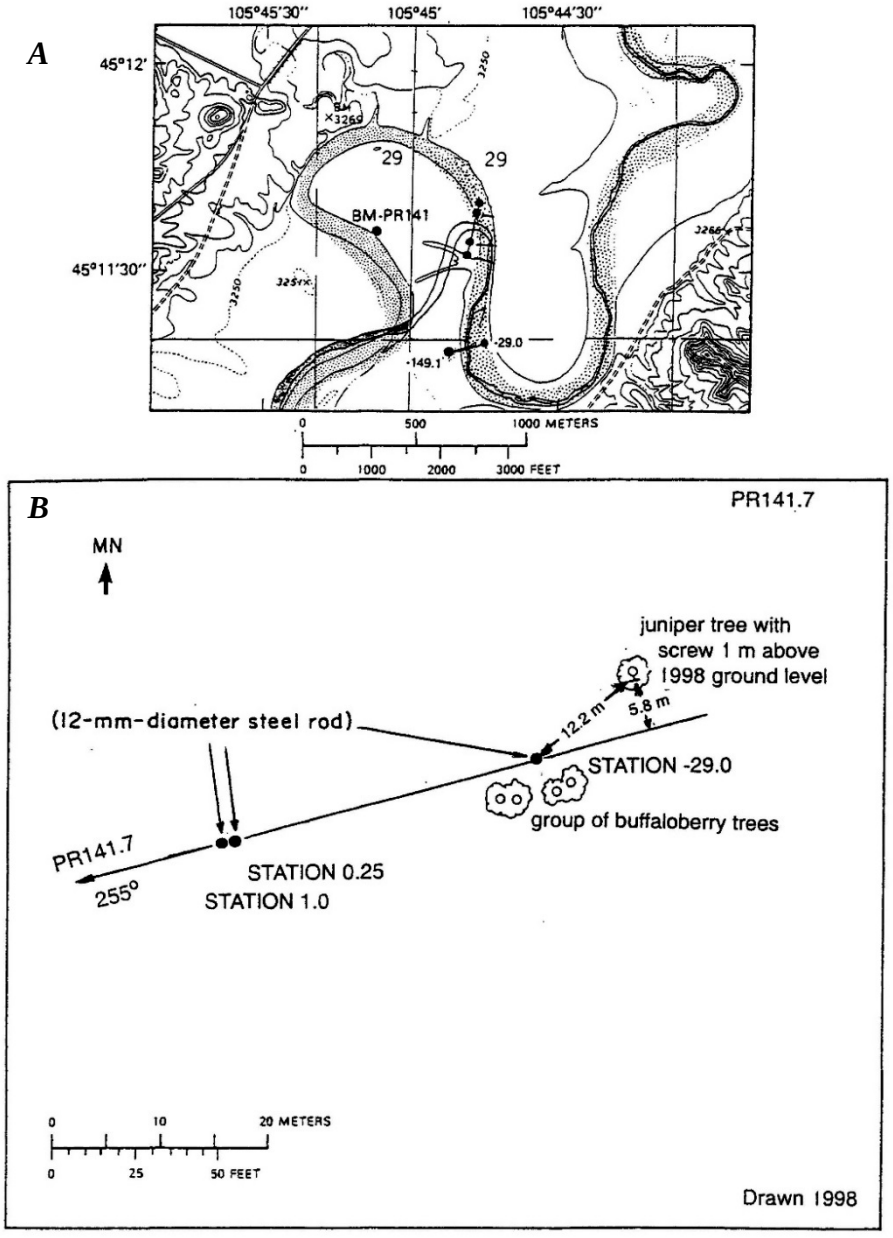

Figure 69. Location maps for cross section PR141.7. *A*, Location of cross section PR141.7, bench mark BM–PR141, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Huckins School quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of reference pins on the left bank. MN is magnetic north.

This cross section was resurveyed annually from 1993 to 1998, and then after a 14-year hiatus, in 2012, and again in 2015 and 2016 (fig. 70). Estimates of the flood-plain elevations in 1993 were made in 1994 by digging holes at 16 locations between stations 0.0 and 48.5 until evidence was found for the 1993 flood plain surface.

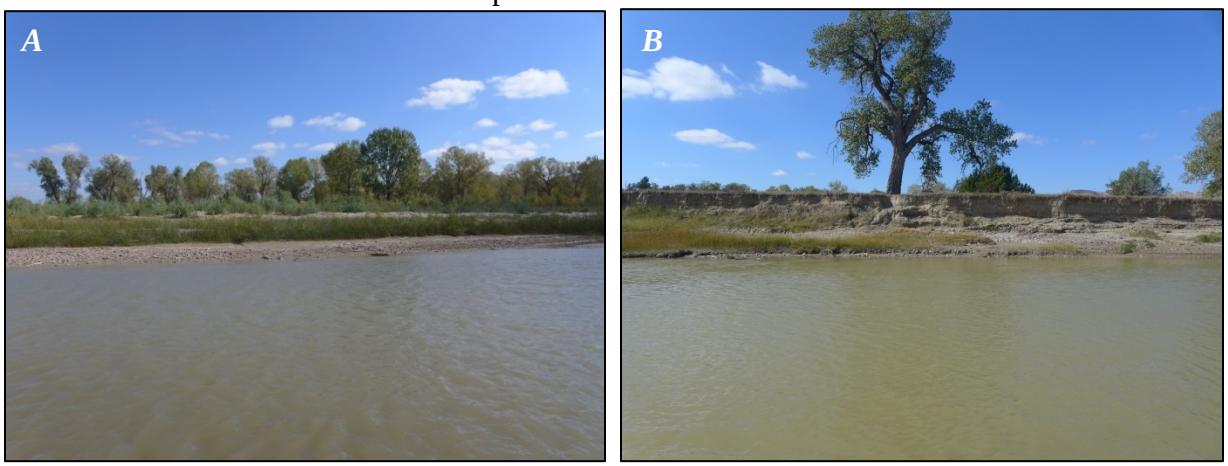

Figure 70. Views of cross section PR141.7 on September 29, 2015. *A*, View is of the left bank where ice floes deposited sediment in 1994. Flow is from left to right. *B*, View of the right bank. Flow is from right to left. Cross section PR141.7 ends about 1.0 meter upriver from the large cottonwood tree on the right bank.

The purpose of this site is to monitor the ice-deposited sediment. The snowmelt flood in 1995, which eroded many banks and deposited large amounts of sediment, also deposited sediment on top of some of the ice-deposited sediment from stations 12 to 50 and left a sand bar between stations 60 and 80. In 1997 some of the ice deposited sediments were eroded between stations 33 and 50. The large flood in 2008 was probably responsible for most of the sediment deposited between stations 50 and 90, which filled in the channel between the sand bar and the left bank and raised the elevation of the sandbar by 0.20–0.40 m. However, the irregular surface in 2012 suggests additional sediment deposits related to an ice-breakup flood—perhaps the same ice-break flood that deposited sediment at PR122A in 2012. Data are available in Moody and Meade (2017).

PR147 Narrative

Cross section PR147 was established in 1975 on a straight reach of Powder River (figs. 71 and 72) that is stabilized, to a significant degree, by sandstone bedrock. Ledges of sandstone crop out in the bed of Powder River, both upriver and downriver (within distances of 100–200 m) of section PR147. These ledges served, decades earlier, as crossing places in the river (for example, Hubert Gay and his sister, in the 1920s and 1930s, fording Powder River to attend Huckins School).

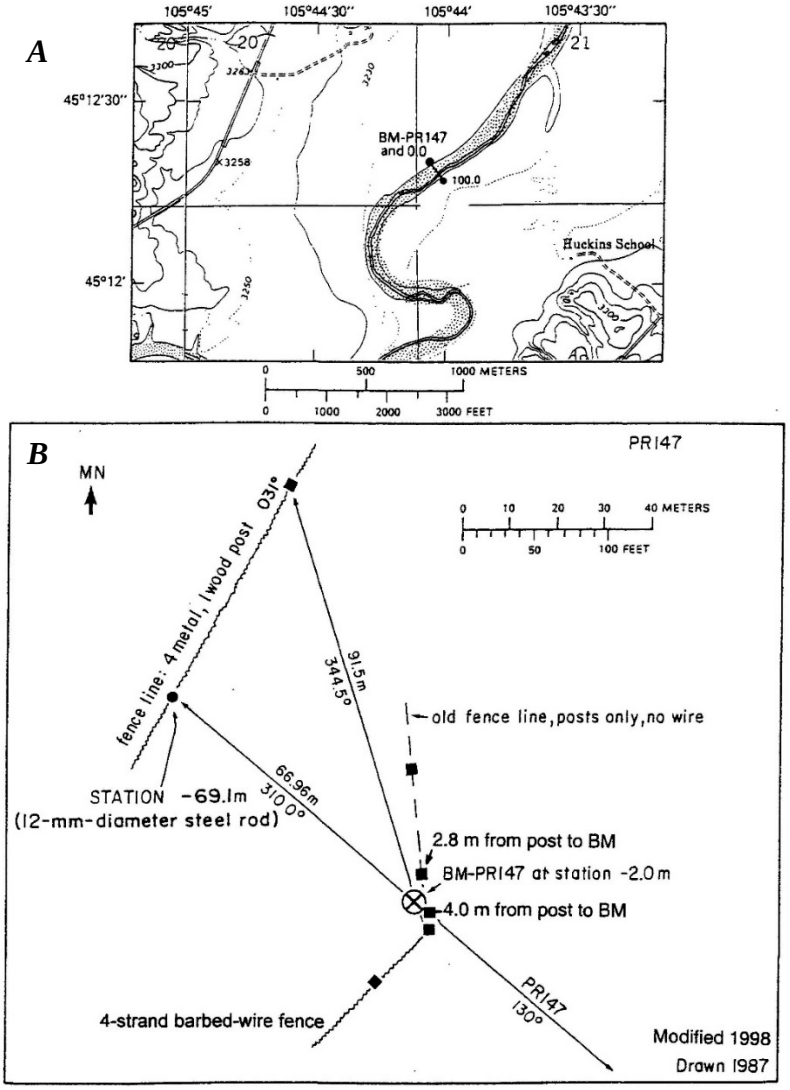

Figure 71. Location maps for cross section PR147. *A*, Location of cross section PR147, bench mark BM–PR147, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Huckins School quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of reference pins on the left bank. MN is magnetic north.

Cross section PR147 was resurveyed annually from 1977 through 1980, not again until 1984, and then every following year through 1998. Because it had shown so little channel change between 1978 and 1998, it went unsurveyed for the next 15 years. It has been resurveyed in 2013, 2015, and 2016 (see Moody and Meade, 2017, PR147_SciBase2.xlsx for survey data).

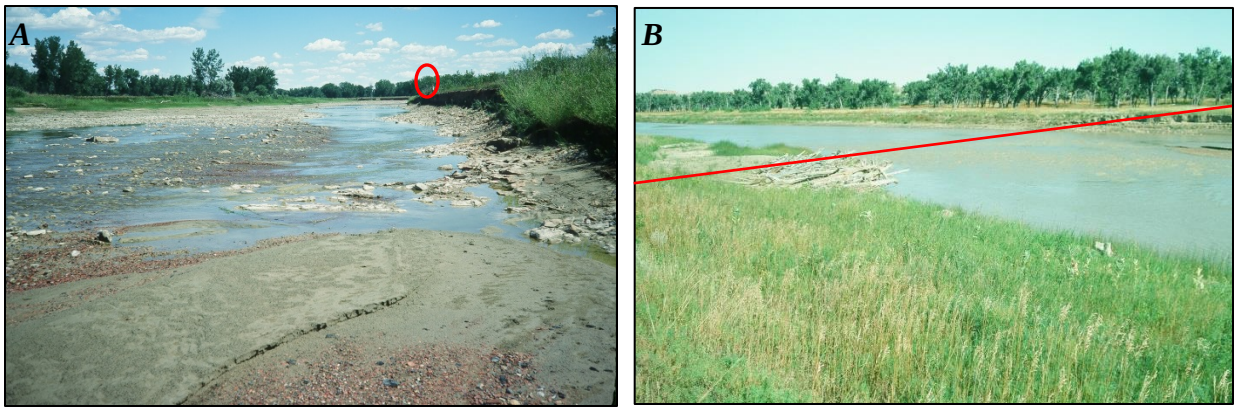

Figure 72. Views of cross section PR147 in 1977 and 1993. *A*, Downriver view was taken on July 23, 1977. E. Meade (about 1.6 meters tall, inside the red oval) is standing on the line of section on the right bank. *B*, Downriver view from the left bank was taken on August 28, 1993, showing a woody debris pile on section and a new sand bar. Red line indicates the approximate line of section.

Cross section PR147 was both widened and deepened by the flood of 1978 (fig. 5 of Meade and Moody, 2013). The right bank was eroded laterally by 5 m. The left bank developed a 6-m-wide scour hole, probably dug during the flood by the turbulence that must have been induced by the presence of a large pile of flood-deposited woody debris.

Change came slowly to section PR147 after the flood of 1978. During the next 35 years (1979–2013), the right bank was eroded by another 5.5 m; 3.3 m of which happened during a single year, 1995; and 1.1 m of which happened 2 years earlier, in 1993. The left-bank scour hole was refilled, mostly during 1991 and 1993, until, by 1995, a new flood plain had developed between stations 15 and 27. The riverward bank of the new flood plain was eroded laterally during 1995 and at some other time(s) after 1998, so that by year 2013 (when the next resurvey was completed, fig. 73), the edge of this bank had retreated to station 22. At some time between 1998 and 2013, a 6-m-wide bench (Page and Nanson, 1982) of new sediment was deposited under the right bank (see also PR120, PR125, PR130, and PR136 narratives), adding to the cross section a volume of new material approximately equivalent to the volume removed from the left bank during the same 15-year period.

The other notable feature of cross section PR147 is a mid-channel sandbar that developed on the downslope of a gravel-bedded riffle whose crest intersected the section between stations 32 and 40, as it extended from the right bank of the river approximately 150 m upriver from the section to the left bank of the river approximately 30 m downriver from the section. After the 1995 flood, this sandbar began to emerge when about 0.2 m of new sediment was left on top between stations 57 and 79, and by 1996 it was populated with cottonwood seedlings growing in an additional 0.5 m of sediment between stations 62 and 72. This was probably the foundation on which a larger island evolved in the middle of the channel between 1998 and 2013, and had increased in elevation by about 0.7 m during this period.

During year 2000, the leveling survey of cross section PR147 was extended on the right bank to station 594, which was the location of the high water mark for the flood of 1978. The cross section was not surveyed in 2014, but resurveyed in 2015 after the two snowmelt floods (280 m^3/s, May 28, and 283 m^3/s, June 6). Again, in 2015, the section showed little erosion or deposition of sediment (fig. 74).

Figure 73. Downriver view of cross section PR147 on September 29, 2013. J. Moody (about 1.9 meters tall) is in the river standing on the line of section. A mid-channel island with a secondary channel to the right is in the upper right of the photo.

Figure 74. Multiple views of cross section PR147 on September 29, 2015. *A*, View from the right bank. The left bank has pampas-type grass growing on the area of the woody debris pile in 1977. *B*, View from the left bank. The right bank, which is probably Lightning-level terrace (Leopold and Miller, 1954), is topped with grayish sagebrush, the lower bench is covered mostly by sedges, and the secondary channel is between the right bank and the island. *C*, Downriver view taken while standing in the middle of the secondary channel with the island on the left. *D*, Upriver view was taken on the midchannel island showing the main channel going to the right and the secondary channel to the left in the photograph.

PR151 Narrative

Cross section PR151 was established in 1975 and is just upriver from a large bluff outcrop of the Fort Union Formation that forms the right bank below the section (fig. 75).

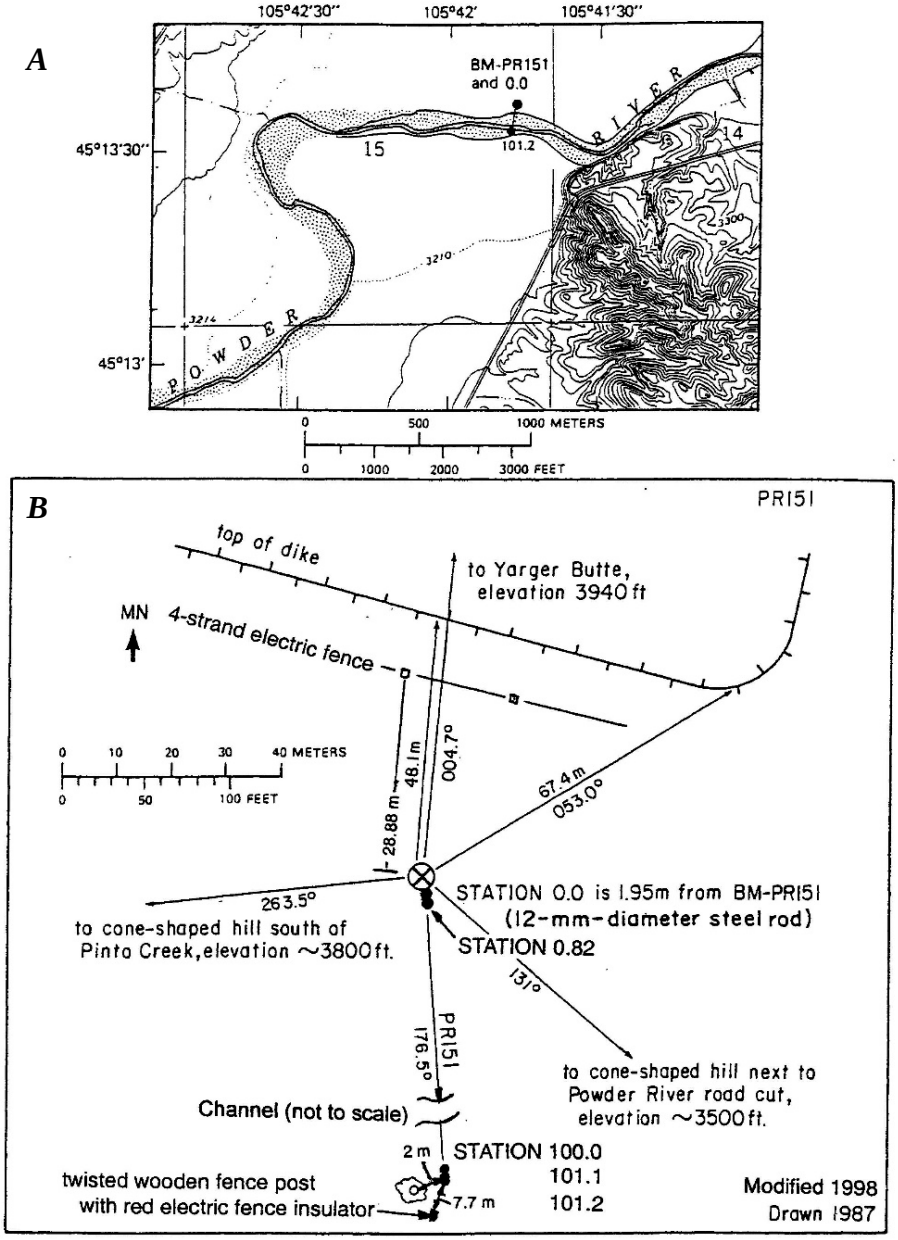

Figure 75. Location maps for cross section PR151. *A*, Location of cross section PR151, bench mark BM–PR151, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Huckins School quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and some reference pins on the left and right banks. MN is magnetic north. Four-strand electric fence was not present in 2015. A reference pin was put in on the left bank at station 13.0 in 2012.

The right bank of the cross section is on the Lightning-level terrace (Leopold and Miller, 1954) and the left bank is on the inset flood plain formed after the flood of 1978 (Moody and

others, 1999; see also PR120, PR125, PR136, and PR156A narratives). The left-bank flood plain steps upwards onto a Moorcroft-level terrace (Leopold and Miller, 1954; Moody and Meade, 2008) farther from the river. When the section was established in 1975, a small island was near the left bank and about 1.5 m above the thalweg of the main channel (fig. 76). Cross section PR151 was resurveyed annually during the 4 consecutive years 1977–80, resurveyed in 1982, and resurveyed annually during the 15 consecutive years 1984–98. After a 13-year hiatus, the section was resurveyed every year from 2012 through 2016 (see Moody and Meade, 2017, PR151_SciBase2.xlsx for survey data).

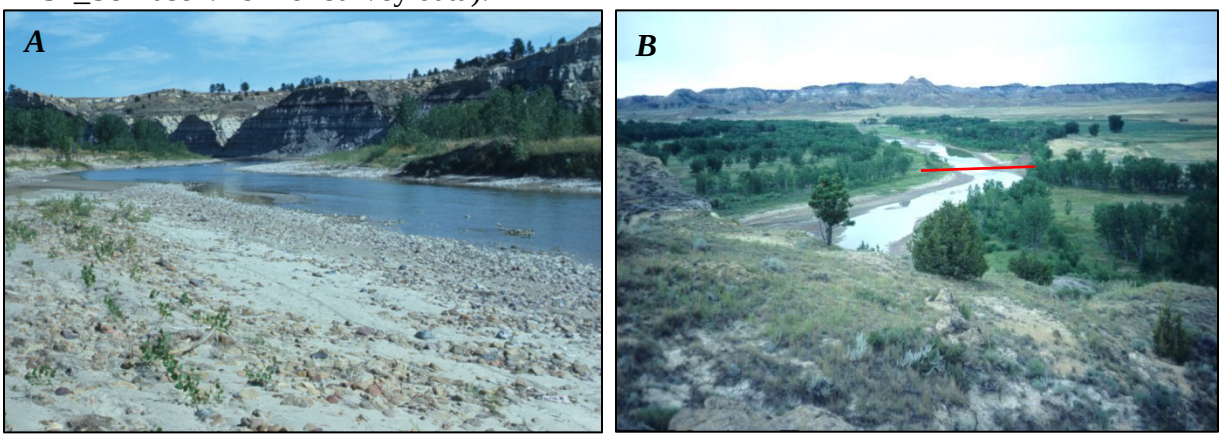

Figure 76. Views of cross section PR151 in 1975 and 1977. *A*, Downriver view was taken on September 7, 1975, looking through the cross section. The Fort Union Formation forms the high bluff in the center of the photograph. *B*, Upriver view was taken from the high bluff in figure 76*A* on July 23, 1977. The red line indicates the approximate line of section crossing the downriver end of a small island.

The flood of 1978 eroded the right bank of the small island causing it to lower in elevation by about 0.3 m (figure 16 of Meade and Moody, 2013). Additionally, substantial overbank sediment was deposited as lee dunes (Moody and Meade, 2008) downriver from cottonwood trees on the right bank (fig. 77). Between 1979 and 1984 the secondary channel separating the remnant of the small island from the left bank was filled in and a new flood plain surface was formed (Moody and others, 1999). This new surface accreted upwards by about 0.1 m in 1987, by another 0.1–0.2 m in 1993, and by still another 0.2–0.3 m in 1995.

Ice-jam floods in February and March often deposit fine and coarse sediment on the flood plain and low terraces (figs. 78 and 79). Ice-flood deposits are localized and not necessarily along the entire river. Other Powder River cross sections that had ice-flood deposits were PR141A and PR120.

Figure 77. Aerial view of cross section PR151 on May 25, 1978. View is downriver and was taken during the waning stages of the flood of 1978. The red line is the approximate line of section. White areas show the extent of sand newly deposited by the flood on flood plain and terraces. Photograph taken by B. Ringen.

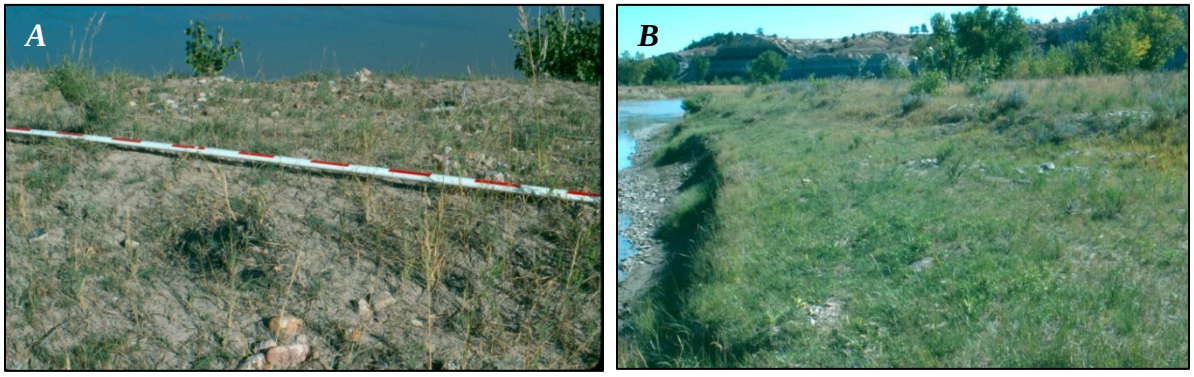

Figure 78. Ice-related deposits of sediment at cross section PR151 photographed on September 20, 1994. *A*, Gravel pods are about 30 meters (m) upstream from PR151 and about 3 m above the riverbed. One pod contains coal. The red bars on the survey rod are 0.2 m long. *B*, View is downriver along the right bank showing gravel pods that were deposited about 100 m upriver from PR151 during an ice break-up flood. Pods on the higher Lightning-level terrace and on the flood plain are about 2.5 and 3 m above the riverbed.

Figure 79. Photograph of ice deposited on the flood plains downriver from cross section PR151. Upriver view was taken on March 11, 1995. The red line indicates the approximate line of section.

Little change was measured between 1995 and 2014. The major change was the appearance of benches (Page and Nanson, 1982) along both banks that narrowed the width of the low-water channel (fig. 80; see also figs. 41 and 74). Further additions of sediment to the left-side flood plain surface amounted to 0.1–0.2 m between 1998 and 2012.

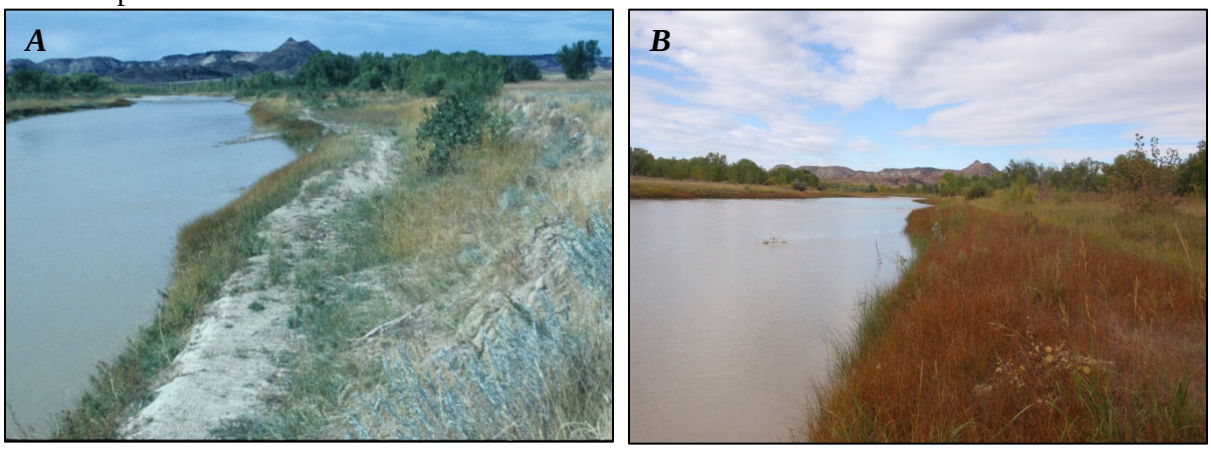

Figure 80. Upriver views of cross section PR151 in 1995 and 2013. *A*, Photograph was taken on September 27, 1995. The left bank is on the right side of the photograph with a small bench highlighted by the newly (1995) deposited sand (either side of station 36) near the base of the flood plain. *B*, View was taken on September 30, 2013, standing on the line of section at station 43. The predominantly red vegetation is sedge (*Scirpus* spp.) growing closest to the water on a "bench" below the level of the green-colored inset flood plain (Moody and Meade, 2008).

There was no erosion of the section caused by the snowmelt floods in 2015 (280 m^3/s, May 28, 2015, and 283 m^3/s, June 6, 2015), but deposition of about 0.2 m of sand near the edge of the left-bank flood plain from stations 33 to 35, and about 0.1 m of silty mud across the flood plain from stations 30 to 18. This inset flood plain (Moody and others, 1999) is now about 1.4 m above the elevation of the secondary channel in 1975.

Two sediment cores were collected from the Lightning-level terrace on the right bank (2.5 m upriver from station 88.5) on October 3, 2015, for dating by optical stimulated luminescence (OSL). The cores were 0.69 and 1.39 m below the top of the terrace surface.

PR156 Narrative

Cross section PR156 was established in 1977 across a large gravel-bed riffle, which had been used in previous years as a fording place across Powder River (fig. 81). We thought cross section PR156 had been washed away by the flood of 1978, but later found some of the reference pins using a metal detector so that the cross section could be re-established.

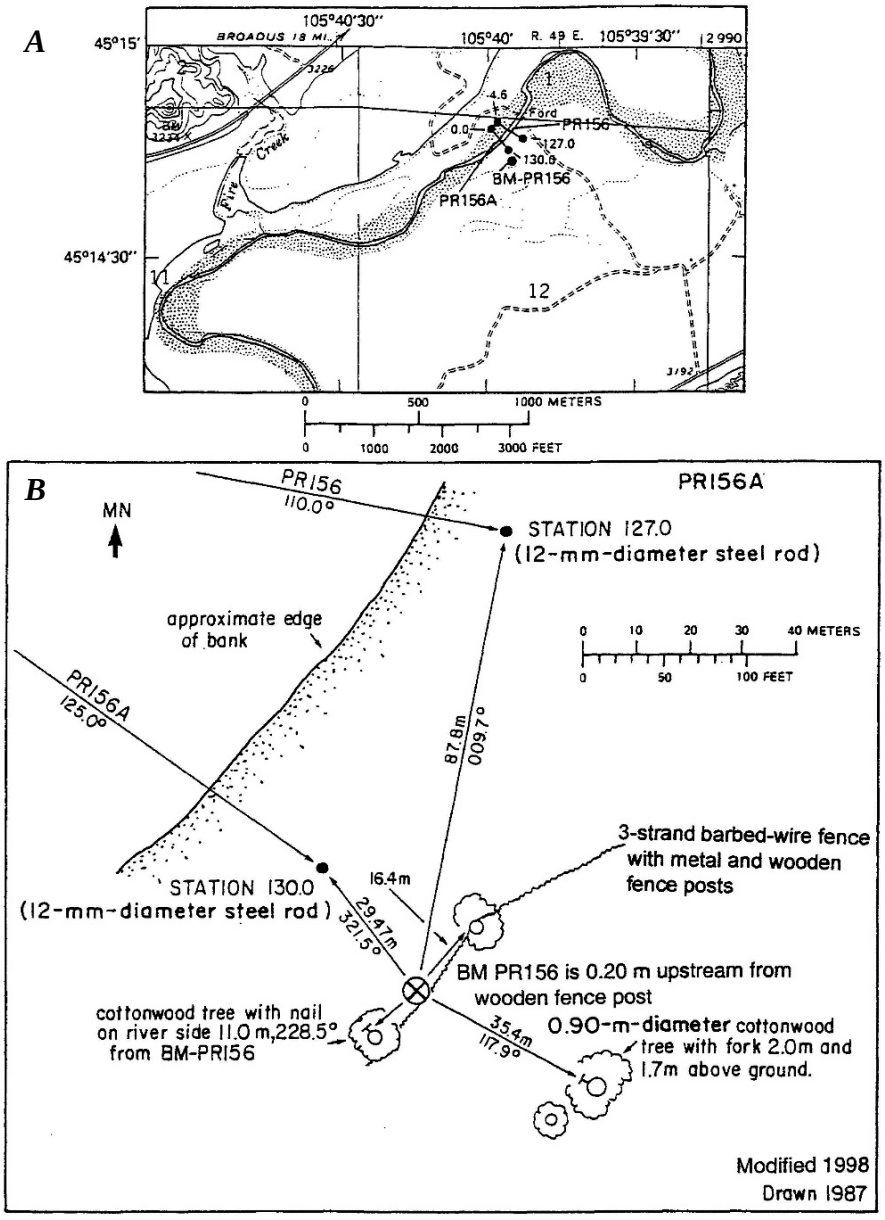

Figure 81. Location maps for cross section PR156. *A*, Location of cross section PR156, bench mark BM–PR156, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Huckins School quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and some reference pins on the right bank. MN is magnetic north. There is an additional reference pin at station 159.2 of section PR 156A under the 3-strand barbed-wire fence.

The site was chosen for its attractive amenities, such as easy access by way of old roadways to the ford, and a large cottonwood tree (*Populus sargentii*) to shade the level and tripod (fig. 82). The riffle crosses Powder River at an angle, with its upriver end at the right bank. Surveys were done every year from 1977 through 1998, with the exceptions of 1981 and 1983 (see Moody and Meade 2017, PR156_SciBase2.xlsx for survey data).

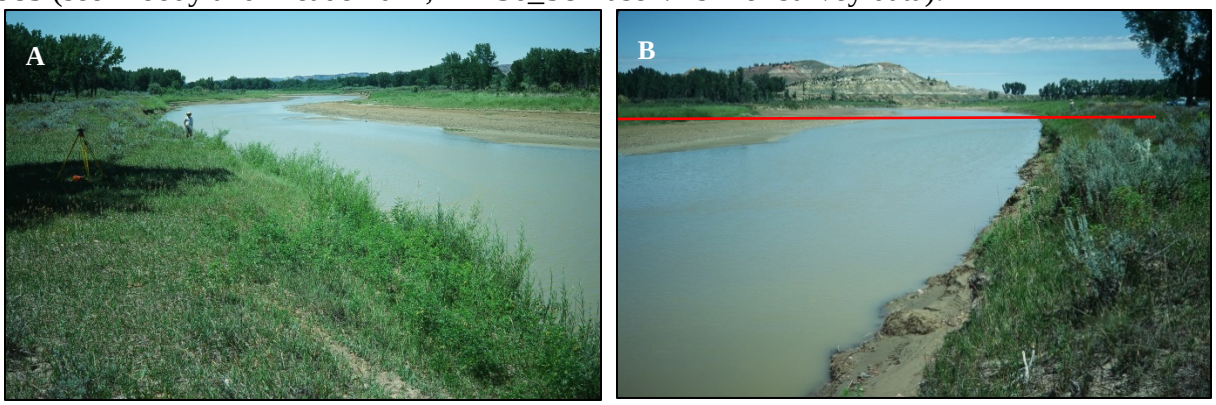

Figure 82. Views of cross section PR156 on July 14, 1977. *A*, View is upriver with tripod under a shade tree. E. Meade (about 1.6 meters tall) is standing on the line of section. *B*, View is downriver and red line indicates the approximate line of section.

During the flood of 1978, the river channel was widened substantially by the lateral removal of approximately 10 m width of flood plain from the left bank, and approximately 20 m width of a 2-m-high Lightning terrace (Leopold and Miller, 1954; Moody and Meade, 2008) (including the shade tree) from the right bank (fig. 5 of Meade and Moody, 2013). During the flood of 1978, one characteristic depositional form on the flood plains and some Lightning-level terraces (Moody and Meade, 2008) were lee dunes downriver from shrubs, trees, or clumps of trees. These dunes were composed mostly of sand (fig. 83).

Figure 83. Lee dunes on the left bank of cross section PR156 on September 1, 1978. View is downriver showing lee dunes deposited downriver from trees or clumps of cottonwood trees. J. Moody is approximately 1.9 meters tall.

During the years 1979–98, most of section PR156 remained mainly stable (which was to be expected of a large riffle), alternately gaining or losing a few decimeters of sand in the above-the-riffle waters near the left bank. Under the right bank, meanwhile, there gradually developed, between stations 97 and 111, a new flood plain which had reached a thickness of about a meter by the time of our last survey in 1998. As at several other cross sections, sedimentation at PR156 has been affected by ice break-up floods (fig. 84).

Figure 84. Upriver view of ice flowing across cross section PR156 on March 11, 1995. View is approximately 30–40 meters (m) downriver from section PR156. Ice breakup is moving onto the new inset flood plain (Moody and others, 1999). J. Moody (about 1.9 m tall inside red oval) stands about 10 m upriver from section PR156A.

PR156A Narrative

Cross section PR156A is just upriver from PR156 and was established after the flood of 1978 when we thought PR156 had been washed away (fig. 85). The cross section begins on a Lightning-level terrace (Leopold and Miller, 1954) and then steps down onto the inset flood plain formed after the flood of 1978 (Moody and others, 1999; see also PR120, PR125, PR136, and PR151 narratives). The right bank is on the Lightning-level terrace (Moody and Meade, 2008). Section PR156A was resurveyed annually for 2 consecutive years 1979–80, resurveyed in 1982, and resurveyed annually during the 15 consecutive years 1984–98. For graphic portrayals of geomorphic features of this segment of Powder River valley, see figure 2 of Moody and Meade (2008). We made an abbreviated survey in 1999 when preparing to write the paper on flood plain ontogeny (Moody and others, 1999), and then did full surveys from 2011 through 2016 (see Moody and Meade, 2017, PR156A_SciBase2.xlsx for survey data).

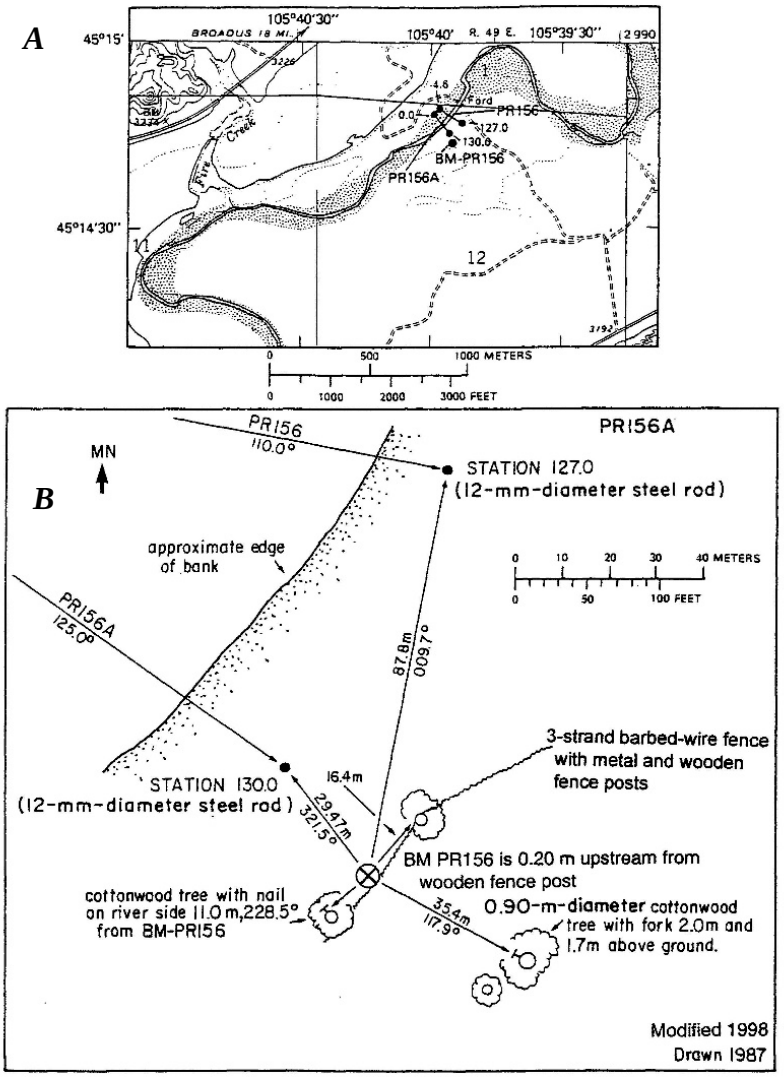

Figure 85. Location maps for cross section PR156A. *A*, Location of cross section PR156A, bench mark BM–PR156, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Huckins School quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and some reference pins on the right bank. MN is magnetic north. There is an additional reference pin at station 159.2 under the 3-strand barbed-wire fence.

The flood of 1978 left sand on a wide surface sloping riverward away from the base of a Moorcroft-level terrace on the right bank (fig. 86). This surface relatively quickly aggraded between 1980 and 1982, leaving a distinct quasi-level, approximately 40-m wide flood plain surface. Between 1982 and 1984, the lowest areas of this flood plain surface aggraded 0.1–0.2 m. Beginning in 1986, the right-side flood plain expanded primarily along the riverward edge as a levee, mostly between stations 60 and 65 (fig. 87), vertically adding 0.10–0.40 m of new sand in 1987, another 0.10–0.40 m in 1993, and yet another 0.10–0.25 m in 1995.

Figure 86. Photograph of the right-bank flood plain of cross section PR156A on August 4, 1978. View is downriver showing sand deposits left by the flood of 1978. J. Moody is about 1.9 meters tall. Mature cottonwood trees (*Populus sargentii*) are on a Moorcroft-level terrace.

Cross section PR156A is at about the upriver limit of the Russian olives (*Elaeagnus angustifolia*) that have colonized the flood plain downriver (farther north) since the flood of 1978 (fig. 1). Here they are scattered with a density of perhaps 5 per 100 m^2, whereas downstream at cross sections PR167, for example, the density is perhaps on the order of 30 per 100 m^2, and upstream at PR151 there are no Russian olives as of 2016.

Figure 87. Comparison of the right bank of cross section PR156A in 1986 and 2013. *A*, Upriver view of the right bank taken on August 20, 1986. J. Moody (about 1.9 meters [m] tall) is standing on the line of section at station 63 (elevation 970.35 m above sea level) on top of newly (1986) deposited berm of sand, 0.3–0.4 m thick. *B*. September 30, 2013. Similar upriver view as in *A* taken on September 30, 2013, but elevation of station 63 is now 971.28 m above sea level, and Russian olive trees have colonized the right bank flood plain.

In 1995, there were several ice-break-up floods in February and March (fig. 88) and two relatively large peaks in the snowmelt runoff (194 m^3/s, May 11, 1995; 168 m^3/s, June 11, 1995). These floods left a nearly uniform deposit of 0.10–0.15 m across the new inset flood plain (Moody and others, 1999). This was followed by a quiescent period from 1995 to about 2007.

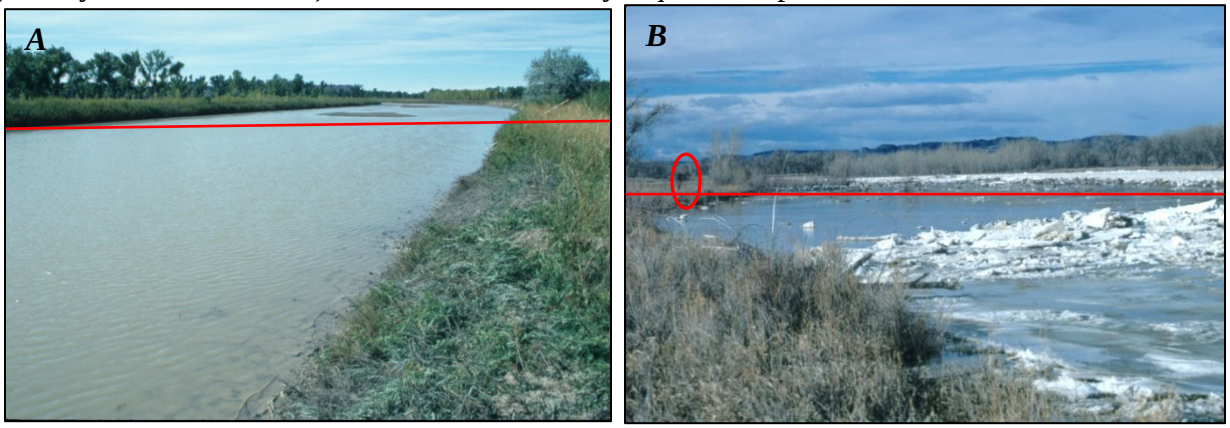

Figure 88. Upriver views of cross section PR156A. in 1994 and 1995. Red lines indicate the approximate line of section. *A*, Photograph was taken on September 22, 1994, standing on the left bank with a Russian olive tree in the distance. *B*, Photograph was taken on March 11, 1995, from the right bank showing the advancing edge of an ice-break-up flood. J. Moody (about 1.9 meters [m] tall) in the red oval is standing approximately 10 m upriver from the line of section.

During the flood of 2008 (329 m^3/s, May 27), another 0.10–0.15 m of sediment was deposited across the new flood plain, and additional sediment was deposited on a bench (Page and Nanson, 1982) at the base of the outer bank of the flood plain (figs. 87*A*, 89, and 90) that had developed since 1999 (also see PR120, PR125, PR136, and PR151 narratives).

Little change was observed between 2008 and 2014. While the 2015 snowmelt floods did not erode this section, they deposited about 0.2 m of new sediment on the bench (fig. 90), a new layer (0.2 m thick) of sand on the levee between the bench and the inset flood plain at station 63, and a wedge of sediment across the flood plain that tapered from a thickness of 0.2 m at the levee to 0.05 m of mud in the trough adjacent to the Lightning-level terrace at about station 103.

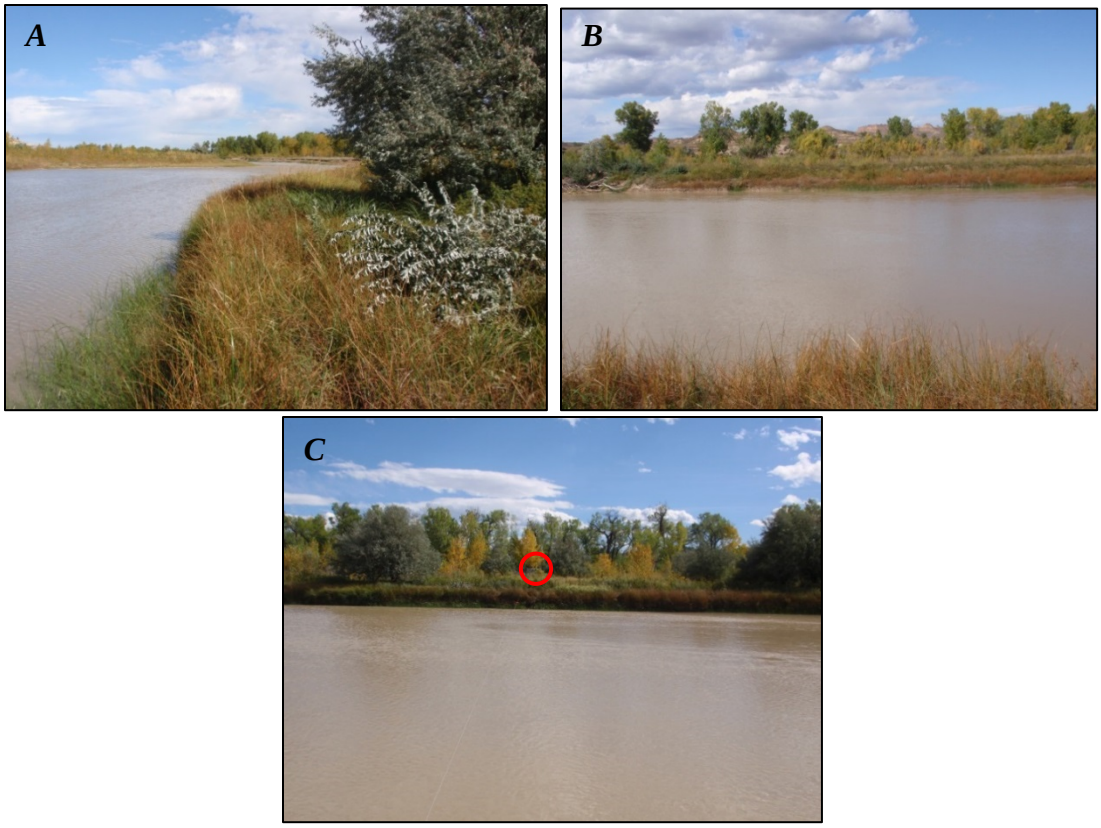

Figure 89. Views of the right and left banks of cross section PR156A on September 30, 2013. *A*, Downriver view from the right bank standing at station 58 on the new bench. *B*, View is along the line of section towards the left bank standing at station 58. *C*, View of right bank standing at station 10. Line of section goes between the cottonwood tree with two trunks (inside red circle) at station 103 (also see fig. 90).

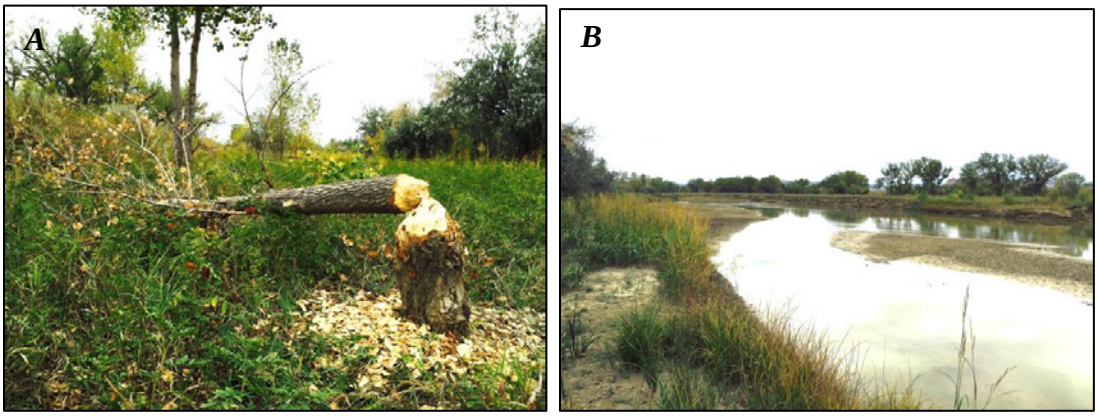

Figure 90. View of cross section PR156A on October 3, 2015. *A*, View is upriver at the landward edge of the right-side inset flood plain (Moody and others, 1999) marked by the cottonwood tree with two trunks at station 103 (see fig. 89). The cottonwood tree cut down this year (2015) by beavers was no more than 37 years old, as it had begun growing after the flood of 1978. Photograph taken by D. Martin. *B*, View upriver standing at about station 58 on the bench that formed sometime after 1999 and is now (2015) about 1.2 meters wide.

PR163 Narrative

Cross section PR163 was established in 1977 near the apex of a bend in Powder River (fig. 91), whose cut bank was originally a 2.5-m-high Lightning-level terrace (Leopold and Miller, 1954; Moody and Meade, 2008) on the left margin of the channel, and a point bar and flood plain on the right margin. Based on dendrochronology, the point bar had been developing at this site since 1862 (Schook and others, 2017). This cross section was resurveyed annually (except for 1981 and 1983) through 2002. In 1996, the leveling survey of section PR163 was extended rightward to station 650. Station 650 was the location of the right edge of the high water of the flood of 1978. After a hiatus of 8 years, it was again surveyed in 2011 through 2016 (see Moody and Meade, 2017, PR163_SciBase2.xlsx for survey data).

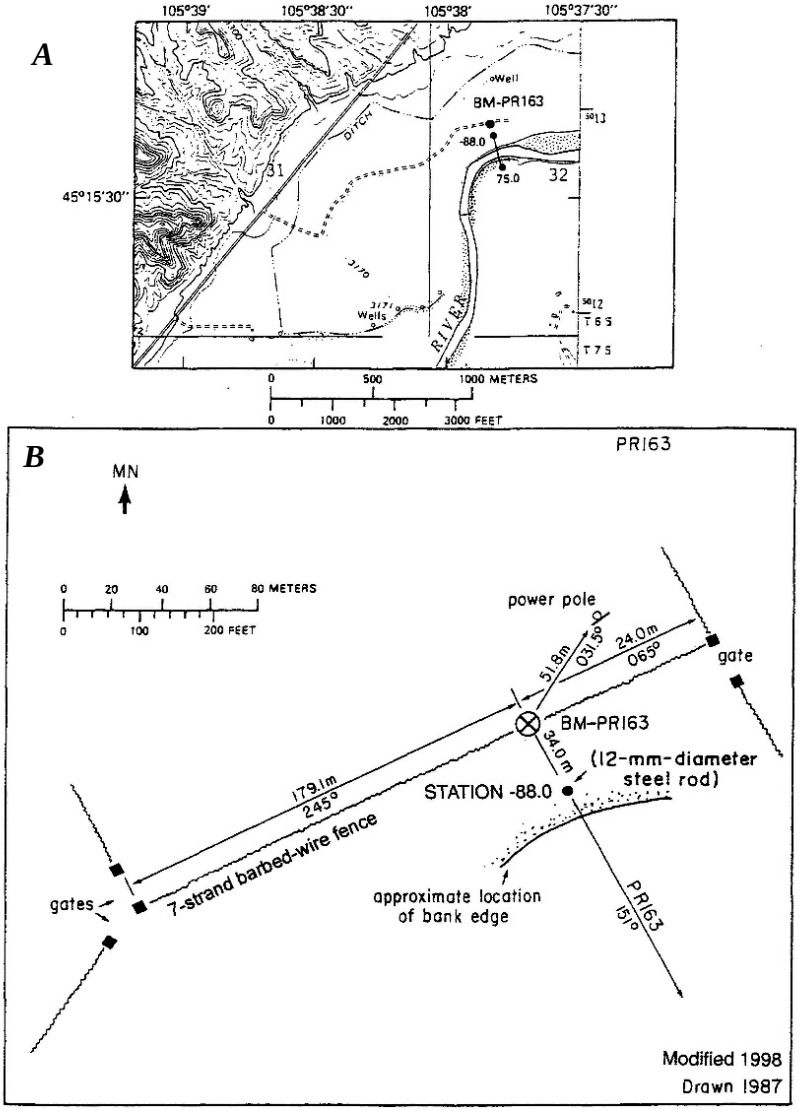

Figure 91. Location maps for cross section PR163. *A*, Location of cross section PR163, bench mark BM–PR163, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Yarger Butte quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark under a fence line and some reference pins on the left bank. Reference pin at station -88.0 was removed by erosion. Reference pins at -100.0 and -102.0 were added in 2000 and 2012, respectively. Distance noted along the fence as 24.0 meters (m) should be 84.0 m. MN is magnetic north.

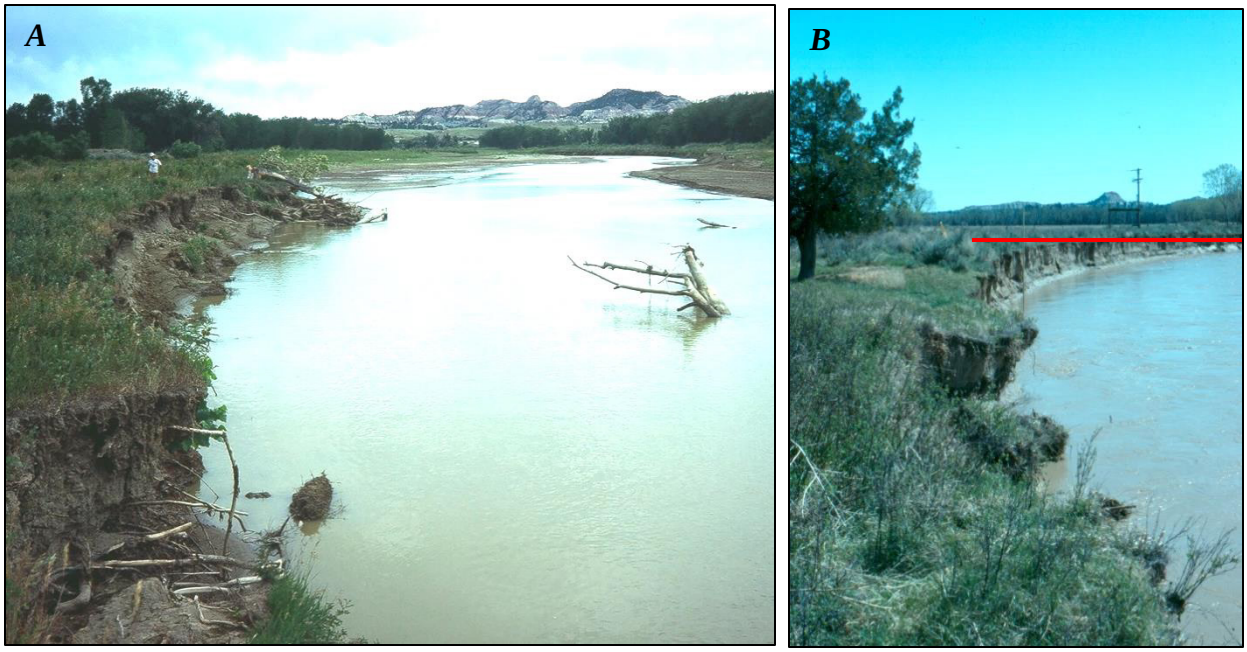

Figure 92. Comparison of the left bank near cross section PR163 in 1977 and 1993. *A*, Downriver view along the left bank, which, at the time of this photograph (July 13, 1977), was at the level of a Lightning-level terrace. E. Meade (about 1.6 meters [m] tall) is standing on the line of section at about station 8. The left bank was eroded by the flood of 1978 and moved laterally 65 m to the left during the flood. The downriver end of the point bar is in the upper right of the photograph. *B*, Downriver view (May 11, 1993) along the left bank, which is now cut into a Moorcroft-level terrace that eroded an additional 12 m to the left between 1978 and 1993. Water elevation is 963.10 m in this photo. Red line indicates the approximate line of section.

The greatest accretionary channel displacement during the flood of 1978 that we were able to document fully on Powder River was measured at cross section PR163 (fig. 19 of Meade and Moody, 2013). During 2 weeks of flooding, the left-bank Lightning-level terrace was eroded back a lateral distance of 65 m, displacing some 160 m^3 of terrace sediment for each meter of channel length (fig. 92), which left only a 3-m wide remnant of the Lightning-level terrace in front of a Moorcroft-level terrace. The right-bank flood plain was extended leftward some 55 m by the deposition of an about 2-m thickness of new sediment in the preflood river channel (stations 10 to 45) and an about 1-m thickness of new sediment atop the old point bar (stations 45–65). In addition, a scroll bar was deposited in a segment of the cross section (stations -20 to +10) where, 2 weeks earlier, had stood a 2.5-m-high fluvial terrace. Flood waters that crossed the neck of the bend left overbank deposits of silt and sand, mostly 0.1–0.3 m thick, on a 500-m rightward extension of cross section PR163 (fig. 6 of Moody and Meade, 2008). Overbank material was also deposited by floodwaters that overtopped the left-bank Lightning-level terrace, but most of this freshly deposited sediment was remobilized and carried away downstream as the cut bank receded during the flood; only a thin (about 0.1 m thick) remnant survived the flood at stations -55 to -60.

Since the flood of 1978, the left bank has continued to erode back into the Lightning-level terrace and, since 1985, into the Moorcroft-level terrace (figs. 92 and 93). Slump blocks are common along the left bank, which generally faces southeast (fig. 93).

Figure 93. Comparison of upriver views of the left bank of cross section PR163 in 1993, 1995, and 1996. *A*, Photograph was taken on August 30, 1993. J. Pizzuto (about 1.8 meters [m] tall) is standing on the line of section. The tree behind him is the same tree near the edge of the left bank in figure 92*B*. *B*, Photograph was taken on September 25, 1995. J. Moody (about 1.9 m tall) is standing on the line of section. *C*. Photograph was taken on January 14, 1996. Red and white survey rod is lying on the line of section. Bank erosion often results in slump blocks and is enhanced by melting snow and perhaps by the freeze-thaw process at this bend that faces approximately southeast.

From 1978 through 1995, the scroll bar that was deposited during the flood of 1978 accumulated sediment intermittently (on a year-to-year time scale) between stations -15 and +15, until the crest of its upper surface was near the level of the existing flood plain (fig. 94), and a trough or swale separated the two features. Meanwhile, a new point bar developed between stations -15 and -35 (Moody and Meade, 2014). Between 1995 and 2014, the riverward edge of this point bar was extended laterally leftward to about station -55 (fig. 95).

As of 2014, the Moorcroft-level terrace bank had lost another 36 m, or an average of 1 meter per year since the flood of 1978. Larger-than-average amounts of erosion of the left bank were recorded in the surveys done in 1984 (2.9 m), 1991 (3.0 m), 1993 (2.0 m), 1995 (3.4 m), 1996 (5.0 m), 1999 (2.0 m), and 2011 (9.7 m, most of which probably was eroded in 2008).

In 2013 and 2014, 10 sediment cores (2 replicates) were collected from the 3.7-m high left bank (Moorcroft-level terrace, elevation of top of the terrace is 965.39 m above NGVD 29) for dating by optical stimulated luminescence (OSL). The cores were collected 2 m downriver from the line of section (fig. 95) and 0.2–0.4 m apart along a vertical profile starting at 2.5 m below the terrace tread. (fig. 96). These cores will provide estimates of the deposition rates of this Moorcroft-level terrace.

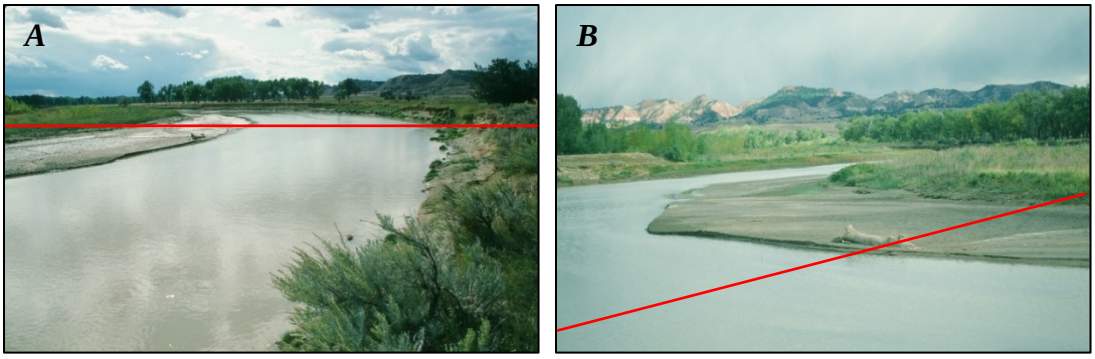

Figure 94. Upriver and downriver views of cross section PR163 on September 21, 1994. Red lines indicated the approximate line of section, which crosses the root ball of the tree trunk that is on the sandbar. The base of the scroll bar on the right bank is where the green grass begins at about station -15 in both photographs above. Water discharge is about 1.5 cubic meters per second. *A*, Upriver view of the point bar along the right edge of water. *B*, Downriver view from a point about 80 meters above the cross section showing the broad point bar.

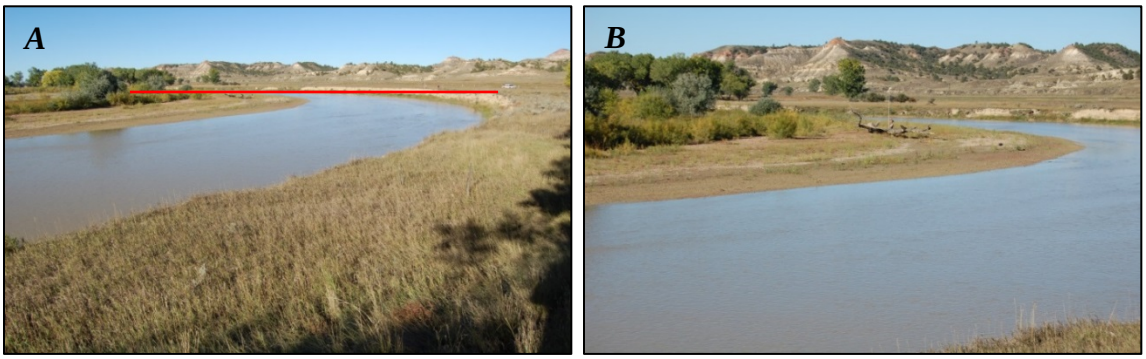

Figure 95. Upriver views of cross section PR163 on October 1, 2013. *A*, The line of section runs between the tail gate of the white Chevrolet Suburban and the log on the point bar shown by the red line. *B*, Log on the point bar is the same log seen in photograph taken on September 21, 1994 (fig. 94). J. Moody is standing next to the log at station -27.

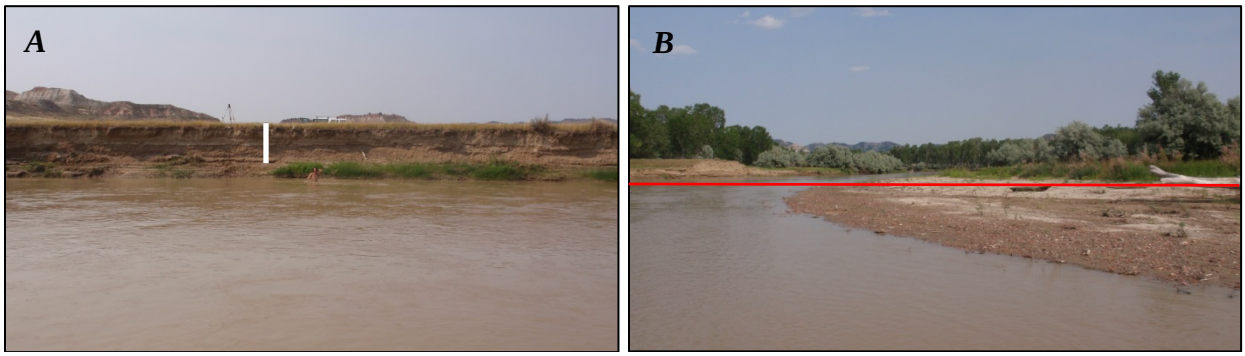

Figure 96. Views of cross section PR163 on July 17, 2014. *A*, Photograph of the left bank with the tripod on the line of section. B. Laub (about 1.7 meters [m] tall) is standing in the thalweg, and the white bar indicates the approximate location of the optical stimulated luminescence sediment core profile. Water level is at 962.73 m above National Geodetic Vertical Datum of 1929 (2.68 m below the top of the bank), and the water discharge is 16.7 cubic meters per second. *B*, View is downriver. The root wad of the whitish cottonwood tree (*Populus sargentii*) seen in figure 95B is just outside of the photograph, but is on the line of section indicated by the red line. Right edge of water on the line of section is at station -46.0.

The snowmelt floods in 2015 (May 28, 2015, 280 m^3/s; June 6, 2015, 283 m^3/s) eroded an additional 2.7 m from the left bank, leaving numerous slump blocks at the base of the bank, (fig. 97*A*) and deposited about 0.3 m of gravel on the point bar (fig. 97*B*) on the right side of the channel. The large cottonwood snag that had marked the line of section on the point bar for many years (figs. 94, 95, and 96) was washed downriver. High water was estimated to have been at an elevation of about 964.6 m so that it deposited sand on the berm of the flood plain (station -16.0) and a thin layer (less than 0.01 m) of mud at station 75 near the original right bank in 1977.

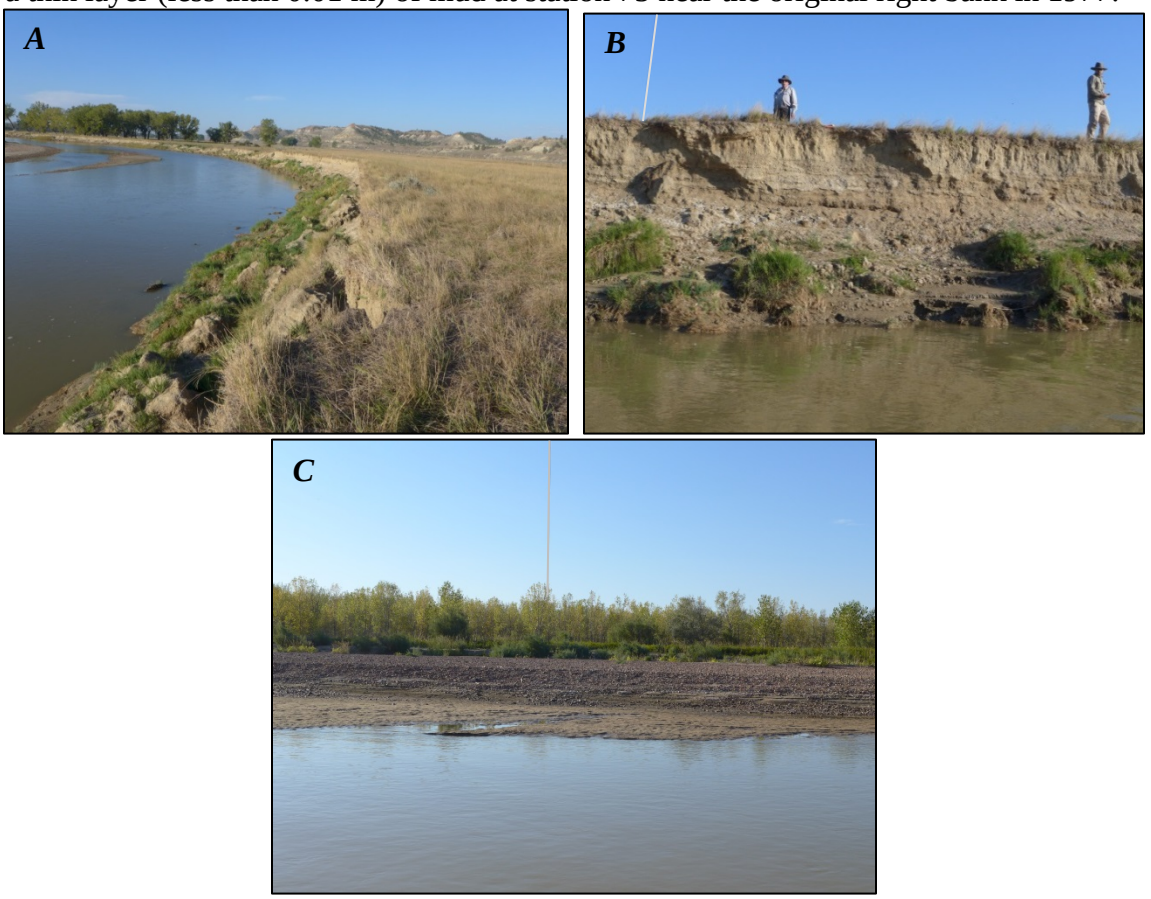

Figure 97. Views of cross section PR163 on September 27, 2015. *A*, View is upriver along the left bank (Moorcroft-level terrace). Slump blocks at the base of the bank were probably a consequence of the snowmelt floods in May and June of 2015. *B*, View is of the left bank. The tagline (grey line) marking the line of section can be seen in the upper left of the photograph and to the left of R. Meade (about 1.8 meters (m) tall). A series of optical stimulated luminescence cores were collected in 2013 and 2014 in a vertical profile from the bank beneath where R. Meade is standing; however, the actual bank material was removed during the May and June 2015 snowmelt floods. A. Torres (about 1.7 m tall) is standing downriver of the section. *C*, View is of the right bank with the water level at 962.31 m above the National Geodetic Vertical Datum of 1929 (NGVD 29). Recently (2015) transported gravel (about 0.3 m thick) covers the point bar (elevation 963.29 to 963. 65 m above NGVD 29) in front of the scroll bar indicated by the green vegetation (elevation of crest is 964.44 m above NGVD 29). The tagline (grey line) marks the line of section.

In 2016, an approximately 2-m wide trench was dug just downriver from the line of section from station -40 to 30 to determine the fluvial point-bar architecture (Ghinassi and

others, 2017). This trench cut through three deposits from the floods of 1978, 1985, and 2008 (figs. 98 and 99).

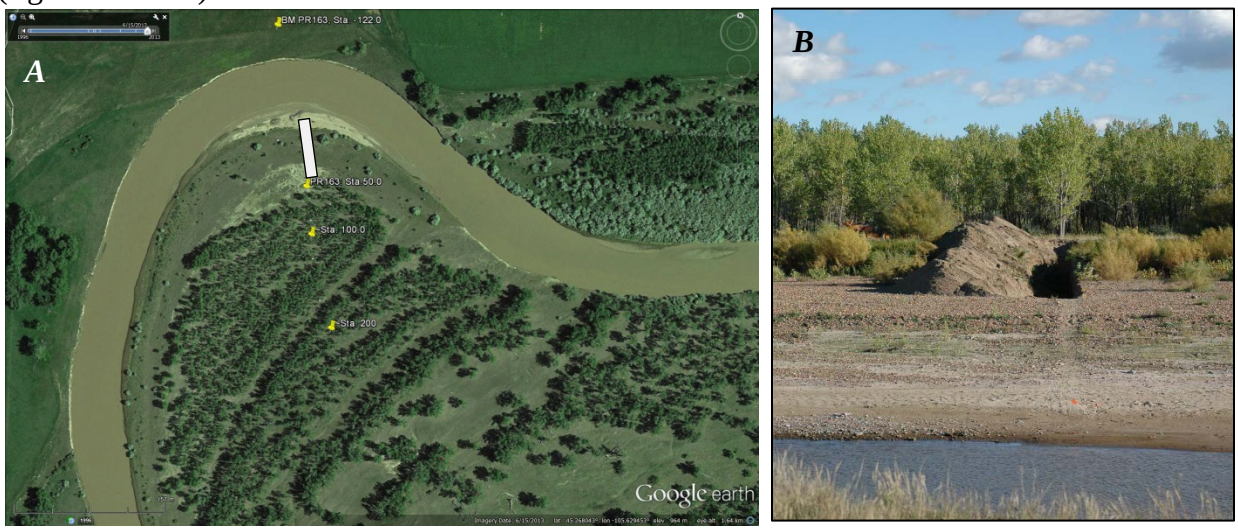

Figure 98. Location of trench dug on the point bar at cross section PR163 in September 2016. *A*, Trench (grey bar) was about 2-meter (m) wide and about 1 m downriver and parallel to the cross section and point-bar axis. Yellow pushpins are labelled with the station number (meters from the original zero pin on the left bank) *B*, View of trench taken from the left bank by D. Martin.

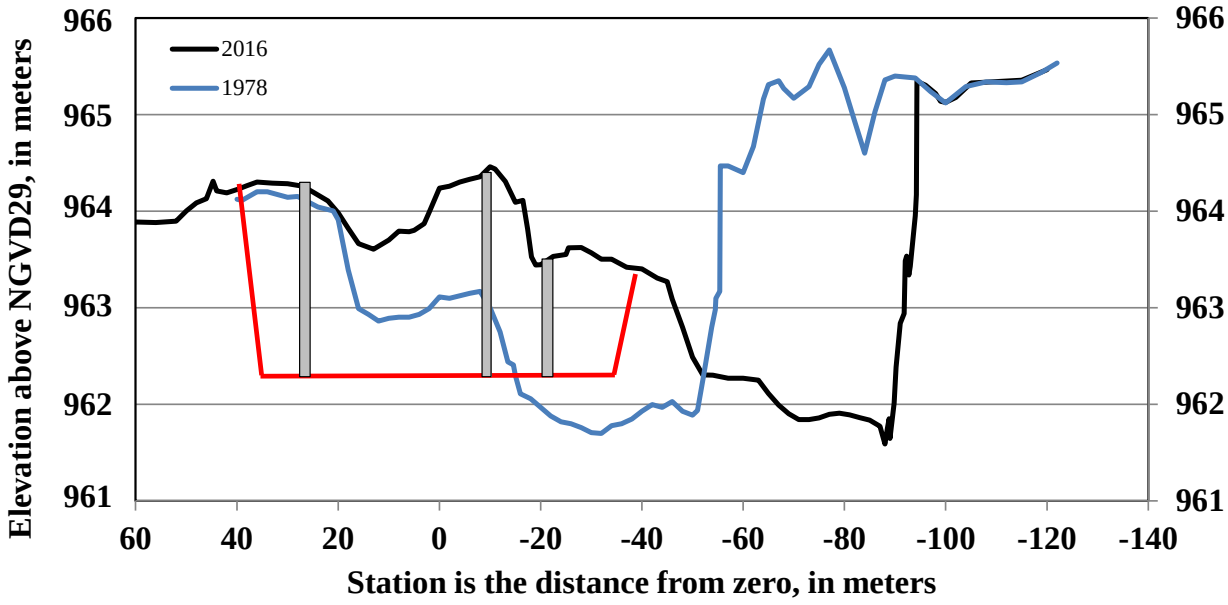

Figure 99. Profile of cross section PR163 showing the location of the trench. Vertical scale exaggeration is 20X. View is upriver and outline of the trench is shown in red. The remnant Lightning-level terrace is the blue line between stations -55 and -60. Moorcroft-level terrace is between stations -60 and -120 with an irrigation ditch at approximately station -84. The crest of the scroll bar was at station -8 in 1978 and was at station -10 in 2016. The present point bar is between stations -28 and -60. The short spike in topography at station 44.7 was a vegetation mound. The three vertical grey bars indicate the location of the photographs (station 24.0, -10.0, and -22) shown in figures 100, 101, and 102, respectively.

The deposits from the flood of 1978 were mostly sand and gravels in dipping beds. They showed a general coarsening upward from mostly sand near the bottom of the trench to mostly gravels near the top of the trench (fig. 100).

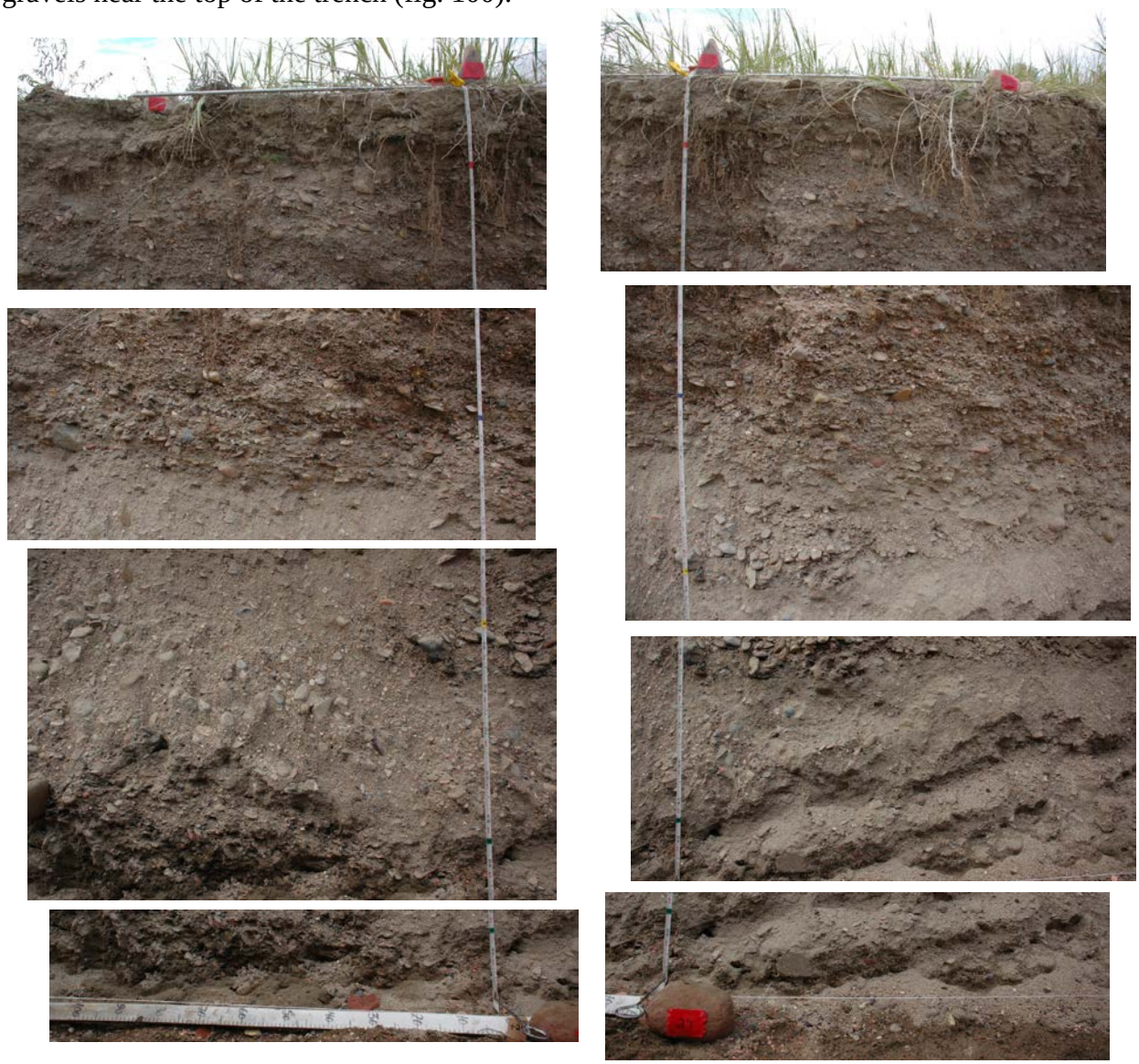

Figure 100. Photographs of the deposits from the flood of 1978 at station 24.0 of section PR163 on September 9, 2016. The vertical distance from top of trench to the white meter stick is approximately 1.9 meters. The triangular rock with red tape is at station 24.0, and the two other rocks with red tape are at station 25.0 (to the left) and 23.0 (to the right), giving a field of view of 2 meters. The photographs overlap each other but have not been superimposed because they are not georectified. These gravel deposits were loose, unstable, and prone to slumping if disturbed.

The deposits from the flood of 1985 were mostly medium sand with laminations of coal which are evident in the bottom one-half of the photographs taken at station -10 (fig. 101, that is below the bedding contact that has been highlighted by removing the fine sand). Above the bedding contact, the sediments are mostly silts representing overbank deposition that increased the height of the scroll bar.

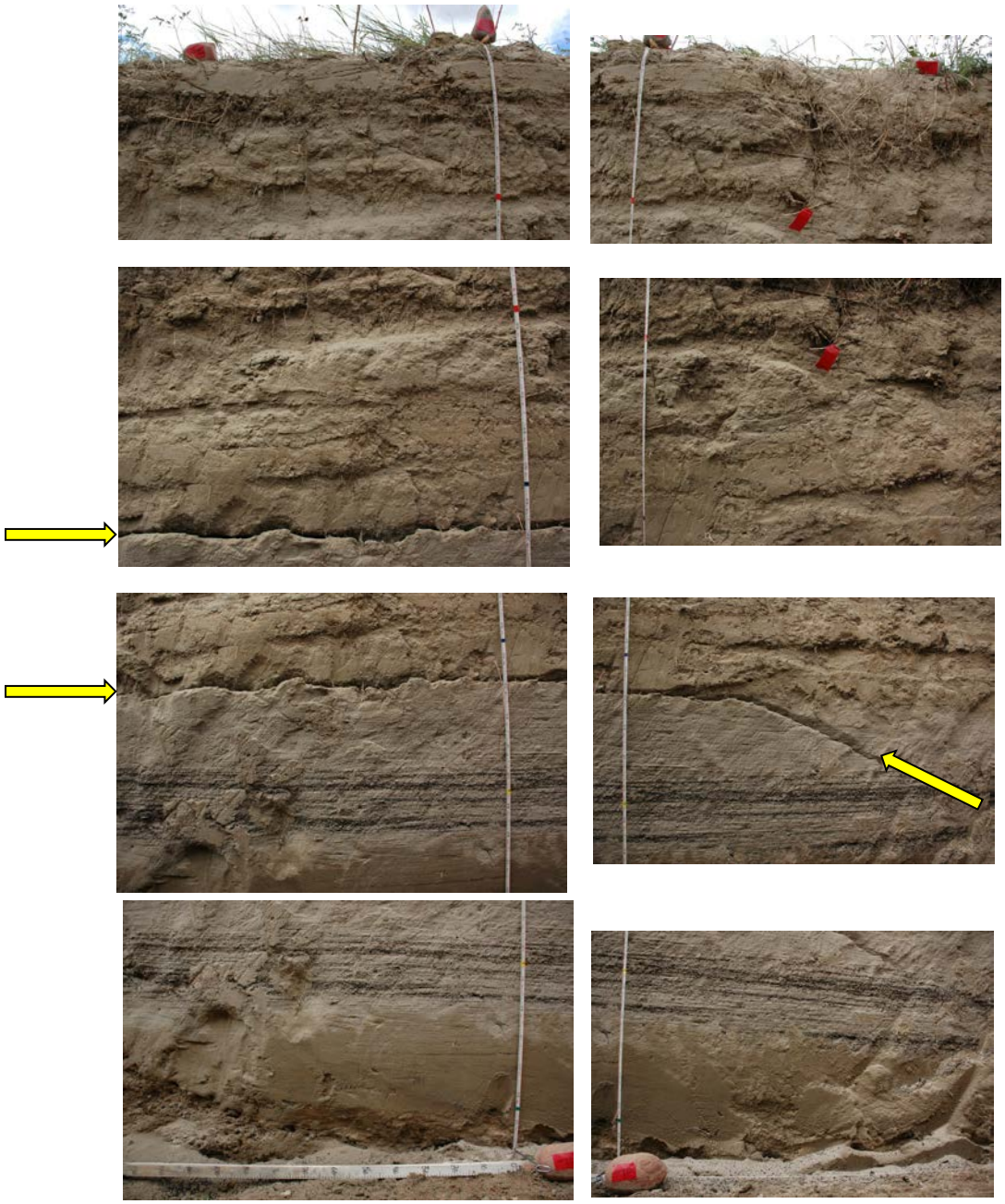

Figure 101. Photographs of the deposits at station -10.0 of section PR163 on September 9, 2016. The vertical distance from top of trench to the white meter stick is approximately 2.1 meters. The triangular rock with red tape is at station -10.0, and the two other rocks with red tape are at station -9.0 (to the left) and -11.0 (to the right), giving a field of view of 2 meters. The photographs overlap each other but have not been superimposed because they are not georectified. The yellow arrow points to the bedding contact between the mostly medium sand unit and coal laminations deposited by the flood of 1985 below, and later overbank silty units deposited above.

The deposits from the flood of 2008 were mostly likely the horizontally bedded sand and gravel strata seen in figure 102. We resurveyed cross section PR163 in 2002 but not again until 2011 so that we do not have before-and-after survey data for the flood of 2008.

Figure 102. Photographs of the deposits at station -22.0 of section PR163 on September 9, 2016. The vertical distance from top of trench to the white meter stick is approximately 1.2 meters. The triangular rock with red tape is at station -22, and the two other rocks with red tape are at station -21.0 (to the left) and -23.0 (to the right), giving a field of view of 2 meters. The photographs overlap each other but have not been superimposed because they are not georectified. The sediment between the two yellow arrows in the upper left photograph is assumed to represent deposition from the flood of 2008.

PR167 Narrative

Cross section PR167 was established in 1977 in the upriver limb of a large meander bend of Powder River in sections 21 and 28 of T6S, R50E (the bend described as “near Daily Ranch” in fig. 9 of Gay and others, 1998) (fig. 103). Resurveys were done during the years 1978–80, 1982, 1984–98, 2011, 2014, 2015, and 2016 (see Moody and Meade, 2017, PR167_SciBase2.xlsx for survey data).

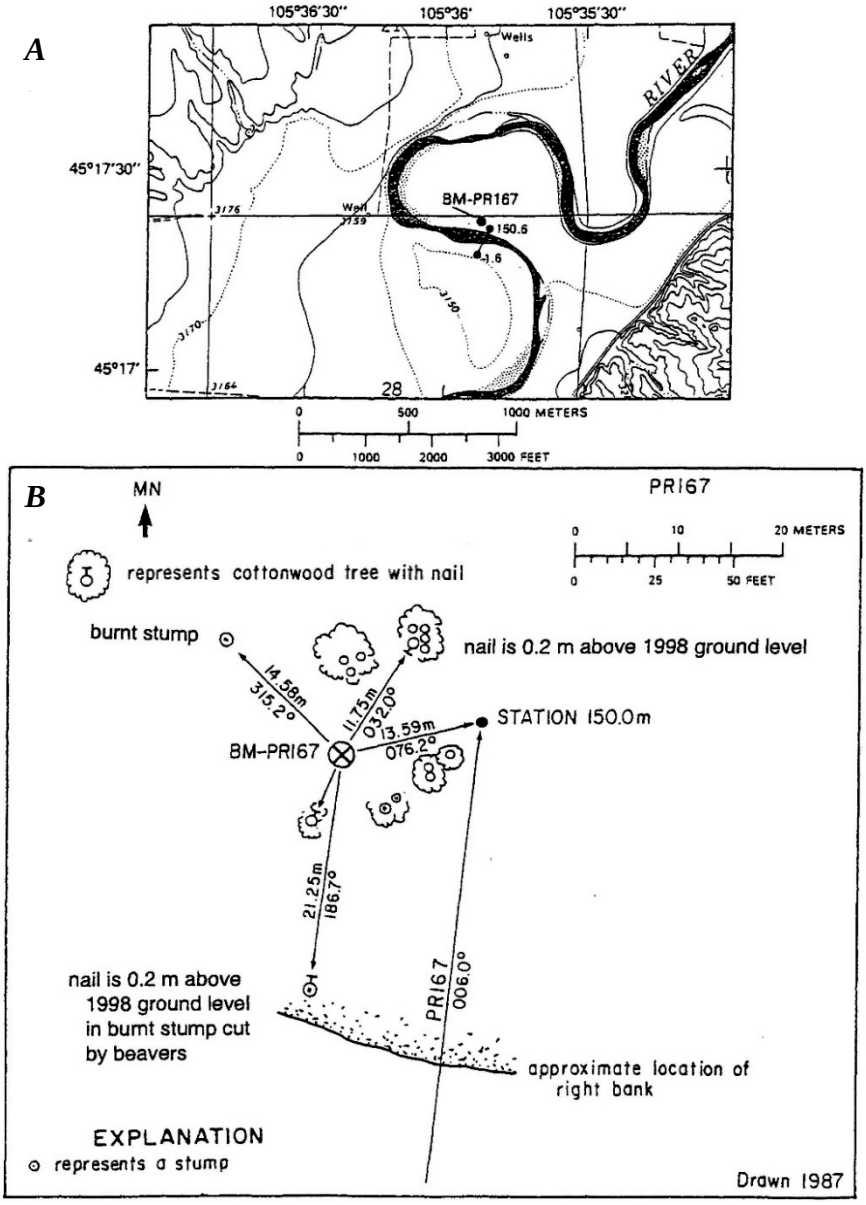

Figure 103. Location maps of cross section PR167. *A*, Location of cross section PR167, bench mark BM–PR167, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Lonesome Peak quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and a reference pin on the right bank. Another reference pin not shown is at station 150.6. The right bank has eroded back 6.4 meters (m) since 1998 so that the stump with nail (at 0.2 m above the 1998 ground level) near the right bank is gone. MN is magnetic north.

The large meander bend that includes section PR167 (fig. 104) has been expanding at its crest at least since the arrival of homesteading settlers in this segment of Powder River Valley more than a century ago (sheet 2 of Martinson and Meade, 1983). During the great flood of 1923 (which is the largest known flood), a house and artesian well on a left-bank Moorcroft-level terrace at the bend crest were undermined by the bank erosion. The bank erosion has continued (moving the left edge of the bend-crest channel at least 100 m leftward since 1923), such that the main channel of Powder River now flows to the left of the old artesian well, and the decapitated well continues to flow, at a rate of a few liters per minute, onto the point bar that has since formed on the inside of the meander bend (Meade and Moody, 2013, p. 25) (fig. 104*B*).

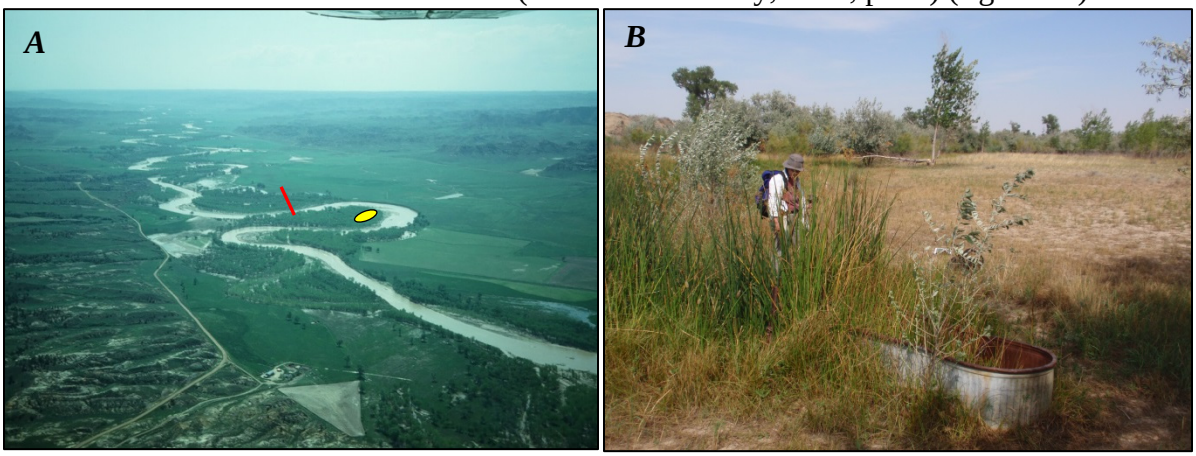

Figure 104. Photographs showing the location of the artesian well near cross section PR167 in 1978 and 2016. *A*, Upriver view taken on May 25, 1978, by B. Ringen of the large meander bend with the red line indicating the approximate line of section. Yellow oval indicates the approximate location of the artesian well in *B*. *B*, View looking downriver. Water from the artesian well collects in the corrugated steel tub and then flows down the point bar approximately parallel to the river direction. Photograph was taken on August 22, 2016. E. Griffin is about 1.5 meters tall.

During the early years of our study, cross section PR167 closely epitomized Luna Leopold's (1994, p. 5) generalization: "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 stable, meaning more or less constant, but the position of the channel is not." This "equilibrium" between erosion and deposition was especially manifested at cross section PR167 during the 1978 flood (fig. 6 [second panel] of Meade and Moody, 2013), when the 2-m-high right-bank Lightning-level terrace (Leopold and Miller, 1954) was eroded laterally some 26 m, displacing about 66 m^3 of terrace material for each meter of channel length, while an equivalent quantity of new sediment was laid in lesser thicknesses of 0.2–0.6 m over a much wider section width (greater than 100 m) onto the point bar, flood plain, and terrace on the left side of the channel (fig. 105).

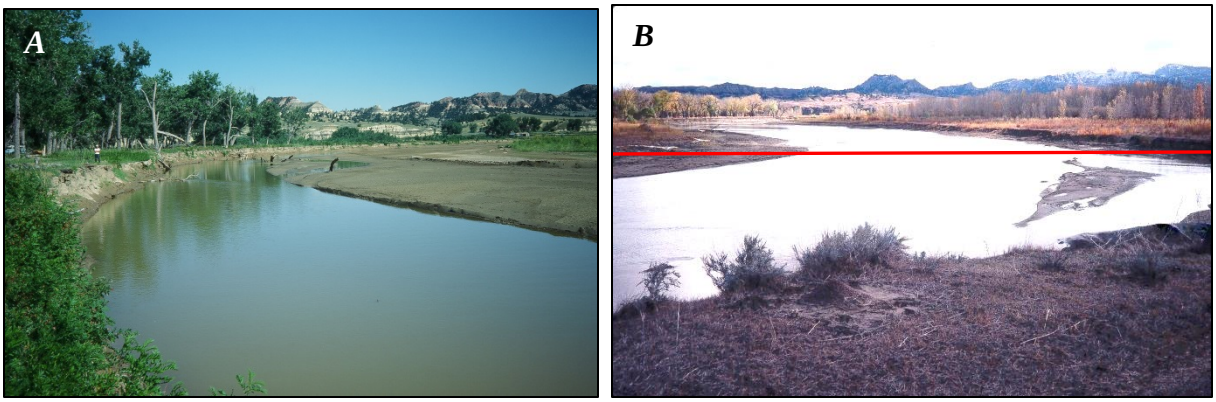

Figure 105. Views of cross section PR167 before and after the flood of 1978. *A*, Upriver view along the right bank was taken of July 13, 1977, and E. Meade (about 1.6 meters tall) is standing on the line of section. *B*, Downriver view taken on October 21, 1979. Left bank has seedlings of Russian olives that sprouted from seeds brought in by the flood of 1978. Red line indicates the approximate line of section.

The neck of the large meander bend that includes cross section PR167 has become progressively narrower, at least since 1939 (the date of the earliest known aerial photographs, which were used in the cartographic compilation of sheet 2 of Martinson and Meade, 1983). This narrowing is most likely due to the progressive erosion of the inner banks of the bend (such as the bank erosion recorded since 1977 at section PR167). We cannot predict whether this bend will eventually be cut off by having its neck width reduced to zero by bank erosion (a "neck" cutoff) or by the upvalley growth of gullies that proceed by headcutting their ways across the neck (a "chute" cutoff). Headcutting gullies formed the cutoff channels at PR122A and PR141A during the 1978 floods, and several such gullies have already headcut themselves part way across the neck of the meander bend that includes section PR167 (fig. 9 of Gay and others, 1998).

Since the early 1990s, however, the shape of the cross-channel profile of section PR167 has altered significantly (see Moody and Meade, 2017, PR167_SciBase2.xlsx for survey data) as the volume of new material that was deposited and accumulated on (and in) the left side of the channel not only exceeded somewhat the volume of material eroded from the right-side cut bank, but also accumulated in such a way as to narrow the width of the low-water channel of the river. The left bank of Powder River at cross section PR167, instead of being a gently sloping surface, as it was formerly, now has a levee (stations 57–67), which was about 1.1 m above the sand bar in 1993 (fig. 106) and in 2014 was about 2 m above the sand bar.

The left bank is now stabilized (as of 2014) by a small but dense thicket of Russian olive (*Elaeagnus angustifolia*) and tamarisk (*Tamarix ramosissima*) trees (fig. 107) that stand 2–4 m tall and extends from station 70 to station 10. From 1998 to 2014 under the Russian olives, no sand was deposited between stations 10 and 25 and about 0.03–0.05 m of sand was deposited between stations 25 and 57.

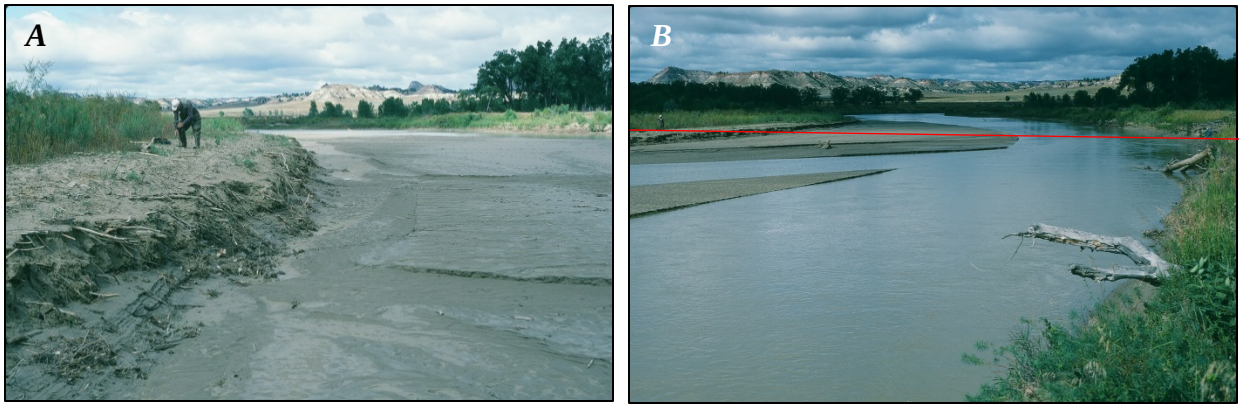

Figure 106. Downriver views of cross section PR167 on September 2, 1993. *A*, New sand deposited on the point-bar levee. J. Pizzuto (about 1.8 meters tall) is standing on the line of section near station 57. *B*. Red line indicates the approximate line of section. J. Pizzuto is standing on the line of section near station 60.

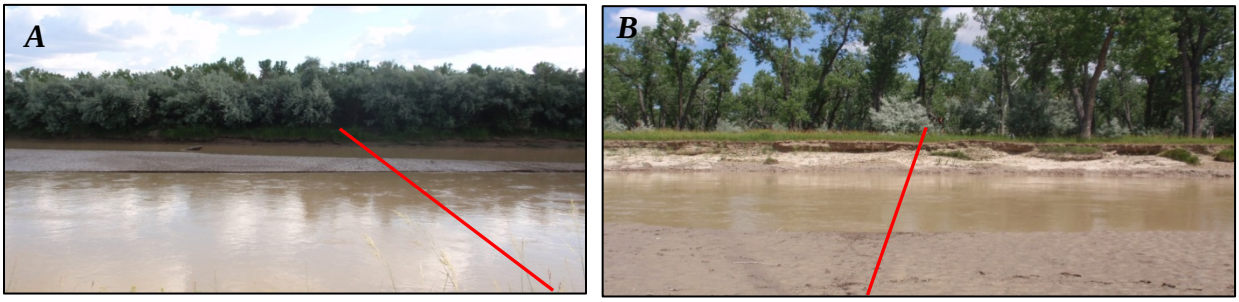

Figure 107. Cross-channel views of cross section PR167 on July 16, 2014. Red lines indicate the approximate line of section. *A*, View shows the left bank with the riverward edge of a 60-m-wide thicket of Russian-olive and tamarisk trees occupying the flood plain from station 10 to station 70 (approximately at the edge of the left bank). These have been trimmed along the line of section forming a narrow tunnel through the thicket. *B*, View shows the right bank with a metal pole and orange flagging that is on the line of section.

This cross section was virtually unchanged by the snowmelt floods in 2015 (May 28, 2015; 280 m^3/s; 6 June 6, 2015; 283 m^3/s). About 1 m of the right bank was eroded, and only about 0.2 m of sediment was deposited on the left-bank point-bar levee between stations 57 and 64. Minimal sediment (less than 0.05 m) was deposited among the Russian olive and tamarisk trees in the thicket on the left bank flood plain. Sediment cores were collected for dating the 2.5-m Lightning-level terrace on the right bank by OSL from three locations (0.5, 1.0, and 1.7 m below the top of the right bank) in a vertical profile (fig. 108).

Figure 108. Views of the vegetation and right bank of cross section PR167 on October 1, 2015.
A, Photograph taken by Deborah Martin of the typical size of mature cottonwood trees (*Populus sargentii*) that are growing on a Lightning-level terrace along the right bank, which was at station 132 in 2015.
B, Upriver view along the right bank standing on the line of section. Top of the right bank (Lightning-level terrace) was at station 132 with an elevation of 959.8 meters (m) above the National Geodetic Vertical Datum of 1929 (NGVD 29) in 2015. Water level elevation was 957.3 m above NGVD 29. Optical stimulated luminescence (OSL) sediment cores were collected 7.4 m downriver from station 132.

PR175 Narrative

Cross section PR175 was established near the crest of a point bar with convenient access to the left bank from the nearby road (fig. 109). It was established in 1977 and resurveyed each year through 1998, but not in 1981 or 1983 (table 1; also see Moody and Meade, 2017, PR175_SciBase2.xlsx for survey data).

The cut bank was on the left bank, but during the 1978 flood the river first eroded 7 m into this cut bank, then cut across the inside of the point bar, perhaps starting in an old chute channel between stations 133 and 143 (fig. 110), and left a new cut bank at station 178. Probably during the waning stages of the 1978 flood, the river filled in the old channel leaving an average of about 1 m of newly deposited sand spread across more than 100 m (see fig. 7 of Meade and Moody, 2013).

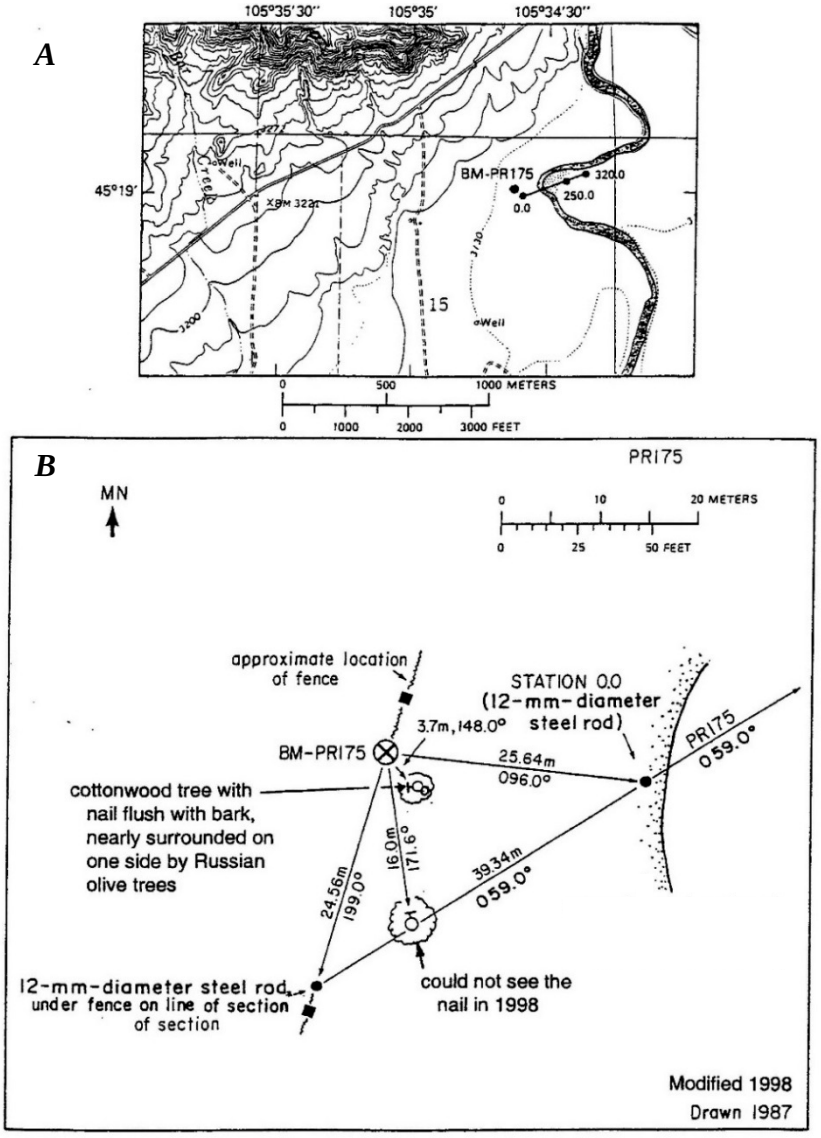

Figure 109. Location maps for cross section PR175. *A*, Location of cross section PR175, bench mark BM–PR175, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Lonesome Peak quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and the 0.0 reference pin on the left bank. MN is magnetic north.

The cutoff and the new sand provided two interesting stories at PR175. The first story was channel migration. After moving the cut bank about 170 m toward the right bank during the 1978 flood, the river almost immediately began to erode the new cut bank back towards the left side of the channel. The action then shifted to the right bank, which was built up as a series of bars that were intermittently deposited and eroded from 1984 through 1995. By 1995, a predominant right bank had been built such that the top of the bank lay at about the same elevation as the top of the left bank.

Figure 110. Aerial view of cross section PR175 on May 25, 1978. This view upriver towards the southwest was taken by B. Ringen about 1 week after peak flow during the flood of 1978. Red line shows approximate line of section at bank-full elevation. The left cut bank of the preflood (1977) channel shows on the upper right section of the photograph. The channel newly formed by the flood of 1978 is shown flowing between the emerging sandbar in the left center of the photograph and the nearly submerged sandbars in the right center of the photograph.

The second story was vegetation succession. The top of the locally 2-m-thick layer of new sand deposited by the flood of 1978 (fig. 111) provided an ideal surface for the germination of cottonwoods whose growth could be monitored during each succeeding cross-sectional survey of PR175.

Plots were established in 1979 and measurements of were made of the heights and densities of seedlings of willows and cottonwoods (fig. 112). These measurements were repeated in 1980, but by 1982 Russian olives had germinated and were already crowding out the native vegetation. The native vegetation study was abandoned.

Figure 111. Photograph of sand deposited during the flood of 1978 at cross section PR175. This deposit is on the left bank about 23 m downriver from station 176. Photograph was taken on August 11, 1979.

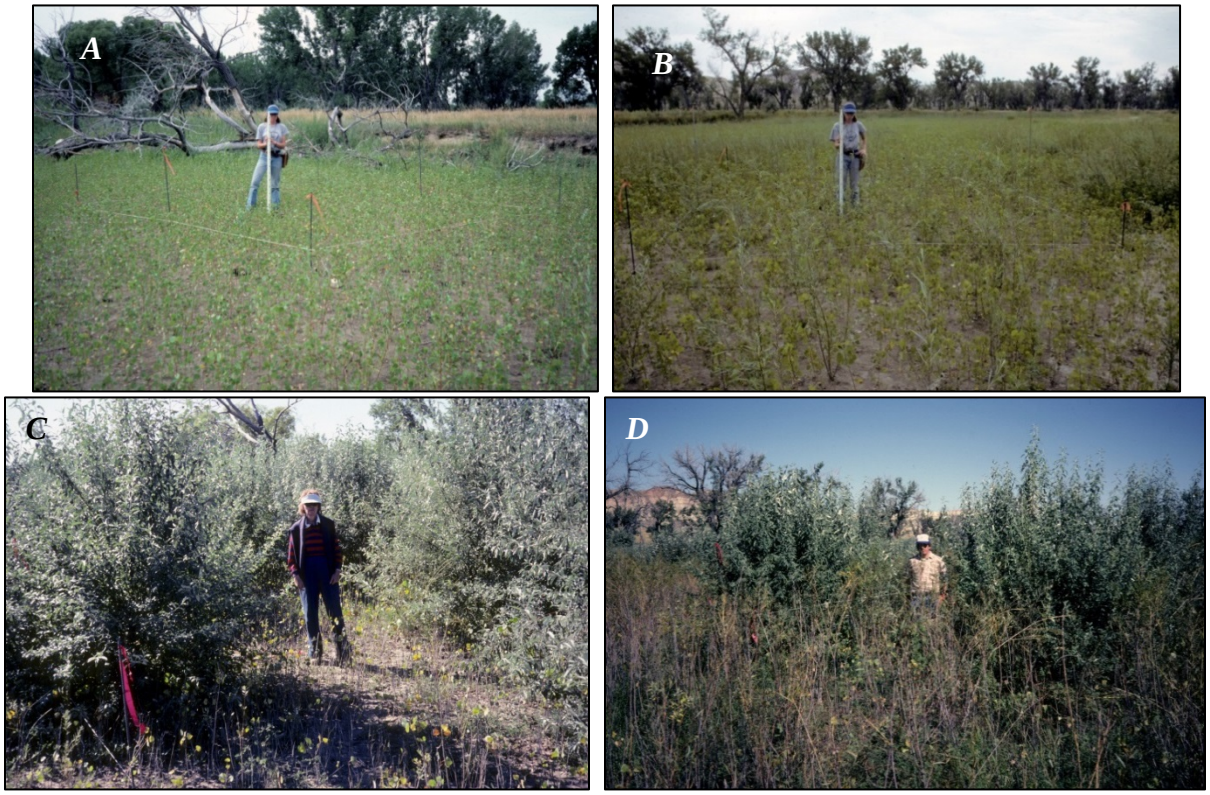

Figure 112. Series of photographs showing the changes in vegetation at cross section PR175 after the flood of 1978. *A*, August 20, 1979. View showing the vegetation from station 17 to 22. View is to the southwest and obliquely upstream. H. Martinson is about 1.6 meters (m) tall. *B*, August 20, 1979. View showing the vegetation from station 34 to 39. View is towards the north and downstream. H. Martinson is about 1.6 m tall. *C*, September 19, 1982. View showing the vegetation from station 17 to 22. View is to the southwest and obliquely upstream. S. Stewart is about 1.7 m tall. *D*, September 19, 1982. View showing the vegetation from station 34 to 39. View is towards the north and downstream. M. Karlinger is about 1.8 m tall.

PR180 Narrative

Cross section PR180 was established in 1977 a short distance downriver of the crossover point between two prominent meander bends in Powder River, about 25 km upriver of the Highway 212 bridge at Broadus (figs. 1 and 113). The cross section was resurveyed every year until 2002 except for 1981 and 1983 and then again from 2013 through 2016 (table 1; also see Moody and Meade, 2017, PR180_SciBase2.xlsx for survey data).

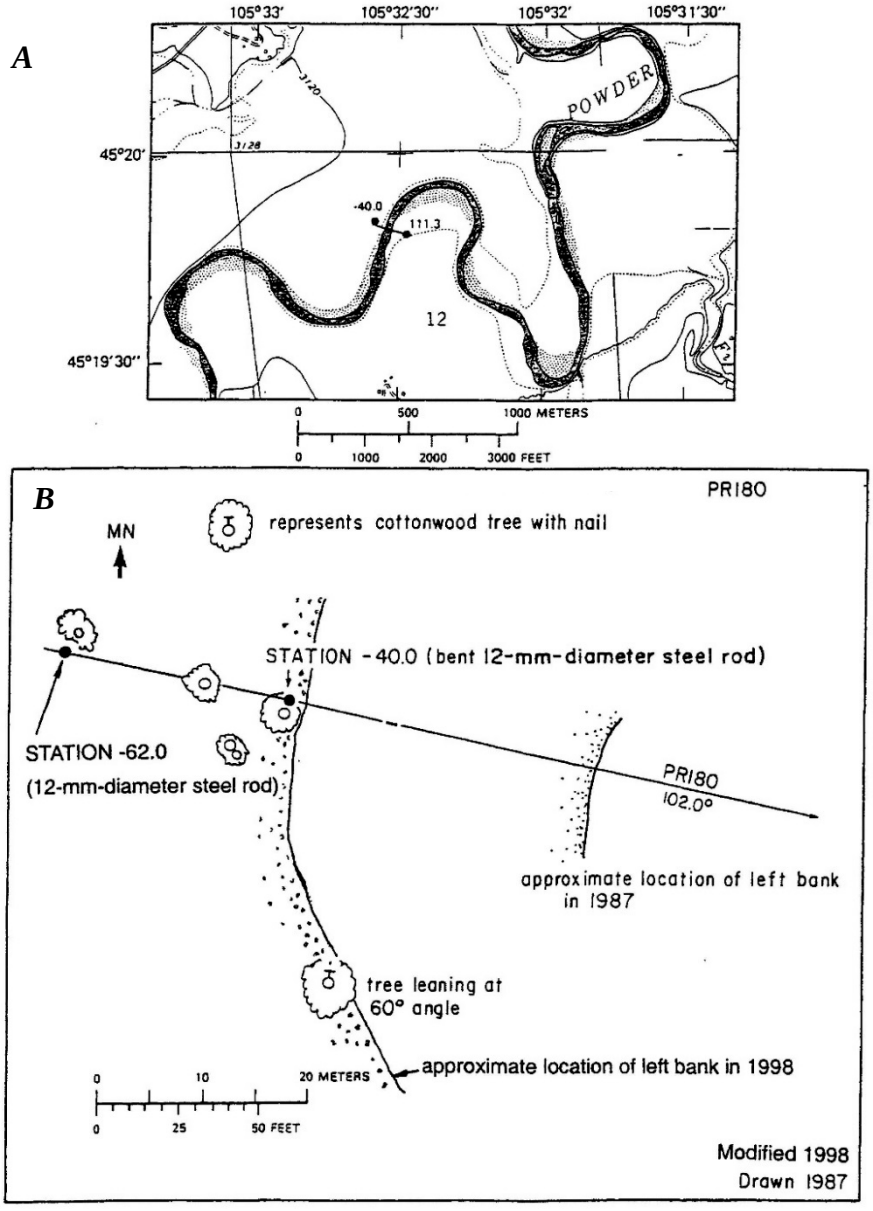

Figure 113. Location maps for cross section PR180. *A*, Location of cross section PR180, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Lonesome Peak quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of some reference pins on the left bank. The bench mark was removed by erosion in 1997, and the reference pin at -40.0 was removed by the river in 2000. A reference pin was put in at station -50.0 in 2001 and at station -103.5 (under a fence line) in 2014. MN is magnetic north.

The cross-sectional shape of PR180 is typical of curved river reaches worldwide in that a prominent and active cut bank in a 3-m high Moorcroft-level terrace (Leopold and Miller, 1954; Moody and Meade, 2008) on one side (left, in this instance) faces a gently sloping point bar on the other side (figs. 114 and 115).

Figure 114. Aerial view of cross section PR180 on May 25, 1978. This downriver view was taken about 1 week after peak flow during the 1978 flood by B. Ringen. Red line shows approximate line of section at bank-full elevation.

Figure 115. Views of cross section PR180 on July 15, 1977. *A*, View is upriver. E. Meade (about 1.6 meters [m] tall) is standing on the line of section. *B*, View is downriver. E. Meade and tripod are on the line of section.

Likely owing to its location at the time near the planimetric crossover point between two meanders (fig. 114), the cross section at PR180 was changed relatively little during the flood of 1978. There was less than 2 m of lateral cut bank erosion, and a thickness of 0.2–0.8 m of new sediment was deposited atop some 30-m width of the right-side flood plain. See the upper panel of figure 18 of the report by Meade and Moody (2013), and compare the magnitudes of the flood-induced changes with those shown for other active cross sections in figures 17 and 19 of the same report.

During the two decades following the flood of 1978, however, cross section PR180 was among the most actively changing of those we were monitoring regularly. While the general two-dimensional shape of the cross section remained more or less constant (in the “classic” manner, as described by Leopold, 1994, p. 5), the section itself was laterally translated many tens

of meters to the left. From 1978 through 1997, the left-side cut bank (fig. 116) retreated 49 m, with the greatest annual increments during 1984 (5.4 m), 1986 (6.0 m), 1987 (4.9 m) 1991 (8.6 m), 1993 (4.5 m), 1995 (4.3 m), 1996 (2.9 m), and 1997 (2.8 m).

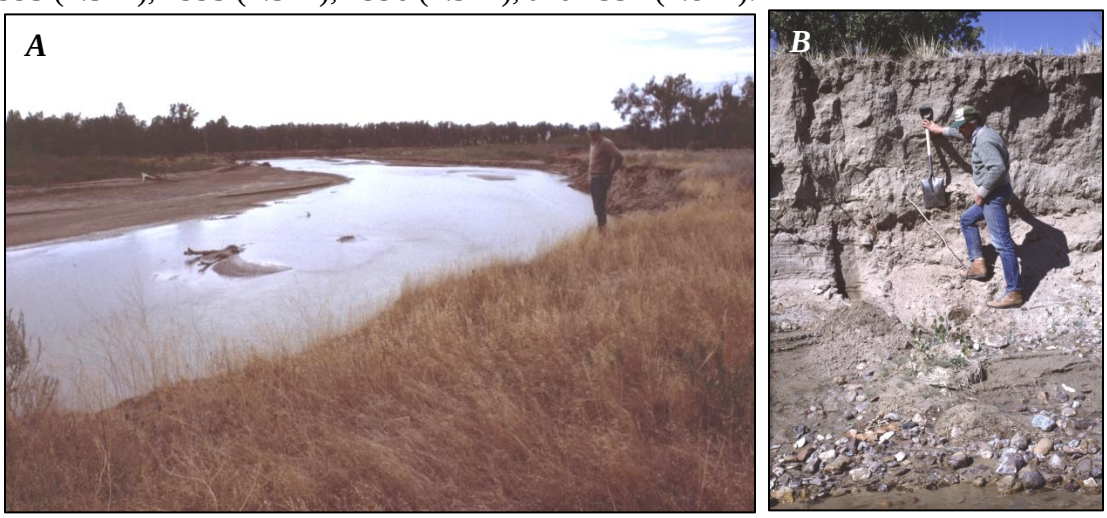

Figure 116. Views of cross section PR180 on August, 21, 1986. *A*, Upriver view shows J. Moody (about 1.9 meters [m] tall) standing at station -5.0. *B*, View is of the left bank (Moorcroft-level terrace) about 5 m upriver from the cross section. Shovel tip is at the contact where older overbank sediment (not from the flood of 1978) overlies even-older point-bar sediment.

During the same two decades, the point bar and flood plain on the right bank received new deposits of sediment in cumulative thicknesses of 1–2 m across a width of some 60 m. See the lower panel of figure 18 of the report by Meade and Moody (2013). Most of this new accumulation was deposited during 3 years: 1991, 1993, and 1995 (fig. 117).

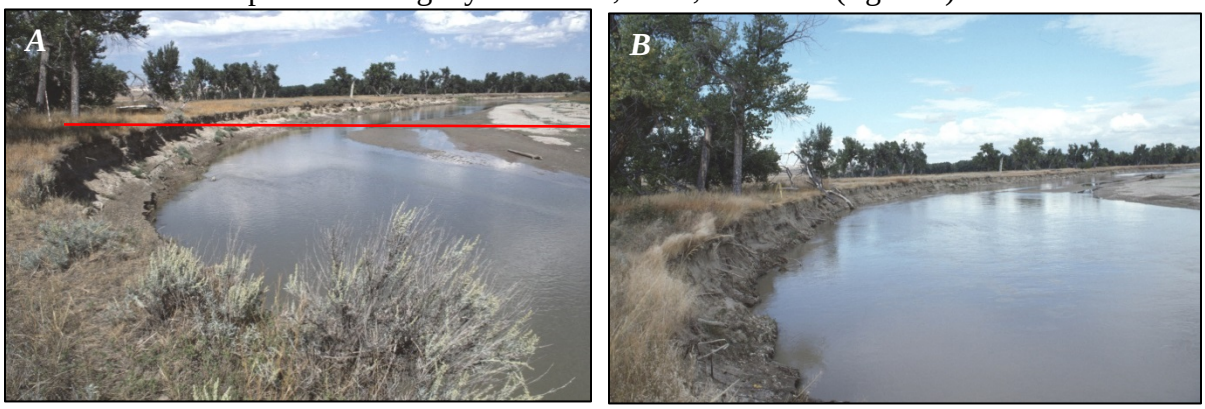

Figure 117. Views of the left bank of cross section PR180 in 1994 and 1995. A, Downriver view was taken on September 18, 1994, with the red and white survey rod approximately on the line of section. Red line shows the approximate location of the line of section at bankfull elevation. B, Downriver view was taken on September 30, 1995, and the yellow tripod is approximately on the line of section. The left bank was eroded about 4 meters laterally during the year between the 1994 and 1995 photograph dates.

Channel changes at cross section PR180 have slowed considerably since 1997. During 1997–2014, the left-side cut bank retreated only 5.2 m—a 17-year total quantity of bank erosion that was exceeded during the individual years 1984, 1986, and 1991 (fig. 118). Cumulative new

deposition on the right-bank point bar also decreased: since 1997, 0.1–0.6 m of new sediment was deposited across a flood plain width of some 25 m.

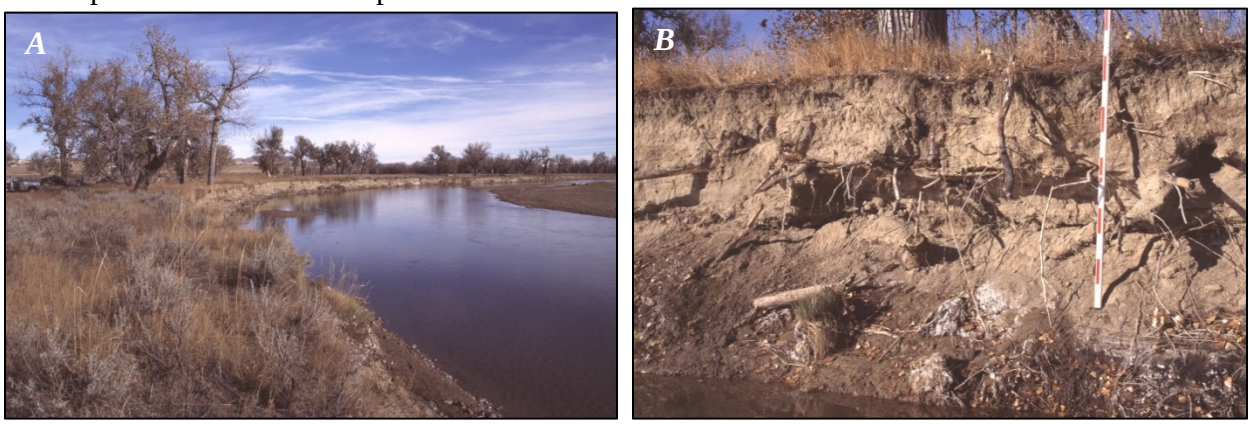

Figure 118. Views of cross section PR180 on October 22, 1996. A, View is downriver and the line of section passes just upstream from the two prominent trees near the left bank. Same two trees can be seen in photographs on September 18, 1994, and September 30, 1995 (fig. 117). Left bank has eroded about 3 meters (m) since September 1995. Tripod is not on the line of section. B, Survey rod is at station -38.0, and each rod division is 0.2 m. Top of left bank (Moorcroft-level terrace, elevation 949.8 m above the National Geodetic Vertical Datum of 1929) is 2.7 m above the water level and 3.3 m above the thalweg adjacent to the left bank.

The changes to cross section PR180 since 1978 reflect the multidecadal passage of a planimetric meander crest through the cross section. The erosion at cross section PR180 took place on the left bank (fig. 119), and the leftward-eroding meander bend was downriver of the 1978 section (fig. 114), thus this planimetric meander crest appears to have migrated upvalley.

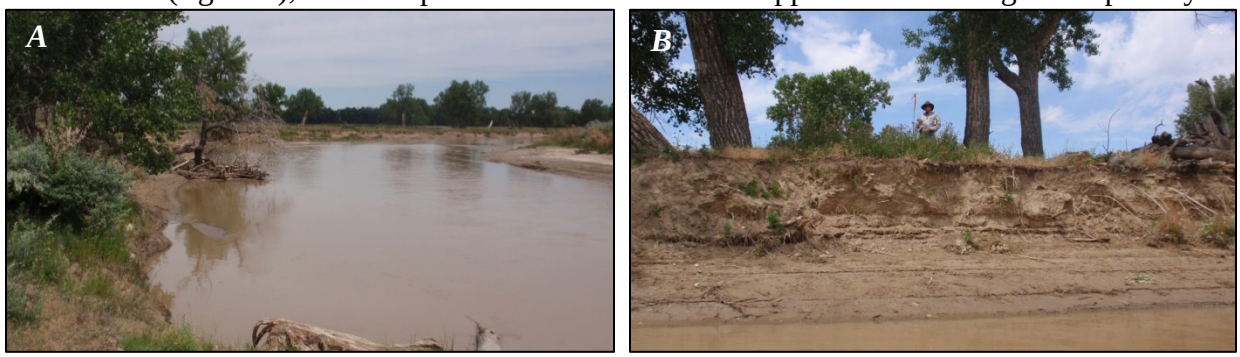

Figure 119. Views of cross section PR180 on July 15, 2014. A, Downriver view is along the left bank showing the active eroding bank downriver from cross section PR180. The point bar can be seen on the right edge of the photograph. B, A range pole is to R. Meade's right (about 1.8 meters tall) on the line of section on the left bank.

High water during the two snowmelt floods in 2015 was not bank full. The two peak discharges on May 28, 2015 (280 m^3/s) and June 6, 2015 (283 m^3/s) were estimated to be about 0.8 m below the top of the left bank (fig. 119*B* and 120*A*), but floodwaters flowing over the right bank deposited a layer of sand, which was about 0.5 m thick closest to the channel (station 28.0) and tapered in thickness away from the channel to about 0.1 m at station 72.0, where a thicket of Russian olives and tamarisk begins. There was virtually no deposition within the thicket even though there was evidence of floodwaters in the thicket. The point bar at PR180 has had sufficient deposition over the years that it is now elevated and is transitioning into a flood plain.

Four sediment cores were collected for dating the Moorcroft-level terrace (Leopold and Miller, 1954) by OSL along a vertical profile 3 m downriver of the line of section (within the yellow rectangle in fig. 120*A*).

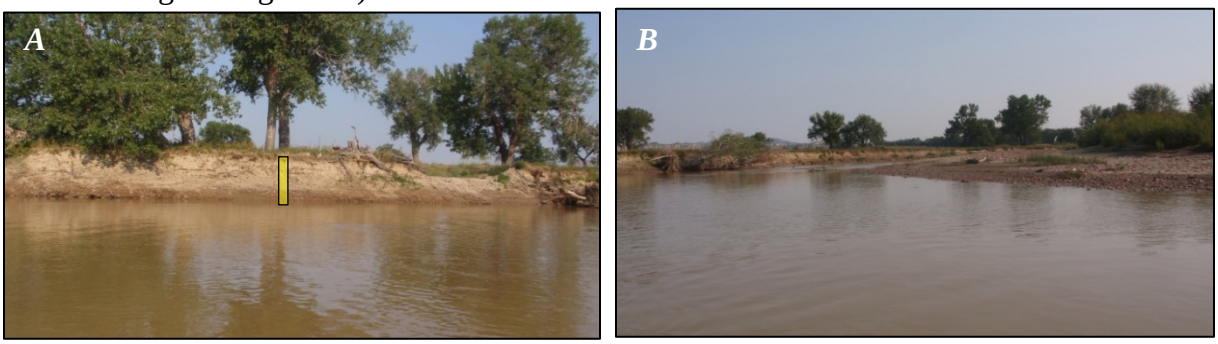

Figure 120. Views of cross section PR180 on August 24, 2015. *A*, View is from the right bank point bar towards the left bank. Top of the left bank (Moorcroft-level terrace) is at an elevation of 949.8 meters above the National Geodetic Vertical Datum of 1929. The yellow rectangle indicates the approximate location of four sediment cores collected for dating by optical stimulated luminescence. *B*, Downriver view shows the gravel covered point bar on the right side of the photograph.

PR183 Narrative

Cross section PR183 was established in 1977 about 160 m upriver from a high bluff (fig. 121). The cross section was resurveyed every year until 1998 except for 1981 and 1983 and then again from 2014 through 2016 (table 1; also see Moody and Meade, 2017, PR183_SciBase2.xlsx for survey data).

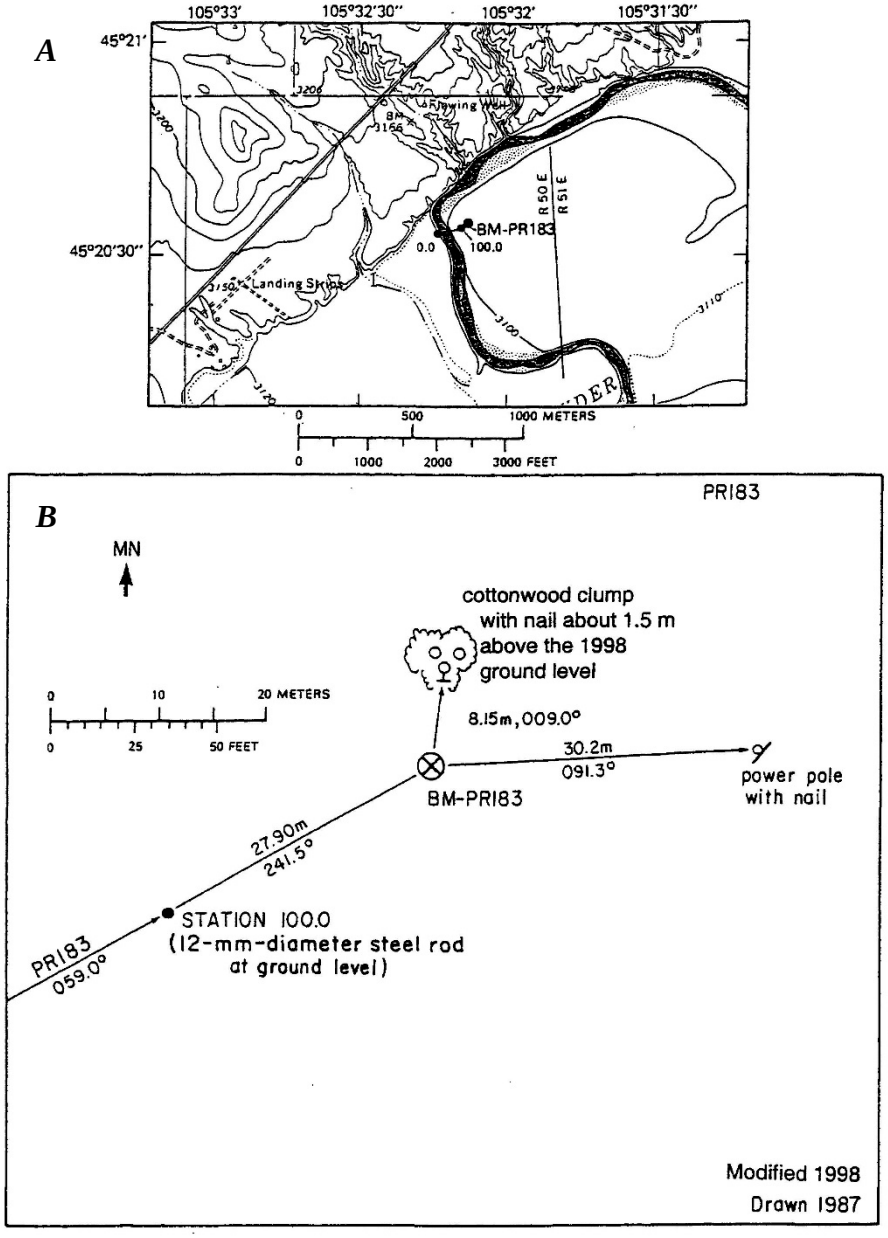

Figure 121. Location maps for cross section PR183. *A*, Location of cross section PR183, bench mark BM–PR183, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Lonesome Peak quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of bench mark and some reference pins on the right bank. An additional reference pin is a station 101.1 on the right bank. MN is magnetic north.

During the flood of 1978, the cut bank on the right side at section PR183 was widened by some 3 m of lateral erosion and by the removal of nearly 1-m thickness of the left-side flood plain or point bar across some 20-m width of channel (fig. 122*A*). Also see figure 5 of Meade and Moody (2013).

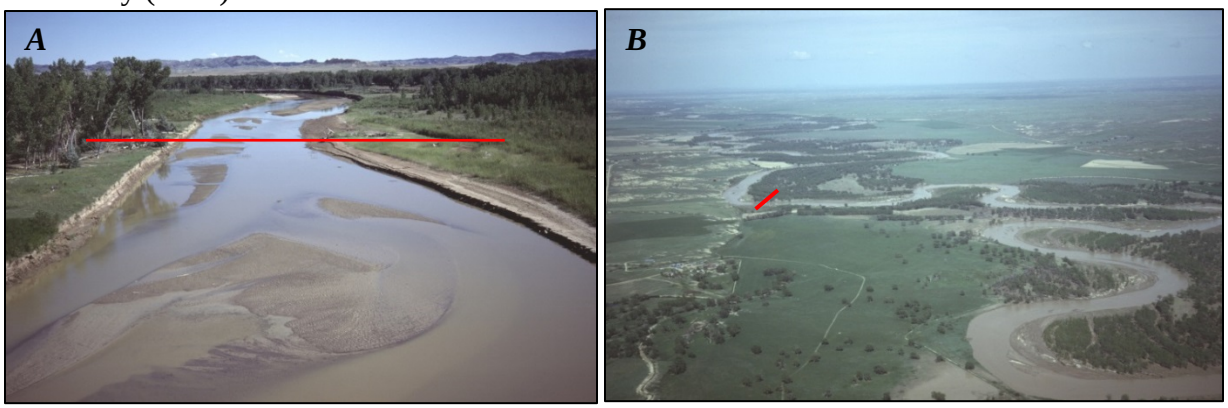

Figure 122. Aerial views of cross section PR183 in 1977 and 1978. *A*, Upriver view taken on July 15, 1977, from the bluff. Red line shows approximate line of section at bank-full elevation. *B*, Downriver view was taken about 1 week after peak flow during the flood of 1978 on May 25, 1978, by B. Ringen. Red line shows approximate line of section at bank-full elevation.

Channel changes since 1978 at section PR183 have been minimal (fig. 123). The right-side cut bank has been eroded laterally only about 2 m during the 36-year period, 1978–2014 (less than the lateral erosion during the 2 weeks of the 1978 flood). And the old preflood segment of flood plain that was removed in 1978 has been incrementally "reinstated"—mostly during 1982, 1987, 1993, 1995, and 2008 between cross-channel stations 30 and 45. Areas of deposition in the channel often became areas of erosion on the following year, and areas of erosion one year were refilled with new sand the following year (fig. 123).

The most significant change has been the growth of Russian olives and tamarisk. These shrubs and small trees have populated mostly the left-bank flood plain (fig. 123), but Russian olives are scattered also on the right bank (fig. 124). Snowmelt floods in 2015 (May 28, 2015, 280 m^3/s; June 6, 2015, 283 m^3/s) did not cause any significant erosion, and only deposited about 0.1 m of sand among the thicket of Russian olive and tamarisk on the left bank (fig. 125).

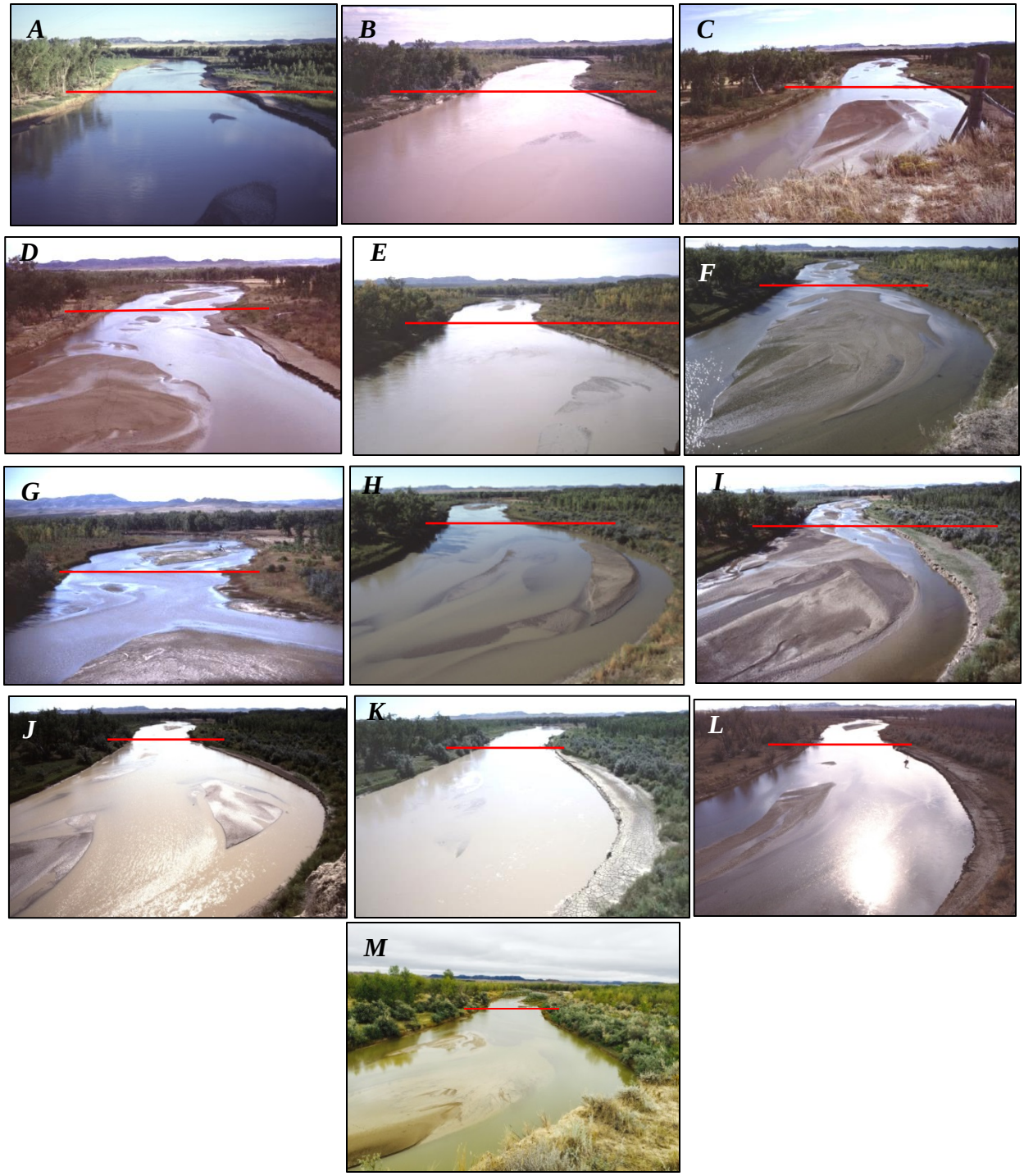

Figure 123. Time series of photographs of cross section PR183. Photographs were taken from the same point on a bluff looking upriver. A thicket of Russian olive (*Elaeagnus angustifolia*) and tamarisk (*Tamarix ramosissima*) trees develops along the left bank flood plain in this series of photos. Red lines indicate the approximate line of section. *A*, August 9, 1978. *B*, September 25, 1982. *C*, September 13, 1984. *D*, August 21, 1986. *E*, September 26, 1987. *F*, September 22, 1988. *G*, September 23, 1989. *H*, September 22, 1990. *I*, September 2, 1991. *J*, August 28, 1992. *K*, August 31, 1993. *L*, October 22, 1996. *M*, October 4, 2015.

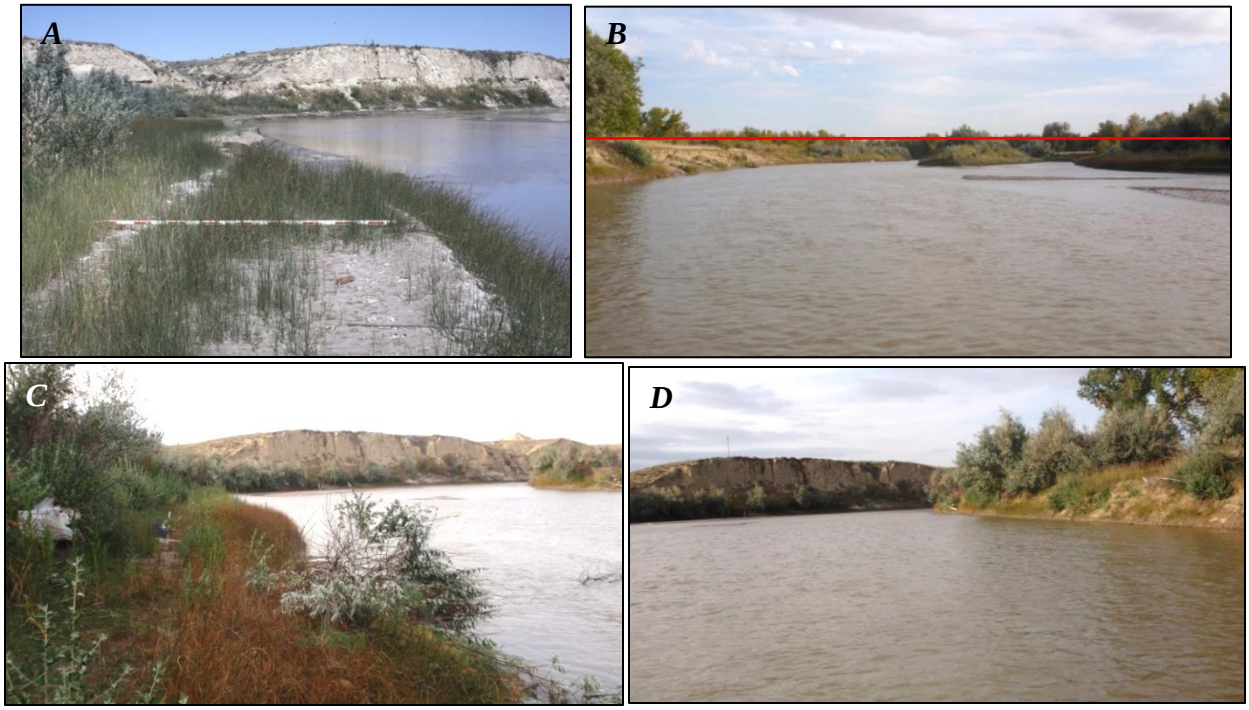

Figure 124. Views of cross section PR183 in 1993 and 2014. *A*, Downriver view taken on August 28, 1993. Notice the size of the Russian olive growing on the left bank. Red and white surveying rod is lying on the line of section. Divisions on the rod are 0.20 meter (m). Photographic point for time series of upriver views (fig. 123) since 1977 is at the most prominent solitary fencepost on the skyline (the same fence post that is shown in the foreground of the upriver view of September 13, 1984, fig. 123*C*) at the edge of the bluff. *B*, Upriver view taken on September 27, 2014, shows Russian olives colonizing an island. Red line indicates the approximate line of section at bankfull elevation. *C*, Downriver view along the left bank taken September 27, 2014. Russian olives branches in the river are just downriver from the line of section. *D*, Downriver view along the right bank taken on September 27, 2014. Russian olive trees have grown to heights of 3–4 m since their germination after the flood of 1978.

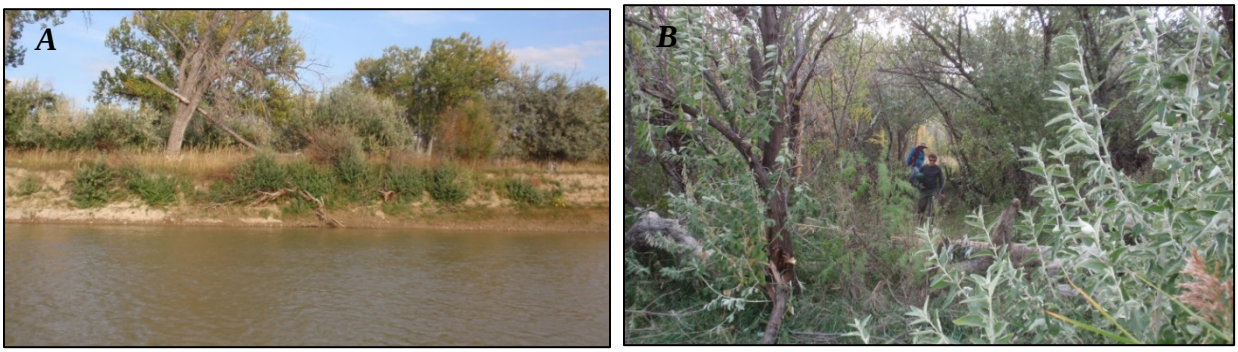

Figure 125. Views of the vegetation at cross section PR183 on September 27, 2014. *A,* View was taken from the left bank looking at the right bank. Cross section passes just upriver of the large cottonwood (*Populus sargentii*) tree in the left-center side of the photograph. *B,* A view taken from the right bank shows the cross section going through a tunnel cut through the Russian olive and tamarisk trees on the left bank.

PR191 Narrative

Cross section PR191 was established in 1977 and is situated in the crest area of a wide bend in Powder River (fig. 126). The section was resurveyed, every year or two, from 1978 through 1998. After a 16-year hiatus, section PR191 was resurveyed in 2014, 2015, and 2016 (see Moody and Meade, 2017, PR191_SciBase2.xlsx for survey data).

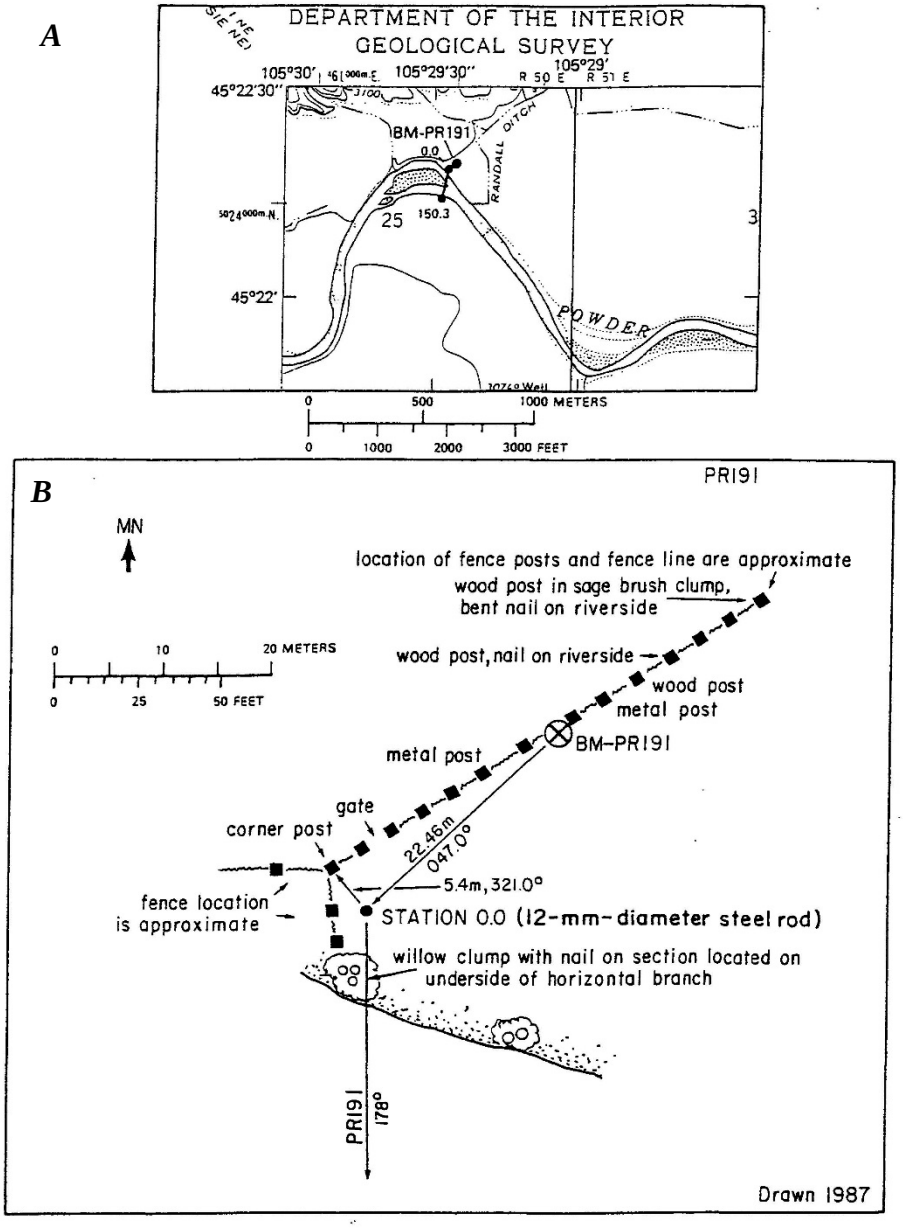

Figure 126. Location maps for cross section PR191. *A*, Location of cross section PR191, bench mark BM–PR191, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Eldon Mountain quadrangle. *B*, Location of bench mark and some reference pins on the left bank. MN is magnetic north. The horizontal branch of the willow tree with the nail is gone. There is a pin at station -0.4, and in 2014 a new pin was added at station 45.0.

The cross section location was suggested by the resident rancher and, thus, was near a pump site (fig. 127) used to irrigate alfalfa meadows. For this reason, the cross section may not be entirely representative of the behavior of an unengineered river. Remnants of old automobile bodies (fig. 128) that the rancher had placed earlier as riprap on the bank of the river to inhibit erosion at the pump site are, as of 2014, in midriver, mostly covered by sand, some 100 to 200 m downriver of cross section PR191.

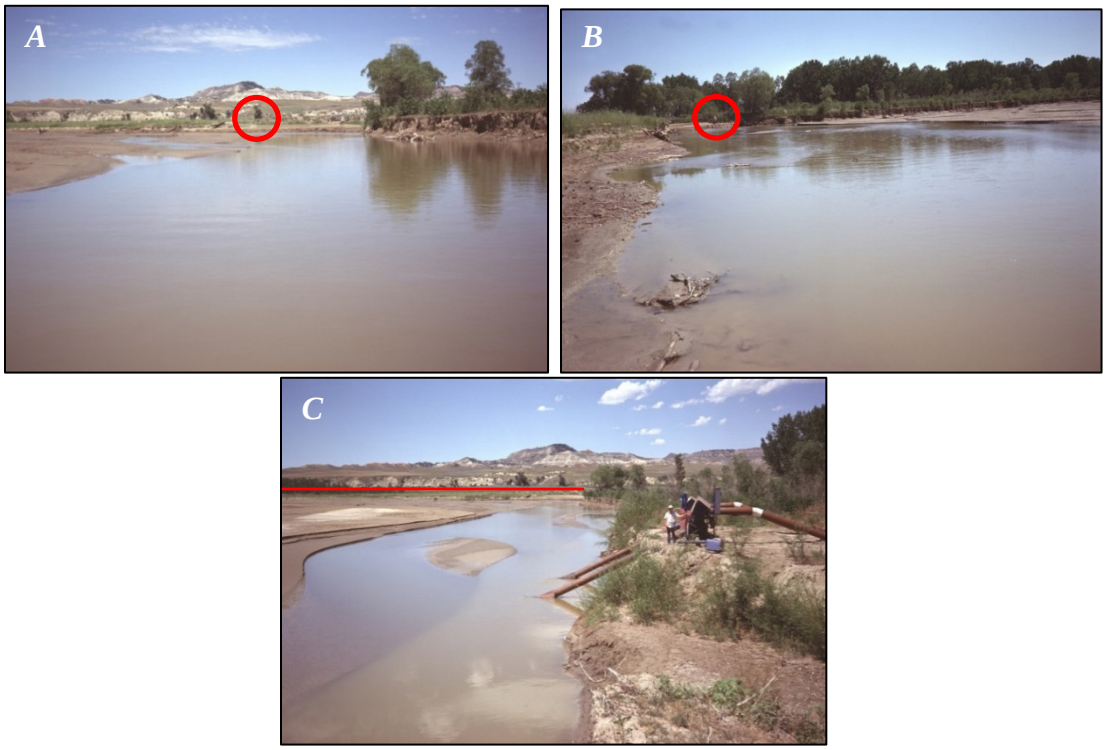

Figure 127. Views of cross section PR191 on July 16, 1977. *A*, View is upriver and E. Meade (about 1.6 meters [m] tall, inside the red circle) is standing on the line of section. *B*, View is downriver, and E. Meade (inside the red circle) is standing on the line of section. *C*, View is upriver. Intake for the Randall irrigation ditch is downstream from cross section PR191, whose approximate location is indicated as a red line at bank-full elevation.

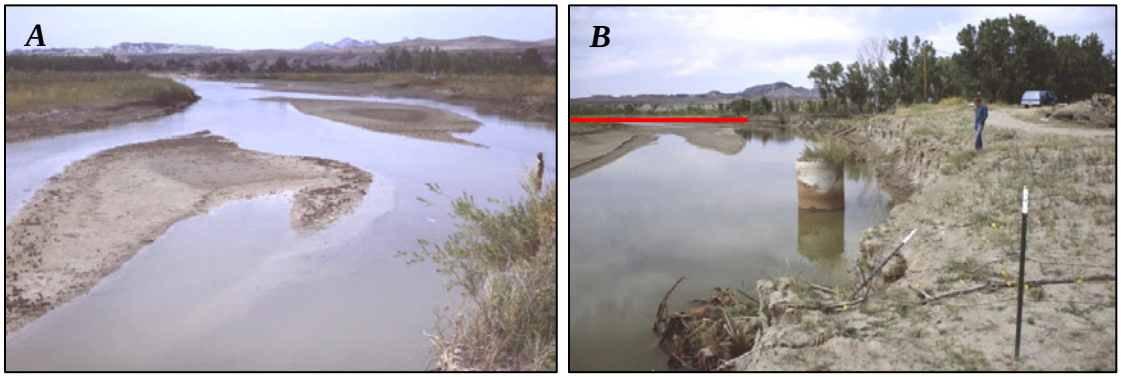

Figure 128. Upriver views of cross section PR191 on September 17, 1988. *A*, Cross section PR191 crosses the upstream end of second sandbar. *B*, Vertical culvert exposed by 1988 bank washout. Remnants of auto bodies in the lower left hand corner of the photo. Red line shows the approximate location of the line of section at bankfull elevation.

During the flood of 1978, the channel thalweg at section PR191 was shifted 56 m to the right (see fig. 7 of Meade and Moody, 2013) to form a minor cutoff channel inside this bend of Powder River. Flood plain reconstruction also began at that time, presumably during the late stages of the flood, and certainly after most of the rightward channel shift had taken place. On the left side, the old preflood channel became new flood plain as 0.5–0.8-m thicknesses of new sand were deposited across a width of some 40 m of the section. On the right side, 0.3- to 0.6-m thicknesses of new sediment were laid on top of a 30–35-m width of older point-bar and flood plain materials. Across the wide bend of Powder River at this location, the 1978 flood waters left overbank deposits of sand, silt, and mud 0.10–0.20 m thick, as far south as station 580 (fig. 7 of Moody and Meade, 2008).

Since 1978, the location of this cutoff channel has been stabilized by successive depositions (most prominently during 1982, 1993, 1995, and, probably, 2008) of new sediment that augmented the flood plains of both its banks. Between 1978 and 1995, a total thickness of approximately 1 meter of new sand and mud was deposited across a 40–45-m width of the left-side flood plain (fig. 129), while half-meter thicknesses of new sand were deposited across a 30–35-m width of the right-side flood plain. Because the right bank of the channel (the inner edge of the channel bend) has been maintained as a cut bank, no point bars have been deposited here during at least the last 36 years.

Figure 129. Upriver view of cross section PR191 along the left bank on September 30, 1995. Red-colored sedge (*Scirpus* spp., Moody and others, 1999) indicates the approximate elevation of bed-full flow (about 12 cubic meters per second).

During the 16-year period, 1998–2014, the changes to cross section PR 191 have been a channel-widening, 7-m lateral erosional shift of the right-side cut bank, and the further deposition of 0.1 to 0.2 m of new sediment atop the left-side and right-side flood plains (fig. 130).

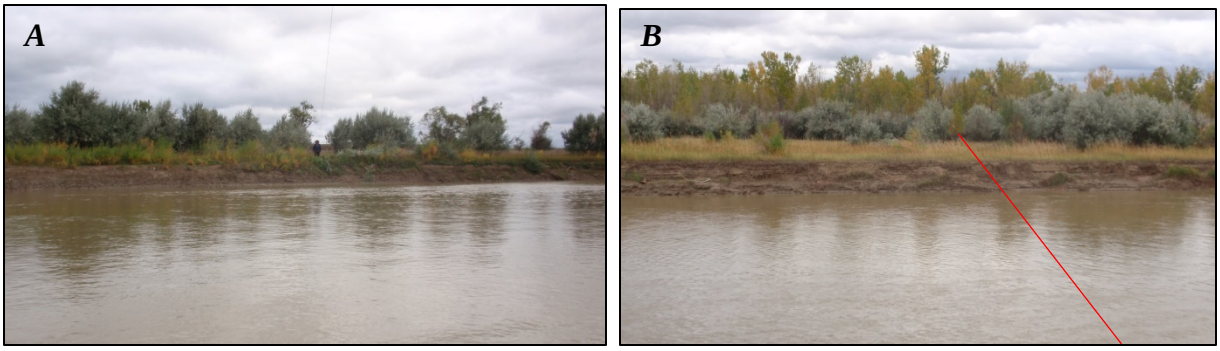

Figure 130. Views of cross section PR191 on October 1, 2014. *A*, View is of the left bank with R. Meade (about 1.8 meters tall) standing over the tagline on the line of section. *B*, View is of the right bank with Russian olives trees in the middle ground and cottonwood (*Populus sargentii*) trees in the background. Red line indicates the line of section.

In 2015, the snowmelt floods (May 28, 2015, 280 m^3/s; June 6, 2015, 283 m^3/s) made substantial changes at PR191. A new layer (about 0.1 m thick) of mostly mud was deposited on the left-bank flood plain (station 12 to 53; fig. 131*A*), and a sandbar, 1 m thick at most stations, was deposited adjacent to the left bank from about station 57 to 80 (fig. 131*B*). The right-bank was eroded back 9 m (fig. 131*C*), lee dunes (0.1–0.2 m high) were deposited downriver from tamarisk and Russian olive trees near the edge of the right bank (stations 120 to 137), and a tapering layer of sand (0.1 m to 0 m) was deposited among grasses in an area with no trees (stations 137 to 152; fig. 131*D*).

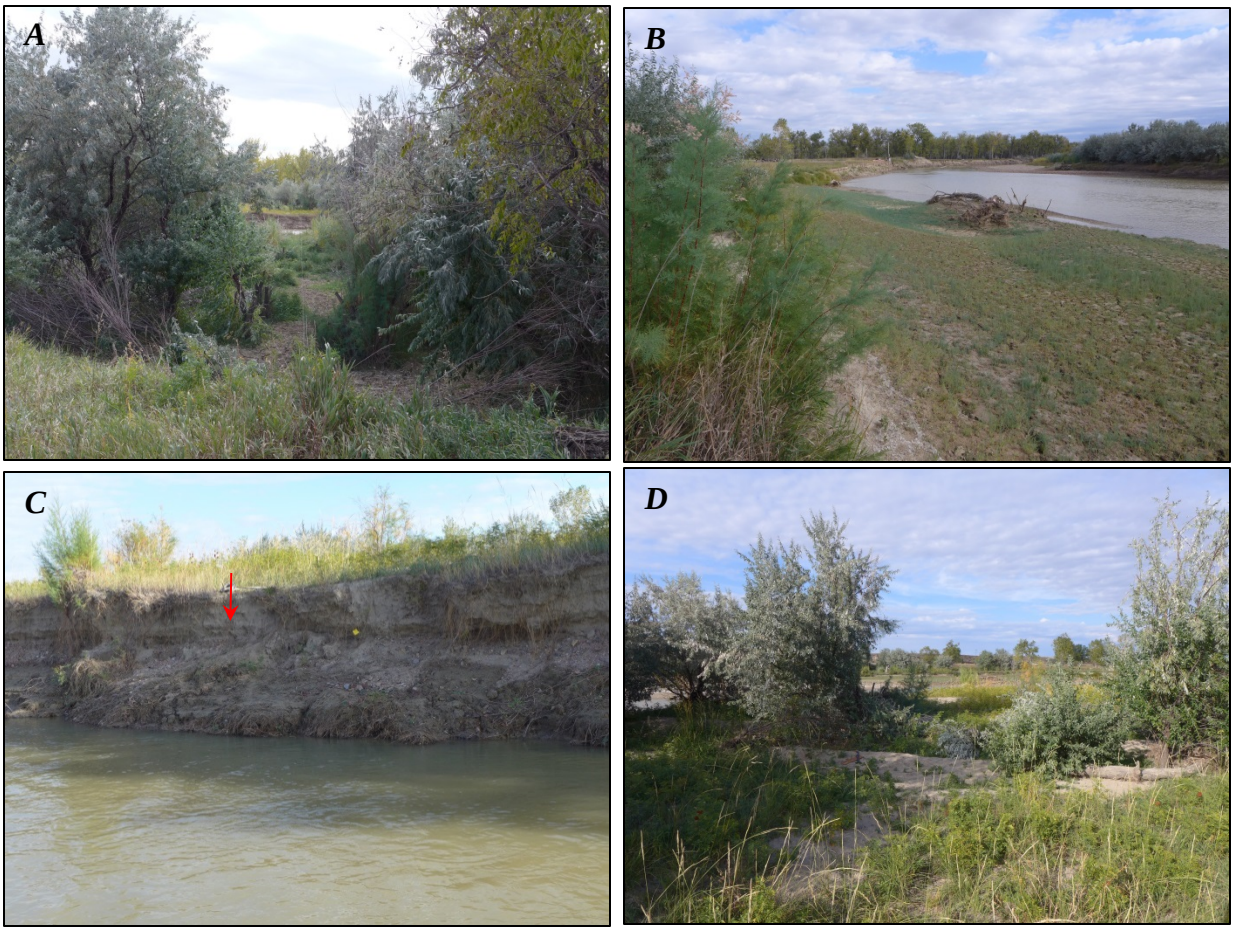

Figure 131. Views of cross section PR191 on September 28, 2015. *A*, View southward along the line of section (from about station 8 through a cut made in the Russian olive trees) shows some of the new mud on the left-bank flood plain from about station 12 to 53. *B*, View is downriver showing a new sandbar deposited adjacent to the left bank. The sandbar is covered with new tamarisk (*Tamarix ramosissima*) seedlings. *C*, Downriver view of the right bank. The elevation at the top of the bank near the tagline reel (below the red arrow) is 936.8 meters (m) above the National Geodetic Vertical Datum of 1929 (NGVD 29), and the water level is 934.9 m above NGVD 29. *D*, View is from about station 145 looking toward the left bank along the line of section. Lee dunes extend across the photograph near the center.

PR194 Narrative

Cross section PR194 was established in 1977 at the inflection point (crossover) on the downriver limb of an actively changing meander bend of Powder River (figs. 132 and 133). Resurveys were done during the years 1978–80, 1982, 1984–98, 2014, 2015, and 2016 (see Moody and Meade 2017, PR194_SciBase2.xlsx for survey data).

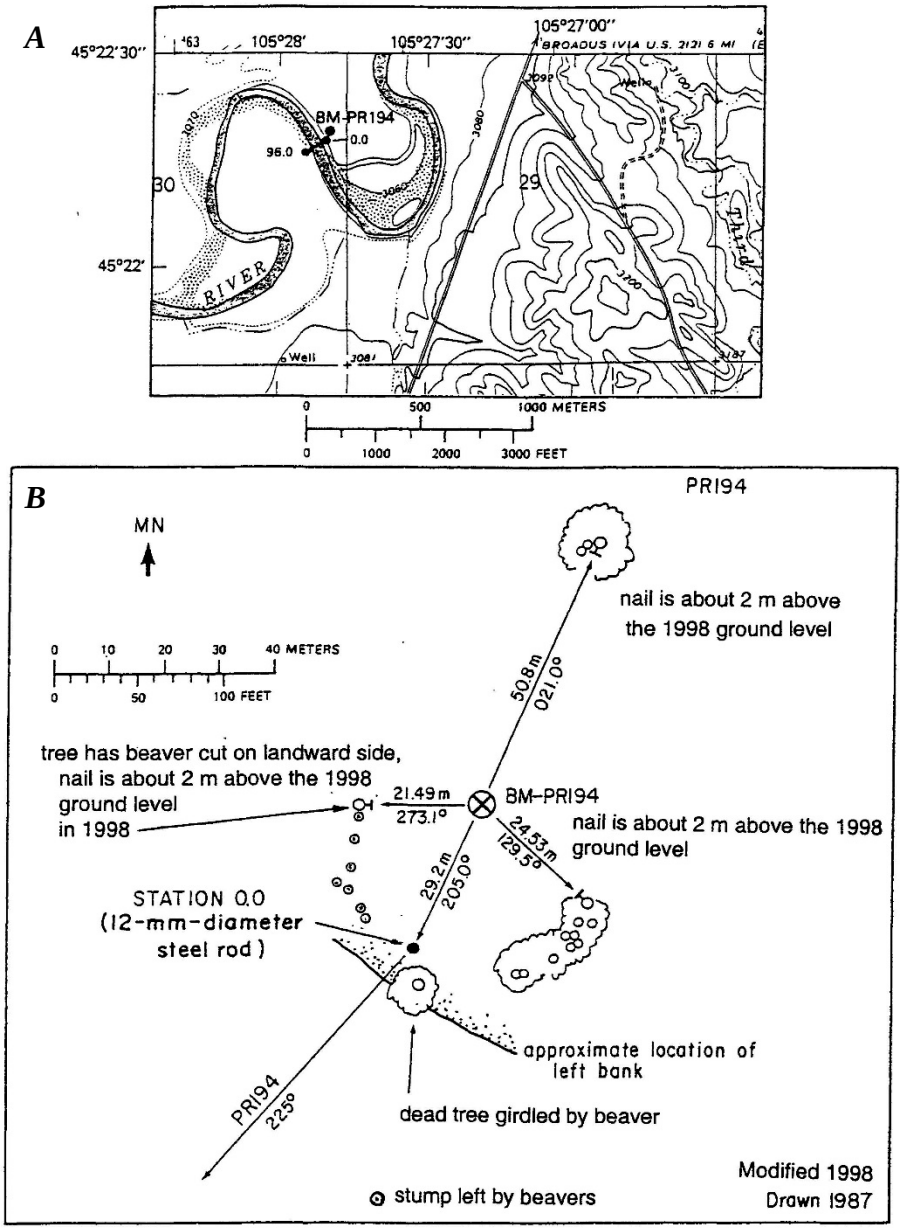

Figure 132. Location maps for cross section PR194. *A*, Location of cross section PR194, bench mark BM–PR194, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Eldon Mountain quadrangle. *B*, Location of bench mark and some reference pins on the left bank. At station -1.2, there is a pin, which is bent. A new reference pin was added at station -10.0 in 2015. MN is magnetic north.

Figure 133. Views of cross section PR194 on July 19, 1977. *A*, View is upriver, and E. Meade (about 1.6 meters tall) is standing on the line of section inside the red circle, and the red line shows the approximate line of section at bank-full elevation. *B*, View is downriver, E. Meade is standing on the line of section inside the red circle, and the red line shows approximate line of section at bank-full elevation.

Because of its location near the crossover (inflection point) of the downstream limb of a meander (fig. 134*A*), section PR194 has shown little significant erosional or depositional change during the last three and a half decades. Little change was recorded here after the flood of 1978 (see the "bottom-line" panels in figures 5 and 6 of the report by Meade and Moody, 2013) other than the deposition of lee dunes downriver from trees on the flood plain (fig. 134*B*).

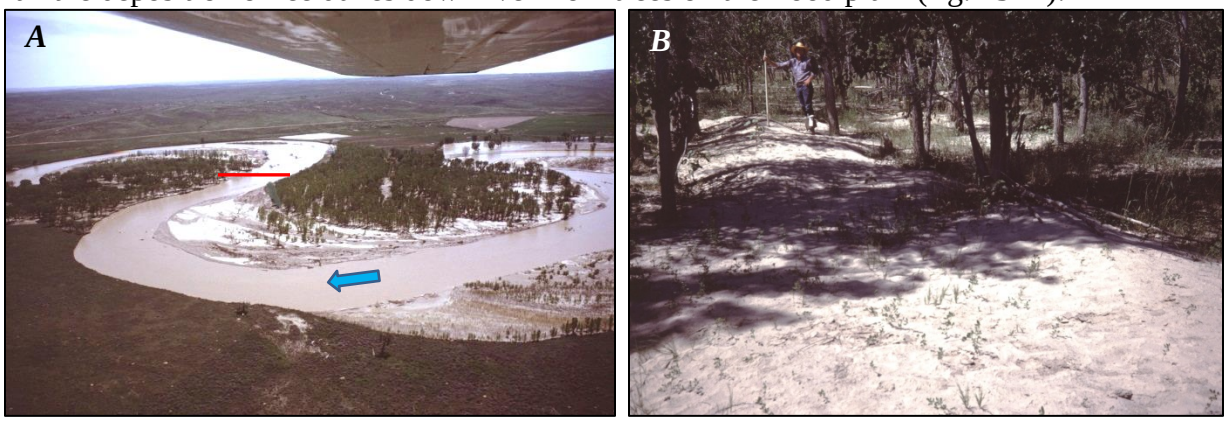

Figure 134. Views of cross section PR194 in 1978. *A*, Aerial view (downriver is to the left) was taken on May 25, 1978, by B. Ringen about one week after the peak of the flood of 1978. Blue arrow indicates flow direction, and red line indicates the approximate location of the line of section at bank-full elevation. *B*, View is upvalley taken on August 8, 1978. J. Moody (about 1.9 meters [m] tall) is standing on a new lee dune left after the flood of 1978 on the right-bank flood plain about 30–40 m back from the river bank.

Starting in 1982, the main postflood change was the building, along the left bank, of a new flood plain, similar to other inset flood plains built at sections PR120, PR136, PR151, and PR156A (Moody and others, 1999). It was remodeled slightly by the annual snowmelt flood in 1995, at which time the flood plain had a width of about 10 m; however, by 2014, this flood plain had been eroded laterally back to a width of about 5 m. During the years since the flood of 1978, the year-to-year changes have been limited mostly to a bit of erosive scour here and a bit of sand deposition there, but without showing any consistent overall trend.

The narrow neck of the large meander bend (fig. 134) makes it susceptible to being cut off. Water from the 1993 snowmelt flood (June 9, 1993, 157 m^3/s) crossed the neck (fig. 135*A*), enlarged gullies on the downriver part of the neck, and caused bank erosion (fig. 135*B*).

Figure 135. Views of the high-water effects at cross section PR194 on June 10, 1993. *A*, View is upriver and was taken at 1630 hours. Water is leaving the main channel at a point some 1,100 meters (m) upriver from cross section PR194 and flowing across the narrow neck (see fig. 132). Secondary channel opening at the bank is about 4.7 m wide and sill depth is approximately 0.10 m. Water level in the main channel is about 0.4–0.6 m below the top of the bank. Water flowed across the narrow neck and back into Powder River below PR194. *B*, View is upriver and was taken at 1300 hours. Bank failure downstream from PR194 (red line indicates approximate location of PR194 at bank-full elevation). The indentations in the bank indicate the location of gully mouths. *C*, Upriver view taken on September 2, 1993, shows new sand that was deposited during high water. Survey rod lies approximately on the line of section. J. Moody (about 1.9 m tall) is standing at the elevation of the bank-full flow (12.5 cubic meters per second).

Some ice-rafted sediments were deposited on the right-bank flood plain by the high flows that followed ice breakups in February and March 1994 (fig. 136). On June 10, 1994, water was observed flowing across the neck of the meander bend and causing substantial bank erosion about 500 m downriver of section PR194.

Figure 136. Photograph of a pod of ice-rafted sand and gravel at cross section PR194 on September 20, 1994. View is upriver. Ice-rafted sand and gravel pile was left on the Lightning-level terrace (Leopold and Miller, 1954; Moody and Meade, 2008) by the high water in February and March of 1994. Base (farther end) of survey rod is at station 103. Longest red and white markers on the rod are 0.2 meter long.

The small inset flood plain that had been built since 1982 was partially eroded (about 5 m) between 1998 and 2014 (fig. 137). Erosion along the left bank upriver since 1977 has changed substantially the orientation of cross section PR194, which now appears rotated relative to the river channel and is no longer orthogonal to the direction of flow.

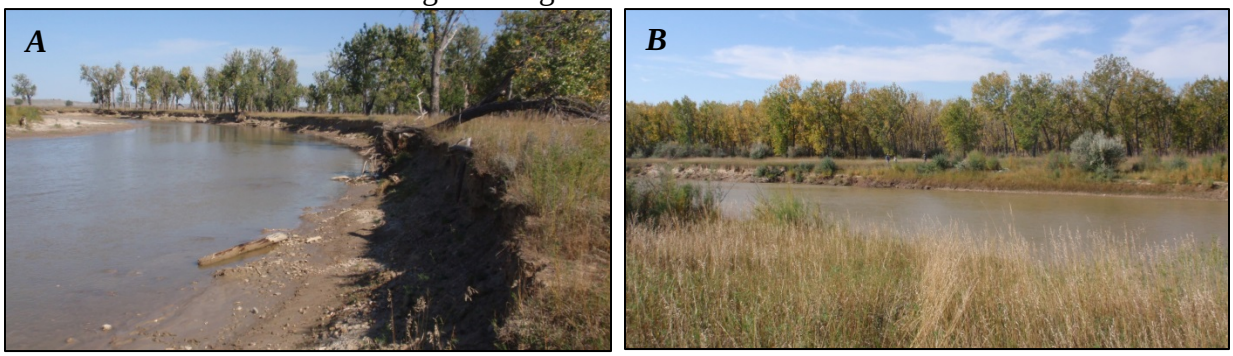

Figure 137. Views of cross section PR194 on September 27, 2014. *A*, View is upriver (taken standing on the line of section) and shows the eroded left bank. *B*, View of the right bank looking downriver.

The snowmelt floods in 2015 (May 28, 2015, 280 m^3/s; June 6, 2015, 283 m^3/s) continued to erode the left bank and completely removed the inset flood plain (fig. 138*A*). There was a net lateral erosion of 13 m of the left bank, but no erosion of the right bank or deposition on the right bank flood plain, which is a Lightning-level terrace. However, sediment was deposited in the mouth of a gully downriver from PR194 (fig. 138*C*).

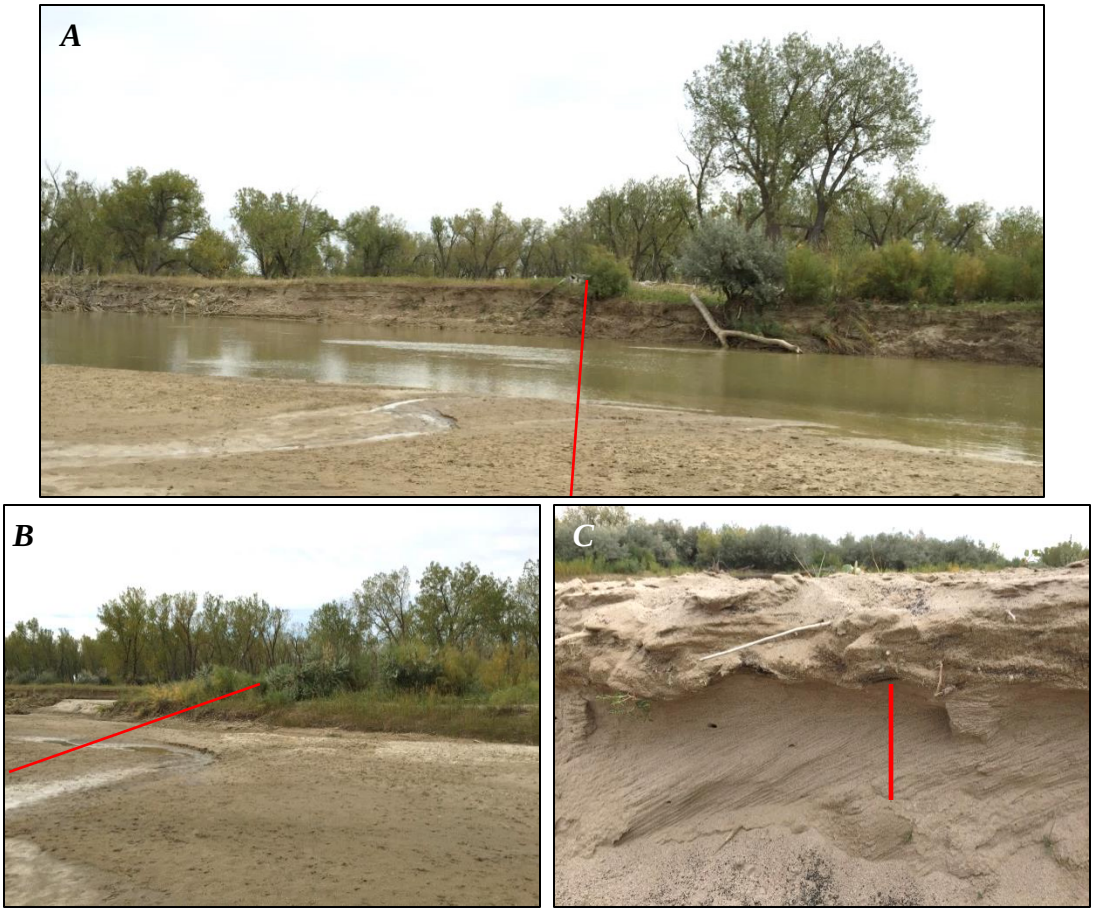

Figure 138. Views of cross section PR194 on October 1, 2015. *A*, View is of the left bank and the line of section is shown by the red line. *B*, View is of the right bank with the approximate line of section shown by the red line. *C*, Close-up view of the sediment deposition in the mouth of the gully at the left of the photo on the left. The vertical red line is about 0.1 meter tall.

PR200A Narrative

Cross section PR200 was initially established in 1977 at a site selected by the landowner, who was interested in learning about some intervention work he had done in the river. The flood of 1978 eroded or covered all reference monuments. A new cross section, PR200A, was established in 1978 using aerial photographs and the bearing of the original cross section PR200 (fig. 139), and resurveyed every year except 1981 and 1983 until 1998 (see Moody and Meade, 2017, PR200A_SciBase2.xlsx). It has not been resurveyed since 1998 (table 1). The amount of overbank deposition on the section could not be calculated but can be estimated from figure 141.

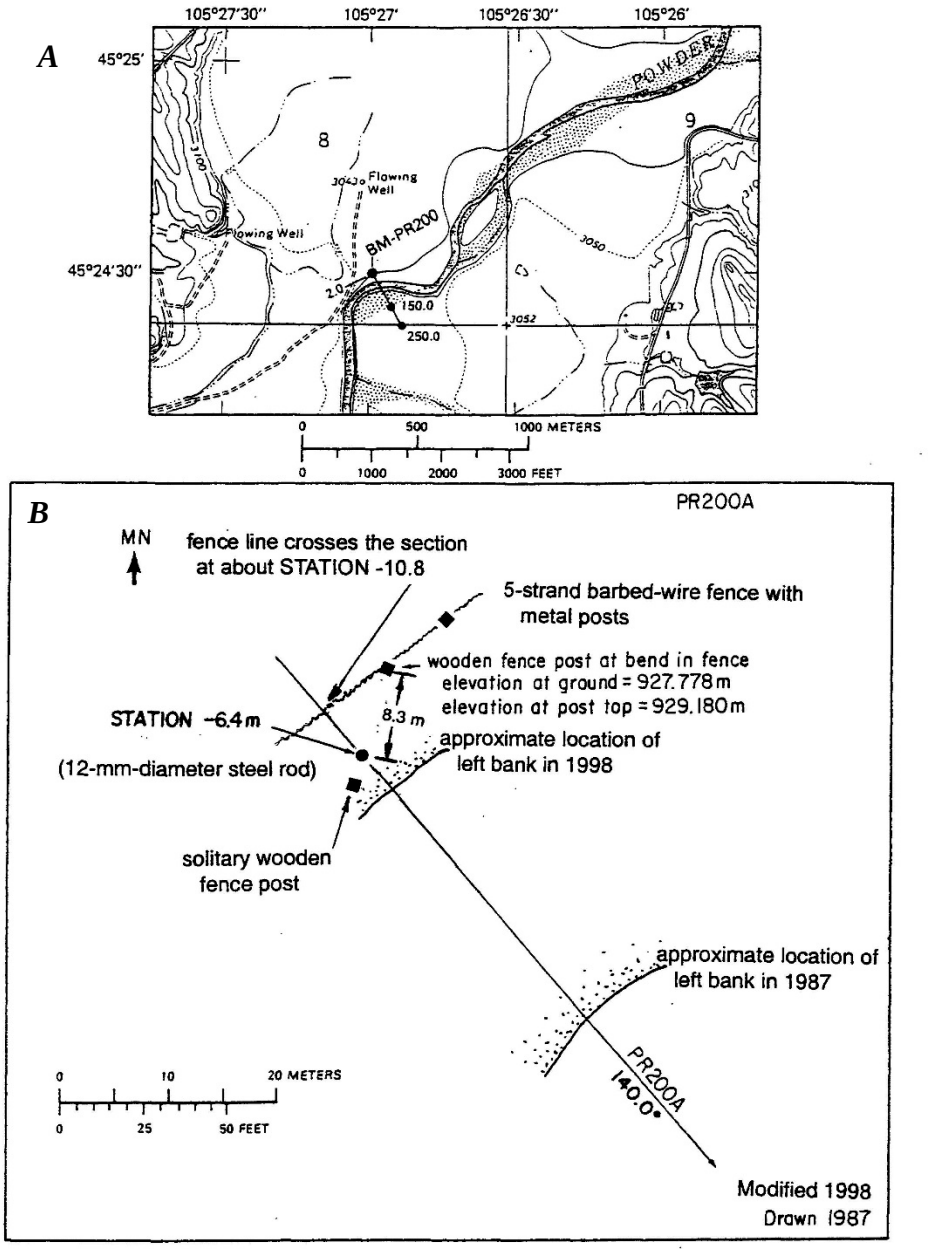

Figure 139. Location maps for cross section PR200A. *A*, Location of cross section PR200A, bench mark BM–PR200, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Broadus quadrangle. Planform configuration was taken from 1969 aerial photos. *B*, Location of the reference pin on the left bank at station -6.4. MN is magnetic north.

Figure 140. Aerial view of cross section PR200A on May 25, 1978. View is looking toward the northwest and the left bank of Powder River where PR200 was established below the crest of the bend. Photograph was taken by B. Ringen during the falling stage of the flood of 1978. Flow is from left to right.

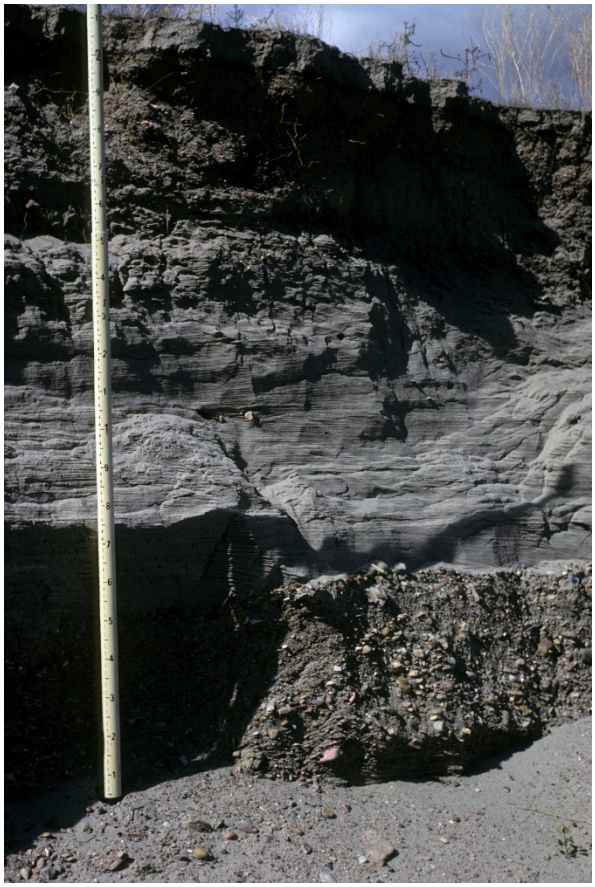

Figure 141. View of 1978 overbank flood deposits at cross section PR200A on September 14, 1984. Freshly cut left bank at station 24. Flood deposits at top of bank are mostly sand and about 10 centimeters thick. Rod is numbered in decimeters.

The new section PR200A had two channels. And the story told by the 20-year (1978–98) record of surveys and resurveys at section PR200A is one of the gradual (nonavulsive) lateral shifts of the main waterway from the left side to the right side of the channel. Originally the left-side channel was the main channel and was centered at about station 40, whereas the right-side channel was a secondary channel centered at about station 220. In 1984, 8 m of the left-bank channel was lost (fig. 141), and then the active erosion shifted to the right-side channel from 1985 to 1992. During the 3 years 1990, 1991, and 1992, the left bank of the right-side channel was eroded leftward a total of 45 m. In 1993, the left banks of both channels eroded (figs. 142 and 143) with the right-side channel bank losing 24 m on the inside of the bend and the left-side channel bank losing about 6 m.

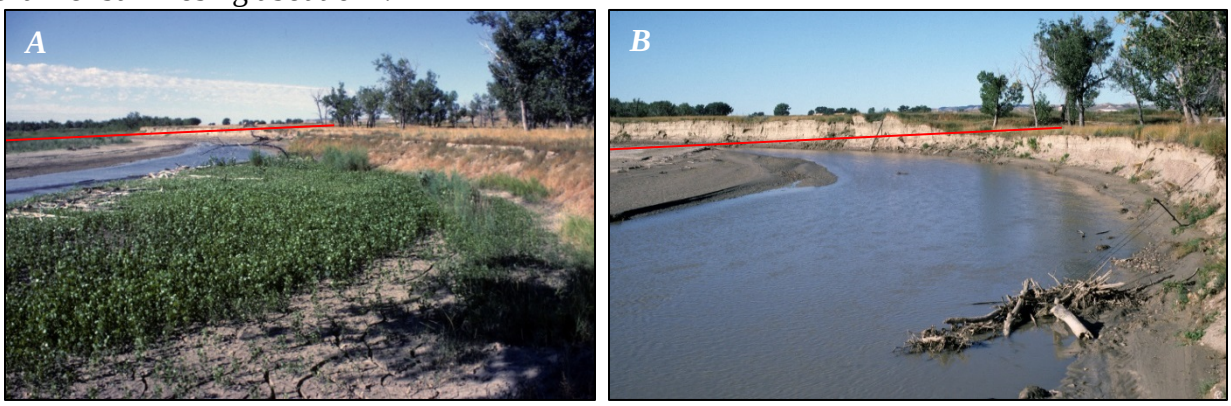

Figure 142. Views of left-side channel of cross section PR200A in September 1991 and 1993. Red lines indicates the approximate line of section. *A*, An upriver view taken from a point about 50 meters (m) below the cross section on September 24, 1991. Cross section begins just upriver of the dead tree near the center of the photograph. Young cottonwood seedlings have germinated on fresh sand in the foreground. *B*, Upriver view showing recently eroded (about 6 m) left bank of left-side channel on September 3, 1993.

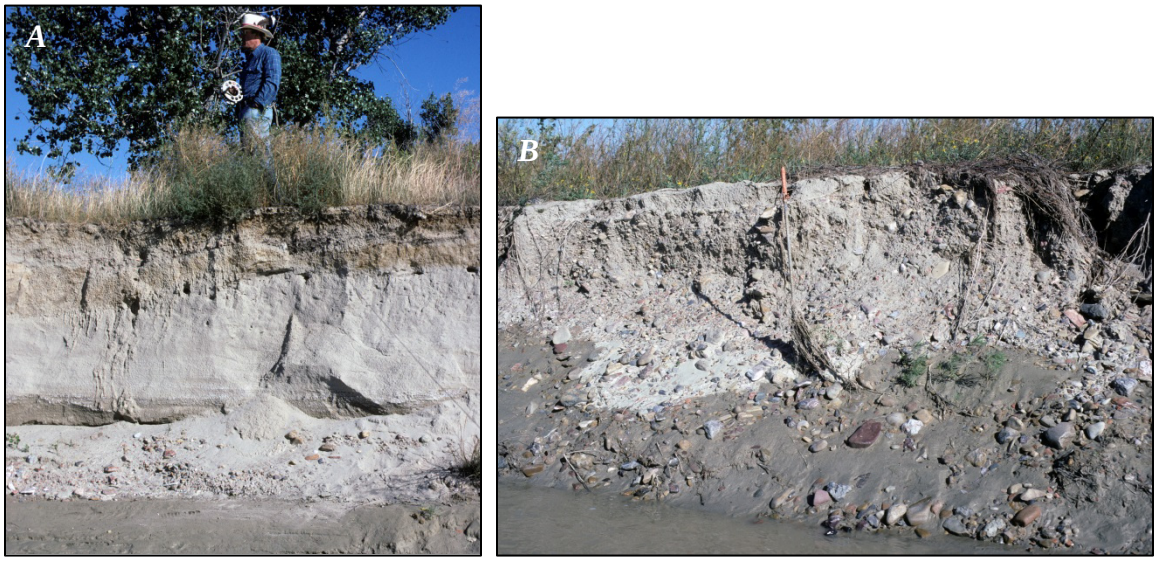

Figure 143. Views of cross section PR200A on September 3, 1993. *A*, The line of section is the grey cable, and J. Moody (1.9 meters [m] tall) is standing at station 16.0. Three depositonal units are shown beneath the 1978 flood deposit. Flow is from left to right. *B*, Sediment has been eroded from around the reference pin (orange tape at top) at station 150.9, which was about 65 m from the right-side channel in 1978.

The erosion continued in both channels from 1994 through 1998 (fig. 144). The left-side channel lost an additional 20 m, and the inside of the bend of the right channel lost an additional 12 m of bank. The right-side channel also became deeper and thus became the main channel of Powder River in 1998.

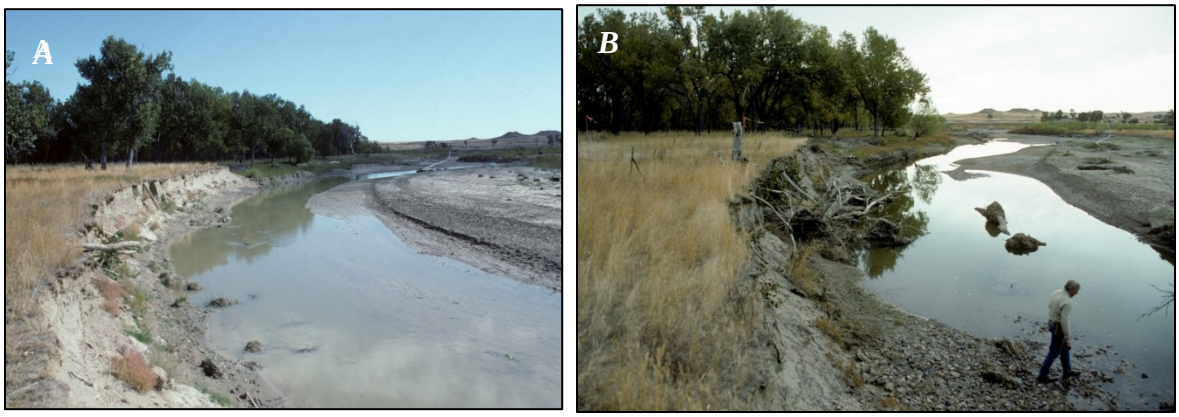

Figure 144. Views of erosion of the left bank of cross section PR200A in 1994 and 1995. *A*, View downriver of the left-side channel on September 18, 1994. *B,* Downriver view was taken on September 29, 1995 of the left-side channel after the flood of 1995 that eroded about 13 meters (m) from the cut bank. Stainless steel vertical wading rods are positioned at stations -6.4 and -1.8. J. Moody is about 1.9 m tall.

PR206 Narrative

Cross section PR206 was established in 1977 in a fairly straight reach of Powder River about 1 km downriver of the Highway 212 Bridge at Broadus (figs. 1 and 145). The section was placed directly below the recently constructed overhead cableway (fig. 146) that was part of the measurement infrastructure of the gaging station, Powder River at Broadus, Mont. (USGS site number 06324710). We regularly resurveyed the section every year or two through 1998. No surveys were then made until 2014 and then again in 2015 and 2016, which left a 16-year gap in the measurement record (see Moody and Meade, 2017, PR206_SciBase2.xlsx for survey data).

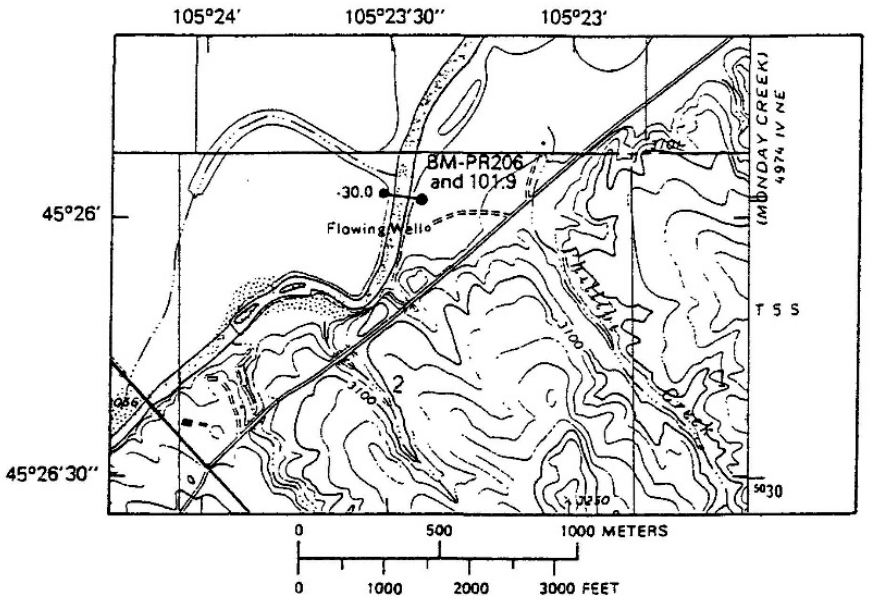

Figure 145. Location map for cross section PR206. Location of cross section PR206, bench mark BM–PR206, and left and right bank reference pins (12-millimeter-diameter steel rod) on the Broadus quadrangle. The bench mark for PR206 was originally a hexagonal bolt (Moody and others, 2002) on the concrete pad for the right-bank deadman that anchored the cableway (fig. 146); however, this was lost by the active bank erosion after 1998. The reference pin at station -50.0 was used for the bench mark in 2014, and a new reference pin was put in at station 190.0, which was used in 2015. U.S. Highway 212 crosses Powder River in the lower left-hand corner of the map.

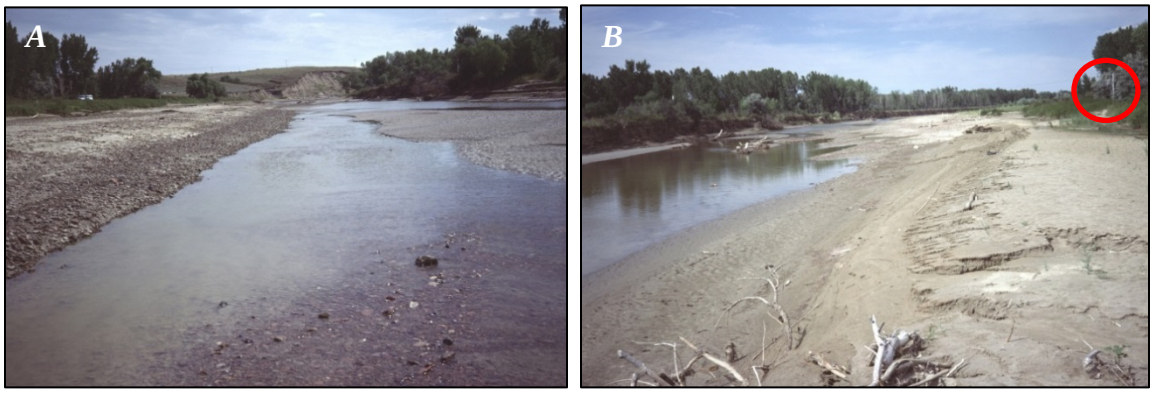

Figure 146. Views of cross section PR206 on July 19, 1977. *A*, View is upriver. The truck is parked on the right bank several tens of meters upriver from the line of section. *B*, View is downriver. Right-bank pylon and suspended cableway are in the red circle.

During the flood of 1978, the river channel was both widened and deepened at cross section PR206. In fact, flood-related deepening was greater in section PR206 than in any of the 18 other cross sections we were able to survey before and after the flood—probably because of the upriver migration of a headcut that had first formed in the channel about a mile downriver when a large meander was cut off in 1975 (Meade and Moody, 2013, p. 8–9).

For more than a decade following the flood of 1978, the principal change was a leftward shift of the channel at cross section PR206, which eroded a 3-m-high Moorcroft-level terrace (Leopold and Miller, 1954; Moody and Meade, 2008) laterally some 45 m between 1979 and 1991. Major increments of erosion of the left bank were recorded during the years 1981–82 (6 m), 1983–84 (15 m), 1986 (5 m), 1987 (4 m), 1990 (6 m), and 1991 (8 m). By 1982, the left-bank pylon that held up the cableway had been undermined by erosion and had collapsed into the river (fig. 147). By 1984, the large concrete pad that had served as anchor to the left end of the cable had also been undermined. The uppermost corner of this pad was surveyed in 1985 at station 3 at an elevation of 917.6 m above NGVD 29. The pad was last seen by us in 1992, at that same station, with its uppermost corner at an elevation near 917.0 m above NGVD 29.

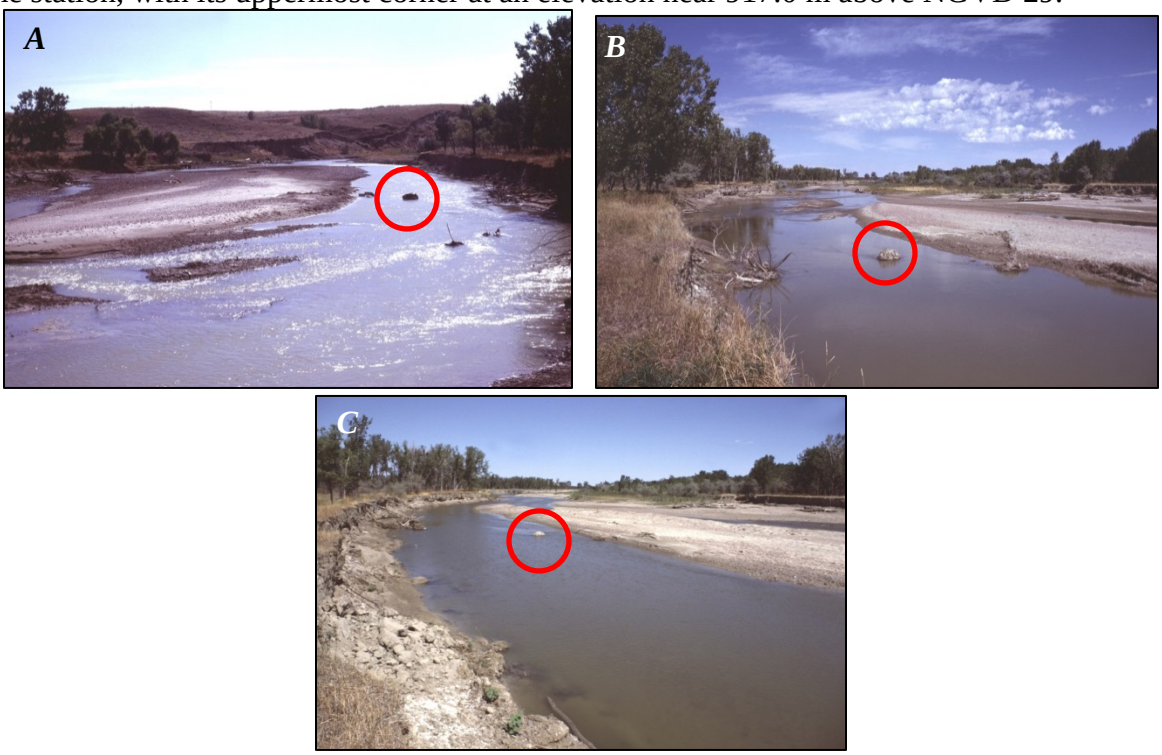

Figure 147. Views of cross section PR206 in 1984 and 1986. Concrete deadman is inside the red circle between stations 4–5. *A*, Upriver view was taken on September 16, 1984. *B*, Downriver view was taken on September 16, 1984. The left bank (Moorcroft-level terrace) has been eroded back, since our first survey of 1977, about 24 m–15 m of which was eroded since the survey of 1982. *C*, Downriver view was taken on August 22, 1986.

For several years (1991–94), a scour hole, about 1 m deeper than the rest of the channel bottom in section PR206, developed around the pad, between stations -2 and +6. The pad was buried under at least 1.5 m of new sand during the high water of 1995, and, as of 2014, it lies buried under about 2 m of accumulated sand. During this same period two inset flood plains (similar to the inset flood plains at PR120, PR125, PR136, PR151, and PR156A; Moody and

others, 1999) developed on each side of the channel, and by 1995 these were about 2 m above the thalweg (figs. 148 and 149).

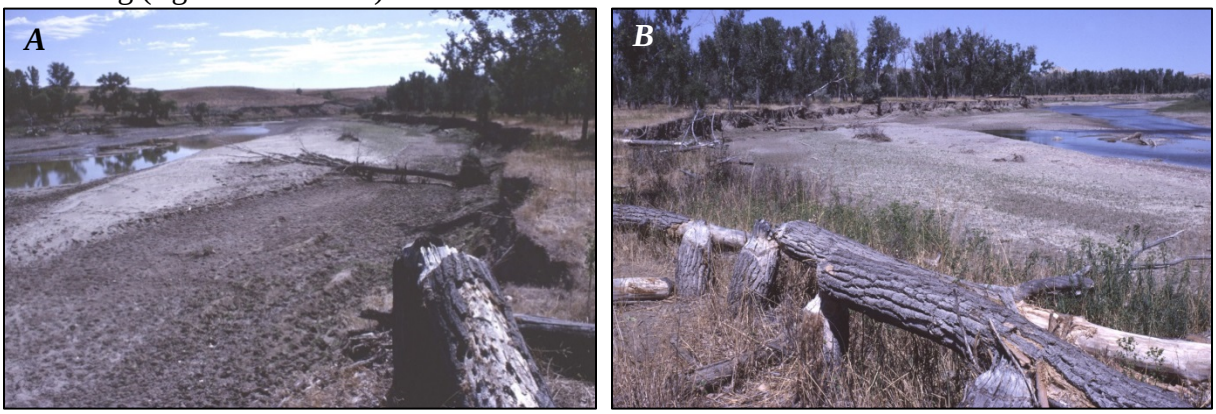

Figure 148. Views of the left bank of cross section PR206 on September 3, 1991. *A*, View is upriver standing on the line of section. The left-bank (Moorcroft-level terrace) was eroded back 8 meters (m) since the previous year's survey (1990) and a total of about 14 m since the survey of 1989. New sediment (between stations -10 to -25) is about 1 m thick on the developing inset flood plain (Moody and others, 1999), which now supports cottonwood (*Populus sargentii*) seedlings. *B*, View is downriver along the left bank. Photographs show the two ends of the cottonwood life cycle. New seedlings on the recently deposited sandbar (forming the inset flood plain), and older cottonwoods cut down by beaver.

Figure 149. View of cross section PR206 on September 19, 1994. View is upriver. J. Moody (about 1.9 meters [m] tall) is standing on a thin layer (0.1 m or less) of sediment deposited by ice-breakup flood between stations 50 and 60 on top of the existing inset flood plain (Moody and others, 1999) along the right bank that is about 2 m above the channel thalweg.

The high-water episode of 1995 began a couple decades of rightward shift of the channel at cross section PR206. During that year, a 10–15-m width of about a 2-m thick flood plain was removed from the right side of the channel, while a 1-m-or-more thickness of new sand was deposited onto the top of a 35–40-m width of the left-side flood plain and extended the edge of the flood plain into the channel as a sloping surface forming a point bar (fig. 150). The advancing of the point-bar surface to the right forces water against the right bank and increases the potential erosion. Another 12-m width of the right-bank flood plain was removed between 1995 and 1998.

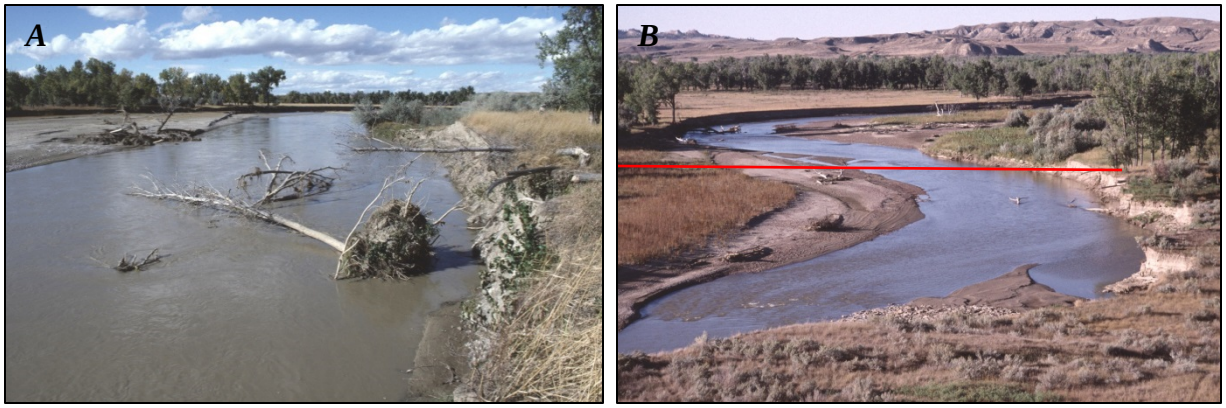

Figure 150. Views of cross section PR206 in 1995 and 1997. *A*, Downriver view taken on October 1, 1995. J. Moody (about 1.9 meters tall) and the tripod are on the line of section at the upper right edge of the photograph. *B*, Downriver view taken on September 23, 1997. The red line indicates the approximate line of section at bank-full elevation across the developing point bar and onto the Moorcroft-level terrace along the right bank. The prominent curvature of the bank downriver from the red line developed during the previous two decades since 1977, at which time this was a mostly straight reach of river.

Massive changes took place in cross section PR206 between 1998 and 2014. Because we made no surveys between these two dates, however, we are able to discuss only the net 16-year change, and we are unable to specify the amounts of erosion and deposition that took place during individual years in response to specific discharges of river water. Erosion of the right bank continued in the forms of removal of a 10-m width of 2-m-thick flood plain and then the massive removal of a 50-m width of 3.5-m-high Moorcroft-level terrace (fig. 151). New sand was deposited in these thicknesses: a few decimeters between stations -35 and 9; 0.5 m between stations 9 and 23; 1 m or slightly more between stations 26 and 55; 2–2.5 m between stations 55 and 90; and tapering down from 2 m at station 90 to 0 m at station 130. We presume that the right-side concrete pad that formerly sat atop the Moorcroft-level terrace between stations 102 and 104 at elevations about 921 m above NGVD 29 now lies invisible at some elevation between 917 and 918 m above NGVD 29, covered by at least 1 m of newly deposited sand.

Six sediment cores for dating by OSL were collected from the Moorcroft-level terrace (Leopold and Miller, 1954; Moody and Meade, 2008) forming the right bank. Three were collected on July 19, 2014, three were collected on October 1, 2014 (fig. 152), and together these six cores formed a vertical profile about 3 m downriver from PR206 (between B. Elba and the cottonwood tree at the edge of the bank in fig. 151*D*).

The snowmelt floods of 2015 (May 28, 2015, 280 m^3/s; June 6, 2015, 283 m^3/s) continued to erode the right bank (about 17 m of bank erosion since the previous survey of 2014), while advancing the left-bank point bar (fig. 153) farther to the right side (about 30 m) in the classic Leopold scenario (Leopold, 1994, p. 5). About 0.2 m of sand was deposited on the left-side point bar at station 0 (near the top of the left bank in 1977), and about 0.8 m was deposited on the crest of the point bar at station 87 (top of the right bank in 1977).

To summarize, this has been one of the most active cross sections on the Powder River. The width from terrace bank to terrace bank of Powder River at cross section PR206 more than doubled in less than four decades. First, by the river laterally eroding nearly 50 m of the left bank, and then by the river switching sides and laterally eroding 67 m of the right bank. This may be indicative of the upriver (or downriver) migration of a meander planform through the section—first eroding the left bank and then eroding the right bank. A response perhaps set in motion by the 1975 cutoff of the old meander 1 mile downriver of section PR206.

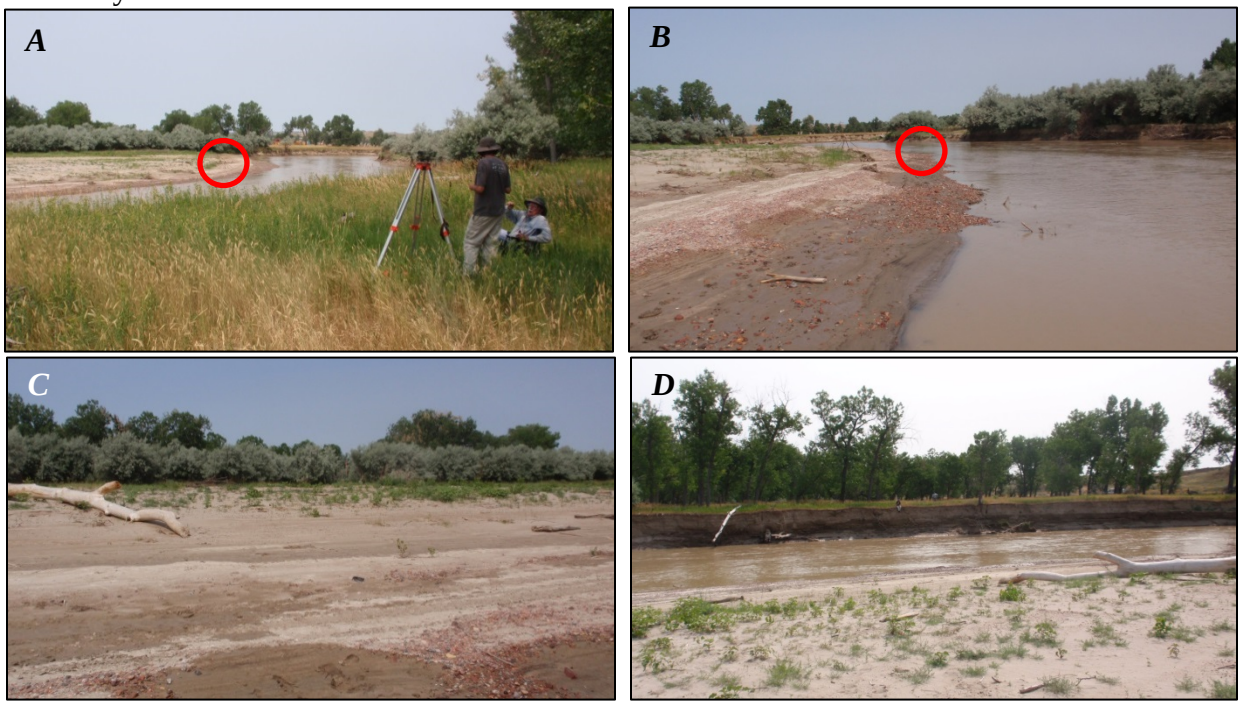

Figure 151. Views of cross section PR206 on July 17, 2014. *A*, View is downriver from the right bank standing on the Moorcroft-level terrace. B. Elba (about 1.7 meters [m] tall) and R. Meade are on the line of section, which goes through the teepee of sticks (inside the red circle) on the left-side point bar. *B*, View is downriver from the point bar on the left side with the teepee of sticks (inside the red circle) on the line of section. *C*, View is of the left bank with downriver to the right. The line of section passes through the gap in the Russian olive trees highlighted by range poles with orange flagging. *D*, View is of the right bank (Moorcroft-level terrace). The tripod and B. Elba (sitting on the edge of the bank) are on the line of section. R. Meade (about 1.8 m tall) is just upriver from the line of section.

Figure 152. Location of sediment cores collected from the right bank of cross section PR206 for optical stimulated luminescence dating. *A*, Exposed tree root, next to B. Elba's feet, is on the tread of the Moorcroft-level terrace forming the edge of the river bank (see fig. 151*D*). *B*, Cores collected on October 1, 2014 are 0.2, 0.5, and 0.9 meter (m) below the terrace tread (see fig. 152*C* at right). *C*, Cores collected on July 19, 2014 are 2.2 and 2.6 m below the terrace tread. Red bars on survey rod are 0.2 m long.

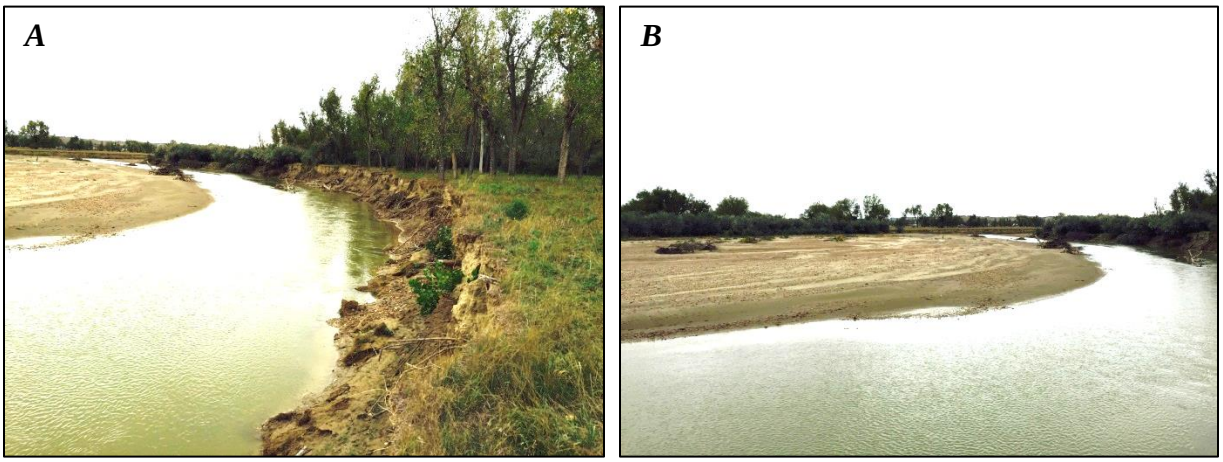

Figure 153. Views of cross section PR206 on October 4, 2015. *A*, View is downriver along the right bank, which was eroded back about 17 meters and the tree at the edge of the bank (figs. 151 and 152) is gone. Sand forming the crest of the point bar on the left side was all deposited during the 2015 floods. *B*, Wider view downriver shows a close up of the left-side point bar.

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This effort spanned 42 years, and a large cast of people made it possible. The beginnings of the project emerged into reality largely because of the early encouragement and timely assistance provided by Carl Nordin, Bruce Ringen, Ned Andrews, and Eric Meade.

Equally encouraging were all the people who pitched in over the years and helped resurvey all the cross-section locations under various weather conditions: Jim Pizzuto and Deborah Martin helped with the resurveys during multiple (5–6) years. Others who came and helped were Toby Ackerman, Patrick Belmont, Brendan Elba, Mike Fitzgerald, Faith Fitzpatrick, Koh-ichi Fujita, Eleanor Griffin, Mike Karlinger, Brian Laub, Donna Marron, Holly Martinson, Shirley Stewart, Nicola Surian, and Alex Torres. Local help was provided by Clark Appleman, Karena Appleman, Kip Appleman, Jaeger Held, Rikki Held, and Jean Hough. And, finally, this project would never have happened without the permission, help, suggestions and observations of the landowners.

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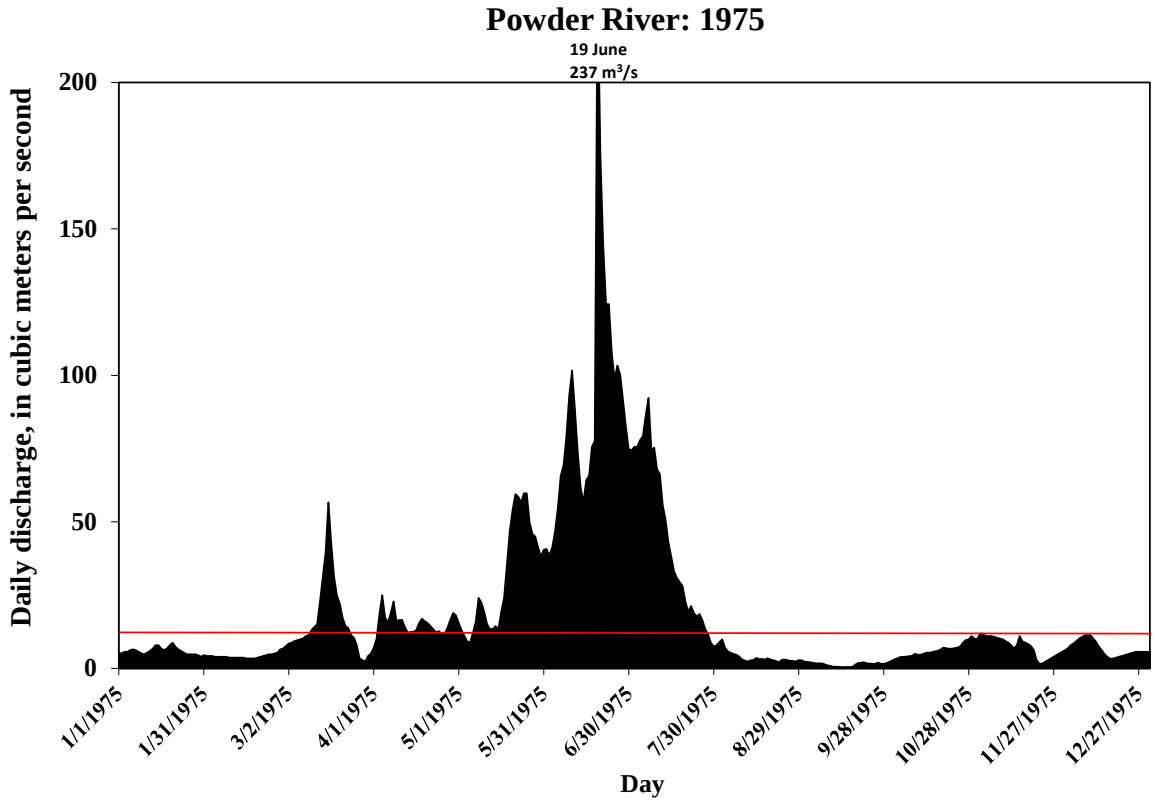
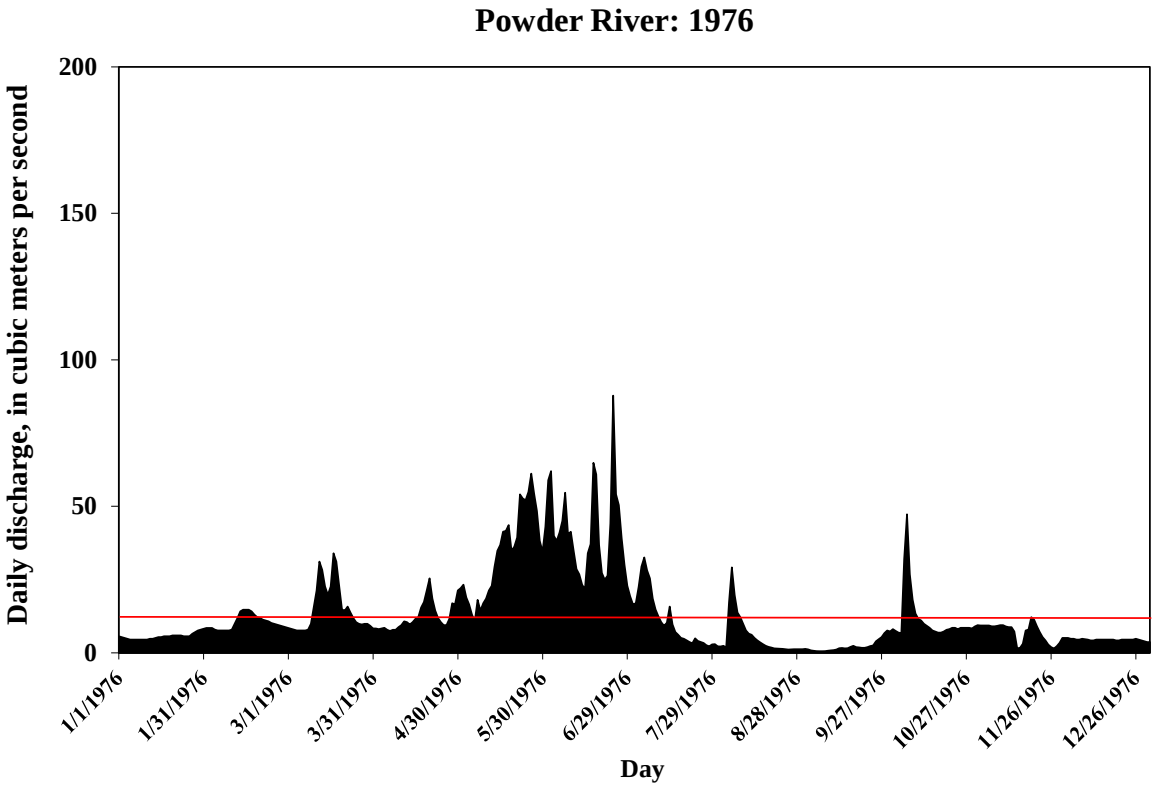
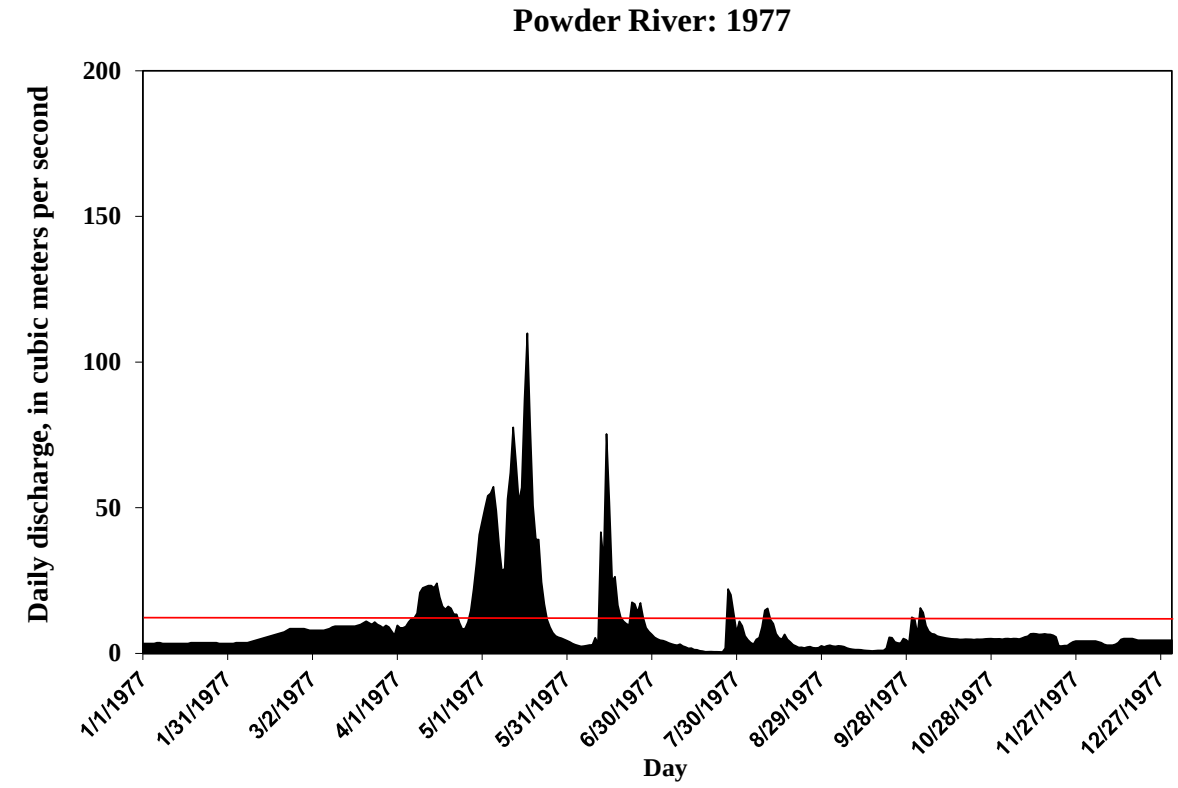
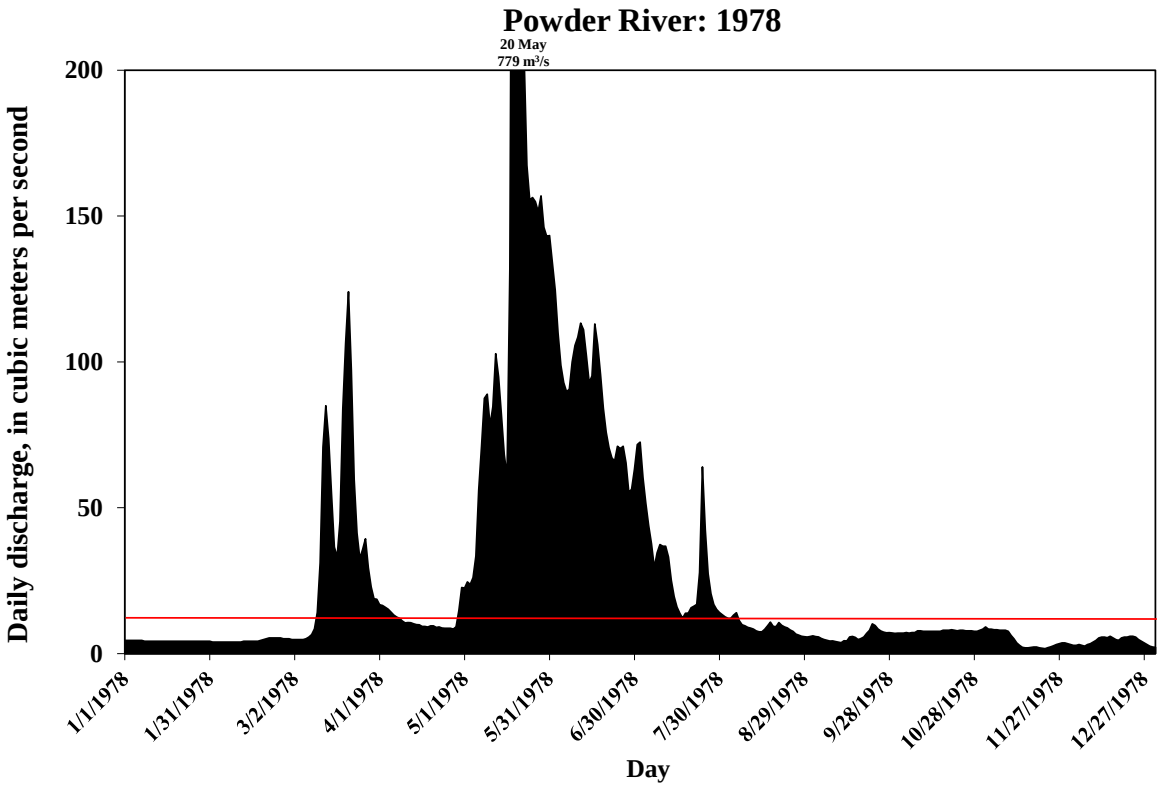
Appendix 1.

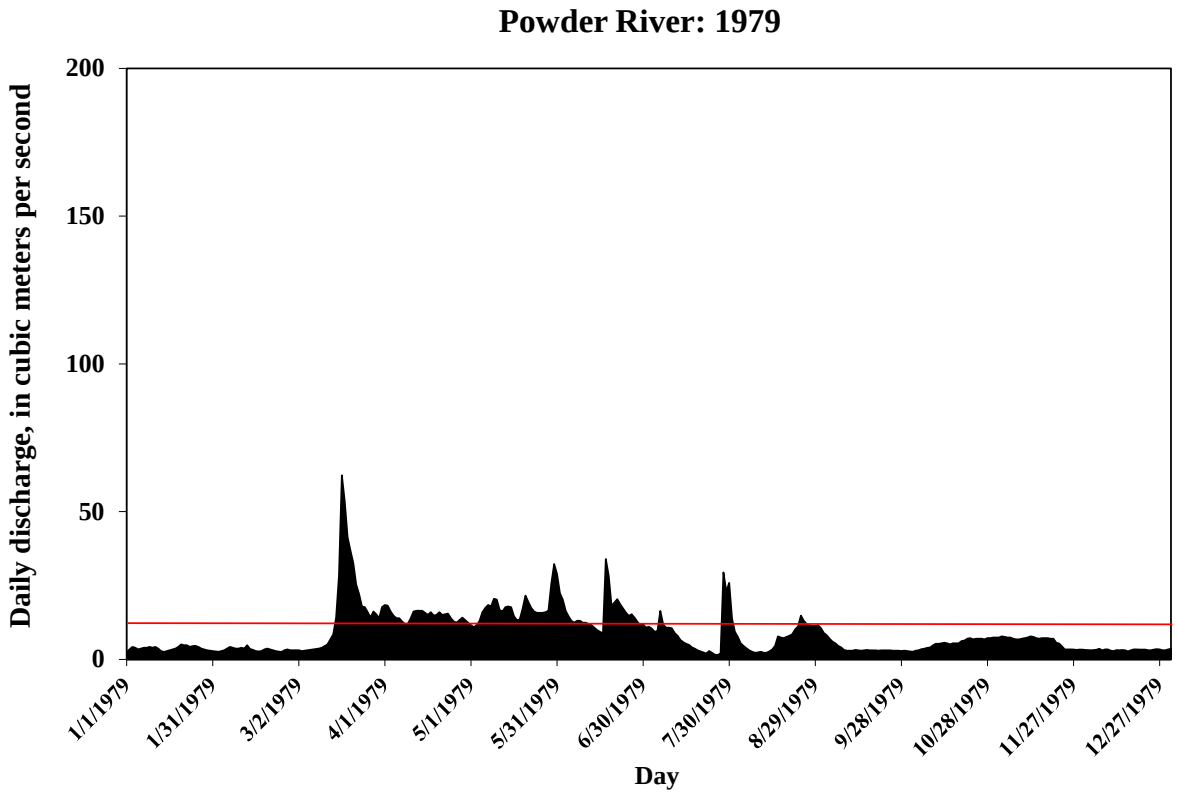
Hydrographs for USGS streamgaging station Powder River at Moorhead, Montana (station number 06324500) showing the daily mean discharge are plotted for each calendar year with the same vertical scale. Peak discharges greater than 200 cubic meters per second are labeled above the top of the hydrograph. The red line is equal to the bed-full flow (12 cubic meters per second; Moody and others, 1999). The daily discharge data are available at https://waterdata.usgs.gov/usa/nwis/uv?site_no=06324500.

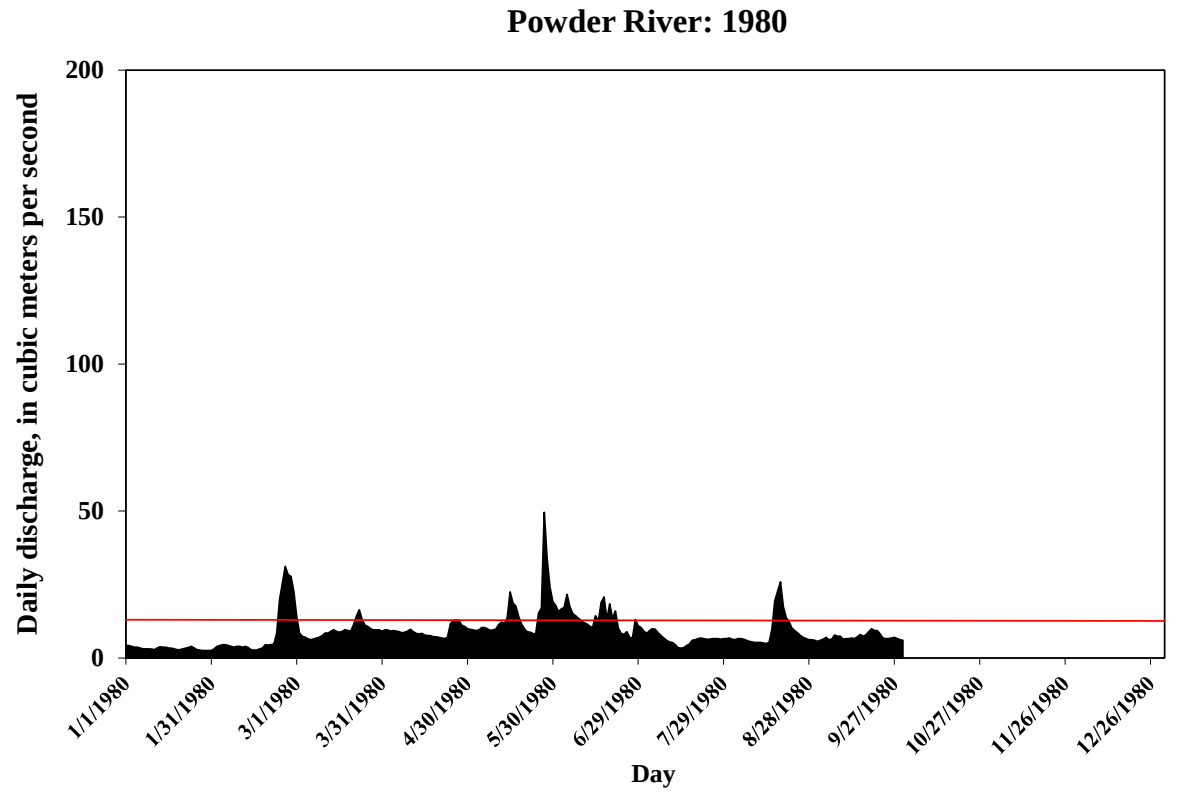

Powder River: 1975
19 June
237 m3/s
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1975
1/31/1975
3/2/1975
4/1/1975
5/1/1975
5/31/1975
6/30/1975
7/30/1975
8/29/1975
9/28/1975
10/28/1975
11/27/1975
12/27/1975
Day

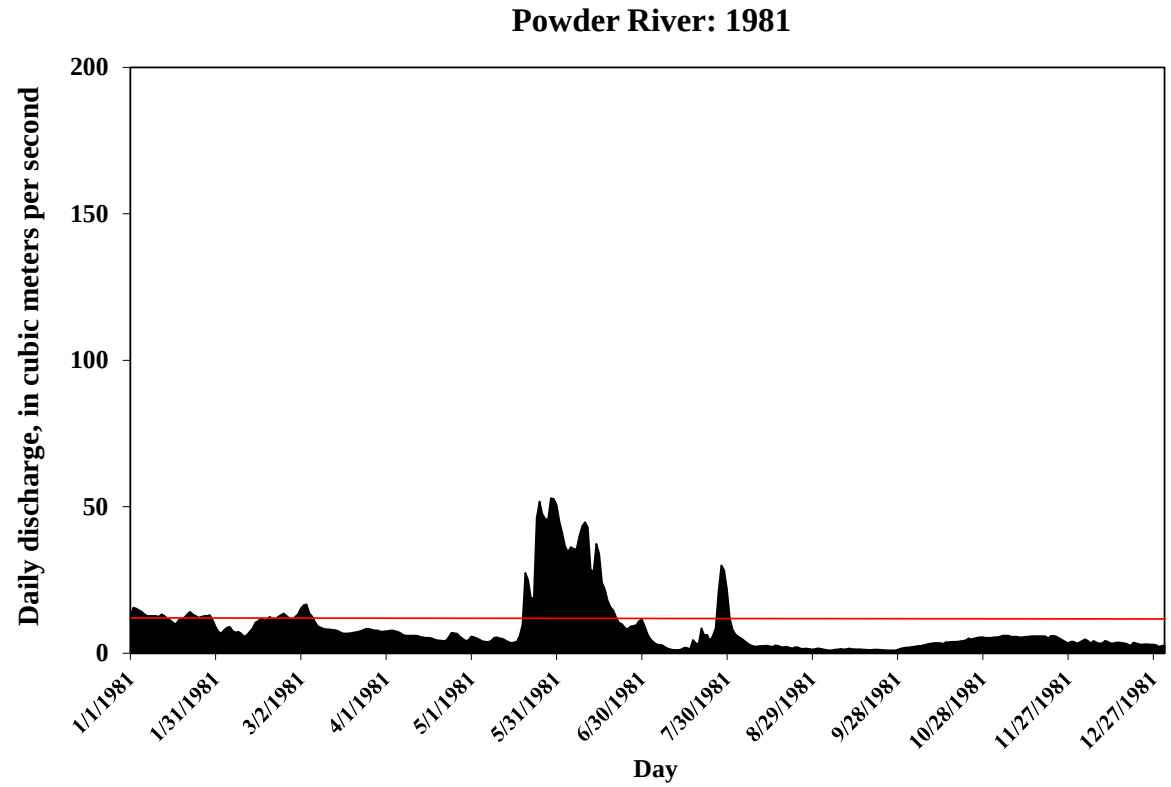

Powder River: 1976
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1976
1/31/1976
3/1/1976
3/31/1976
4/30/1976
5/30/1976
6/29/1976
7/29/1976
8/28/1976
9/27/1976
10/27/1976
11/26/1976
12/26/1976
Day

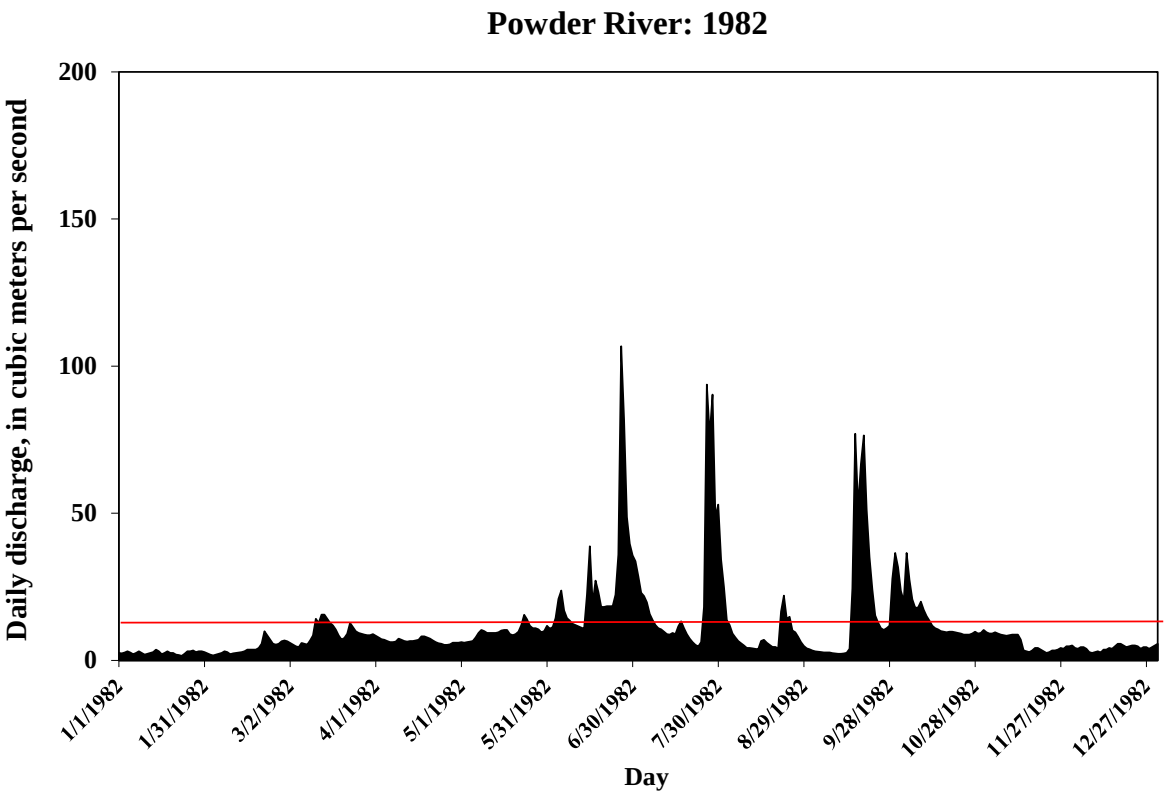

Powder River: 1977
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1977
1/31/1977
3/2/1977
4/1/1977
5/1/1977
5/31/1977
6/30/1977
7/30/1977
8/29/1977
9/28/1977
10/28/1977
11/27/1977
12/27/1977
Day


Powder River: 1978
20 May
779 m3/s
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1978
1/31/1978
3/2/1978
4/1/1978
5/1/1978
5/31/1978
6/30/1978
7/30/1978
8/29/1978
9/28/1978
10/28/1978
11/27/1978
12/27/1978
Day


Powder River: 1979
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1979
1/31/1979
3/2/1979
4/1/1979
5/1/1979
5/31/1979
6/30/1979
7/30/1979
8/29/1979
9/28/1979
10/28/1979
11/27/1979
12/27/1979
Day


Powder River: 1980
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1980
1/31/1980
3/1/1980
3/31/1980
4/30/1980
5/30/1980
6/29/1980
7/29/1980
8/28/1980
9/27/1980
10/27/1980
11/26/1980
12/26/1980
Day


Powder River: 1981
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1981
1/31/1981
3/2/1981
4/1/1981
5/1/1981
5/31/1981
6/30/1981
7/30/1981
8/29/1981
9/28/1981
10/28/1981
11/27/1981
12/27/1981
Day


Powder River: 1982
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1982
1/31/1982
3/2/1982
4/1/1982
5/1/1982
5/31/1982
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8/29/1982
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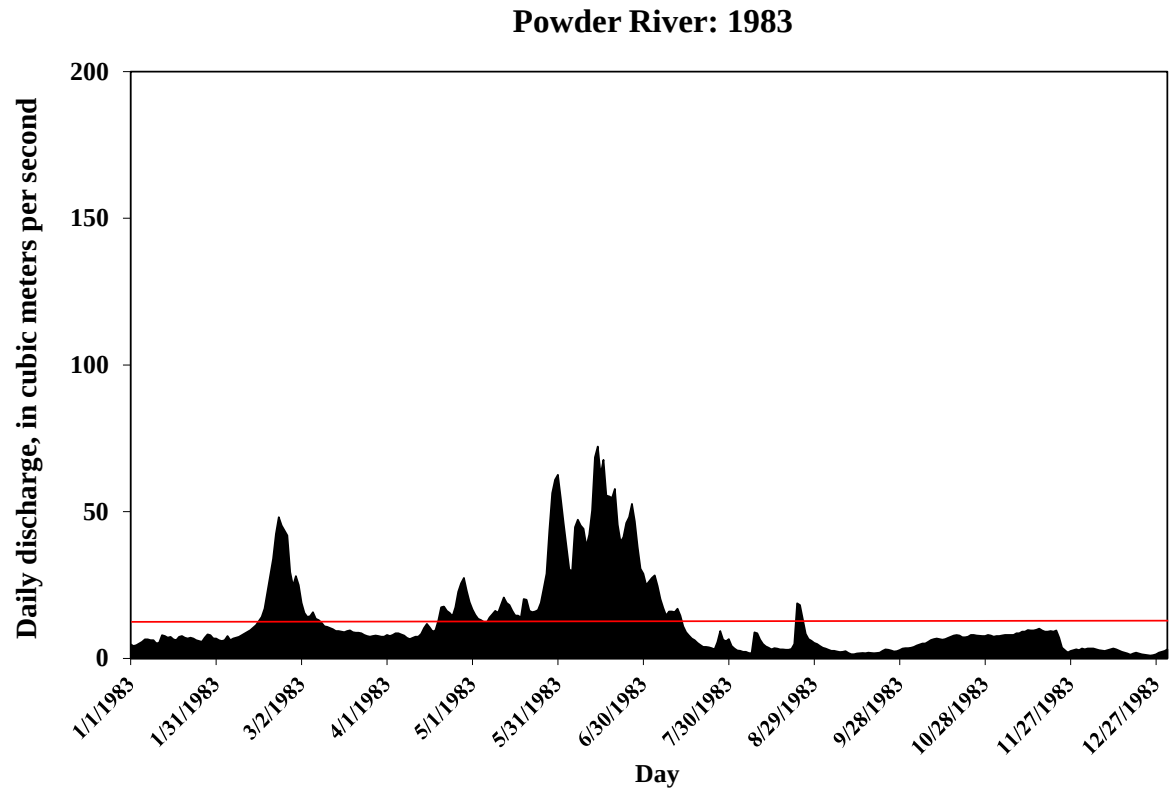
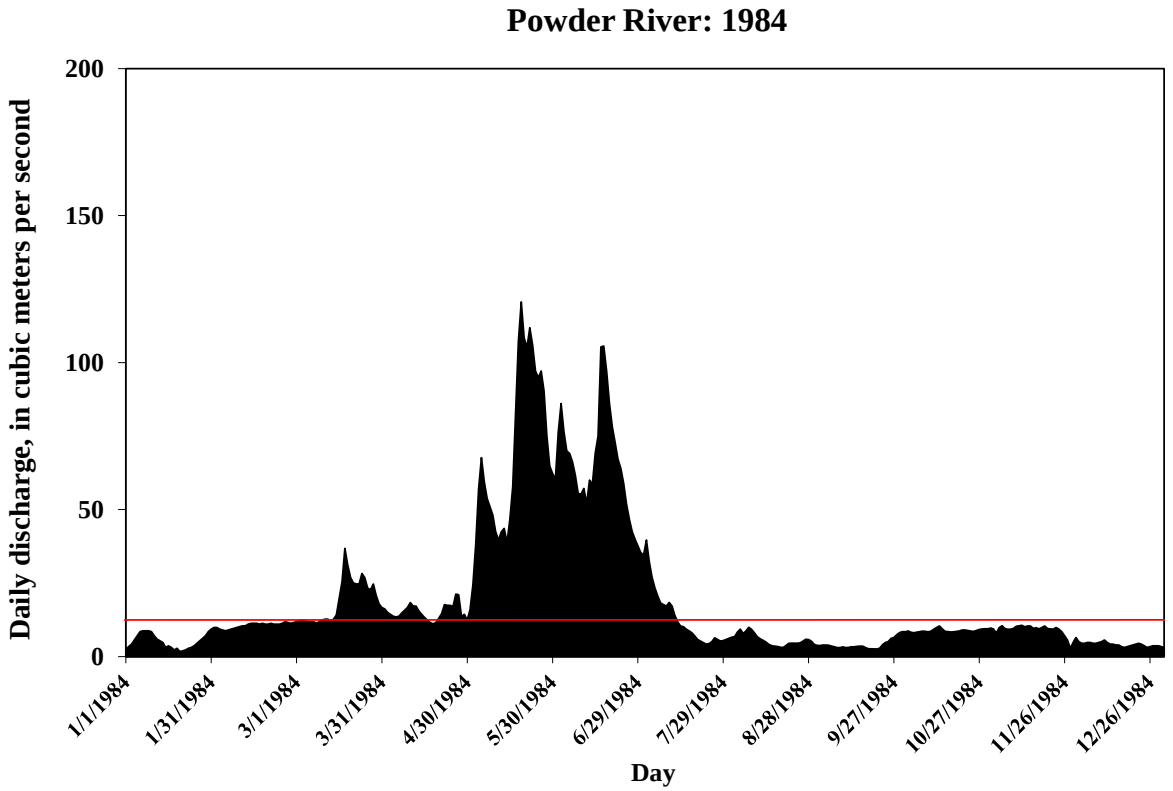
11/27/1982
12/27/1982
Day


Powder River: 1983
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1983
1/31/1983
3/2/1983
4/1/1983
5/1/1983
5/31/1983
6/30/1983
7/30/1983
8/29/1983
9/28/1983
10/28/1983
11/27/1983
12/27/1983
Day


Powder River: 1984
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1984
1/31/1984
3/1/1984
3/31/1984
4/30/1984
5/30/1984
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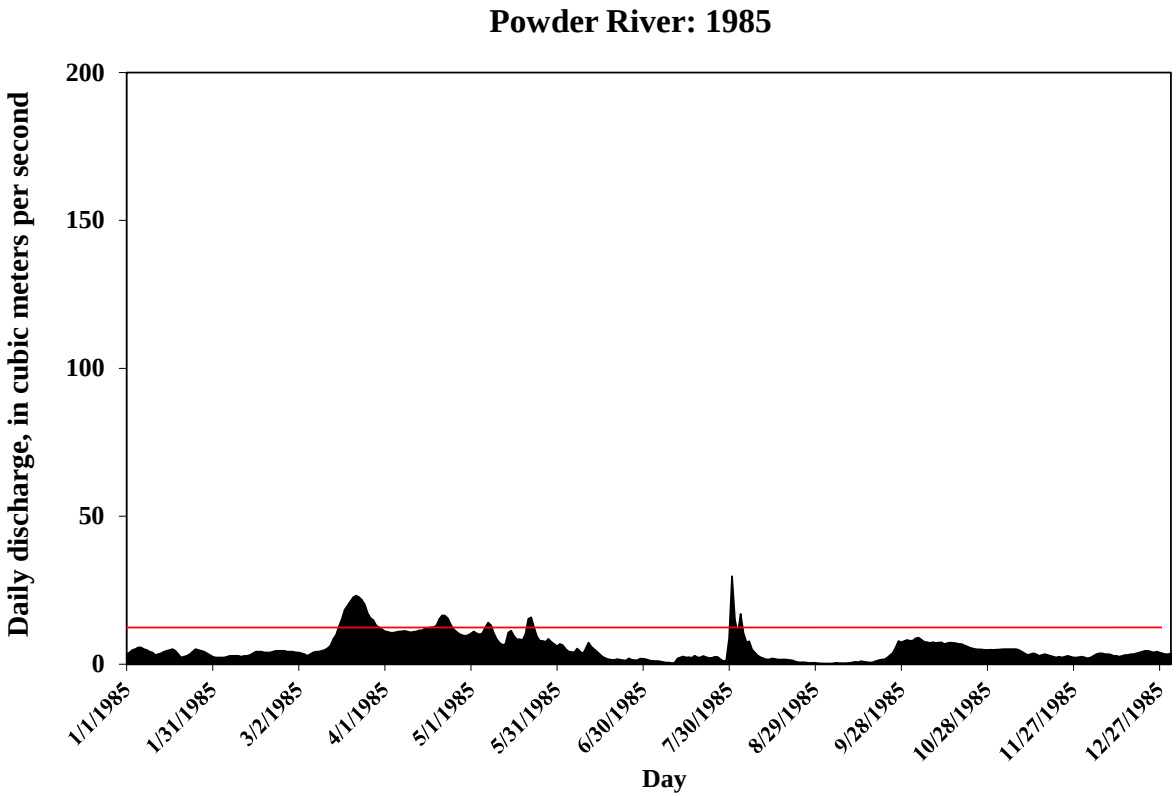
7/29/1984
8/28/1984
9/27/1984
10/27/1984
11/26/1984
12/26/1984
Day


Powder River: 1985
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1985
1/31/1985
3/2/1985
4/1/1985
5/1/1985
5/31/1985
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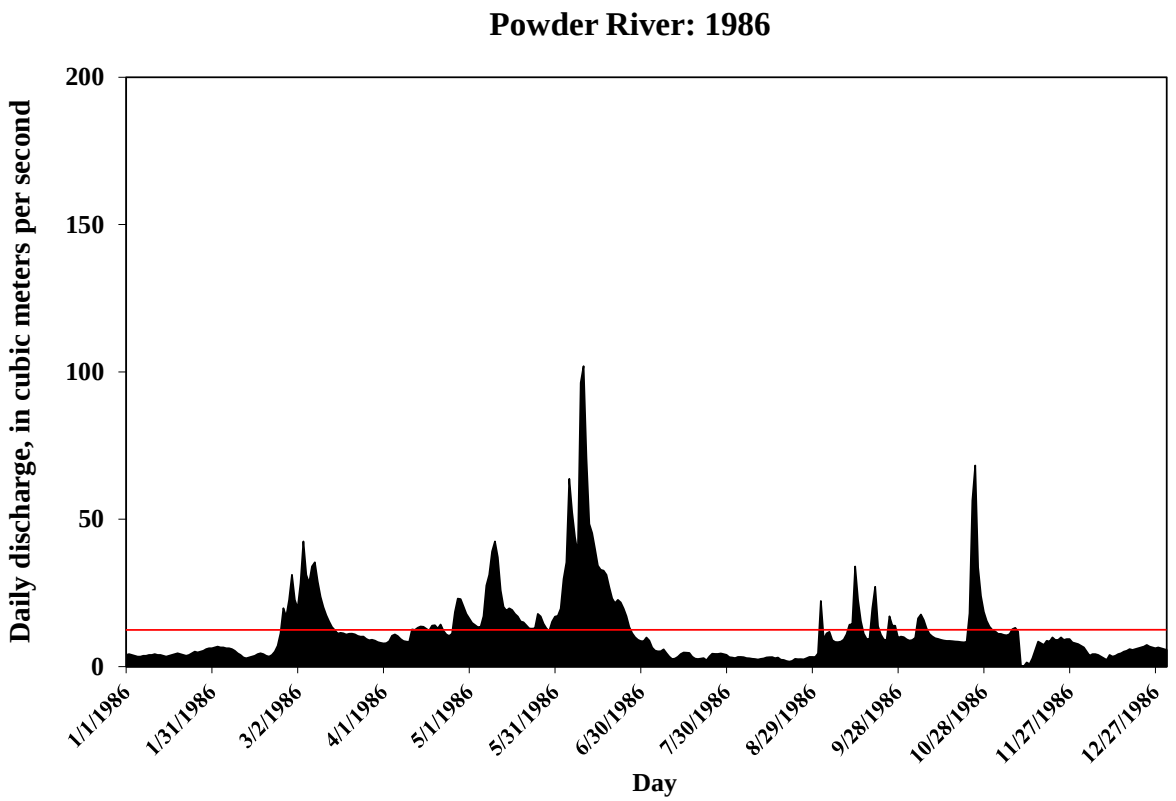
7/30/1985
8/29/1985
9/28/1985
10/28/1985
11/27/1985
12/27/1985
Day


Powder River: 1986
Daily discharge, in cubic meters per second
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150
100
50
0
1/1/1986
1/31/1986
3/2/1986
4/1/1986
5/1/1986
5/31/1986
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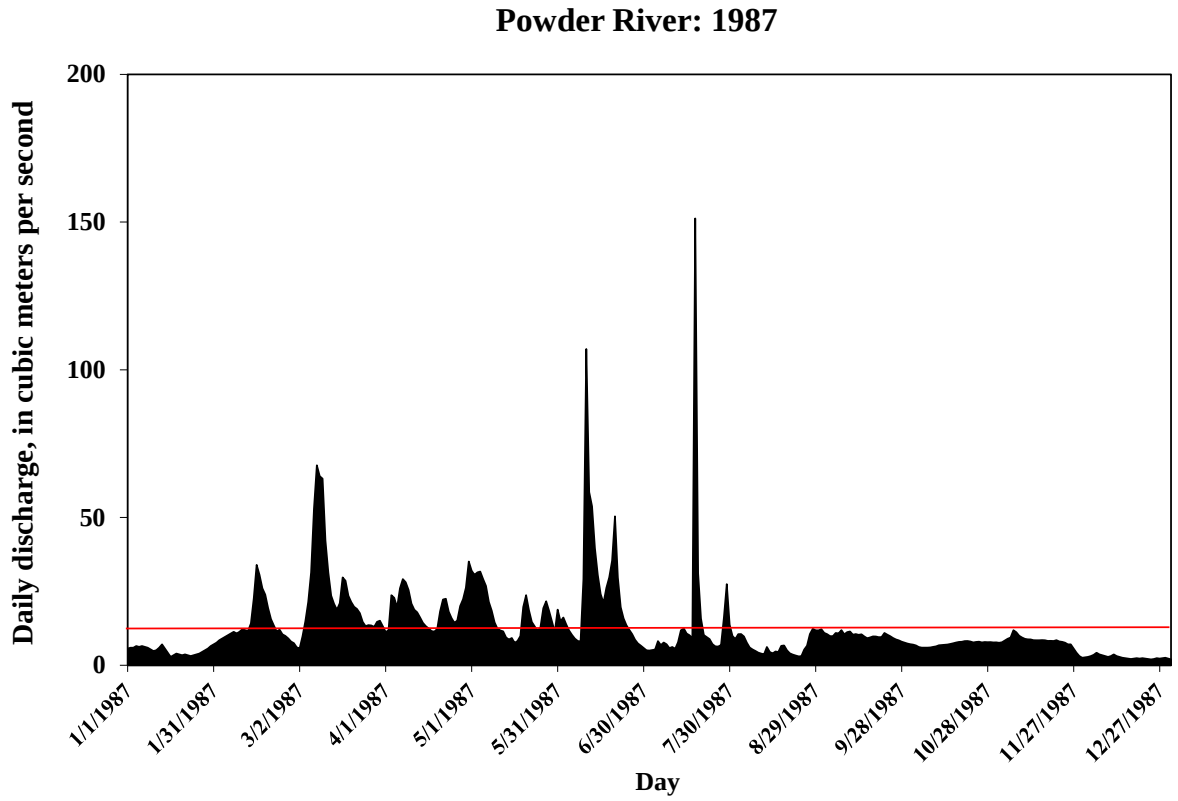
7/30/1986
8/29/1986
9/28/1986
10/28/1986
11/27/1986
12/27/1986
Day


Powder River: 1987
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1987
1/31/1987
3/2/1987
4/1/1987
5/1/1987
5/31/1987
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7/30/1987
8/29/1987
9/28/1987
10/28/1987
11/27/1987
12/27/1987
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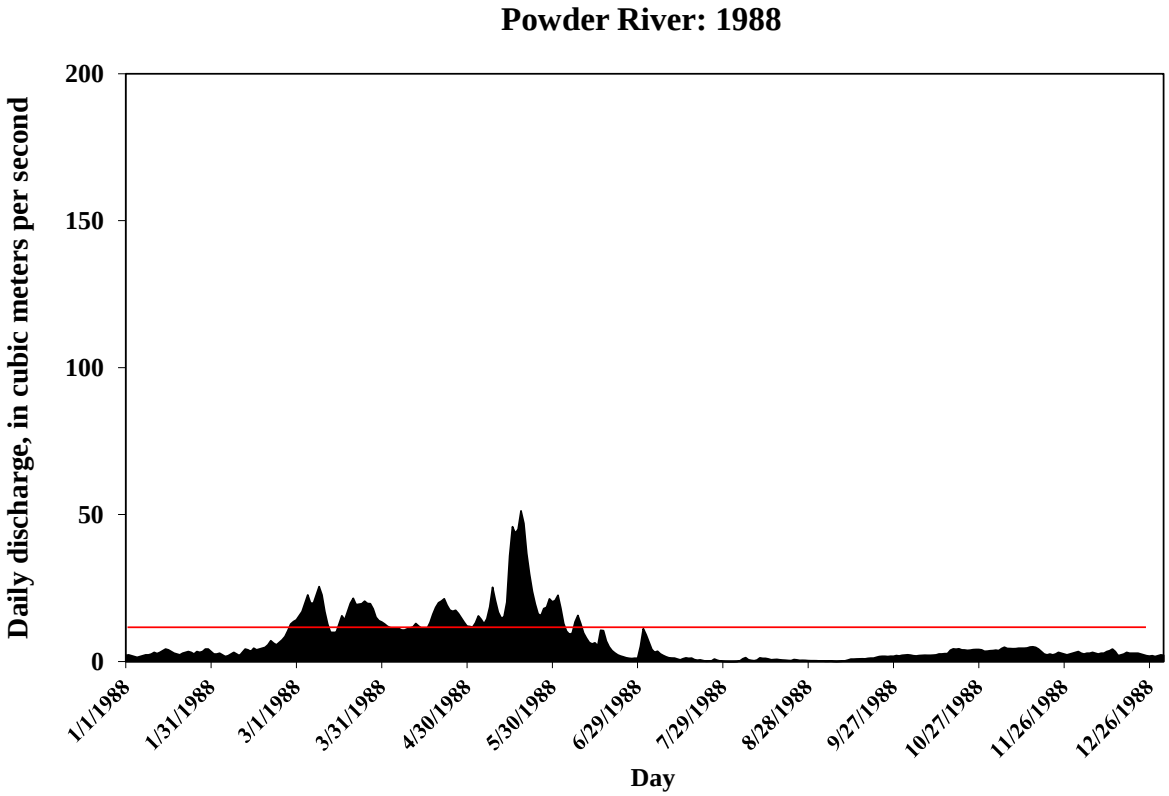
Powder River: 1988
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1988
1/31/1988
3/1/1988
3/31/1988
4/30/1988
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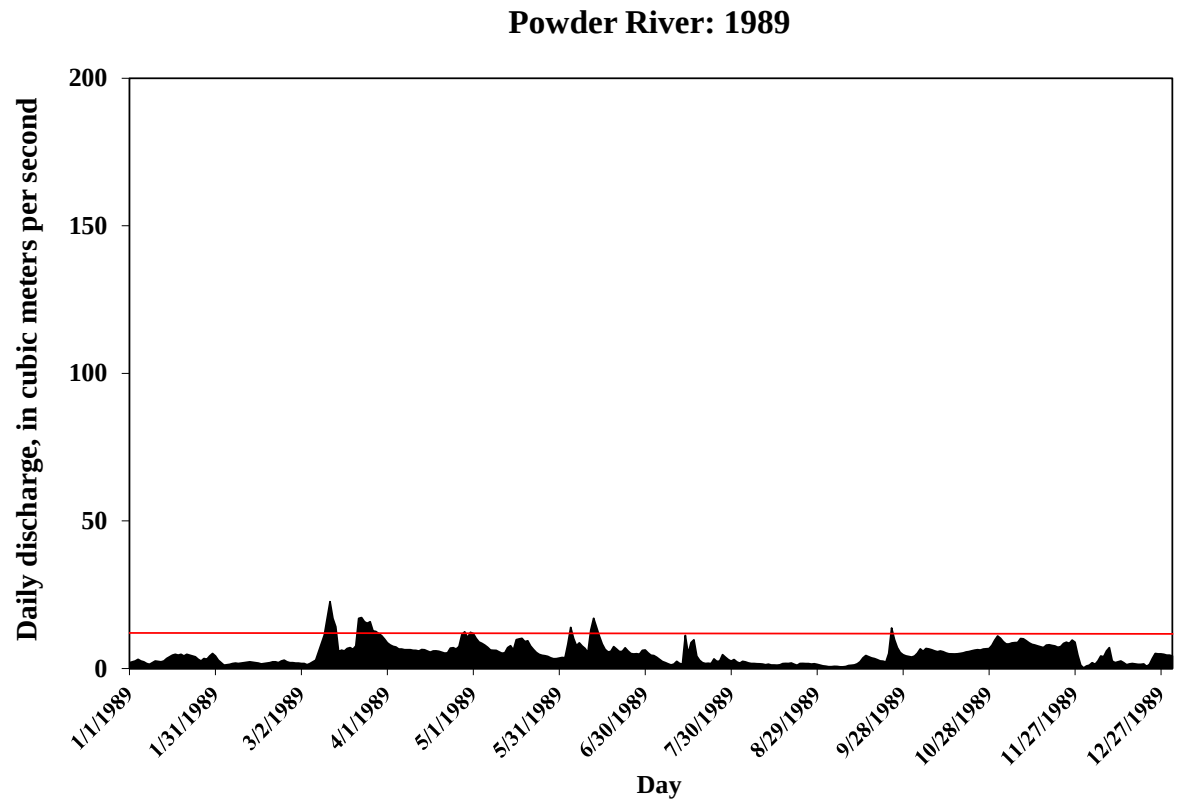
7/29/1988
8/28/1988
9/27/1988
10/27/1988
11/26/1988
12/26/1988
Day


Powder River: 1989
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1989
1/31/1989
3/2/1989
4/1/1989
5/1/1989
5/31/1989
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7/30/1989
8/29/1989
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10/28/1989
11/27/1989
12/27/1989
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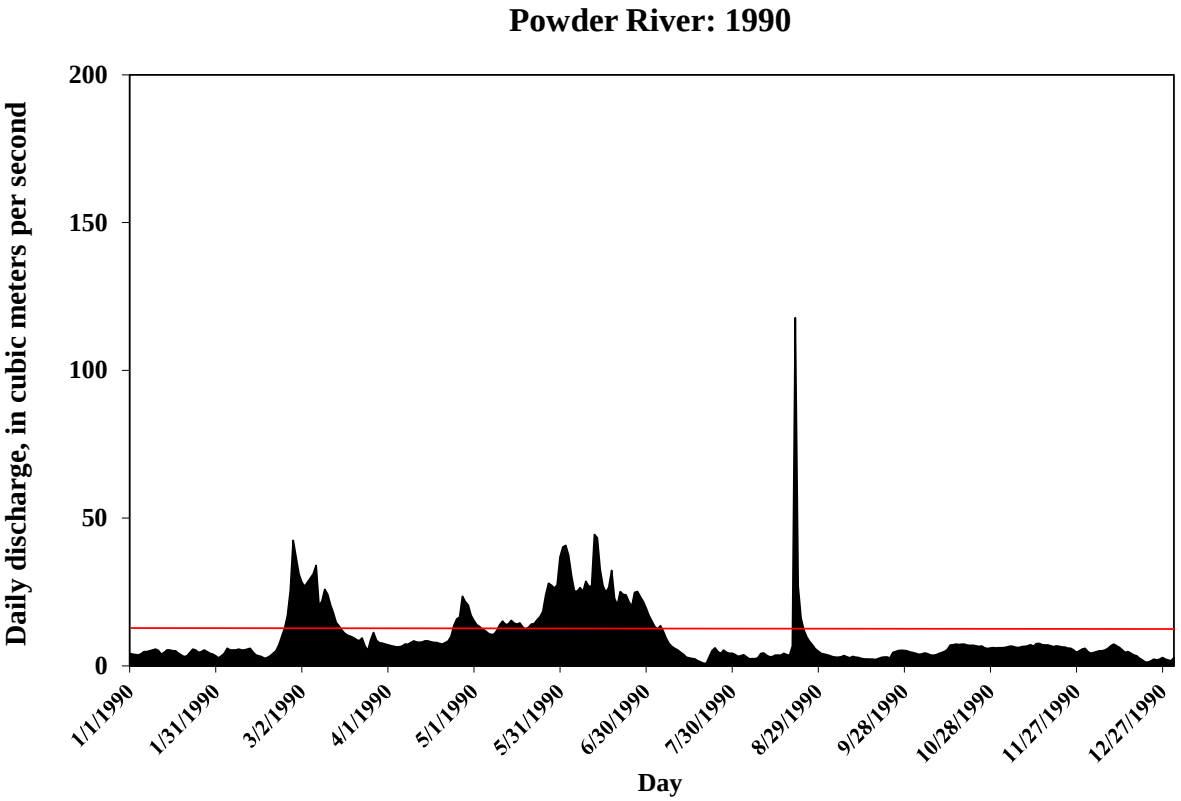
Powder River: 1990
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1990
1/31/1990
3/2/1990
4/1/1990
5/1/1990
5/31/1990
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7/30/1990
8/29/1990
9/28/1990
10/28/1990
11/27/1990
12/27/1990
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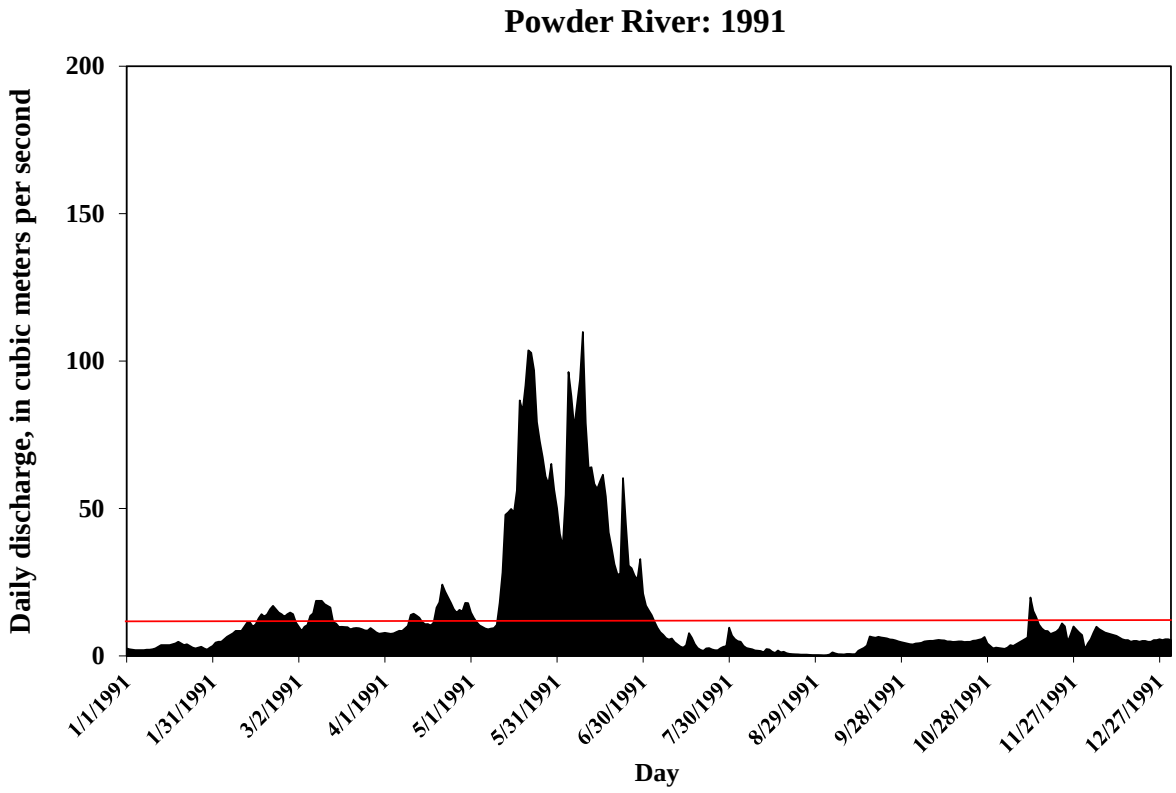
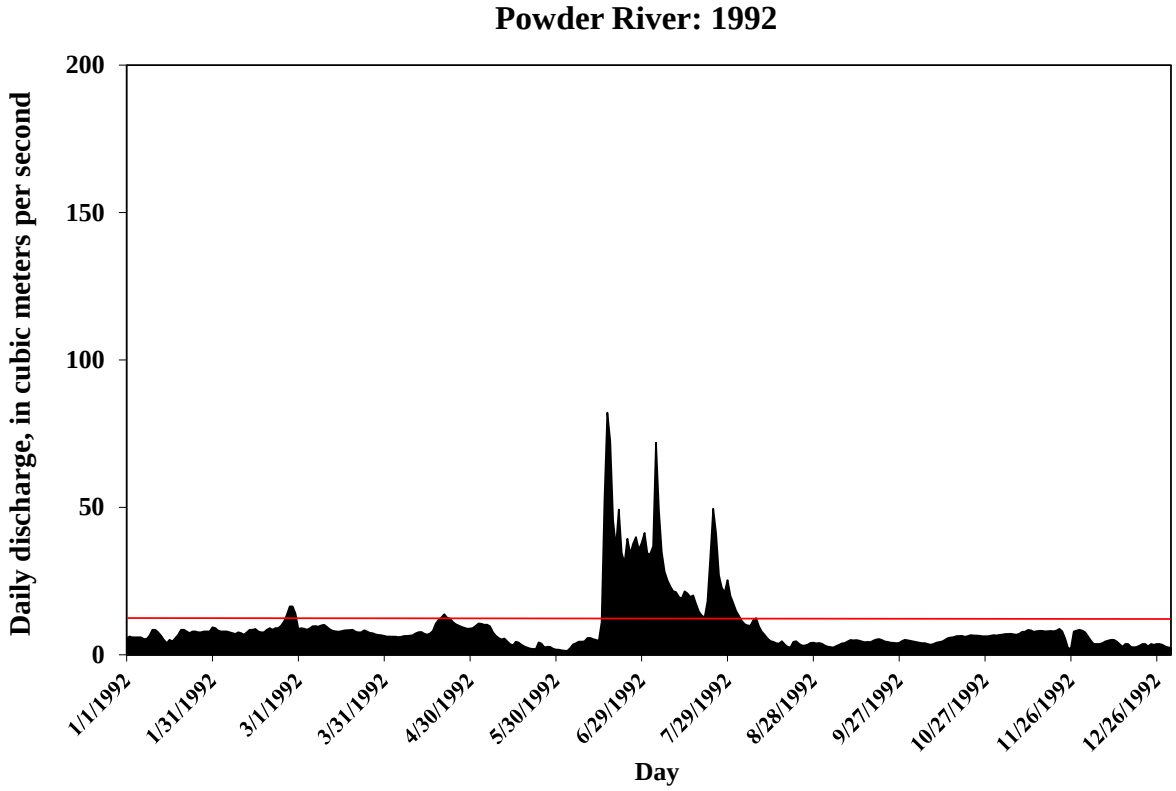
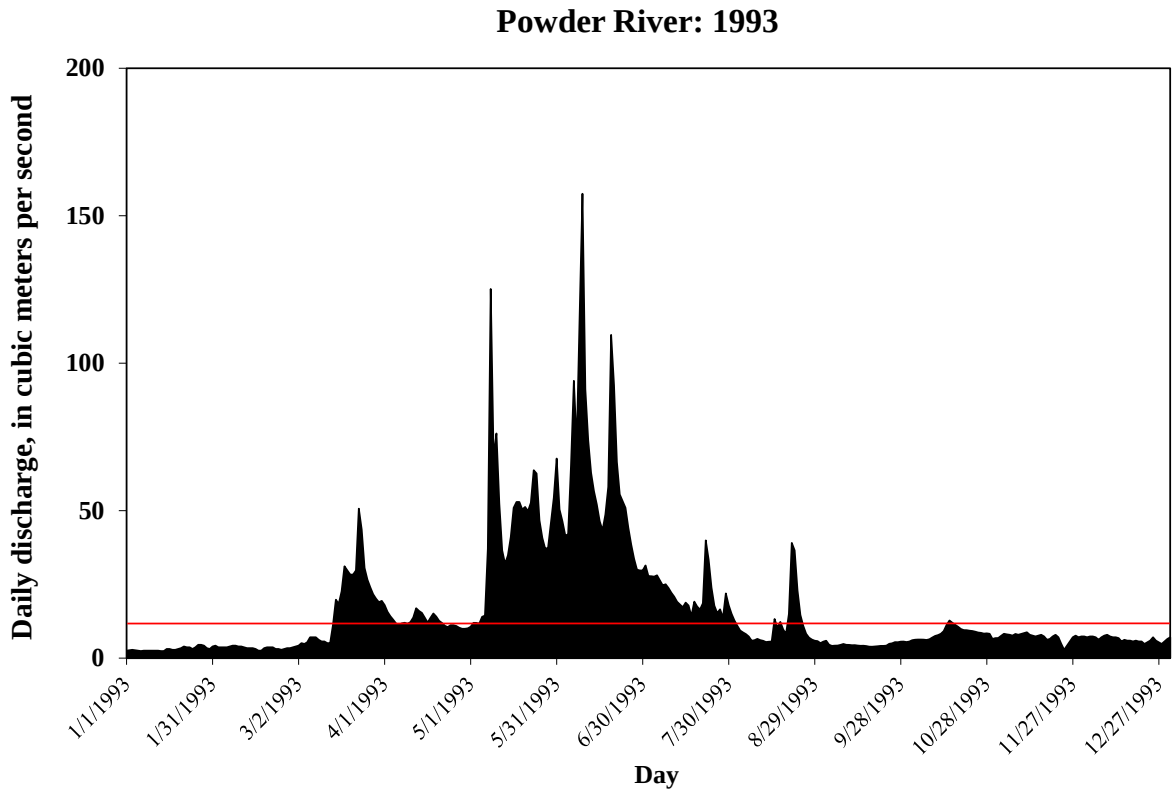
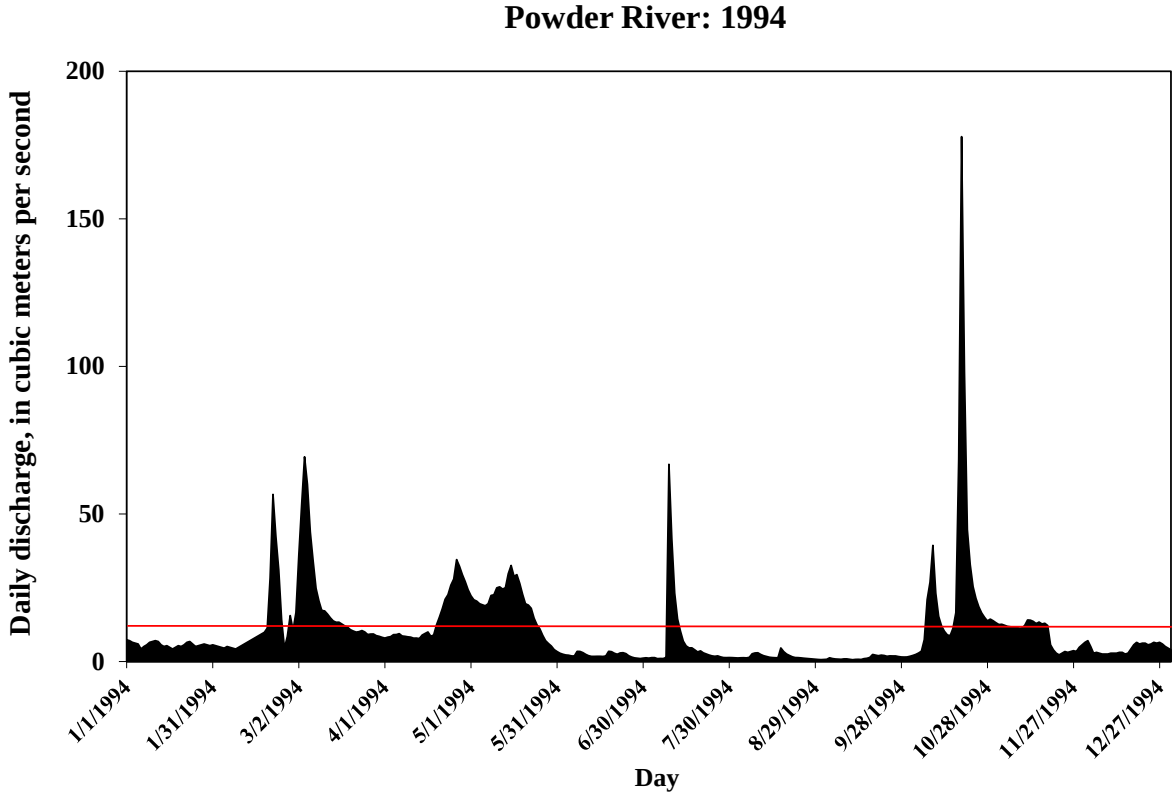
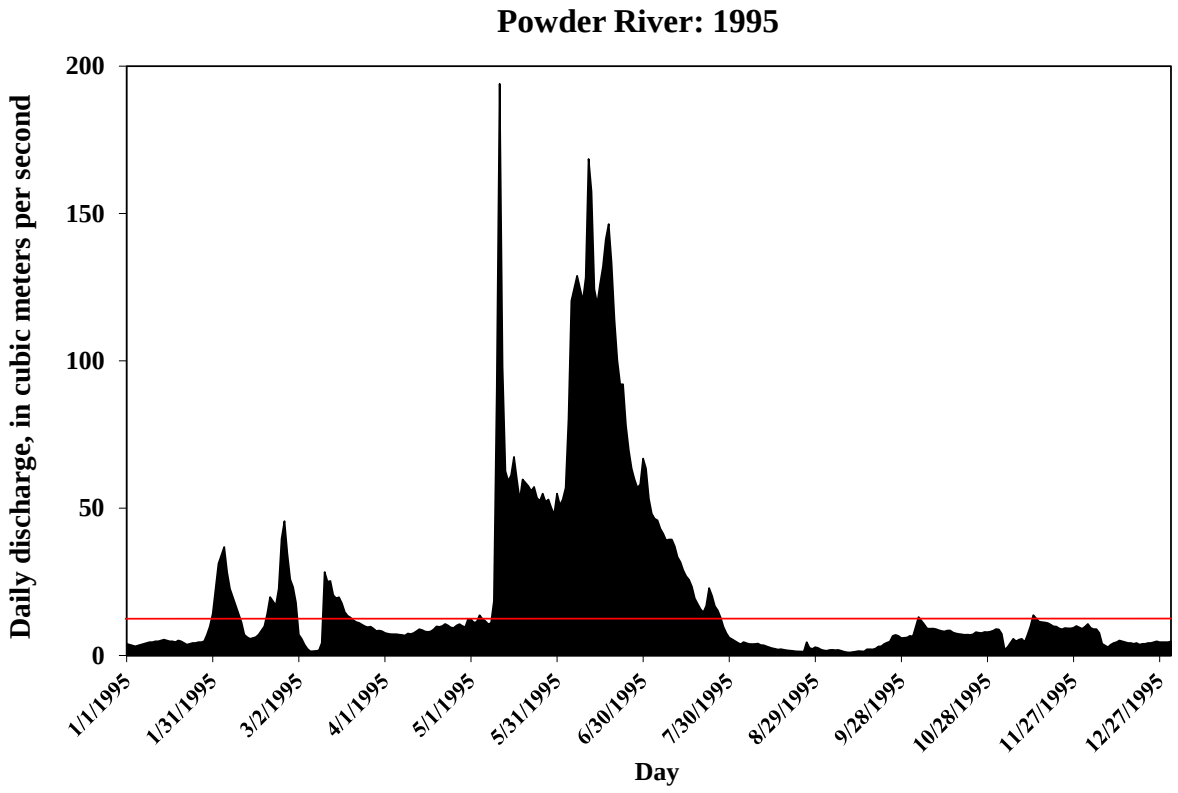
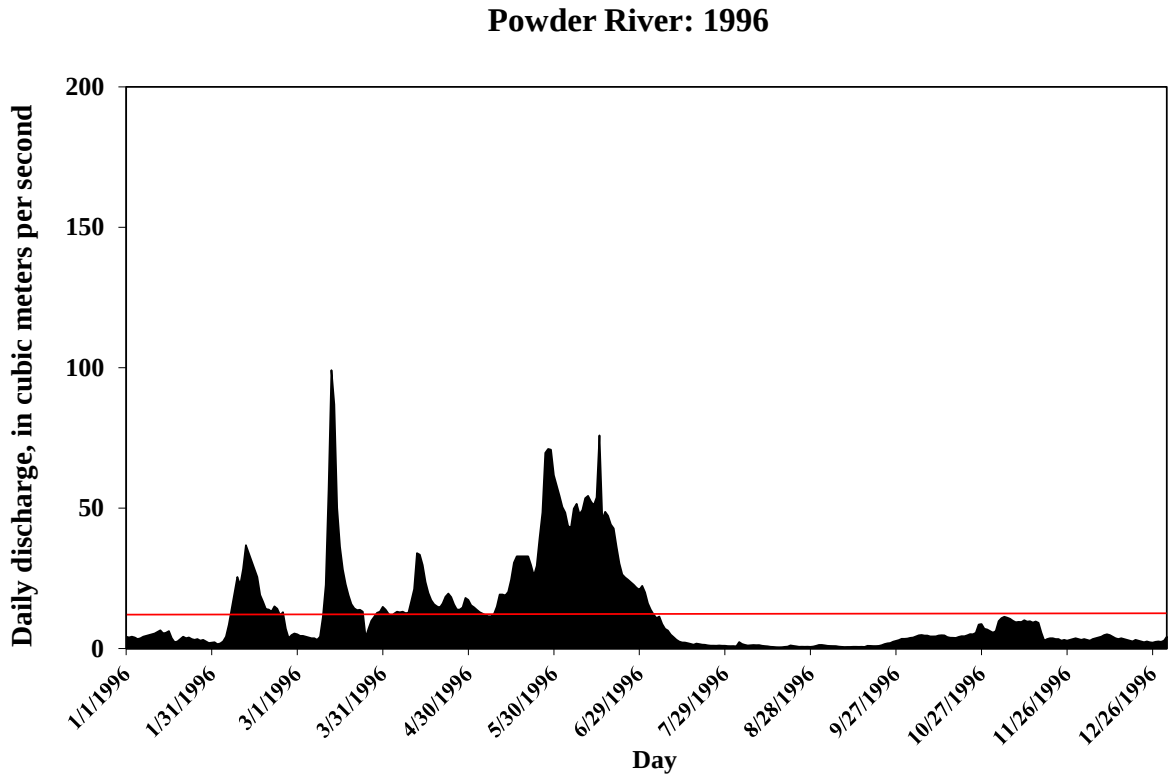

Powder River: 1991
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1991
1/31/1991
3/2/1991
4/1/1991
5/1/1991
5/31/1991
6/30/1991
7/30/1991
8/29/1991
9/28/1991
10/28/1991
11/27/1991
12/27/1991
Day

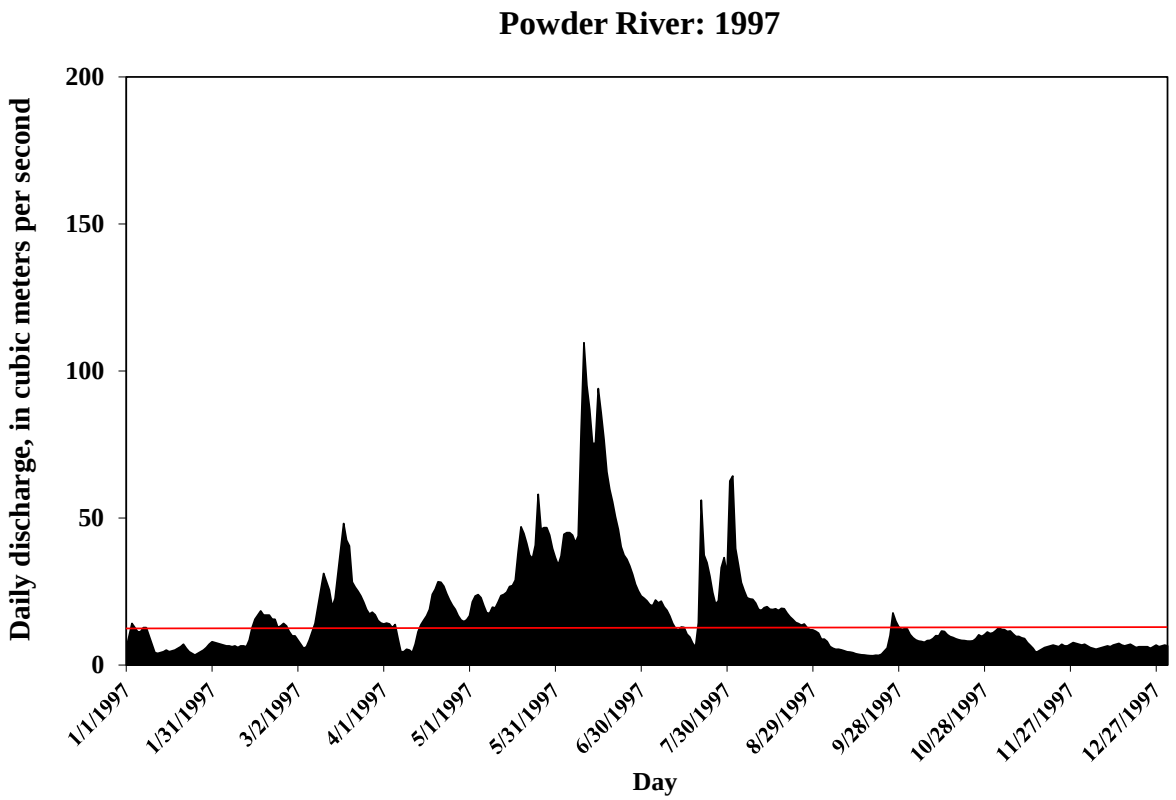

Powder River: 1992
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1992
1/31/1992
3/1/1992
3/31/1992
4/30/1992
5/30/1992
6/29/1992
7/29/1992
8/28/1992
9/27/1992
10/27/1992
11/26/1992
12/26/1992
Day

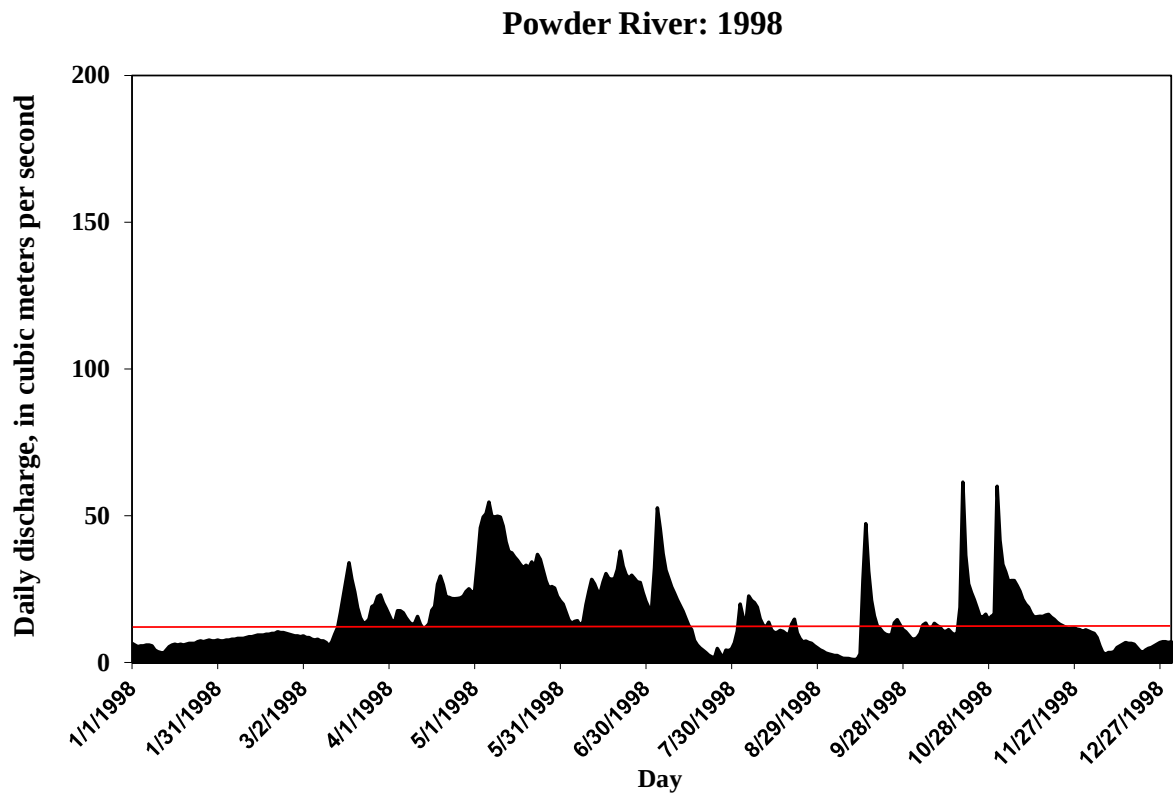

Powder River: 1993
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1993
1/31/1993
3/2/1993
4/1/1993
5/1/1993
5/31/1993
6/30/1993
7/30/1993
8/29/1993
9/28/1993
10/28/1993
11/27/1993
12/27/1993
Day

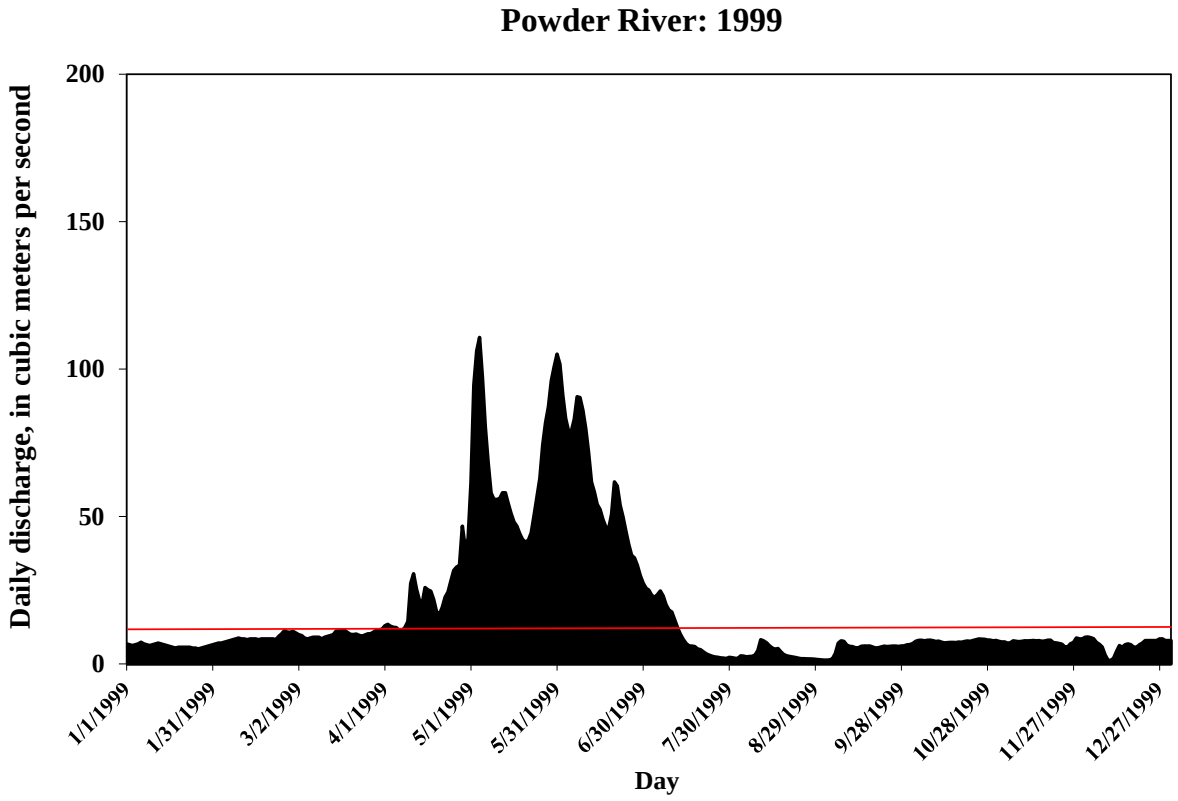

Powder River: 1994
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1994
1/31/1994
3/2/1994
4/1/1994
5/1/1994
5/31/1994
6/30/1994
7/30/1994
8/29/1994
9/28/1994
10/28/1994
11/27/1994
12/27/1994
Day

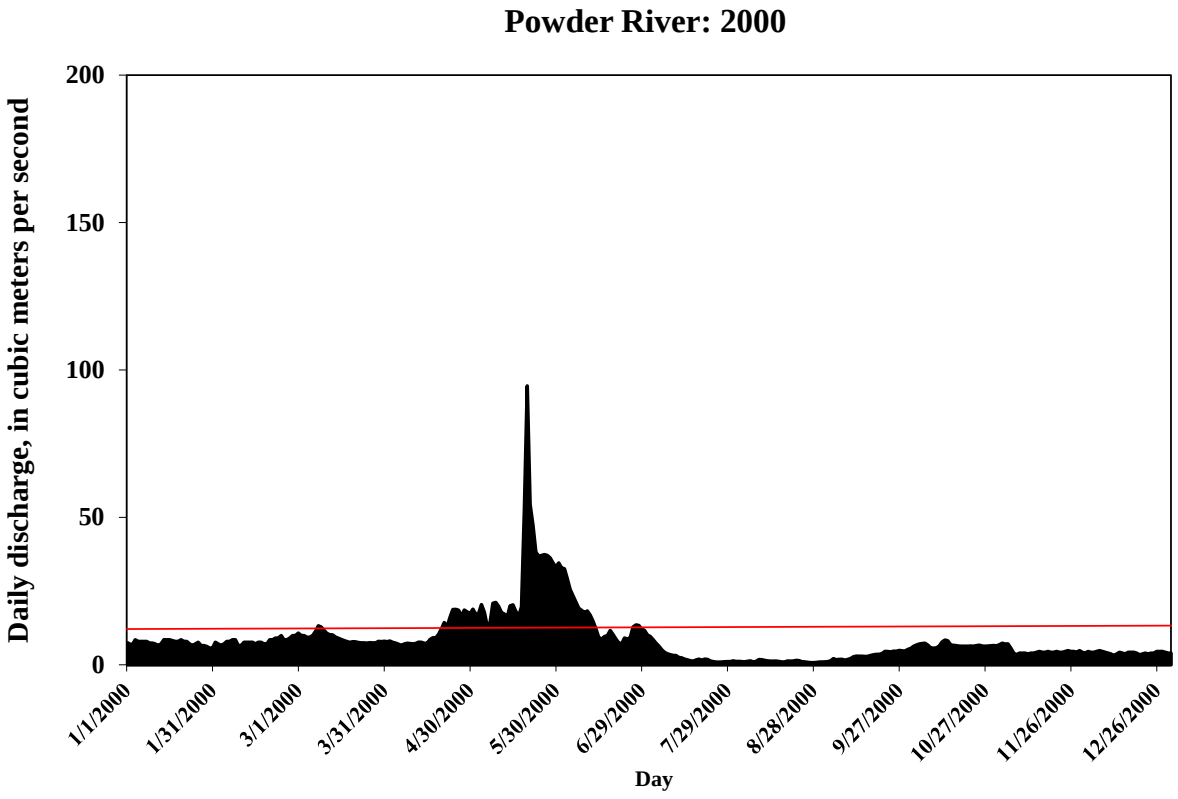

Powder River: 1995
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1995
1/31/1995
3/2/1995
4/1/1995
5/1/1995
5/31/1995
6/30/1995
7/30/1995
8/29/1995
9/28/1995
10/28/1995
11/27/1995
12/27/1995
Day


Powder River: 1996
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1996
1/31/1996
3/1/1996
3/31/1996
4/30/1996
5/30/1996
6/29/1996
7/29/1996
8/28/1996
9/27/1996
10/27/1996
11/26/1996
12/26/1996
Day


Powder River: 1997
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1997
1/31/1997
3/2/1997
4/1/1997
5/1/1997
5/31/1997
6/30/1997
7/30/1997
8/29/1997
9/28/1997
10/28/1997
11/27/1997
12/27/1997
Day


Powder River: 1998
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1998
1/31/1998
3/2/1998
4/1/1998
5/1/1998
5/31/1998
6/30/1998
7/30/1998
8/29/1998
9/28/1998
10/28/1998
11/27/1998
12/27/1998
Day


Powder River: 1999
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/1999
1/31/1999
3/2/1999
4/1/1999
5/1/1999
5/31/1999
6/30/1999
7/30/1999
8/29/1999
9/28/1999
10/28/1999
11/27/1999
12/27/1999
Day


Powder River: 2000
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2000
1/31/2000
3/1/2000
3/31/2000
4/30/2000
5/30/2000
6/29/2000
7/29/2000
8/28/2000
9/27/2000
10/27/2000
11/26/2000
12/26/2000
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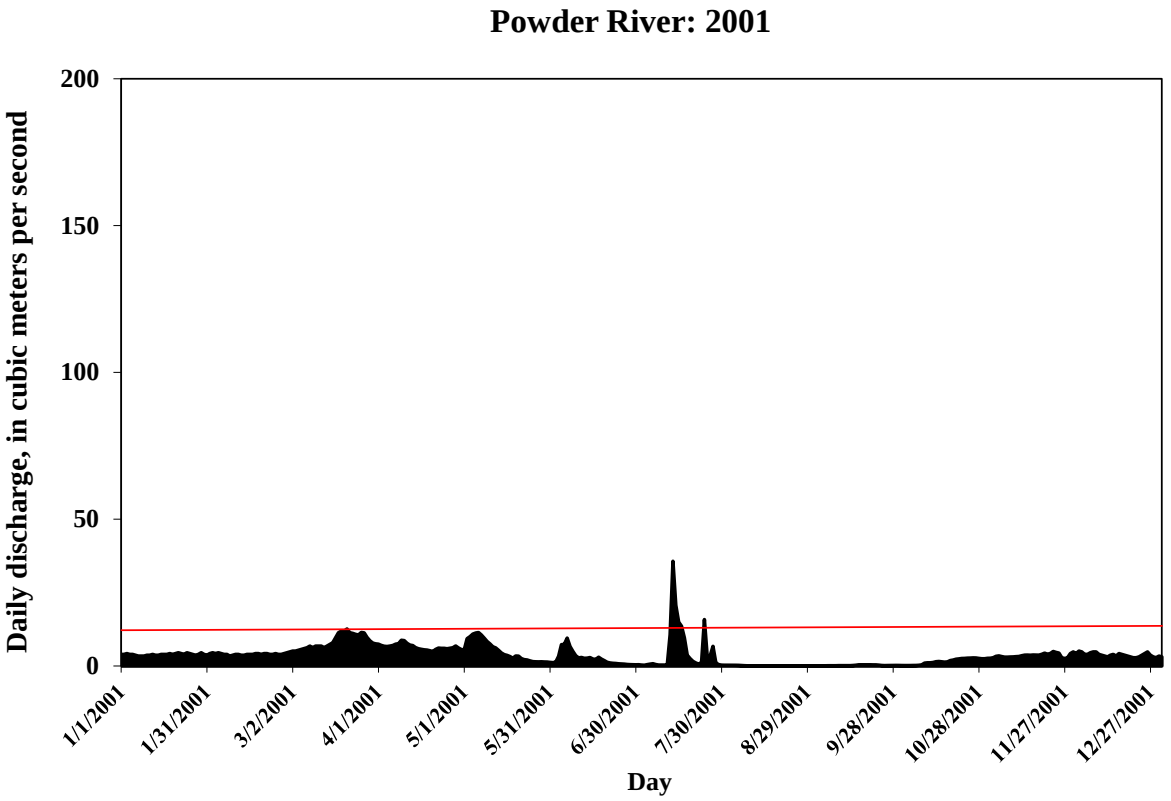
Powder River: 2001
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2001
1/31/2001
3/2/2001
4/1/2001
5/1/2001
5/31/2001
6/30/2001
7/30/2001
8/29/2001
9/28/2001
10/28/2001
11/27/2001
12/27/2001
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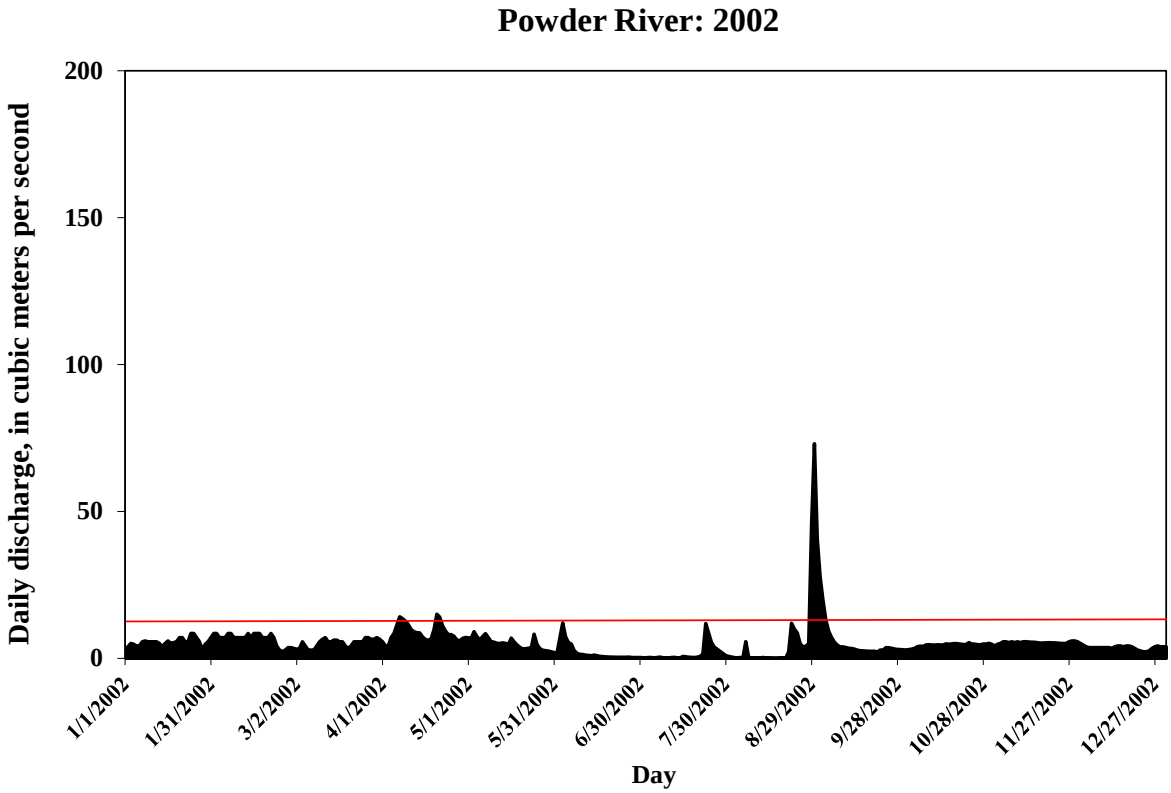
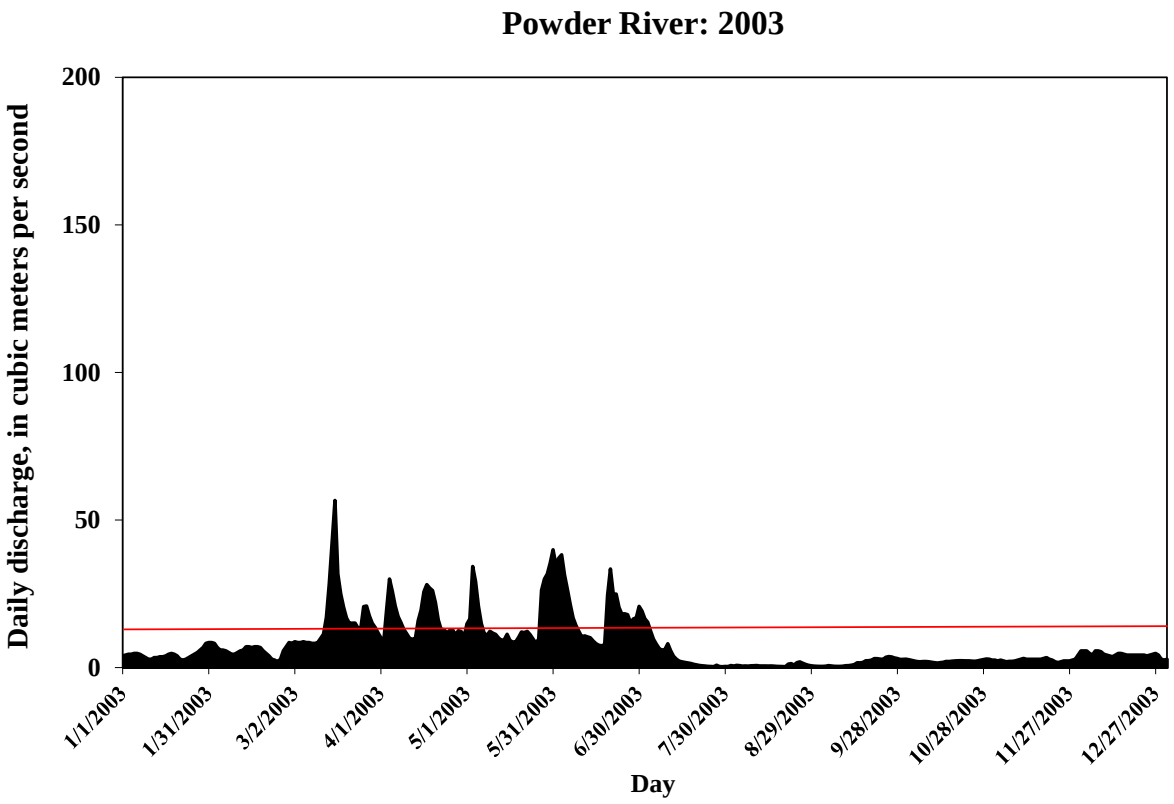
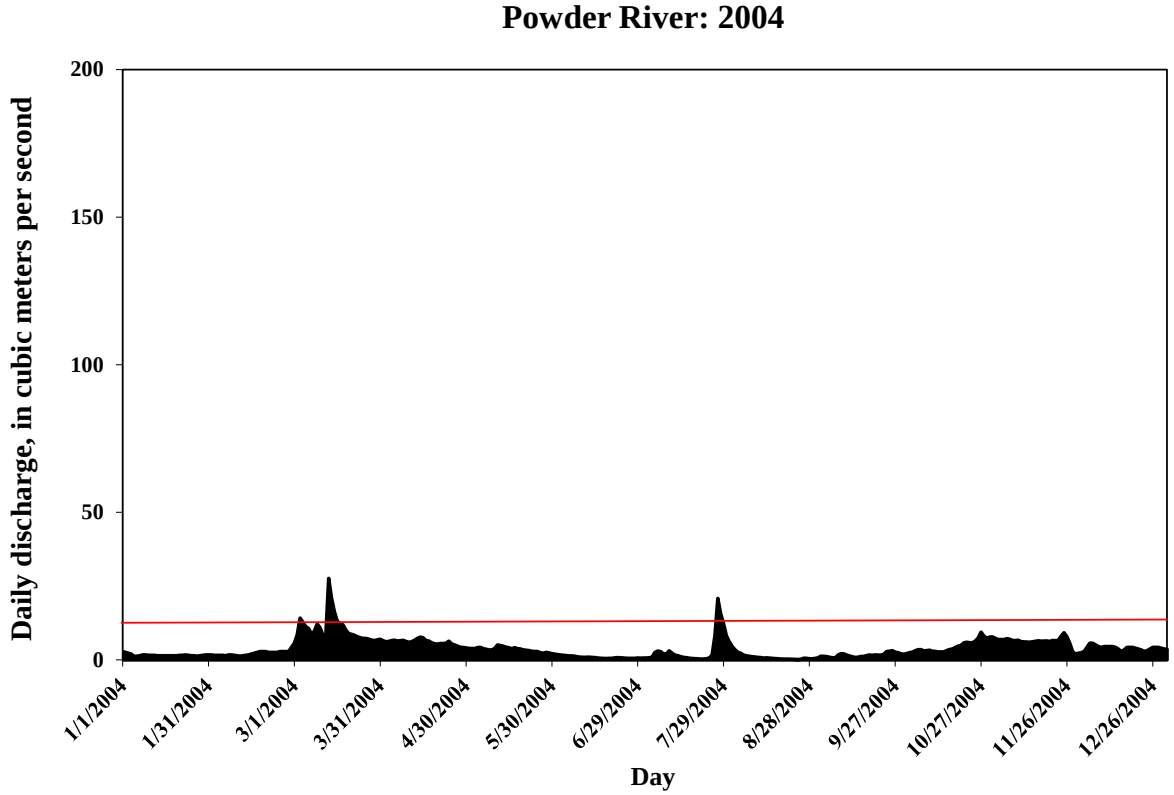
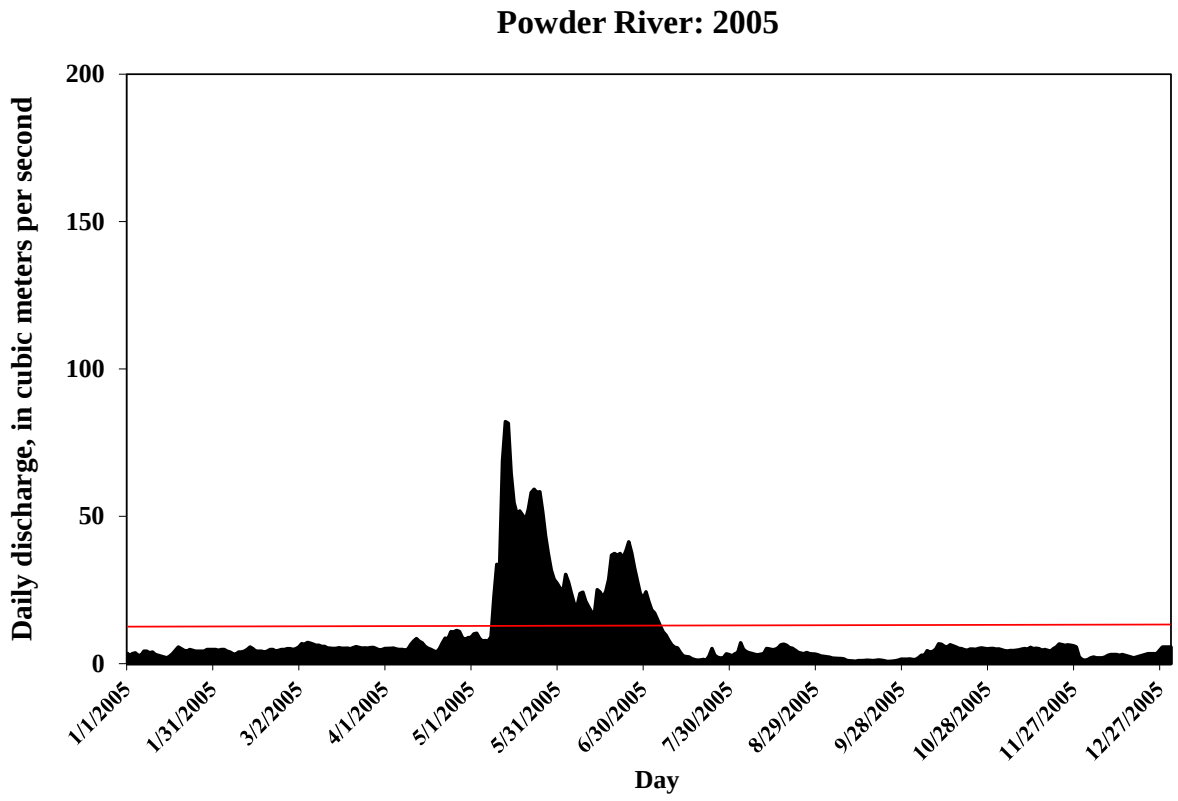
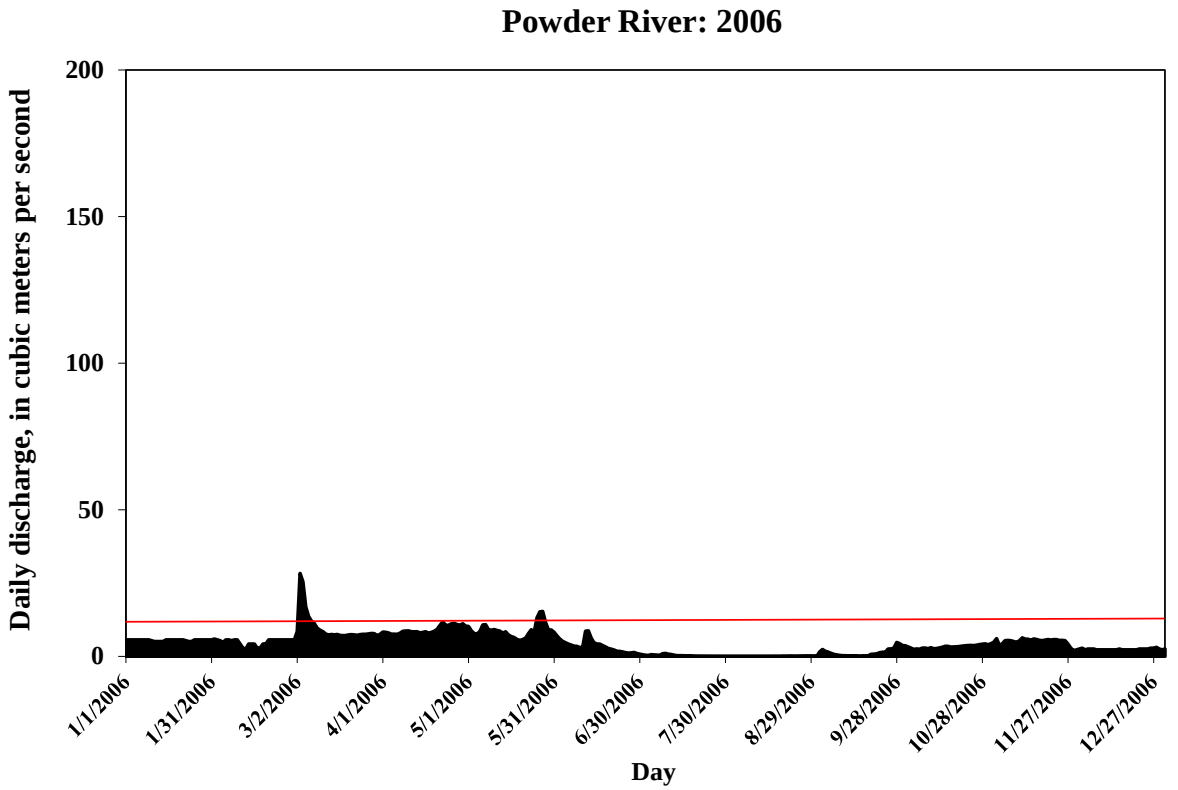
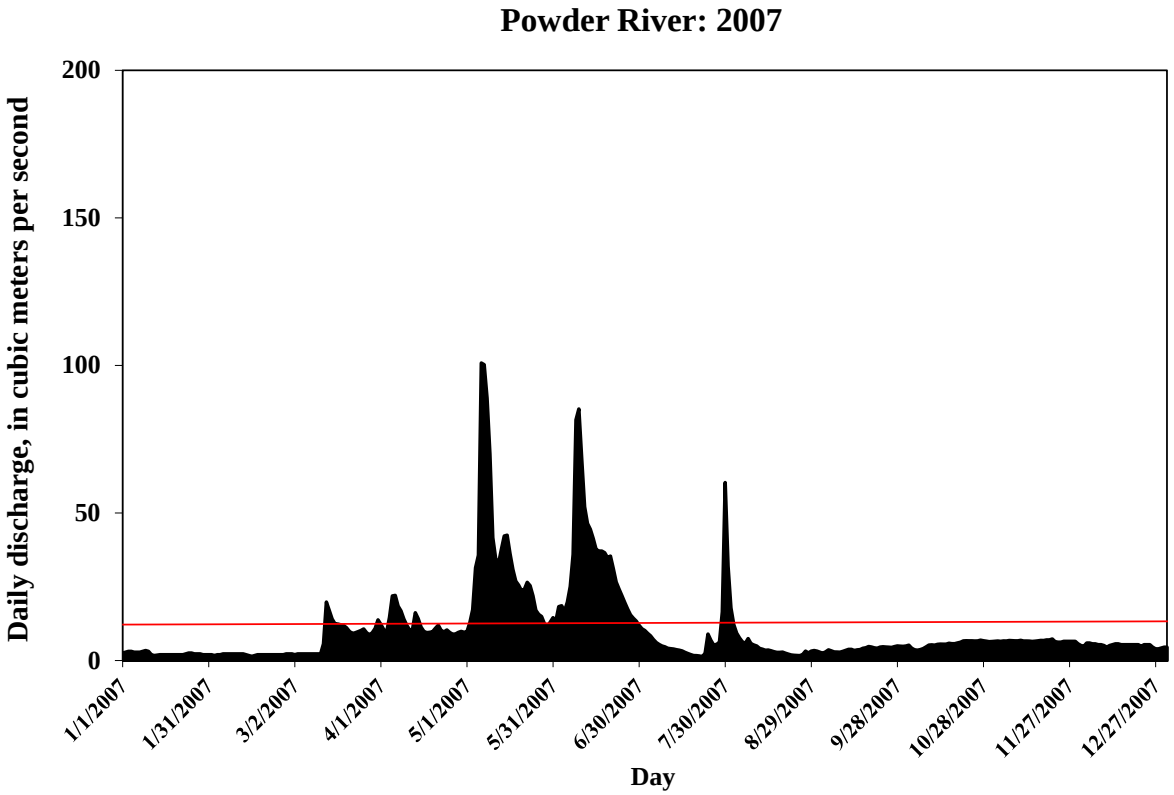

Powder River: 2002
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2002
1/31/2002
3/2/2002
4/1/2002
5/1/2002
5/31/2002
6/30/2002
7/30/2002
8/29/2002
9/28/2002
10/28/2002
11/27/2002
12/27/2002
Day

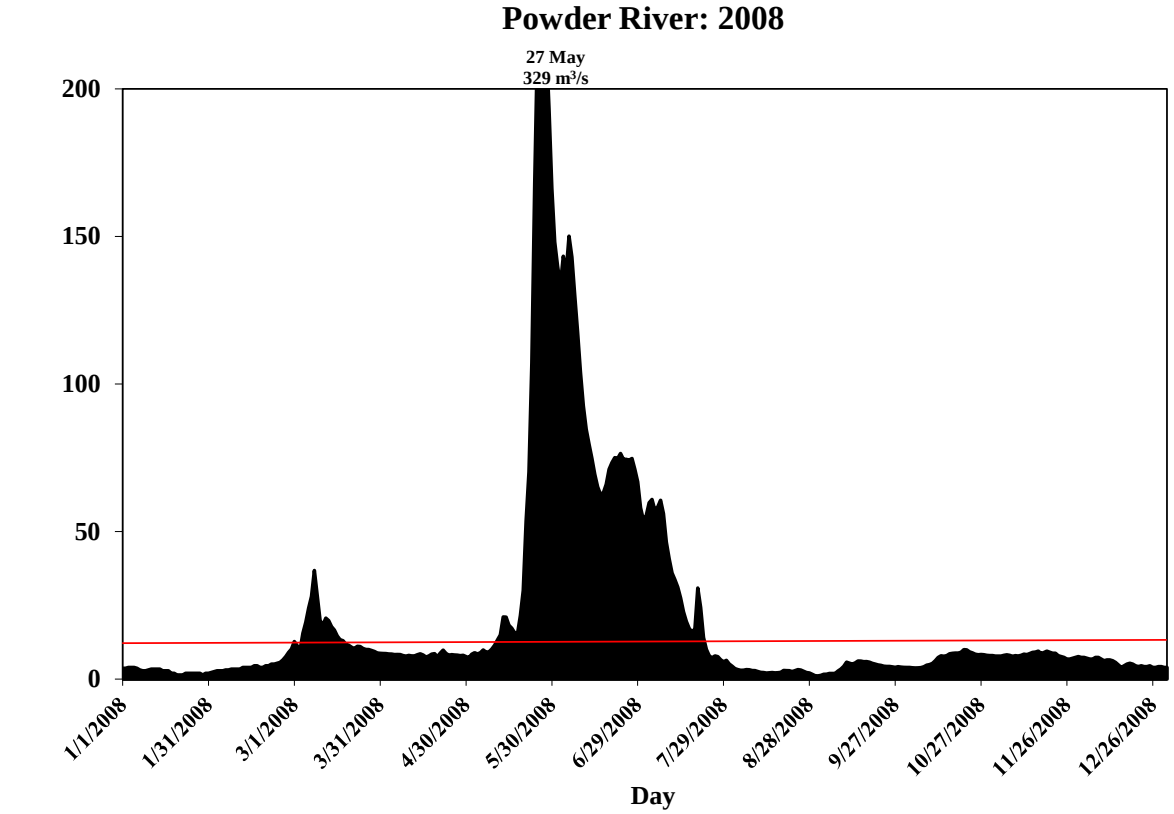

Powder River: 2003
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2003
1/31/2003
3/2/2003
4/1/2003
5/1/2003
5/31/2003
6/30/2003
7/30/2003
8/29/2003
9/28/2003
10/28/2003
11/27/2003
12/27/2003
Day


Powder River: 2004
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2004
1/31/2004
3/1/2004
3/31/2004
4/30/2004
5/30/2004
6/29/2004
7/29/2004
8/28/2004
9/27/2004
10/27/2004
11/26/2004
12/26/2004
Day


Powder River: 2005
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2005
1/31/2005
3/2/2005
4/1/2005
5/1/2005
5/31/2005
6/30/2005
7/30/2005
8/29/2005
9/28/2005
10/28/2005
11/27/2005
12/27/2005
Day


Powder River: 2006
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2006
1/31/2006
3/2/2006
4/1/2006
5/1/2006
5/31/2006
6/30/2006
7/30/2006
8/29/2006
9/28/2006
10/28/2006
11/27/2006
12/27/2006
Day


Powder River: 2007
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2007
1/31/2007
3/2/2007
4/1/2007
5/1/2007
5/31/2007
6/30/2007
7/30/2007
8/29/2007
9/28/2007
10/28/2007
11/27/2007
12/27/2007
Day


Powder River: 2008
27 May
329 m3/s
200
150
100
50
0
1/1/2008
1/31/2008
3/1/2008
3/31/2008
4/30/2008
5/30/2008
6/29/2008
7/29/2008
8/28/2008
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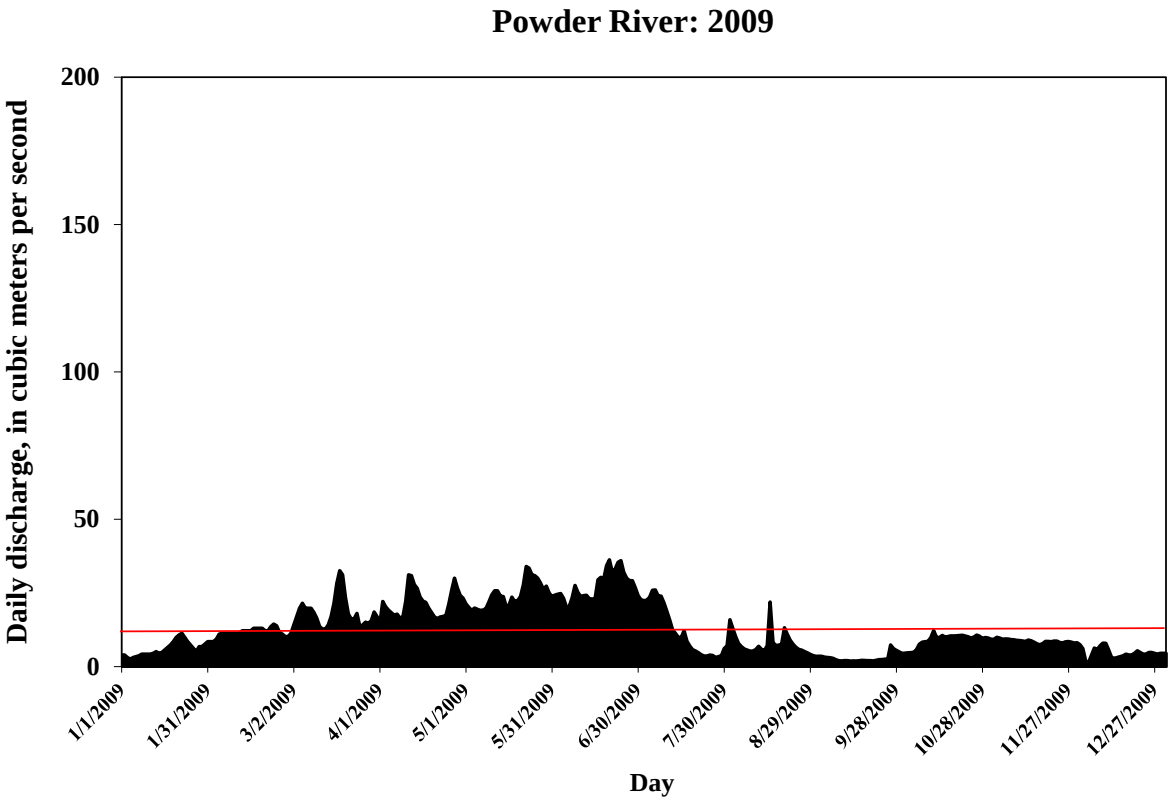
12/26/2008
Day


Powder River: 2009
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2009
1/31/2009
3/2/2009
4/1/2009
5/1/2009
5/31/2009
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7/30/2009
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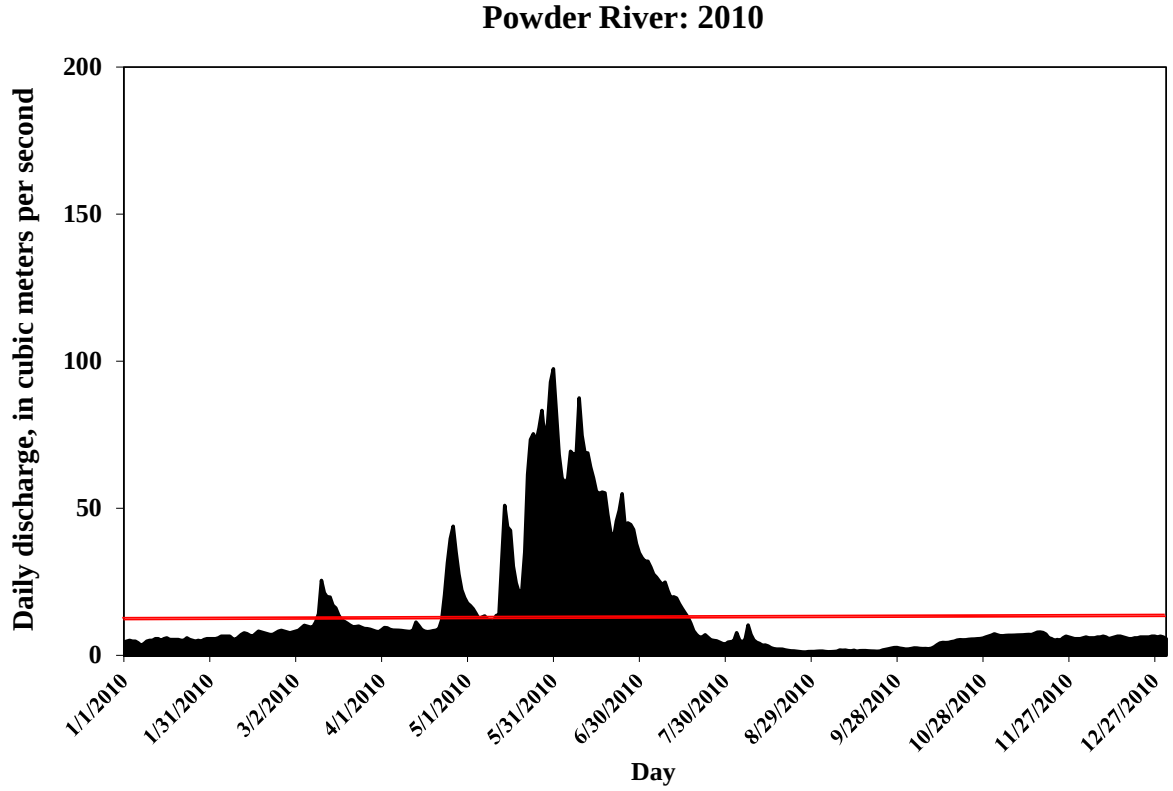
Day


Powder River: 2010
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2010
1/31/2010
3/2/2010
4/1/2010
5/1/2010
5/31/2010
6/30/2010
7/30/2010
8/29/2010
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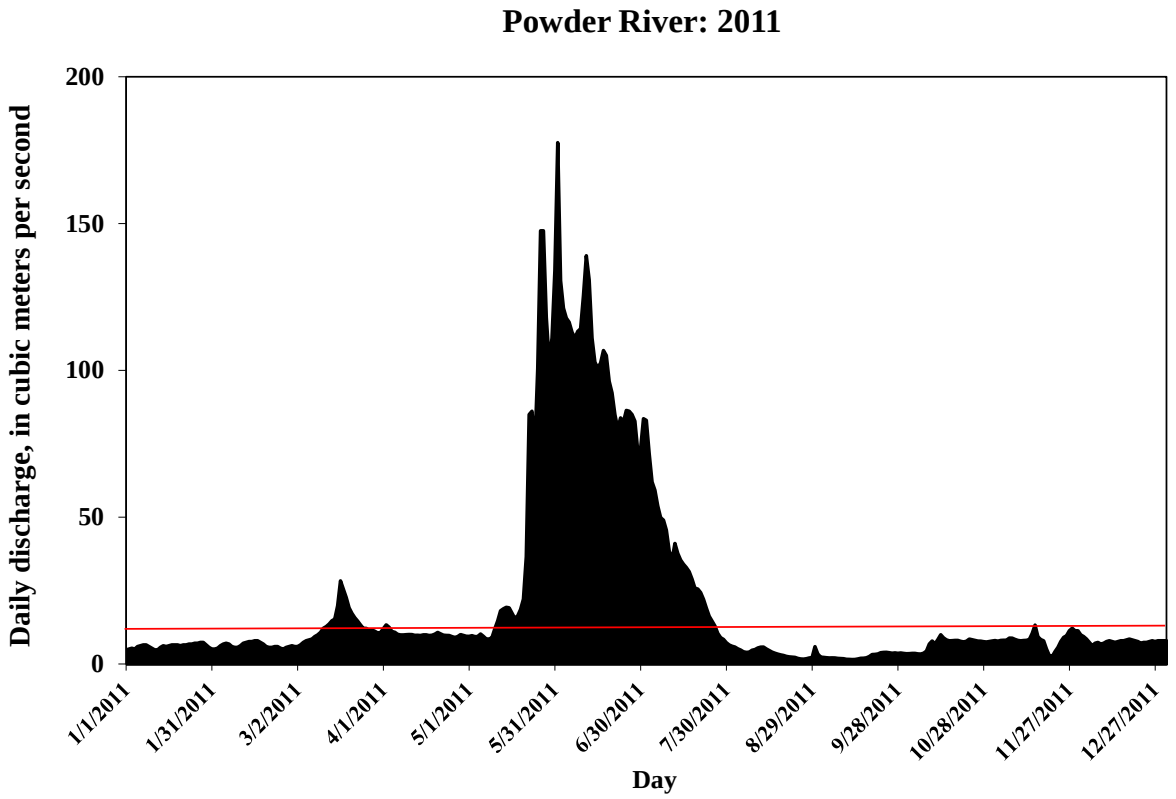
Day


Powder River: 2011
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2011
1/31/2011
3/2/2011
4/1/2011
5/1/2011
5/31/2011
6/30/2011
7/30/2011
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10/28/2011
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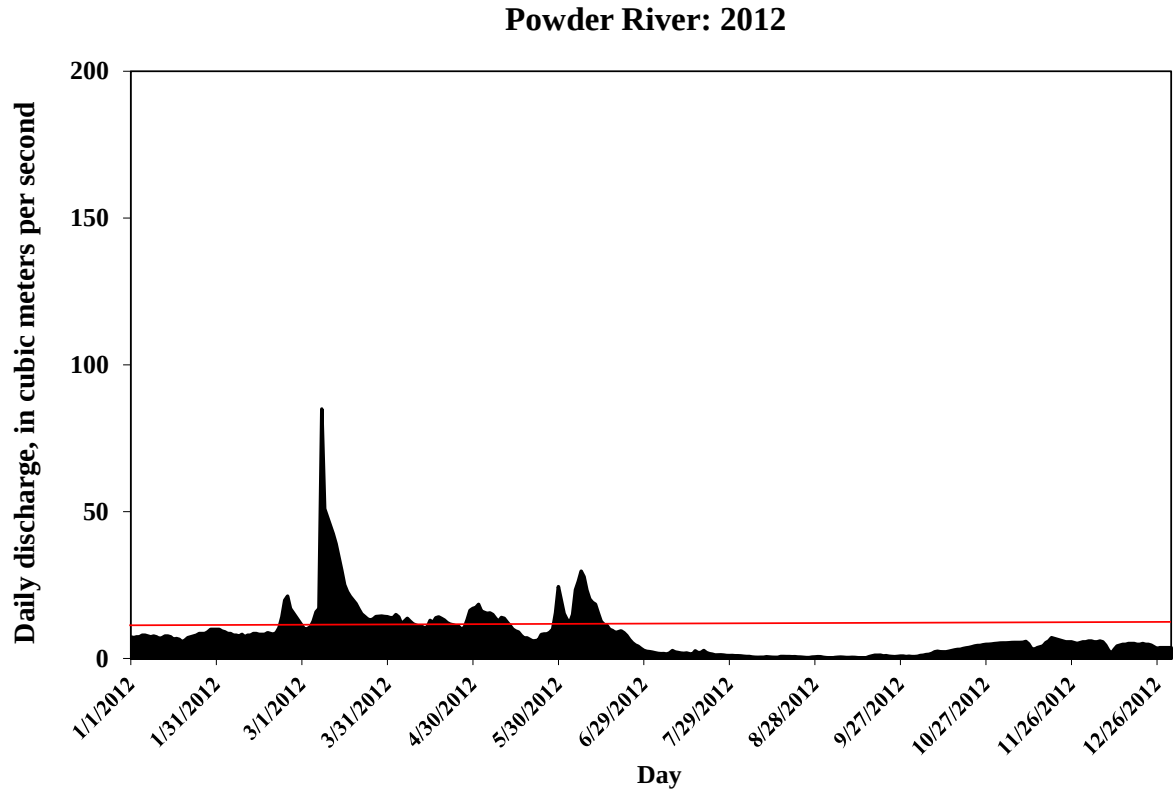
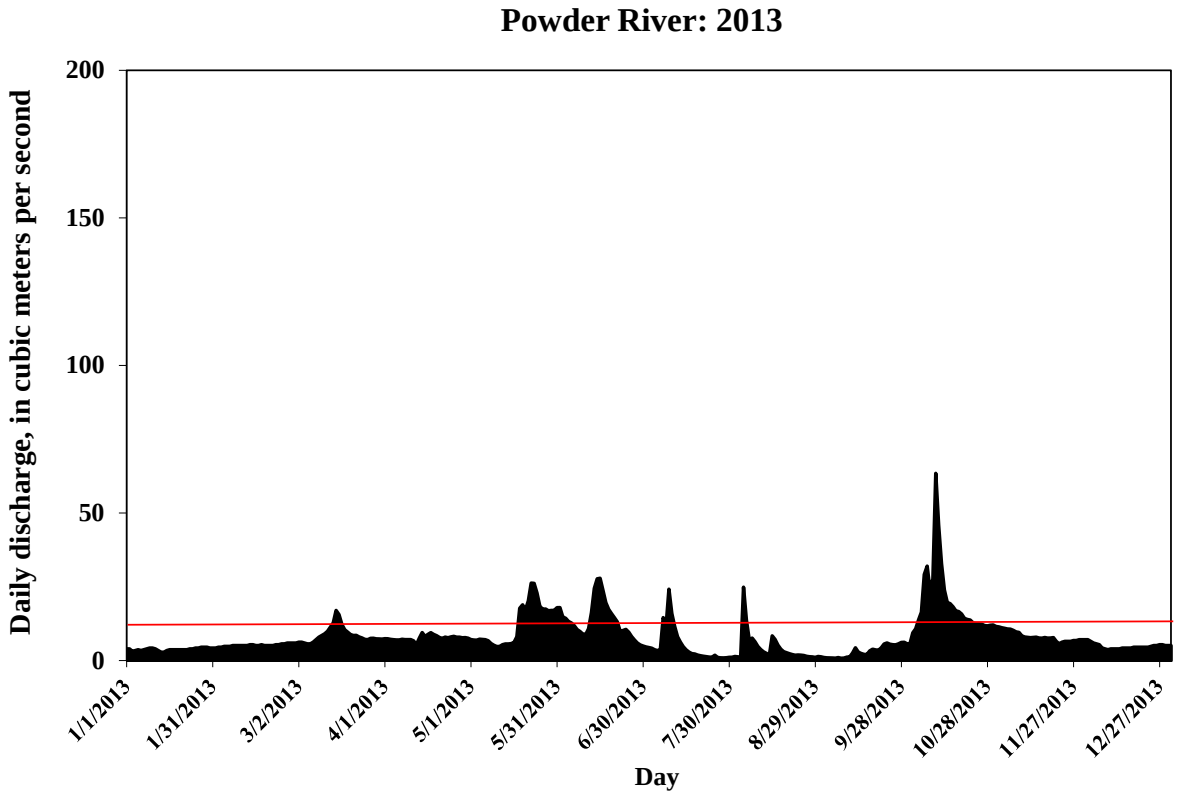
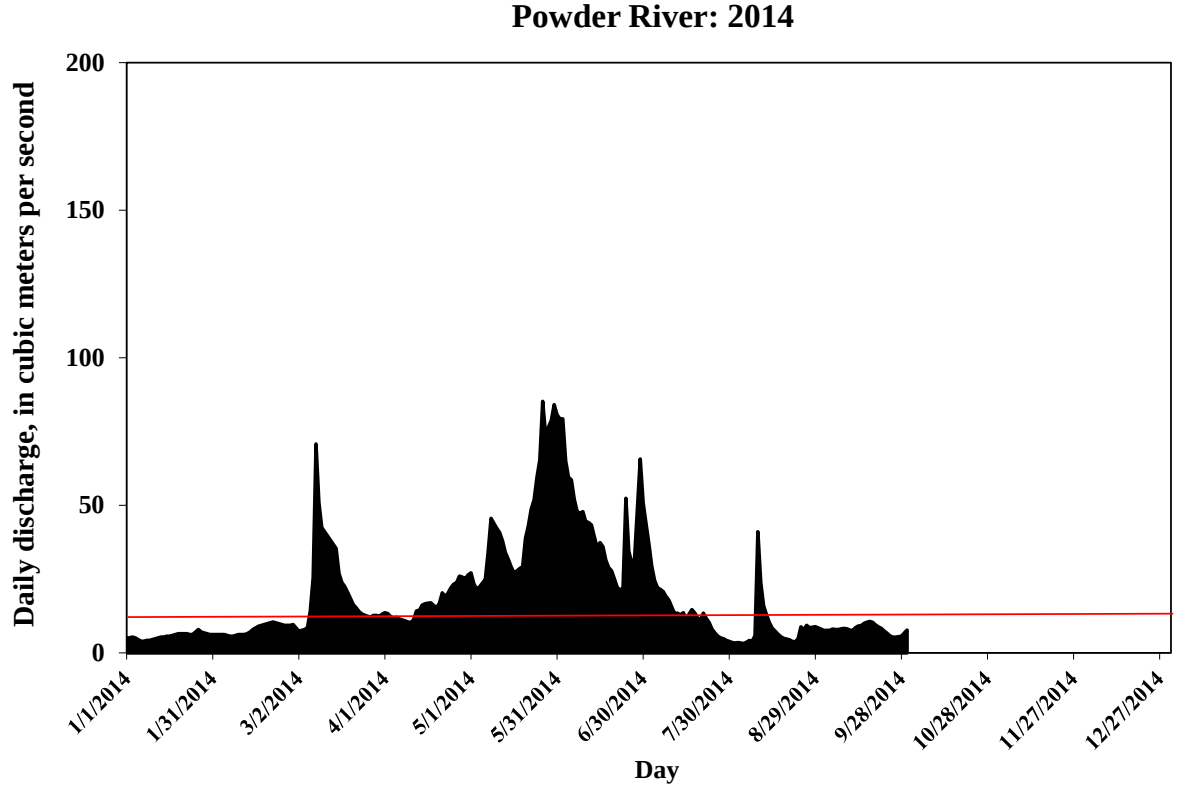
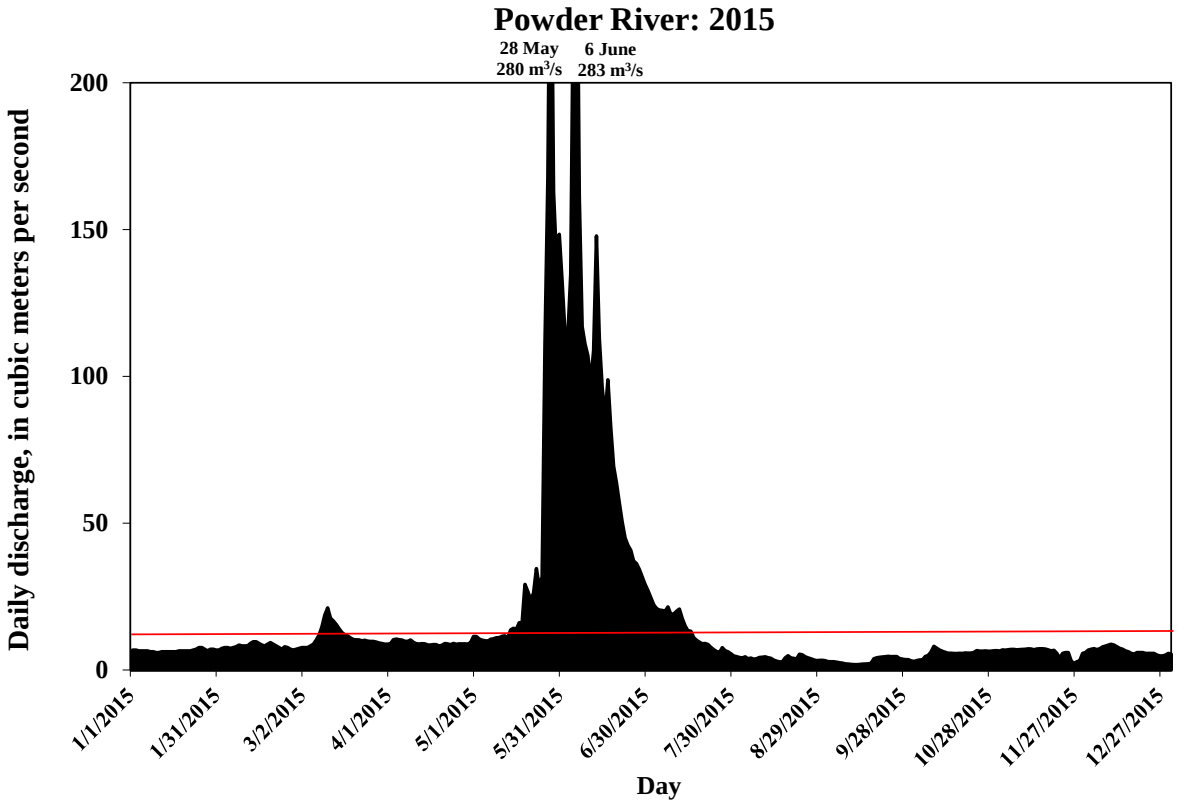
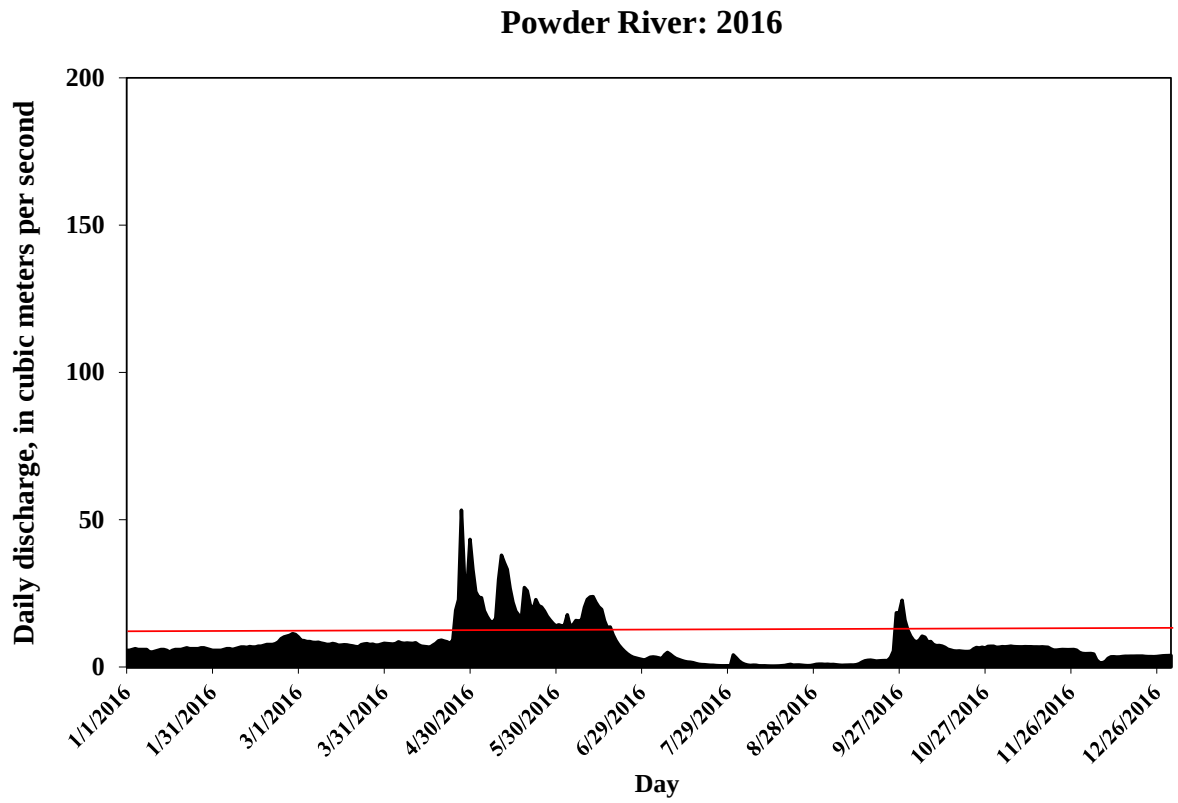
12/27/2011
Day


Powder River: 2012
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2012
1/31/2012
3/1/2012
3/31/2012
4/30/2012
5/30/2012
6/29/2012
7/29/2012
8/28/2012
9/27/2012
10/27/2012
11/26/2012
12/26/2012
Day


Powder River: 2013
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2013
1/31/2013
3/2/2013
4/1/2013
5/1/2013
5/31/2013
6/30/2013
7/30/2013
8/29/2013
9/28/2013
10/28/2013
11/27/2013
12/27/2013
Day


Powder River: 2014
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2014
1/31/2014
3/2/2014
4/1/2014
5/1/2014
5/31/2014
6/30/2014
7/30/2014
8/29/2014
9/28/2014
10/28/2014
11/27/2014
12/27/2014
Day


Powder River: 2015
28 May
280 m³/s
6 June
283 m³/s
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2015
1/31/2015
3/2/2015
4/1/2015
5/1/2015
5/31/2015
6/30/2015
7/30/2015
8/29/2015
9/28/2015
10/28/2015
11/27/2015
12/27/2015
Day


Powder River: 2016
Daily discharge, in cubic meters per second
200
150
100
50
0
1/1/2016
1/31/2016
3/1/2016
3/31/2016
4/30/2016
5/30/2016
6/29/2016
7/29/2016
8/28/2016
9/27/2016
10/27/2016
11/26/2016
12/26/2016
Day

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For additional information visit https://wwwbrr.cr.usgs.gov/projects/GEOMORPH_Powder_River/

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