RECLAMATION
Managing Water in the West

Technical Report No. SRH-2010-1

Bighorn River Side Channel Investigation: Geomorphic Analysis

U.S. Department of the Interior
Bureau of Reclamation
Technical Services Center
Denver, CO

February 2010

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

U.S. Department of the Interior
Bureau of Reclamation
Technical Services Center
Denver, CO

February 2010

Bighorn River Side Channel Investigation: Geomorphic Analysis

Report Prepared by:

Jeanne E. Godaire, M.S.
Geomorphologist
Sedimentation and River Hydraulics Group
Technical Service Center

Peer Review Certification: This document has been peer reviewed per guidelines established by the Technical Service Center and is believed to be in accordance with the service agreement and standards of the profession.

PREPARED BY:

DATE: 2/18/2010

Jeanne E. Godaire, M.S.
Geomorphologist
Sedimentation and River Hydraulics Group (86-68240)

PEER REVIEWED BY:

DATE: 2/18/2010

Ralph Klinger, Ph.D.
Geomorphologist
Sedimentation and River Hydraulics Group (86-68240)

Acknowledgements

This project was funded by the Bureau of Reclamation Montana Area Office, Western Area Power Administration and the Reclamation Science and Technology Research Program. Additional in-kind contributions were provided by Montana Fish, Wildlife and Parks. The study was facilitated by a Memorandum of Understanding among multiple agencies and nonprofit groups including the National Park Service, Western Area Power Administration, State of Montana, State of Wyoming, Friends of the Bighorn River, Friends of the Bighorn Lake, Bighorn River Alliance and Trout Unlimited. Stephanie Hellekson, Lenny Duberstein and Clayton Jordan of the Reclamation Montana Area Office provided management and oversight for this project. Rob Hilldale and Travis Bauer, Technical Service Center, Reclamation, collected the bathymetric data for the cross section survey and longitudinal profile; Earl Radonski, Montana Fish, Wildlife and Parks, provided equipment and navigation for the bathymetric survey. Ken Frazer and Jim Darling, Montana Fish, Wildlife and Parks provided early guidance for the study's direction and long-term observations of the side channels in the study reach. Special thanks to the anglers and landowners along the river that provided their perspectives on river history and for their helpfulness in providing access to property for the river channel survey.

Contents

Page

List of Figures

List of Tables

Executive Summary

Geomorphic analysis of vertical and lateral historical changes on the Bighorn River from Yellowtail Dam to St. Xavier Bridge was conducted in order to investigate the loss of side channels in recent decades. Vertical changes were investigated by examining bed elevation changes at the USGS gage (station no. 06287000, Bighorn River near St. Xavier, MT) and by resurveying historical cross sections established during the Montana Fish, Wildlife and Parks (FWP) wetted perimeter study in 1997 (Frazer, 1997). Lateral changes were investigated through detailed geomorphic mapping on seven sets of historical aerial photography from 1939 to 2006. The following conclusions are derived from this study:

- Analysis of cross sections at the U.S. Geological Survey (USGS) stream gaging station (Bighorn River near St. Xavier, MT) and at the locations of the FWP wetted perimeter study (Frazer, 1997) show that the bed elevations in the main channel have remained relatively stable throughout the post-dam period and channel incision has not been significant. At the USGS gaging station, the mean bed elevation of the channel fluctuated up to 3.3 ft from 1935 to 1965 prior to the construction of Yellowtail Dam and Afterbay and remained relatively stable throughout the post-dam period from 1967 to 2000, fluctuating up to a maximum of 0.9 ft. At the repeat cross sections, changes in bed elevations have been less than 1 ft from 1997 to 2009.

- The channel positions of the main stem and side channels have been in similar locations since 1980 and reflect a stable river system in which large-scale lateral movement of the channel halted between one and two decades following dam construction. This reflects the reduction in peak flows and sediment supply that are required for channel change in this system.

- Geomorphic complexity, reflected by active channel area, has been decreasing since 1961 as side channels are abandoned and unvegetated channel bars are covered with vegetation. This reflects the reduction in peak flows and sediment supply that are required to scour channels and modify bars as well as deposit sediment in new areas, facilitating the formation of new bars and channels. The reduction in active channel area from 1939 to 1961 reflects the recovery of the channel from the 1935 flood of record and possibly the effects of reduced peak discharges from the construction of Boysen Dam in 1952.

- Observations of channel conditions during 2009 indicate that several critical side channels are becoming disconnected from the main channel; this is based on the presence of fine sediment accumulations at side channel entrances and mouths that suggests that the channels are filling in with sediment and the establishment of vegetation in side channel mouths as well as along their lengths. This information is confirmed by geomorphic mapping, in which side channels inundated in 1939 were not inundated in 2009 despite a larger discharge in the main channel.

- Historical channel mapping identified several side channels that were abandoned between 1961 and 2009. These include side channels 8E, 8F, 10B, 13, and 15D. Field observations during 2009 also indicate that several side channels are at risk of abandonment, showing fine sediment and vegetation accumulating in the channels. These include side channels 4, 8A, 10A, 11, 12A, 12C, 15A, and 15C.

1.0 Introduction

The construction of large dams on the Bighorn River in the 1950's and 1960's, including Yellowtail Dam and Afterbay, created a new hydrologic regime in the Bighorn Valley. With this change came transitions in the ecosystem and the change to a coldwater fishery capable of supporting a thriving trout population. With the river opened to anglers beginning in the 1980's, the stocking of trout and monitoring of populations through electrofishing and angler surveys prompted detailed observations of the river and its aquatic habitat. Many of the observations that initiated this study were noted through the tracking of fish populations and the concern over the disappearance of side channel habitat.

In recent decades, river technicians, scientists and anglers have noted the progressive abandonment of side channels downstream of Yellowtail Dam and Afterbay, consisting of shallowing at side channel connections with the main channel and dewatering at low flow releases. Due to the high productivity and recreational use of the trout fishery downstream of the dam, habitat for rainbow and brown trout is of critical concern. Through informal agreements, the Bureau of Reclamation and FWP agreed that a minimum flow release of 1500 ft^3/s in the Bighorn River was necessary downstream of the Afterbay to maintain side channel connections with the main channel and minimum aquatic habitat. Concern over channel incision and the decrease in flows entering side channel areas prompted a wetted perimeter study of three critical side channels within the first 3 miles downstream of the dam in order to determine whether the minimum flow values were still adequate (Frazer, 1997). While the flow value of 1500 ft^3/s was determined to still be valid as a minimum flow value, concern over the side channels persisted, as side channel depths continued to decrease to the point where boat navigation became difficult to impossible in some of the side channels during the lower discharges. While other smaller scale studies were initiated by Reclamation in the last two decades (Klumpp, 1997; Klumpp, 2005), this study is the first substantial study that utilizes fluvial geomorphology to investigate side channel habitat downstream of Yellowtail Dam and Afterbay.

1.1 Objective

The objective of this study is to investigate the loss of side channel habitat along the Bighorn River between Yellowtail Afterbay and St. Xavier Bridge by documenting the lateral and vertical changes to the river channel.

1.2 General response of rivers to dam construction

Several authors have summarized site-specific studies that document the effects of large dams to understand larger patterns in geomorphic changes related to dam construction (i.e., Collier et al 1996; Willams and Wolman, 1984). These studies reflect variability in channel response that depends on climate, geology and the dam itself, among other considerations (i.e., Grant et al. 2003). Many studies document changes that include decreases in flood peaks, sediment concentrations and suspended load as well as degradation of the channel bed, channel armoring and vegetation encroachment along the channel (e.g., Williams and Wolman, 1984). Other studies have documented channel aggradation in areas where tributary loads exceed the sediment transport capacity of the altered hydrologic regime (i.e., Collier et al 1996; Everitt, 1993), while some studies document relatively little change compared to pre-dam conditions (i.e., Williams and Wolman, 1984; Inbar, 1990).

Graf (2006) found that large dams from a variety of locations across the continental United States and of similar size to Yellowtail Dam reduce annual peak discharges in regulated reaches between 56 and 67 percent on average and reduce the range of daily discharges by 64 percent on average when compared to similar unregulated reaches. This result is comparable to the reduction of 55 percent in annual peak discharges downstream of Yellowtail Dam. Graf (2006) also found that geomorphic complexity, reflected in the area of active channel or geomorphic features that are modified by the present flow regime, is significantly reduced following dam construction. The reduction in complexity was calculated to be 72 percent less than in unregulated reaches, on average. The largest losses in geomorphic complexity were calculated for interior western rivers and Great Plains rivers, where the highest annual hydrologic variability exists and is thus subject to potentially greater changes in hydrology and geomorphic processes.

The reduction in geomorphic complexity can have significant impacts to the riparian ecology as well as the complex species interactions among both aquatic and terrestrial organisms downstream of the imposed structures (Ligon et al 1995). For example, channel simplification, which includes the conversion of multi-thread reaches to single thread reaches, reduces the areas where spawning gravels are recruited and deposited, thus limiting the areas that are suitable for spawning. Reduction in geomorphic complexity may also limit other types of environments, such as rearing habitat, by eliminating areas in the channel with lower velocities. Ligon et al (1995) document changes in the McKenzie River, Oregon, due to two flood control dams built on tributaries that have reduced peak flows on the mainstem to bankfull discharge. This reduction in flows has acted to stabilize the channel, limiting the modification and creation of mid-channel bars and islands, areas that are depositional zones for spawning gravels. As the smaller side channels fill in with sediment, the channel is converted from a multi-thread to a single-thread system, and areas where these gravels can deposit continue to decrease. The geomorphic changes also affect other types of habitat in that areas of backwater, which are important for rearing habitat for juveniles, are lost as the smaller channels disappear.

1.3 Study reach description

The area covered by this study extends for 16 miles from the Yellowtail Afterbay to St. Xavier Bridge (Figure 1). Geomorphic mapping was extended for an additional 5.6 miles to Mallards Landing Access in order to encompass all reaches under investigation by FWP for brown and rainbow trout habitat. The FWP reaches include the Upper Electrofishing Section (Yellowtail Afterbay to Lind Access, River Mile (RM) 0-3.8), the Standard Electrofishing Section (Side channel 5 to Soap Creek, RM 2.4-9.6) and the St. Xavier Electrofishing Section (Rotten Grass Creek to Mallards Landing Access, RM 17.6-21.6) (Fredenburg, 1987). The study reach has a stream gradient of 0.0016, a sinuosity of about 1.2 and a mean annual discharge of about 7,900 ft^3/s in the post-Yellowtail Dam period (1966-2008). Channel complexes are numbered from upstream to downstream; each active channel in the complex is also assigned a letter for reference (Figure 1; Appendix A). For the first 16 miles, these designations are based on FWP's designations (Fredenburg, 1984); for channel complexes from RM 16 to 21.6, new designations are made since no previous designations were known to exist.

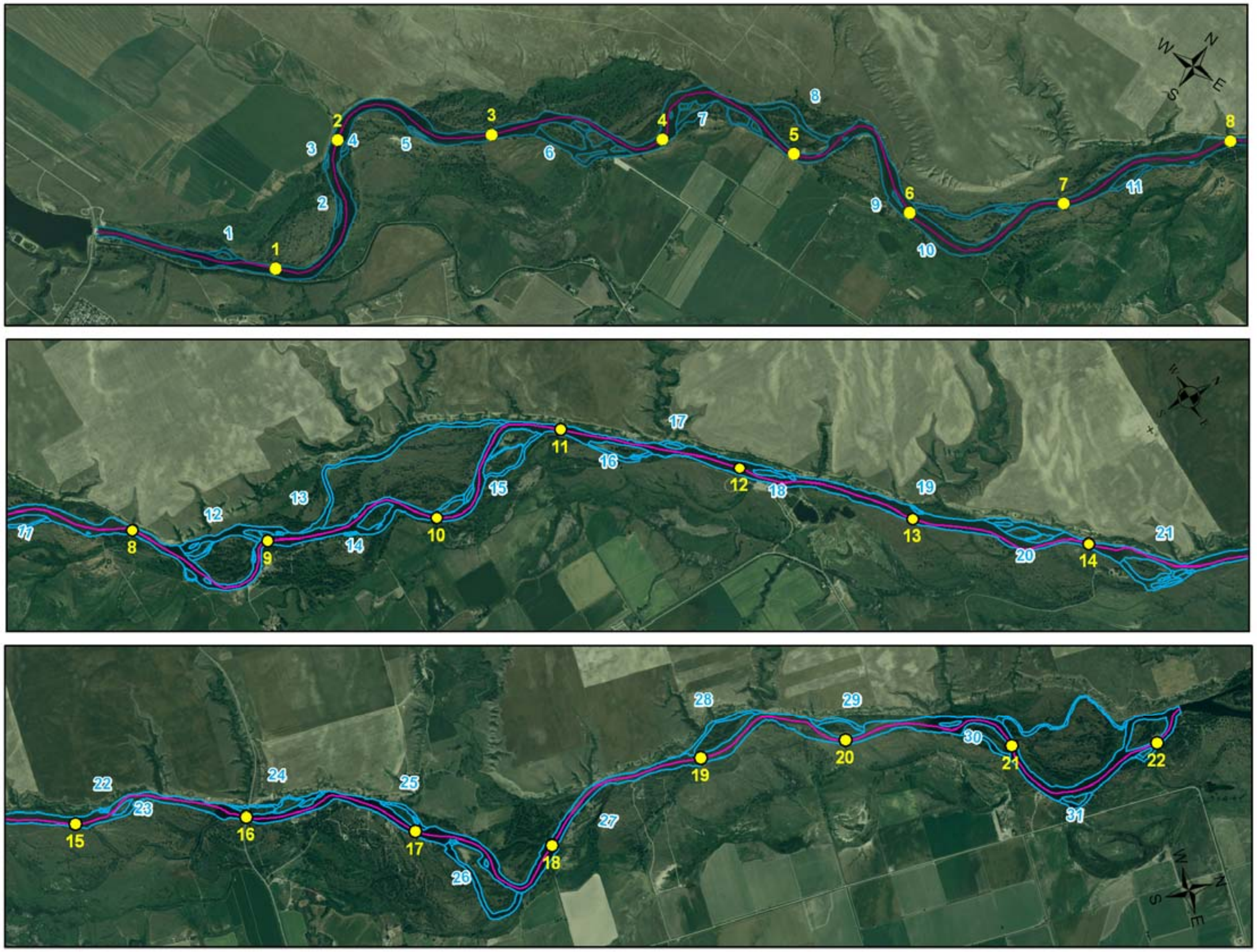


Figure 1. General map of the study reach with locations of channel complexes (blue labels) and RM (yellow labels).

2.0 Previous work

Previous scientific studies that are relevant to this project include published geologic literature, which document the Quaternary history of the Bighorn River Valley in Montana, historical channel change studies that investigate channel changes due to anthropogenic influences, and habitat and river management studies that apply scientific information to address sediment and hydrologic issues related to aquatic and terrestrial habitat. The pertinent literature is described in the following sections.

2.1 Geologic literature

Numerous maps and reports document the geology of the study area and were compiled for a variety of purposes including mineral and gas exploration, surface and ground water resources, tectonics, and Quaternary history. Of interest for this study are those references that focus primarily on the Quaternary history of landscape development in the lower Bighorn Basin. The purpose of this literature review is to provide a brief summary of the references that are most pertinent to the study at hand.

Alden (1932) documented a sequence of four terraces along the lower Bighorn River, which he interpreted to range in age from Quaternary to Tertiary. Later studies by Richards (1955) and Hamilton and Paulson (1968) recognized six terrace levels and interpreted that four of the terraces were Quaternary in age and two were Tertiary in age. Agard (1989) recognized 12 terrace levels and provides a correlation table to link the Quaternary mapping from the various studies. Several studies discuss the glaciofluvial origin for these terraces as well as evidence for Quaternary tectonism in the lower Bighorn Basin (i.e., Reheis, 1983; Reheis, 1985).

2.2 Historical channel change studies

Koch et al (1977) examined geomorphic changes to the Bighorn River downstream of Yellowtail Dam before and after dam construction as part of a larger study investigating the effect of altered streamflow on the Yellowstone River. The river was divided into five reaches or sections based on similar geomorphic characteristics. Section 1 is the most pertinent to this study and extends from Yellowtail Afterbay Dam to just upstream of the confluence with Hay Creek. To analyze changes, the authors measured channel length, area of the river channel, vegetated islands, island gravel bars, lateral gravel bars and riparian area using aerial photography from 1939 and 1974. General conclusions for the entire study reach from Yellowtail Dam to the confluence with the Yellowstone River (71 miles) were that the river maintained its length and total riparian area; however, a gain of about 38 percent of bank riparian area was measured and corresponded with a similar loss in river area. Vegetated islands decreased by 23 percent, an area of about 1,469 acres. Island gravel bars decreased by 86 percent, an area of 1,401 acres, while lateral gravel bars decreased by 34 percent, an area of 131 acres. While the loss of island gravel bars was greatest downstream of the dam, lateral gravel bars actually increased in sections 3 and 5, which may be caused by the movement of sediments from upstream sections and the influence of large tributaries, such as the Little Bighorn River, in delivering additional sediment to the channel. In section 1 specifically, vegetated islands decreased by 23 percent, a total of 104 acres, island gravel bars decreased by 86 percent, a total of 189 acres, and lateral gravel bars decreased by 70 percent, a total of 56 acres. Koch also found that the average size of gravel bars decreased while the average size of vegetated islands increased; the process by which this occurs includes smaller gravel bars and islands combining into larger islands through a process of channel incision; this was accompanied by vegetation encroachment onto the gravel bars, which reduced the area of the bars and increased the area of vegetated islands.

2.3 Habitat and river management studies

Frazer (1997) conducted a wetted perimeter analysis downstream of Yellowtail Dam and Afterbay in order to determine if the flow levels requested under an informal agreement between Reclamation and Montana FWP in 1986 were still valid for three important side channels. Three cross sections were measured upstream of each side channel that are 0.6 (cross section 1), 2.3 (cross section 2) and 3.1 (cross section 3) miles downstream of the Afterbay dam. The wetted perimeter/inflection point (WETP) method was used to develop wetted perimeter-discharge relationships that are plotted and used to detect an inflection point below which the wetted perimeter and consequently aquatic habitat rapidly decreases. The inflection point defines the minimum flow required to maintain a low level of aquatic habitat. Discharges corresponding to these inflections points were measured as 50, 40 and 50 ft^3/s for cross sections 1, 2 and 3, respectively. These minimum flows in the side channels corresponded to discharges in the main channel ranging from 2,000 to 2,500 ft^3/s. Based on these results, Frazer concluded that 1,500 ft^3/s was still valid as a minimum discharge for side channel habitat. Below this discharge, many of the side channels would be dewatered, which would be detrimental to trout populations.

Klumpp (1997) conducted a literature review of existing hydraulic and geomorphic data in order to document issues that have arisen on the Bighorn River since the adoption of the Bighorn River Management Plan in 1987. From this review, Klumpp concluded that annual peak discharges were reduced by 50 percent following the construction of Yellowtail Dam. Klumpp also reviewed the geomorphic study conducted by Koch et al 1997), which was also reviewed for this report and summarizes sediment data, including bed material and suspended sediment, collected in February 1997 at locations similar to Frazer's (1997) study and in the vicinity of Soap Creek. Results showed that particle size (D_{50}) decreased with distance downstream; particle size at Soap Creek decreased considerably and was attributed to the influence of the sand and silt issued from the Soap Creek watershed. Based on the review, Klumpp concluded that the decrease in gravel bars and vegetated islands was due to the reduction in sediment supply and flood flows to the reach, which is the mechanism through which bars erode and redeposit. Klumpp suggested that a new equilibrium would be reached in which gravel bar area and number would stabilize rather than continue to decrease indefinitely. She also concluded that controlled floods may be able to transport gravels to new locations to help restore some islands; however, it is possible that these types of flows may be detrimental to the river upstream of Soap Creek because there are no significant sediment sources between the Afterbay and Soap Creek. She recommended testing the effectiveness of controlled floods with 2-3 day duration releases of 15,000 to 20,000 ft^3/s.

Klumpp (2005) conducted a hydraulic analysis to determine the ability of the river to flush fine sediment that had accumulated in spawning gravels during a period of low flow releases downstream of Yellowtail Dam and Afterbay between 2000 and 2003. The study analyzed sediment mobilization for discharges ranging between 2,500 and 5,000 ft^3/s for a distance of 13 miles downstream from the Afterbay. The study found that flows over the entire discharge range would be sufficient to mobilize gravels, which would then be adequate to flush the fine sediment. The results were based on limited sediment data, including bed-load, suspended load and bed material data, and cross section data, which were gathered from existing topographic maps. It was recommended that additional data should be collected and modeled to improve the predictive capability of the model. Klumpp also recommended that if flushing flows were implemented, it would be advisable to establish control cross sections to monitor changes before and after the flushing flows.

A number of progress reports were prepared as part of the Bighorn Lake and Bighorn River Post-Impoundment Study and Upper Bighorn River Investigations by Montana FWP (Fredenburg, 1984; 1986; 1987; Frazer, 1999). These reports describe the results of fish shocking surveys and other biological investigations in two sections of the Bighorn River, the standard section from side channel 5 to Soap Creek and the St. Xavier section from Rotten Grass Creek to Mallard Landing Access. An additional section, termed the Upper section, was added in 1985 as part of a nitrogen supersaturation study (White et al 1986) and extends from the Afterbay Dam to 3-mile Access. Survey of these sections was begun in 1981 following the U.S. Supreme Court decision that determined ownership of the channel bed belonged to the State of Montana. Early progress reports created a river mile index beginning at Yellowtail Afterbay and continuing downstream for a distance of 43 miles. Side channels and side channel complexes were also delineated for the first 16 miles downstream of the Afterbay using 1980 U.S. Department of Agriculture (USDA) photographs, which were flown at a discharge of 3,990 ft^3/s (Fredenburg, 1984). Some information is available in these reports that documents where spawning activity was observed (i.e., Fredenburg, 1986; Fredenburg, 1987). These reports found that nearly all rainbow trout spawning was observed within 9 miles of the Afterbay Dam and that spawning in the St. Xavier section was limited by fines in the gravel substrate, delivered mainly by tributaries such as Soap Creek. However, more recent reports suggest that the lower section may be gaining importance for the overall trout fishery (Frazer, 1999). Several reports also describe or document which side channels are wetted at varying river discharges (Fredenburg, 1984; 1986). These reports will be important for understanding the more recent changes in side channel wetting and dewatering.

3.0 Setting

3.1 Physiography

The Bighorn River basin is located in the northern Great Plains physiographic province, which is characterized by extensive plains and small mountain ranges. Its headwaters extend into the Middle Rocky Mountains province in Wyoming which consists of intermontane valleys separated by the mountain ranges of the middle Rocky Mountains. From its headwaters in the Wind River Range in Wyoming, the Wind River flows through Wind River Canyon to the Wedding of the Waters where its name changes to the Bighorn River. The Bighorn River flows northward through alluvial valleys of northern Wyoming and the bedrock-controlled Bighorn Canyon of southern Montana to the study area. Major tributaries to the Bighorn River upstream of the study area include the Nowood River, Greybull River, and Shoshone River, all of which originate in northern Wyoming.

The Bighorn River downstream of Yellowtail Dam drains an area of 19,667 square miles. Tributaries that join the river in the first 16 miles of the study reach are few but include Mountain Pocket Creek and Soap Creek, which enter from the south and Hay Coulee and several small unnamed gulches that enter from the north. Downstream of RM 16 between St. Xavier Bridge and Mallard Landing, Rotten Grass Creek and Beauvais Creek enter the Bighorn River from the south and north, respectively and have larger watersheds that contribute greater flow and sediment to the river channel.

Several large dams have been constructed upstream of the study area. Yellowtail Dam and Afterbay was constructed in 1966 on the main stem and forms the upstream boundary of the study area. Boysen Dam, was constructed in 1952 on the Wind River at the upstream end of Wind River Canyon; the original Boysen Dam was built downstream of the present Boysen Dam by a private investor in 1908; however the dam began to impact the Burlington Northern railroad tracks built in 1911 and was dynamited in 1915 following a court decision (Mullen, 1916**).** Buffalo Bill Dam was built on the Shoshone River in 1910 near Cody, Wyoming and modified several times historically, the latest being 1990.

3.2 Geologic setting

In the study area, the Bighorn River near Fort Smith exits the Bighorn Canyon, which is composed of steeply dipping and resistant Mississippian through Jurassic age sedimentary rocks that were uplifted during the mountain building episode (Laramide orogeny) that formed the Rocky Mountains. Downstream of Fort Smith, the Bighorn River flows across less resistant Cretaceous shales for the remainder of the study reach (Hamilton and Paulson, 1968).

Agard (1989) mapped a sequence of 12 alluvial terraces in the study area, ranging in age from Pliocene (5.3-1.8Ma) to Holocene (<10ka) and in height from about 10 ft to greater than 900 ft above the Bighorn River. Agard's mapping is the most detailed when compared to previous studies, which only recognize a sequence of 4 terraces (Alden,

1932) and 6 terraces (Richards, 1955; Hamilton and Paulson, 1968). The Pleistocene and Pliocene alluvial deposits consist of poorly sorted gravel and sand, fining downstream to include greater proportions of sandy matrix between the gravels. Younger (Holocene) terraces and floodplain alluvium along the Bighorn River consist of a greater proportion of sandy alluvium when compared to the older terraces. The older terraces are predominantly strath terraces, with about 9-18 ft (3-6 m) of gravel capping Cretaceous bedrock, although some of the alluvial deposits may have thicknesses of 18-30 ft (6-10 m). The terraces in the study area represent episodes of stability or aggradation during a period of regional incision of the Bighorn Basin from Pliocene time onward. The preservation of older terraces solely on the west side of the valley suggests a net eastward migration of the Bighorn River from the Pliocene to Middle Pleistocene. While the terraces cannot be directly tied to glacial deposits in the upper Bighorn Basin, Agard suggests a glaciofluvial origin for these deposits. Several are tentatively correlated to glaciofluvial terraces in the upper Bighorn Basin that can be directly traced to Pleistocene glacial sequences.

Agard (1989) also suggests that the area has been tectonically active during the Quaternary, a factor not recognized in prior studies of the area. Several lines of evidence are put forward to support this idea: (1) several of the terraces near Fort Smith that range in age from about 1.2 to 0.5 Ma are warped or offset; these locations correspond to the location of the Soap Creek dome, a regional structural feature, (2) the six older terraces are only preserved on the western side of the valley, indicating a net eastward migration that may be structurally controlled, and (3) the channel planform of the Bighorn River from mile 10 to 15 changes abruptly from anabranching to straight and parallels a normal fault mapped on the east side of the valley, suggesting that the river is fault-controlled in this reach. It should also be noted that the general position of the river channel in the study reach is on the west side of the valley. This may relate to structural control as its position does not appear to be related to tributary fan deposition or other fluvial mechanisms. Downstream of the study area, two other lines of evidence are noted by Agard. First, the abrupt transition of the river channel from the west side of the valley to the east side at Two Leggins Creek corresponds to a mapped lineament that aligns with several mapped faults in the area. It is possible, however that this abrupt change corresponds to sediment input from Two Leggins Creek rather than any structural control. Second, the fact that the higher, older terraces converge in the downstream direction, whereas the lower and younger terraces diverge points to isostatic rebound related to erosion of the overlying sediments during Pliocene and Quaternary time.

3.3 Hydrology/meteorology

The largest flows that impact the study reach are related to snowmelt during the late spring and early summer. During this time, soil moisture is maximized, snowmelt is rapid, and there is an abundance of extratropical cyclone activity delivering moisture into the northern Great Plains (Hirschboeck, 1991). In this scenario, warming trends or thaws induce snowmelt; the accelerated melting of the snowpack quickly saturates the soil and generates surface flow to the major rivers in the area. Rapid warming and melting will produce the largest flood peaks, which happened in 1935 water year when the Bighorn River produced its peak of record near St. Xavier. During this flood, discharge remained above 10,000 ft^3/s for about one month, rising sharply to produce a peak discharge of 37,400 ft^3/s. It is not known whether additional moisture from extratropical cyclone activity contributed to this flow, although a possible analog would be the May 1978 flood, in which rainfall combined with snowmelt to produce widespread flooding in south-central Montana on the Bighorn River, Tongue River and Powder River basins (Paulson et al. 1991).

The closure of Yellowtail Dam in 1966 resulted in a reduction in annual peak discharge by about 55 percent on average with a mean from 1935-1965 of about 17,600 ft^3/s to a mean from 1966-2008 of about 7,900 ft^3/s (Figure 2). Annual peak flows were also more variable in the pre-dam flow regime with a minimum value of 6,900 ft^3/s in 1954, a maximum value of 37,400 ft^3/s in 1935 and a standard deviation of about 7,300 ft^3/s. It should be noted, however, that the construction of Boysen Dam in 1952 also reduced flood peaks to the lower Bighorn River prior to the construction of Yellowtail Dam. Flows during the post-dam period from 1966-2008 had a minimum value of 2,030 ft^3/s, a maximum value of 25,300 ft^3/s in 1967 and a standard deviation of 4,800 ft^3/s. In the pre-dam flow regime, annual peak discharges occurred almost exclusively in the months of May, June and July, with the majority of peaks occurring in June. These were snowmelt floods derived from the upper watershed that flowed through Bighorn Canyon to the study reach. While quite a few of the annual peak discharges in the post-dam flow regime occur during May, June and July, there is a wider range of months in which the annual peak discharge is recorded; in fact, every month with the exception of September has recorded at least one annual peak discharge since 1966. These annual flows were probably not directly related to runoff events in the upper watershed, but rather were releases related to the operation of Yellowtail Dam.

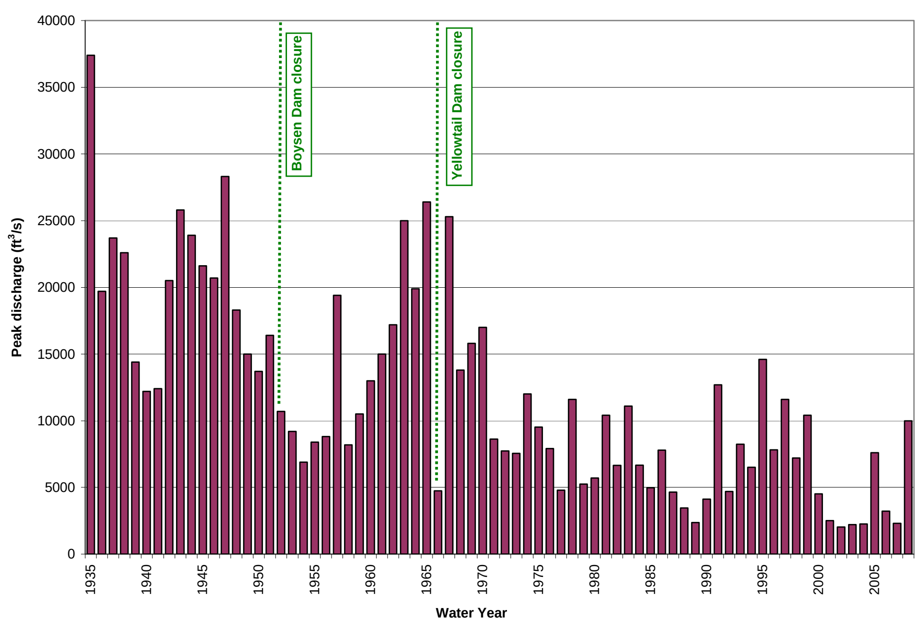


Figure 2. Annual peak discharges on the Bighorn River near St. Xavier, Montana (USGS gaging station #06287000).

4.0 Methods

4.1 Aerial photo rectification

To document channel changes downstream of Yellowtail Dam and Afterbay during the historical period, scanned aerial photos were acquired for approximately each decade from 1939 to 2006 from a variety of sources (Table 1). The photographs cover the river from Yellowtail Dam to Mallard Landing along the Bighorn River at a scale sufficient to map river features (1:20,000 to 1:40,000). General Land Office (GLO) Plat maps were also acquired, but were not utilized for the study because the mapped area on the plat maps did not completely cover the study reach. The aerial photos from 1939 through 1991 were scanned at a resolution of about 21-25 microns (about 1000-1200 dpi) and primarily rectified using automated synchronization. Because of the changes in ground conditions between 1939 and the 2006 orthophoto base image, an automated synchronization for the rectification of the 1939 photos proved insufficient. For each scanned photo, 30 or more control points were identified by eye from vegetation, buildings, or road intersections that existed in both images were identified for use with the geocorrection tool in Environmental Systems Research Institute, Inc. (ESRI) ArcGIS ArcMap v8.3. Because the river channel was the focus of this project, the rectification of imagery further from the channel may not be sufficient for other uses beyond the scope of this project.

The 2006 aerial photography used as the orthophoto base was acquired from the USDA National Agriculture imagery program (NAIP); this imagery is rectified by USDA and has a 2-meter ground sample distance and a horizontal accuracy that matches within 12 m of ground control points.

Table 1. List of aerial photography and maps acquired in the Bighorn River geomorphic analysis

Year	Scale/Resolution	Film Type	Agency
2006	2m	Natural color	USDA/NAIP
1991	1:40,000	Black & white	NAPP
1980	1:40,000	Black & white	NRCS
1970	1:40,000	Black & white	ASCS
1961	1:20,000	Black & white	ASCS
1954	1:20,000	Black & white	USDA
1939	1:20,000	Black & white	USDA
late 1800’s	1:31,680	GLO Plat Map	BLM

4.2 Geomorphic mapping

The goal of the geomorphic map is to document the presence and position of physical features including historical channel tracks, mid-channel islands, gravel bars, side channels, overflow channels, bedrock, stream terraces, and any human constructs such as levees or revetments along the Bighorn River. These physical features were mapped for each year of aerial photography, including the most recent photography using heads-up digitizing in ArcGIS at a scale of about 1:6,000. For the most recent (2006) photography, the features were digitized initially on aerial photography and then field checked. Other features, such as bedrock exposures along channel banklines and in the channel bed and human constructs, were predominantly mapped during fieldwork. The map provides a history of lateral channel movement, the abandonment and creation of side channels and overflow channels, and the revegetation or scouring of mid-channel islands and gravel bars.

4.3 Cross section survey/longitudinal profile

Data for the cross section survey and longitudinal profile were collected primarily during the April 2009 field work; supplemental data for the cross sections were also collected during June 2008 field work. The bathymetric data were acquired using an Acoustic Doppler Current Profiler (ADCP) and Trimble Real Time Kinematic (RTK) Global Positioning System (GPS) was used to acquire the ADCP positions, water surface elevations, and ground observations. The bathymetric survey is estimated to have an accuracy of ±15 cm; ground observations are estimated to have an accuracy of ±2 cm.

The 2009 cross section data were collected at the three sites surveyed during the 1997 cross section survey for the FWP wetted perimeter study (Frazer, 1997). Benchmarks established in 1997 at cross section endpoints were reoccupied in order to compare cross section data and channel changes from 1997 to 2009. Longitudinal profile data were collected as part of the bathymetric river survey for the hydraulic modeling from Yellowtail Dam to Bighorn Access by surveying multiple paths down the channel. An additional single line of data was collected between Bighorn Access and St. Xavier Bridge in order to examine changes in gradient for the entire 16-mile study reach. To construct the longitudinal profile, data points were extracted along the 2006 channel centerline beginning 250 ft downstream of Yellowtail Dam and thereafter at a spacing of 500 ft.

Data for the cross section analysis at the USGS stream gage (Bighorn River near St. Xavier, #06827000) were acquired from the National Records Center in Denver, CO, and Seattle, WA, from 1935-2000. Records from 2000-2005 could not be located either as archived files in any of the USGS offices in Montana. The 2005-2008 surveys were measured by USGS personnel using an ADCP. These data were acquired but were not processed due to initial data analysis of the 1935-2000 records that showed a consistent pattern in cross section geometry (see section 5.2.1 for further information).

4.4 Field measurements of fine sediment deposition

During April 2009 field work, many observations of side channels and overflow channels revealed that fine sediment was accumulating at the entrances and mouths of these channels. During June 2009 field work, measurements of the thickness of fine-grained sediment accumulations were made using a hand auger and small shovel to measure the depth to gravel at the entrances of side channels and overflow channels and in locations downstream of the entrances. While the mouths of side channels and overflow channels also had notable thick accumulations of fine sediment, these thicknesses were not measured due to the depth of water ponded in the channels and difficulty in reaching these areas for measurements.

5.0 Results

5.1 River pattern/morphology

The Bighorn River can be classified as an anabranching system, which is defined by Nanson and Knighton (1996, p. 218) as "…a system of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull." The islands are typically stable for decades to centuries with mature vegetation and may reach the same height as the surrounding floodplain through the process of vertical accretion. Anabranching rivers cannot be neatly categorized as a distinct type on the basis of slope versus discharge and can have characteristics of both meandering and braided rivers.

Nanson and Knighton (1996) separate anabranching rivers into 6 classes based on stream power, bed and bank materials, lateral migration and vertical accretion rates, channel sinuosity, and island length to channel width ratios. A review of the general characteristics of their classification indicates that the Bighorn River channel pattern most closely resembles type 5, described as a gravel-dominated laterally active anabranching river. These rivers are also described in some literature as wandering gravel bed rivers (i.e., Burge, 2005; Church, 1983). Rivers in this category typically have high stream power values that range between 30 and 100 W/m^2 and therefore can be highly active in terms of lateral movement. As is characteristic of the Bighorn River, they can have a dominant main channel with multiple secondary channels and may alternate between single thread and multi-thread reaches. In the study reach, single thread and multi-thread reaches alternate with variable spacing (Figure 3). Channel sinuosity for type 5 anabranching rivers ranges between 1.1 and 1.5; previous sinuosity measurements of the Bighorn River channel place it at the lower end of this range with a value of 1.2 (Klumpp, 1997). The measured slope of 0.0016 in the study reach is also within the range of type 5 rivers described in Nanson and Knighton (1996).

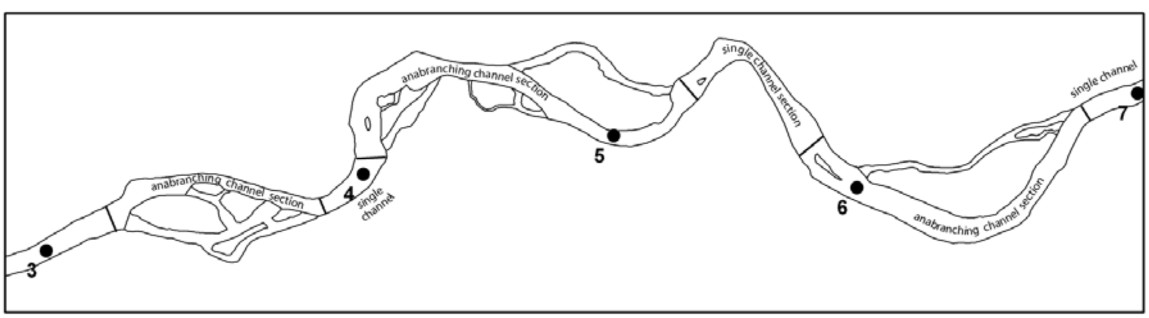


Figure 3. Example of channel morphology in the study reach showing single channel sections separated by anabranching sections.

Descriptions of materials in streambanks for other type 5 anabranching rivers are also generally consistent with Bighorn River bank materials in which a cap of sandy alluvium overlies gravelly substrate (Figure 4). Vertical accretion rates in these systems are typically slow. Anabranching systems exhibit bank resistance, including both vegetation and bank material that plays a large role in the formation of the anabranching channel networks. However this is less of a factor for type 5 anabranching systems because roots do not typically extend deep enough to significantly influence bank resistance.

Figure 4. Example of bank materials showing fine-grained overbank sediment capping gravelly alluvium.

While anabranching systems span a wide range of climatic zones and geologic settings, they have several commonalities through which the anabranching network is formed. Nanson and Knighton (1996) identify two sets of processes that can form multiple channels in terms of erosion-based processes and accretion-based processes. The anabranching network on the Bighorn River is formed by the erosion-based process of channel avulsion, in which overbank flows in combination with channel sedimentation may periodically initiate new channels in floodplain alluvium and in effect cause other channels to be abandoned. A requirement for this process seems to be a variable flow regime, where flood flows are routed overbank due to the inability of the channel to alter its capacity to accommodate larger flows. In the case of the Bighorn River, its lack of change in channel geometry during the pre-dam historical period despite a variable flow regime indicates difficulty in altering its gradient, possibly due to bedrock control, sediment loads or other structural features in the subsurface. The reduction in peak flows and sediment supply following dam construction have essentially locked the channel into its current position by removing the two components necessary for channel avulsion.

Continued growth of vegetation on the islands and encroachment of vegetation onto pre-dam unvegetated bars has aided in the stabilization of channel position in the post-dam flow regime.

5.2 Vertical changes in bed elevations

5.2.1 Gaging station data (1935-2000)

Cross section measurements at the gaging station, Bighorn River near St. Xavier, MT (USGS station #06287000), were gathered from archived files at the Federal Records Center in Denver, CO and Seattle, WA in order to investigate vertical changes in the channel downstream from Yellowtail Dam. Measurements were made multiple times each year from 1935 to 2009, which provides an extensive data set to investigate bed elevations for 30 years prior to the construction of Yellowtail Dam and for 43 years following its construction. Only records from 1935 to 2000 were examined; records from 2000 to 2005 were missing. Although we could also process ADCP cross section data from 2005 to 2008, the results from the measurements up to year 2000 were conclusive and the additional work required to investigate the most recent years of measurement were deemed unnecessary. For each calendar year, both the mean stream bed elevation (MSBE) and maximum stream bed elevation (MAXSBE) were plotted using data from one field survey during that year. Winter and spring measurements were preferred to avoid algae growth that might obscure the channel bottom; however measurements were not used if the technician noted extensive ice cover in the channel, which could increase error in the measurements. Whenever possible, measurements that were noted as “good” were used over measurements noted as “poor”. Smaller magnitude discharges were also preferred in order to ensure that flows were contained within the channel. Discharges during cross section surveys that were utilized from 1935-1965 had values of 2034 ±608 ft^3/s while discharges during cross section surveys from 1966-2000 had values of 3439 ± 1122 ft^3/s.

The mean stream bed elevation was estimated following the method outlined by Jacobsen (1995), where mean flow depth, calculated as cross sectional area/width, is subtracted from the water surface elevation. The MAXSBE is derived using the same formula, except the maximum flow depth recorded in the cross section replaces the calculated mean flow depth.

Results from this analysis are plotted on two separate graphs to reflect the relocation of the gage following the construction of Yellowtail Dam and Afterbay (Figure 5; Table 2). The gaging station is currently located 2.5 miles downstream from Yellowtail Dam at an elevation of 3,158.38 ft. Prior to 1963 and from June 13, 1964 to March 31, 1965, the gaging station was located about 50 ft upstream of the Bighorn canal diversion, or 1.25 miles upstream from its present location, at an elevation of 3,170 ft. Data from 1935-1965 show MSBE fluctuations of up to about 3.3 ft and MAXSBE fluctuations of up to about 4.3 ft. Based on the gage’s location in the bedrock canyon, which would indicate a resistant and stable channel bed, these fluctuations are interpreted as sediment fluxes through the cross section, or in other words the storage and removal of sediment on a fixed channel bottom. When compared to annual peak discharges, sediment storage and removal does not appear to have an obvious correspondence to peak discharges.

Table 2. Streambed elevation fluctuations, Bighorn River near St. Xavier (USGS gage no. 06287000)

Calculation	Maximum (ft) Minimum (ft)	Date	Discharge (ft^3/s)	Fluctuation (ft)
1935-1965				
MSBE	3166.67 3163.34	Apr. 16, 1961 Feb. 15, 1947	1320 2180	3.33
MXSBE	3165.8 3161.5	Apr. 7, 1960 Feb. 15, 1947*	2180 2510	4.3
1966-2000				
MSBE	3156.04 3154.80	Oct. 19, 1999 Apr. 12, 1977	3990 2270	1.24
MXSBE	3152.82 3151.94	Jan. 4, 1967 Apr. 12, 1971	1940 5890	0.88

*Also same minimum bed elevation on April 13, 1948.

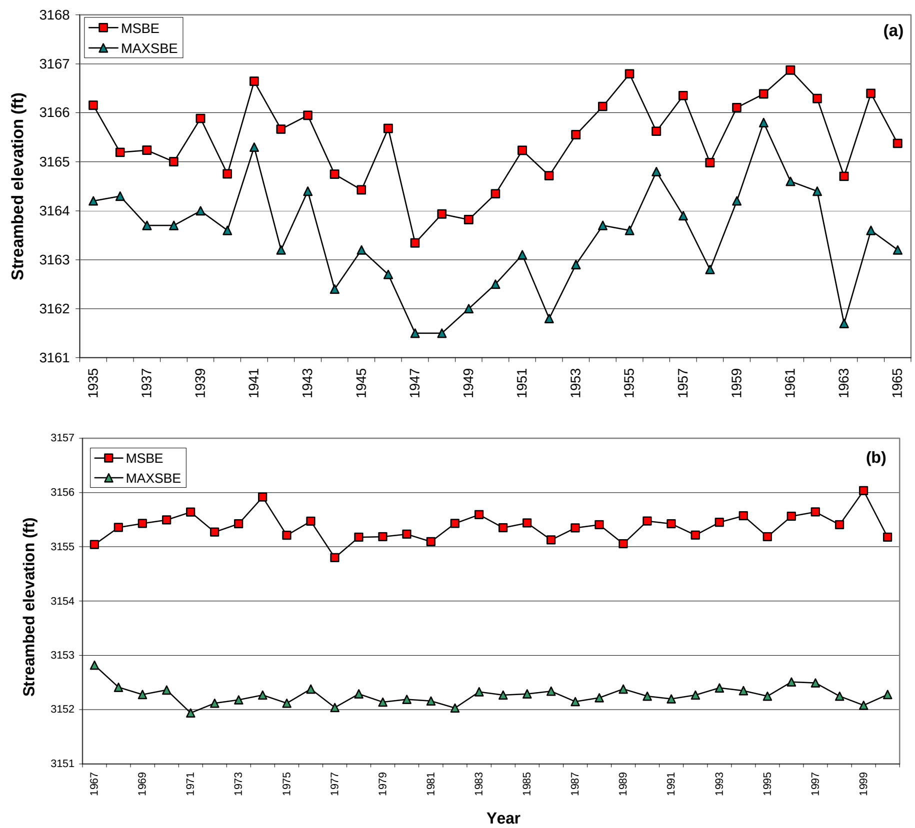


Figure 5. Streambed elevations at USGS gaging station, Bighorn River near St. Xavier, MT (#06287000), (a) 1935-1965; (b) 1967-2000.

Data from 1966-2000 show fluctuations in MSBE of up to 1.2 ft and fluctuations of MAXSBE of up to 0.9 ft. These fluctuations are about 1/3 to 1/4 the magnitude of bed fluctuations prior to dam construction and are remarkably small. These data indicate that the channel has not incised at this location following dam construction, but rather has maintained a consistent bed elevation. This may be due to several factors, including the possible presence of bedrock in the channel, which was not directly observed, rapid channel armoring following dam closure, or reduced sediment fluxes and discharge through the cross section.

5.2.2 Repeat cross sections (1997-2009)

In order to investigate vertical changes in bed elevations within the last decade, cross sections originally surveyed in 1997 by the USGS in cooperation with Reclamation and FWP (Shields, 1997) were reoccupied in April 2009, using the methodology outlined in section 4.3. The cross sections also provide additional data to compare to the gaging station cross section data in section 5.2.1. The cross sections are located at approximately river mile 0.6, 2.5 and 3.2 downstream from Yellowtail Afterbay (Figure 6).

Figure 6. Locations of resurveyed historical cross sections and USGS stream gage.

Benchmarks for each cross section are not surveyed in the original cross section data; it appears that these were placed following the original survey (personal communication, Shields, 2009). Since benchmarks could not be matched between the two surveys, only water surface elevations could be used to compare the cross section data. The discharges recorded during the 1997 (Q_{avg}=4235 ft^3/s) and 2009 (Q_{avg}=3493 ft^3/s) surveys are within 18 % of each other; therefore, these water surface elevations should be comparable. However, when plotted, the water surface elevations are somewhat disparate between the data sets and suggest that the vertical control used between the 1997 and 2009 surveys is offset (Figures 7 to 9). If the 1997 water surface elevations are adjusted to match the 2009 water surface elevations, the cross section geometries match remarkably well and suggest that there has been very little change in the vertical or lateral channel position in the last 12 years. This is the most likely explanation, since typically cross sections do not maintain the same geometry if the channel is aggrading or incising, but rather preferentially deposit or erode in various locations, thus altering the cross section shape. In the adjusted data, XS1 shows little difference in the elevation of the raw and adjusted 1997 survey data; comparison to the 2009 cross section survey shows that the net change in bed elevations is essentially zero, with the area near the left bank slightly lower in elevation and the are on the right bank slightly higher (Figure 7). XS2 shows lateral scour along the left bank and in the center of the channel of about 0.5-1.0 ft (Figure 8). This cross section shows the most change out of the three cross sections, although the scour in the cross section is localized and does not indicate an overall lowering of the channel bed. This cross section also shows the most disparity between the unadjusted 1997 and 2009 elevations; it is not known why these elevations are offset. The shape of both the 1997 and 2009 cross XS3 is very similar and suggests very little change in channel geometry at this site (Figure 9).

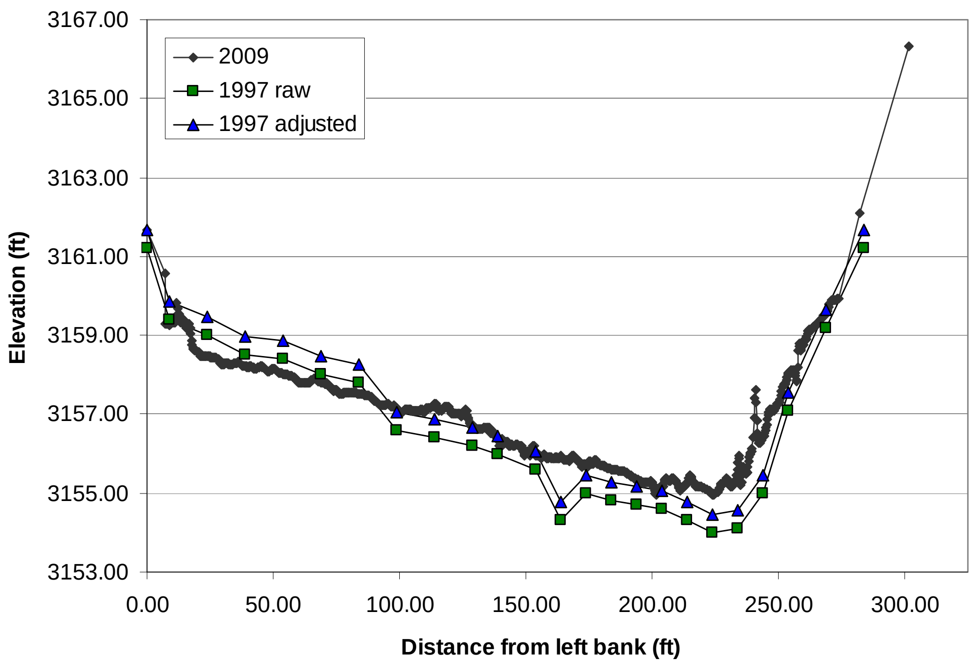


Figure 7. Comparison of cross section survey data at XS1, looking downstream.

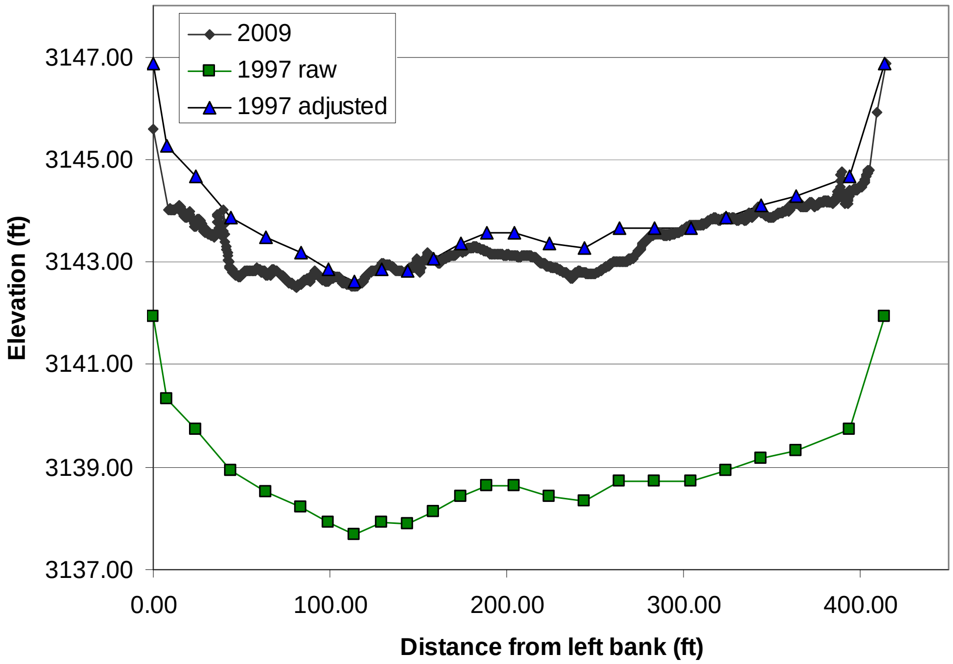


Figure 8. Comparison of cross section survey data at XS2, looking downstream.

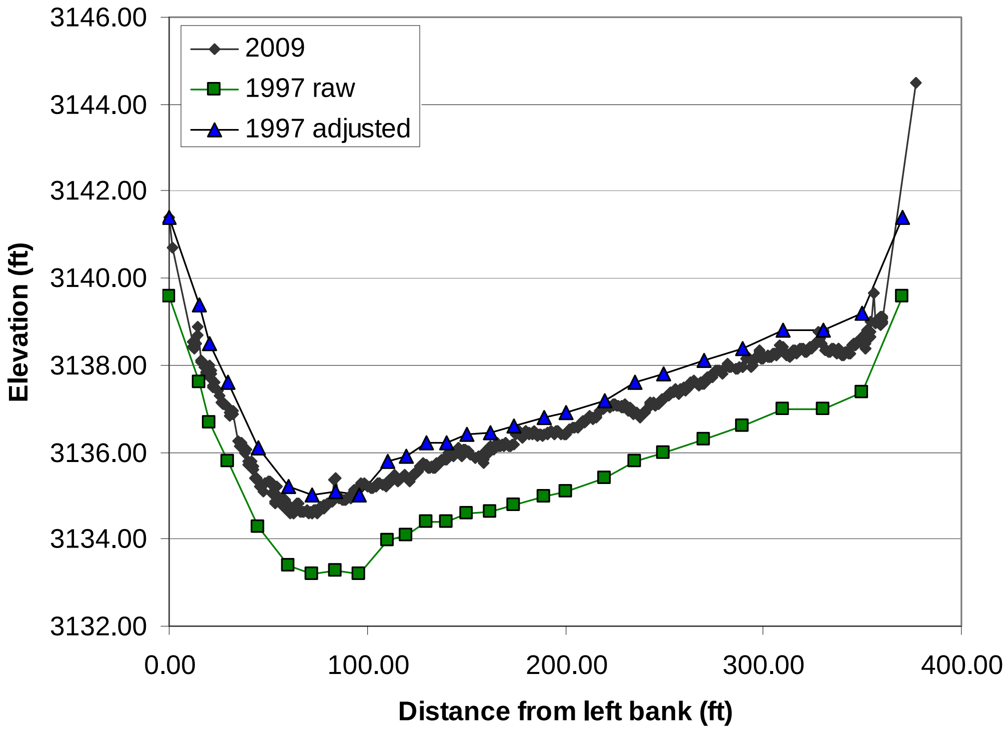


Figure 9. Comparison of cross section survey data at XS3, looking downstream.

5.2.3 Longitudinal profile

A longitudinal profile was surveyed during April 2009 field work in conjunction with the bathymetric and cross sections surveys. Points from the survey were extracted every 500 ft along the centerline of the main channel and plotted with distance from Yellowtail Afterbay to St. Xavier bridge starting at 250 ft downstream of the Afterbay (Figure 10). The longitudinal profile shows an average slope of 0.0016 with maximum fluctuations of about ± 4 ft about the best fit regression line. Scour within 2,000 ft of the Afterbay is evident in the concave shape of the longitudinal profile. It is possible that some of the material was re-deposited within the first mile downstream from the dam; however the low variability in the historical cross section data within 3 miles of the Afterbay indicate that any scoured material was transported downstream and more widely dispersed along the channel length. From the afterbay to channel complex 14, the main channel exhibits shallower depths where multiple channels exist and greater depths in reaches that only have a single channel. This relationship does not appear to be as consistent downstream of channel complex 14, where the channel is mostly confined to a single channel with the exception of a few anabranching sections at channel complexes 20 and 21. Changes in slope at locations where a single channel exists could be related to bedrock outcrops in the channel bed or landslide materials in the channel that slumped from the bluff along the west bank of the river.

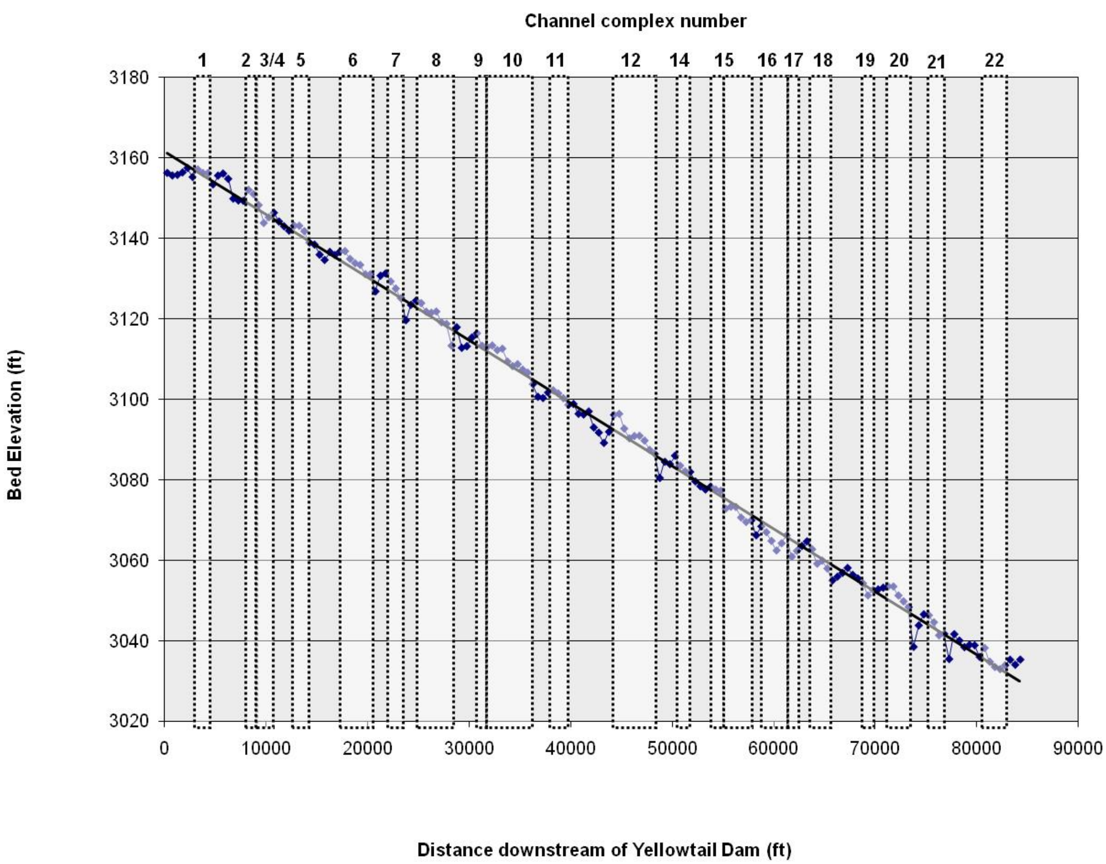


Figure 10. Longitudinal profile, Yellowtail Afterbay to St. Xavier Bridge.

5.3 Geomorphic mapping and analysis

The geomorphic mapping provides a means for the analysis of historical lateral channel change from 1939 to 2006 as well as changes in specific features along the length of the channel. Lateral channel movement as well as the creation and destruction of side channels, islands and bars highlight the dominant physical processes that shape the river channel and ultimately form the aquatic habitat critical for fish survival. Several map units reveal how dam construction has changed the physical attributes and processes along the Bighorn River; these units as well as changes in channel complexes and the overall physical system are described below. Discharge at the time of aerial photography can influence channel area measurements as well as the extent of channel bars and islands. Discharges for aerial photography are listed in Table 3 and vary from 1827 ft^3/s to 3990 ft^3/s, a difference of about 54 percent. Results discussed in section 5.3.2 demonstrate that while discharge does play a role in the coverage of mapped features, it does appear not vary enough to have a large impact on the study's results.

Table 3. Daily discharge for Aerial Photography, Bighorn River

Year	Date	Daily Discharge (ft^3/s)	Max difference in discharges (ft^3/s)
1939	August 16	1850	330 (17%)
	August 18	1650	
	August 20	1980	
1954	August 9	2730	940 (34%)
	September 1	1790	
1961	July 7	1880	1040 (44%)
	July 8	2350	
	July 16	1310	
1970	August 12	2290	20 (1%)
	August 16	2310	
1980	September 26	3990	3990 (0%)
	October 3	3990	
1991	August 21	2670	720 (21%)
	September 19	3390	
2006	July 27	1980	20 (1%)
	July 28	2000	

5.3.1 Definition of map units

Map units were defined using terminology derived from previous studies in the literature and from observations of the types of features present on the Bighorn River. These features were mapped in order to examine pre and post-dam changes in the channel for 21.6 miles downstream of the dam (Figure 11).

<u>Main channel:</u> wetted channel; the widest channel in areas of multiple channels; free of vegetation.

<u>Side channel:</u> wetted to partially wetted channels; narrower width than the main channel at the upstream end; located between the main channel and stream bank or between islands; wetted at both the upstream and downstream ends; may have some disconnected pools along their length; mostly free of vegetation.

<u>Overflow channel:</u> dry channel, predominantly unvegetated; may have occasional pools along its length; may also have a downstream connection with the main channel; no upstream connection.

<u>Unvegetated bar:</u> channel bar that is bare of vegetation or supports only small shrubs and grasses, shows evidence of repeated or recent inundation; includes several types of bars, the most common of which are lateral bars, point bars and mid-channel bars. Lateral bars are located between the main channel and stream bank and are typically elongate forms. Point bars are located along the inside of a channel bend and are more equidimensional in shape. Mid-channel bars are surrounded on both sides by water and typically have a streamlined form which tapers at both ends and is wider at the center of the bar. Bar types were not differentiated, but are noted here to recognize that different forms do occur that may support a variety of aquatic habitat.

<u>Vegetated island:</u> mid-channel bar surrounded by water on both sides and detached from the stream bank by side channels, overflow channels or split flow channels. Vegetation is in the form of dense shrubs and mature trees.

<u>Holocene floodplain:</u> alluvium located outside the mapped channel features; ranges in age from historical to 10,000 years. Abandoned channels are observed in many areas of this floodplain. Boundaries for the Holocene floodplain were derived from Agard (1989).

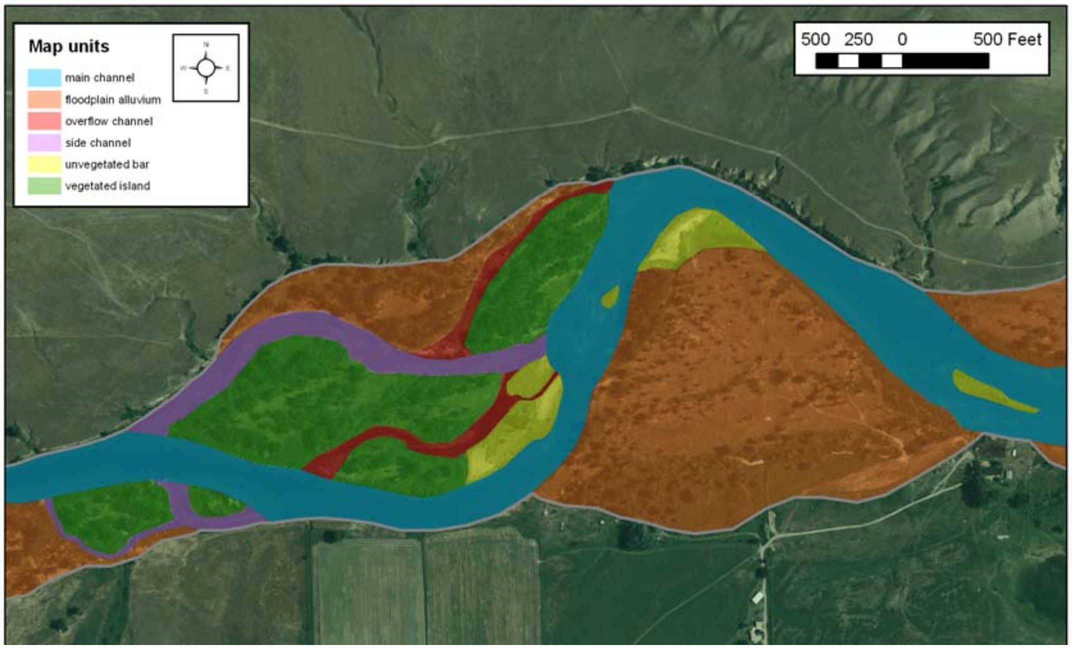


Figure 11. Example of geomorphic mapping along the Bighorn River study reach

<u>Bedrock:</u> consolidated sediments that are less erodible than surrounding alluvium; mostly shale in the study reach and relatively soft compared to other bedrock in the area. If present in the channel bed, it provides a natural grade control that will slow the rate of incision and provide a local base level that will influence upstream channel gradient and morphology; in the banks it will impede the rate of lateral movement (Figure 12). In the channel bed, there could be more bedrock not visible on photography or noted during the float trips.

<u>Human features:</u> include bank protection in the form of rip rap and spur dikes (Figure 13). These features were mapped along the length of the channel to determine if there were any channel changes associated with these features. Most of the human features are limited in extent and do not appear to influence channel position to a great extent.

Figure 12. Example of a bedrock outcrop along the study reach.

Figure 13. Bank protection provided by car bodies on the right bank near RM 6.

5.3.2 Analysis of historical changes in geomorphic features

Results of an analysis of the geomorphic mapping document changes in geomorphic features along the Bighorn River have occurred during the last seven decades. Main channel and side channel areas show a decrease of about 11 and 42 percent, respectively, from 1939 to 1961 and an increase in area following 1970 (Figure 14; Table 4). The overall trend shows a decrease in main channel area from 1939 to 2006, but it is very slight. Side channel area shows a 40 percent decrease from 1939 to 2006; even when considering a difference of 9 percent between 1939 and 2006 average discharges, this decrease is still substantial.

The trend in unvegetated bar area shows a consistent sharp decrease with a 72 percent loss from 1939 to 1980 and a more gradual decrease from 1980 to 2006 of about 65 percent. Decreases from 1939 to 1961 reflect recovery of the channel from the peak of record in 1935, in which lateral bars that had been scoured of vegetation were revegetated, thus decreasing the total area of unvegetated bars. Trends after 1980 show that the major response to dam closure took place from 1961 to 1980, and has been slowed for the last several decades, although the decreasing area of unvegetated gravel bars was still evident in 2006.

The trend in vegetated islands is somewhat more complicated with fluctuations from 1939 to 1961, a sharp decrease from 1961 to 1980 and increasing area from 1980 to 2006. From 1961 to 1980, the sharp decrease in vegetated islands corresponds to a concurrent loss of overflow channels, which were filling in with vegetation, causing the reattachment of the vegetated islands to the floodplain areas. The increase from 1980 to 2006 shows the continued encroachment and maturation of vegetation onto gravel bars that were previously unvegetated. The overall trend for vegetated islands is one of loss due to the loss of overflow channels and the reattachment of many of the larger vegetated islands to the floodplain areas.

Overflow channel areas remained consistent from 1939 to 1961 and show a sharp decrease from 1961 to 1980, corresponding to the loss of large flows and vegetation encroachment in the channels. The slight increase in overflow channels from 1991 to 2006 corresponds with the loss of side channels over the same time period in which side channels were transitioning to overflow channels and began to only receive flow during the largest discharges. The overall trend for the overflow channels is one of loss due to the decrease in peak flow following dam construction.

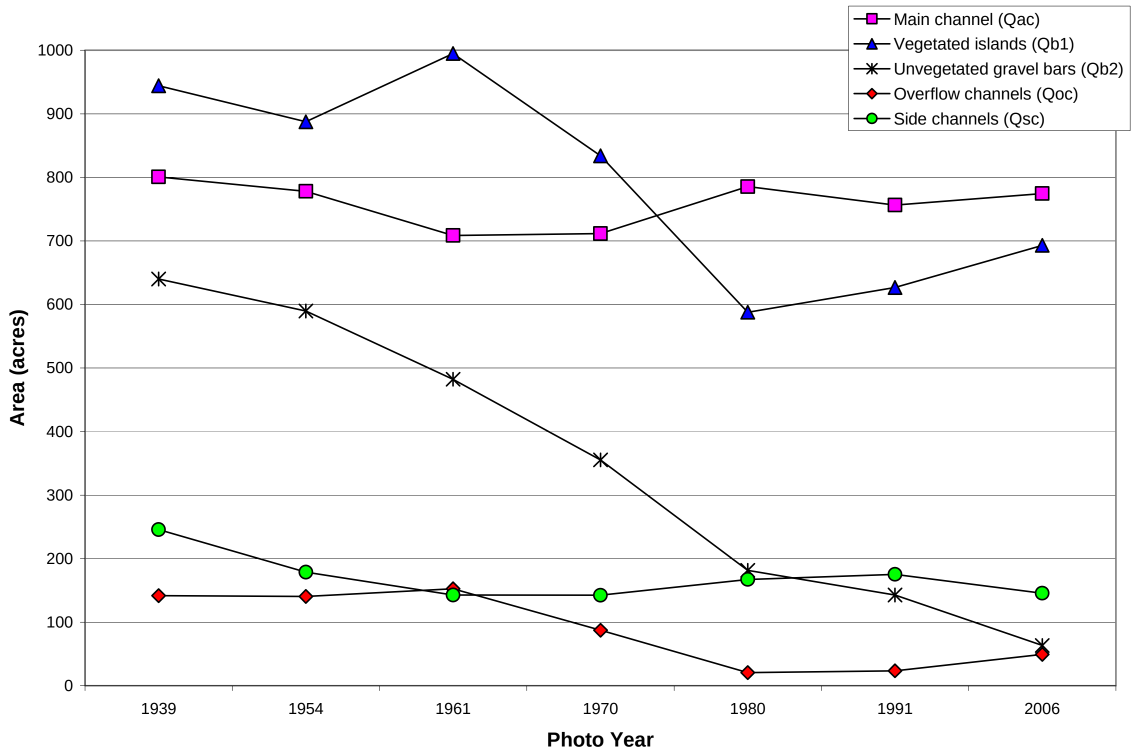


Figure 14. Area calculations of selected mapped features, 1935-2006.

Table 4. Area of selected map units (in acres)

Photo year	Main channel	Vegetated islands	Unvegetated bars	Overflow channels	Side channels	Active channel*	Average discharge
1939	801	944	640	142	246	1686	1827
1954	778	888	590	141	179	1547	2260
1961	709	995	482	153	143	1334	2260
1970	711	834	355	87	142	1209	2115
1980	785	588	182	21	167	1134	3990
1991	756	627	143	24	175	1075	3030
2006	775	693	63	49	146	984	1990
% Change (1961-2006)	+9	-30	-87	-68	+2	-26	

*Active channel = main channel + side channel area + unvegetated bar area

Active channel area, a measure of channel complexity, includes the area of the main channel, side channels and unvegetated bars. These features show the overall area of habitat available in the post-dam flow regime in which flows mobilize sediment frequently and maintain an area clear of most vegetation and inhibit the development of mature vegetation (Figure 15). Active channel area has also decreased over the historical period; from 1939 to 1961, it reflects the recovery of the river channel from the 1935 peak of record and potentially the impacts of Boysen Reservoir on the upper Bighorn River. From 1961 to 2006, the decrease in active channel area reflects the decrease in sediment and discharge necessary to maintain the larger active channel area along the river. Without this, vegetation is allowed to establish on previously unvegetated bars and to encroach into side channels due to lower velocity flow. The decrease in unvegetated bars is the main driver of the overall pattern, since main channel area has remained similar and the total area of side channels is small when compared to the area of unvegetated bars.

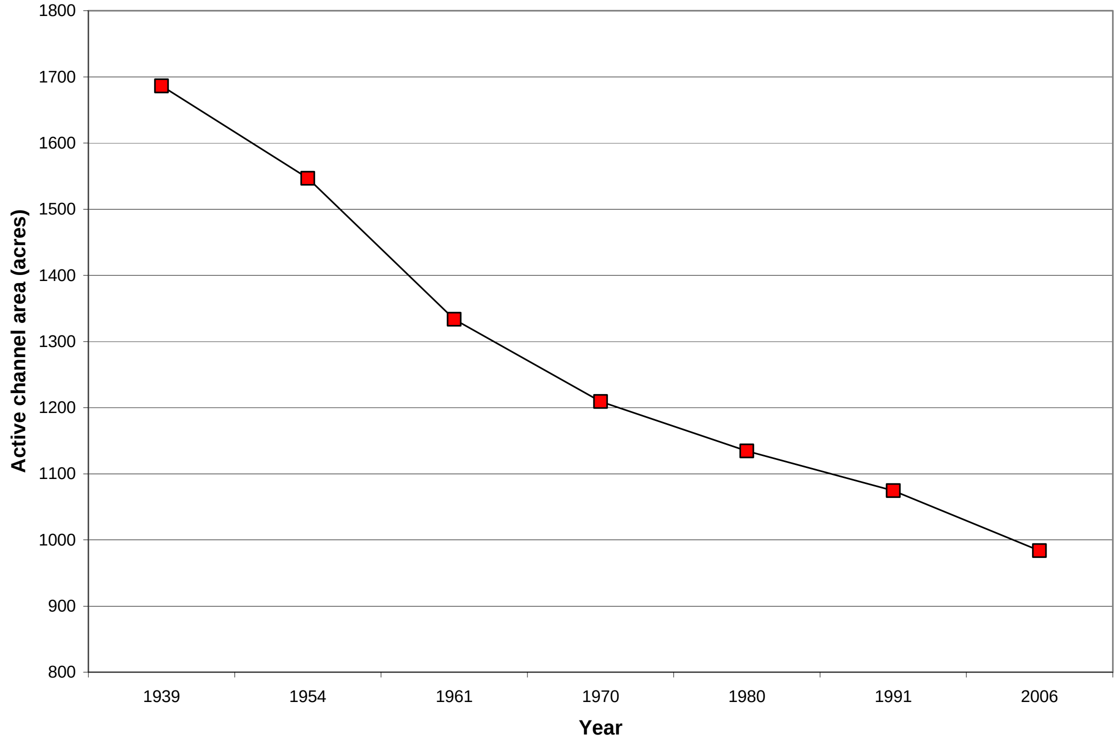


Figure 15. Active channel area measurements, 1935-2006.

Comparison to Koch's (1977) analysis is difficult due to differences in mapping and study reach lengths. Koch defined two study reaches that span the present study reach; reach 1 extended from Yellowtail Afterbay to just above the mouth of Hay Creek; reach 2 extended from above Hay Creek to just above Two Leggins Diversion Dam. The current study reach comprises all of Koch's reach 1 and part of reach 2. Koch did not map overflow channels, or areas that convey high flows and may not be wetted during the time of aerial photography. This difference significantly impacts the area of vegetated islands that would be mapped between the two studies. Koch also combined the results from the mapping of vegetated islands and gravel bars, making it impossible to just compare the gravel bars. The total water area is somewhat comparable; however, side channels were mapped to include unvegetated bars, so this would skew the results toward larger areas at least for the side channels. If the numbers are compared, this study shows an 18 percent decrease for combined main channel and side channel area from 1939 to 1970 while Koch's results show less than 5 percent increase or decrease for the two study reaches from 1939 to 1974.

5.3.3 Individual channel complex history

Historical channel changes and field observations were summarized for each channel complex in the expanded study reach (Yellowtail Dam to Mallard Landing). A channel complex consists of a network of anabranching channels that share channel junctions with each other and the main channel within a short distance. While 2006 mapping demonstrates that not all channel complexes are comprised of more than one channel or even a side channel as defined in this study, all are termed complexes to reflect the historical existence of a more complicated channel network in almost every mapped location. Detailed field observations were made from Yellowtail Dam to Bighorn Access (up to channel complex 18) including the relative velocities and depths in each side channel. For the remaining channel complexes from Bighorn Access to Mallard Landing Access, mapping is described, but no field verifications were made regarding channel mapping or conditions of the side channels. A reconnaissance float was performed, however, during August 2009 field work, and most side channels appeared to have flowing upstream and downstream connections; a notable exception to this observation occurred at the downstream confluence of the large side channel at complex 26, where flow was observed to backwater.

<u>Channel complex 1</u>

Side channel 1 has been in almost the same position since the earliest aerial photography available (Figure 16). In 1939, the channel flowed around an unvegetated bar and received additional flow during large discharges from an overflow channel that entered at its abrupt bend to the east. By 1961, the overflow channel began to fill in with vegetation and the unvegetated bar separating the side channel from the main channel also began to stabilize with vegetation. By 1970, the overflow channel appeared to be inactive, being cut off by a lateral bar along the main channel margin at the entrance to the overflow channel. Vegetation density continued to increase and mature on both the overflow channel and island. However, the downstream end of the overflow channel appears to have maintained a downstream connection with the side channel and serves as a backwater environment. It appears that the entrance to the overflow channel was utilized as a right-of-way for power lines and is kept cleared for this reason. Side channel 1 exists currently as a high velocity channel with cobble substrate. Bedrock was observed at the downstream end of the overflow channel and also and the downstream end of the side channel.

<u>Channel complex 2</u>

Prior to 1961, the area in the vicinity of channel complex 2 existed as a low lateral bar along the left bank inner channel bend whose material was mobilized frequently enough to remain free of vegetation (Figure 16). The complex as it exists today was formed between 1961 and 1970. Grassy vegetation was established on the bars by 1980. The bars are low enough that they are modified at least partially during the more frequent post-dam flows and therefore have not established a dense network of trees or shrubs on their surfaces. The channel complex consists mostly of a pebble-cobble substrate with moderate to high velocity flow through the side channels. Other major changes near channel complex 2 include the loss of a large overflow channel along the left bank between 1961 and 1970 and the loss of a smaller overflow channel on the right bank between 1954 and 1961.

Channel complex 3

The present configuration of side channel 3 was established in 1980 (Figure 16). In 1939, unvegetated bars existed in the area, but no side channel was present. By 1954, the general configuration for side channel 3 was established, with a side channel formed around an unvegetated bar in the area. This general pattern was maintained with minor variations in channel and bar position until 1980, when the side channel stabilized into a form that has not changed considerably for the past several decades. Vegetation encroachment along an extensive lateral bar on the right bank from 1954 to 1980 aided in the stabilization of side channel 3. Observations from April 2009 indicated that this was a low velocity channel with a mucky bottom of fine sediment over a gravelly substrate. However, observations following the high flow during July 2009 revealed that some of this sediment had been scoured, leaving remnant benches of fine-grained sediment along the channel margins.

Channel complex 4

In 1939, the area near side channel 4 was occupied by a small vegetated island in the center of the main channel with an unvegetated lateral bar between the island and streambank (Figure 16). Downstream, several narrow overflow channels cut across vegetated portions of the large point bar on the right bank. In 1954, the general geometry of the channel was established but not well defined. Vegetation encroachment onto the lateral channel bar helped to establish a stable position for the side channel by 1970; this area has continued to vegetate through the present time. This side channel was marginally inundated during field observations and consisted of a silty sand deposit over cobbly substrate and young willows along the channel margins at its entrance. Several mucky backwaters existed at the downstream connection with the main channel and within the sharp bend to the northwest.

Channel complex 5

The general position of this side channel has been present since 1939, although the exact bar shape and channel position were not fully established until 1980 (Figure 16). This bar has grown in size from 1939 to 1980, but has remained relatively unvegetated, receiving inundation frequently enough post-dam construction to inhibit the maturation of woody shrubs and large trees. This channel is currently a high to moderate velocity side channel with a cobble substrate.

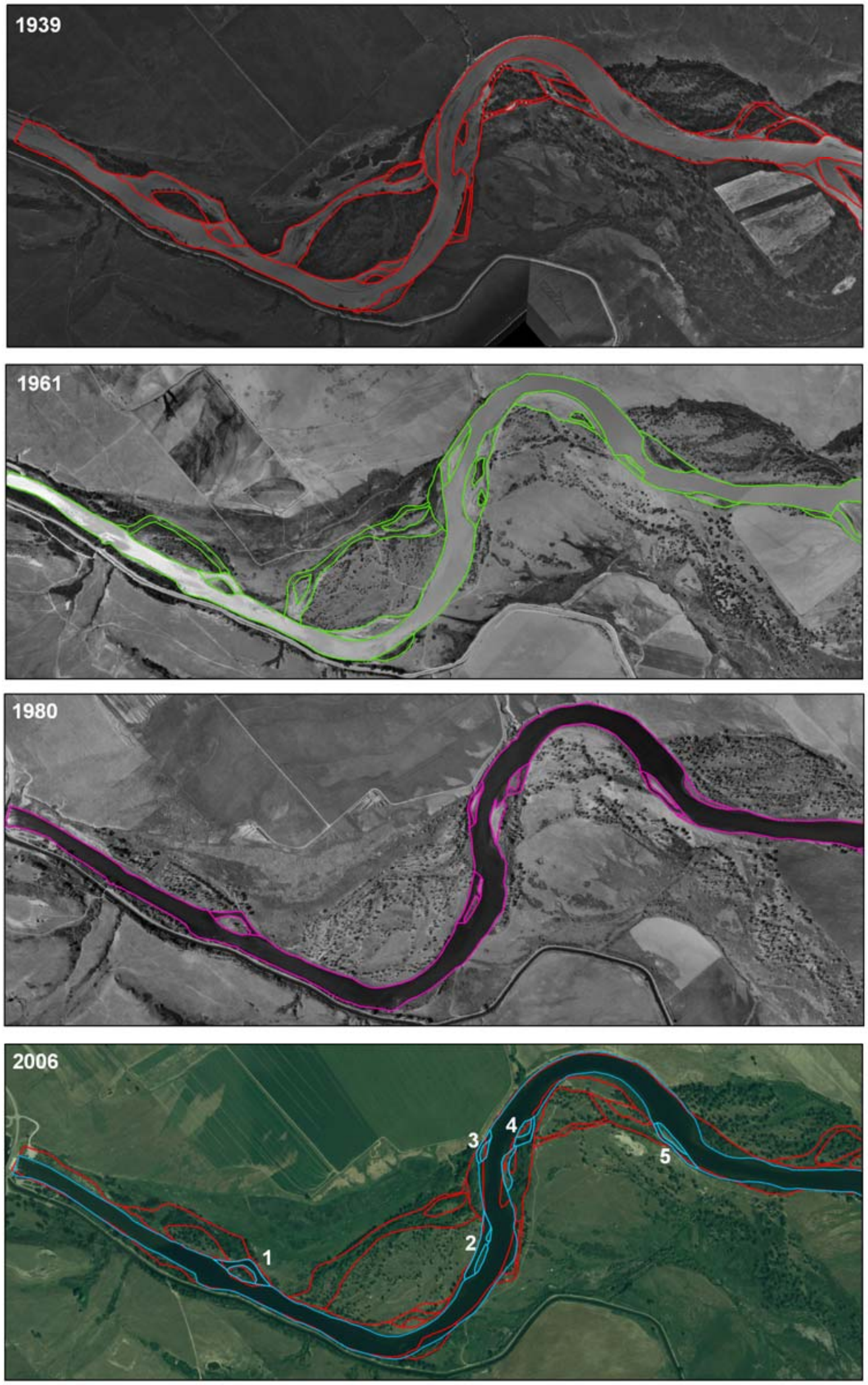


Figure 16. Historical channel mapping for complexes 1 through 5 showing changes from 1939, 1961, 1980 and 2006. The 1939 mapping is overlaid in the 2006 imagery for comparison.

Channel complex 6

Channel complex 6 is located just upstream of the 3-mile (Lind) boat access and consists of multiple channels with pebble-cobble substrates (labeled A through E; Figure 17) and moderate velocities. Minor areas of fine sediment exist where secondary flow currents create low velocity eddies, but the majority of the channel has fast flowing confluences within the multiple branches and with the main channel. 1939 aerial photography shows that several of the channels, including 6A, 6C, and 6D are in similar locations to the present configuration (Figure 17). Additional channels are located upstream on the left bank in 1939, one designated as a side channel and the other as an overflow channel. By 1954, side channel 6E is formed and more vegetation is observed on the mid-channel bar. Between 1954 and 1961, side channel 6B developed and the channels along the left bank have been abandoned. These were probably utilized during the 1935 flood have not been accessed since that time. The present configuration of channels was developed by 1970 and vegetation has continued to increase on the islands through 2006.

Channel complex 7

The 1939 channel pattern in the vicinity of complex 7 consisted of main channel split flow around an unvegetated mid-channel bar with an extensive lateral unvegetated bar and overflow channel along the left bank (Figure 18). Several narrow overflow channels are also mapped in the left bank and right bank floodplain areas. The change in channel configuration began to develop in 1954, in which the right branch of split flow developed into a distinct side channel separate from the main channel and vegetation began to establish on the mid-channel bar. The overflow channel along the left bank was progressively abandoned. Erosion along the right bank between 1961 and 1970 elongated the side channel and lengthened the mid-channel bar into an unvegetated and vegetated component. This channel pattern continued to stabilize through 2006 with further vegetation establishment in the unvegetated bar areas. The overflow channels present in the 1939 aerial photography were abandoned by 1970, at which point the vegetation was large enough to infer that these were not being regularly utilized by the river in the post-dam construction. The side channels within channel complex 7 can be described currently as moderate to high velocity with a pebble-cobble substrate. The only exception to this is side channel 7E, which was not previously mapped by FWP, but exists as a low velocity channel with shallow flow. In April 2009, a beaver dam existed at the downstream end of the side channel, which backed up flow to the sharp bend in the channel and encouraged the deposition of fine sediment in the ponded area. In August 2009, the beaver dam had been significantly eroded by the flood in July and much of the fine sediment had been eroded, leaving a patchy gravelly substrate in the channel bottom.

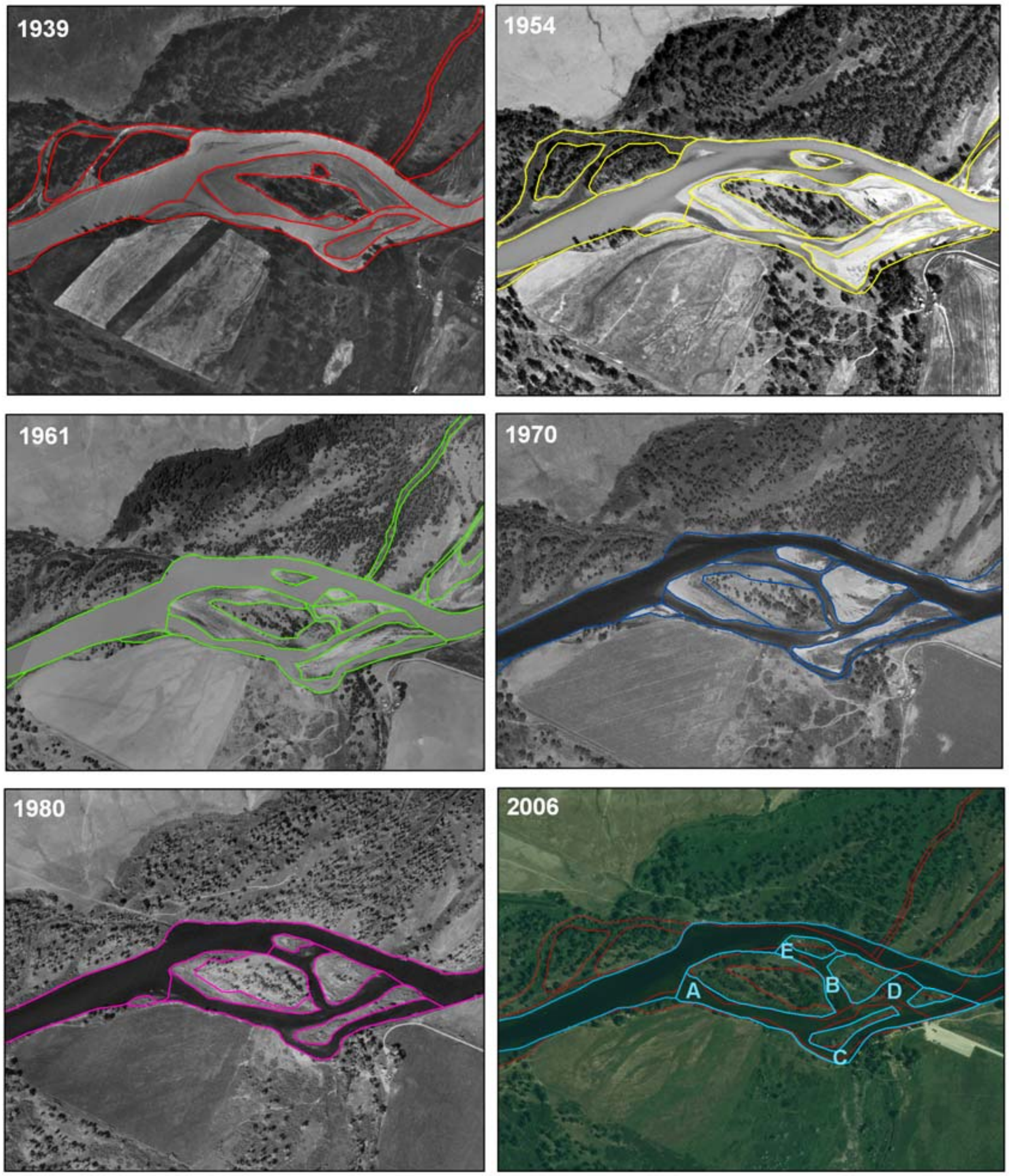


Figure 17. Historical channel mapping of complex 6.

<u>Channel complex 8</u>

Several side channels of channel complex 8 are visible in 1939 including 8A, 8B and 8C (Figure 18). Additional side channels along the left bank (north side) of the river are also visible in 1939 that are either overflow channels or part of the floodplain in 2006. Side channels 8C, 8D and 8E and lateral migration of the main channel toward the east had developed by 1970 while the additional side channels present in 1939 either transitioned to overflow channels or attached to the floodplain. By 1980, all islands were heavily vegetated, which encouraged stability in the channel pattern through 2006. Observations in 2009 revealed that channel 8A has a mucky substrate at both the upstream and downstream ends with low velocity, shallow flow at the upstream end and backwater at the downstream end. Flow in channel 8B is moderate velocity, which slows in velocity toward the downstream end. Sediments are composed of fines over gravel, which increase in thickness downstream; observations before and after the high flow of July 2009 suggest that some of this sediment was scoured from the upstream end while fresh gravel was deposited at the head of the island adjacent to 8B. 8C, also known as the Duck Blind channel, flow can be characterized as moderate velocity with several riffles and a cobbly substrate. Channels 8E and F are overflow channels that have vegetation established at their entrances, but are mostly grassy with intermittent scour holes that form pools along their length. Thin deposits of fine sediment exist at the channel entrance above the low flow water surface and at the downstream connection with the main channel where water is ponded. Both channels are backwatered at their downstream connection with the main channel.

Channel complex 9

The mid-channel bar that exists at channel complex 9 has been present in this general location since 1939 and has remained relatively unvegetated throughout the historical period (Figure 19). This suggests that the bar is relatively low elevation and has received significant flow to destabilize sediment and vegetation on a regular basis. It should be noted that the mapping scheme in this study did not designate a side channel in the area due to the similar width of the channel on both sides of the mid-channel bar. Both channels are relatively deep with moderate to high velocities.

Channel complex 10

In 1939, the area of channel complex 10 existed as an extensive lateral bar with several vegetated islands (Figure 19). The main channel was in a similar position as that mapped in 2006. Vegetation establishment between 1939 and 1954 created several distinct channels including side channel 10A and smaller side channels 10B and 10C, separated from the main channel by unvegetated mid-channel bars. An overflow channel was also present at the upstream end of the complex. By 1980, the side channels had transitioned to overflow channels; 10B exists currently as an unvegetated, gravelly overflow channel while 10C is filled with cattails and fine-grained sediment over gravel and received some minor flow at lower discharges. The overflow channel at the upstream end filled in with vegetation by 1980. Vegetation encroachment of many of the bars can be observed between 1961 and 2006. Channel 10A is the only remaining active side channel in this complex and the entrance contains pebble-cobble bed material. Some scour pools along its length are partially filled with a thin layer of silt. Downstream connections of the split flow channel form low velocity or backwater areas.

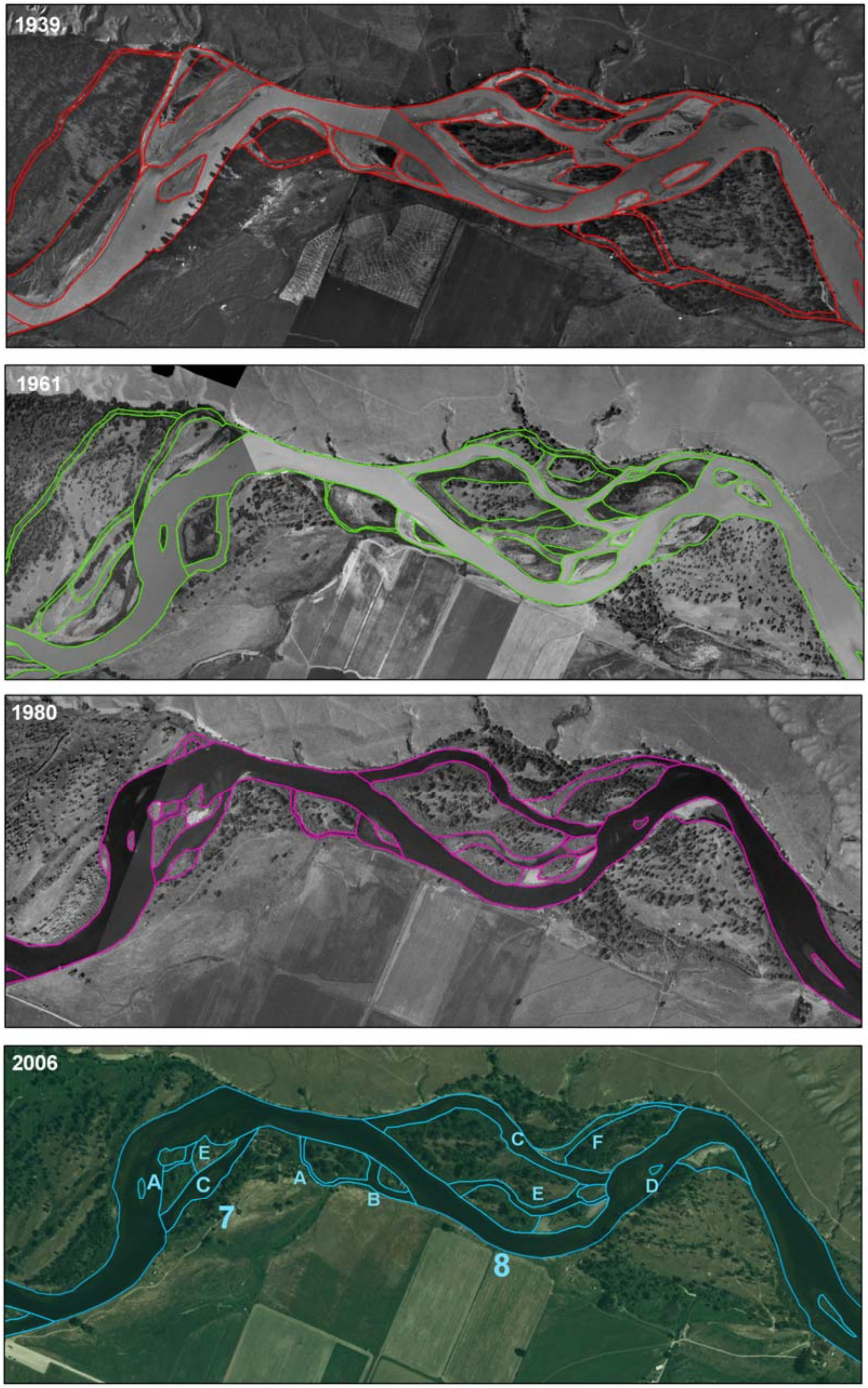


Figure 18. Historical channel mapping for complexes 7 and 8.

Channel complex 11

A mid-channel bar and side channel have existed since 1939 in the vicinity of channel complex 11, but were not established in their current position until 1980 (Figure 19). The channel experienced lateral erosion of the right (east) bank between 1961 and 1970 to establish the 2006 position of the right bank and an unvegetated lateral bar that subsequently developed into side channel 11 between 1970 and 1980. Several other side channels and overflow channels existed in this area in 1939 and were abandoned by 1980. Side channel 11 was observed during 2009 field work to have shallow, low velocity flow at the channel entrance and a layer of silt over gravel in the channel bed with some scour pools. The downstream connection to the main channel formed a backwater and the mid-channel bar had mostly grassy vegetation at its upstream and downstream ends with some larger shrubs and trees in the mid-section of the bar.

Channel complex 12

Channel complex 12 consists of multiple anabranching channels that split around a large, vegetated island. The general channel position of complex 12 has been established since 1939 with overflow channels that flowed through vegetated portions of the islands and several side channels located in unvegetated components of lateral bars (Figure 20). In 1961 through 1980 aerial photography, the gradual disappearance of overflow areas and unvegetated lateral bars can be seen with the greatest change between 1970 and 1980. By 1980 all 2006 channel positions were established and vegetation encroachment to further define the channel positions as they exist currently. Developments between 1991 and 2006 include the formation of two additional side channels, 12J and 12K; these side channels are very short, steep and cobbly riffles with grassy vegetation on the mid-channel bars. Other side channels have high velocities with cobbly bed material with 12C being the only exception, which had shallow flow during 2009 field work and reed canary grass growing in the channel.

Channel complex 13

In 1939, side channel 13, also known as Glines channel, was a large side channel with a greater width and number of unvegetated bars than in 2006 (Figure 21). Two flow paths diverged at the downstream end around an unvegetated bar. In 1970, flow was disconnected at the upstream end with water visible in parts of the channel. The right branch of split flow appeared to be filling in with sediment. From 1970 to 1991, a gradual increase in vegetation can be seen with a few bushes or trees visible at the upstream connection with the main channel. By 2006, a significant increase in vegetation at the side channel entrance is visible. This channel was observed to have shallow flow during 2009 field work with grass, willows and cattails growing in the channel entrance. Fine sediment was also noted in the channel entrance and downstream from the entrance, which covered the gravel bed in most locations.

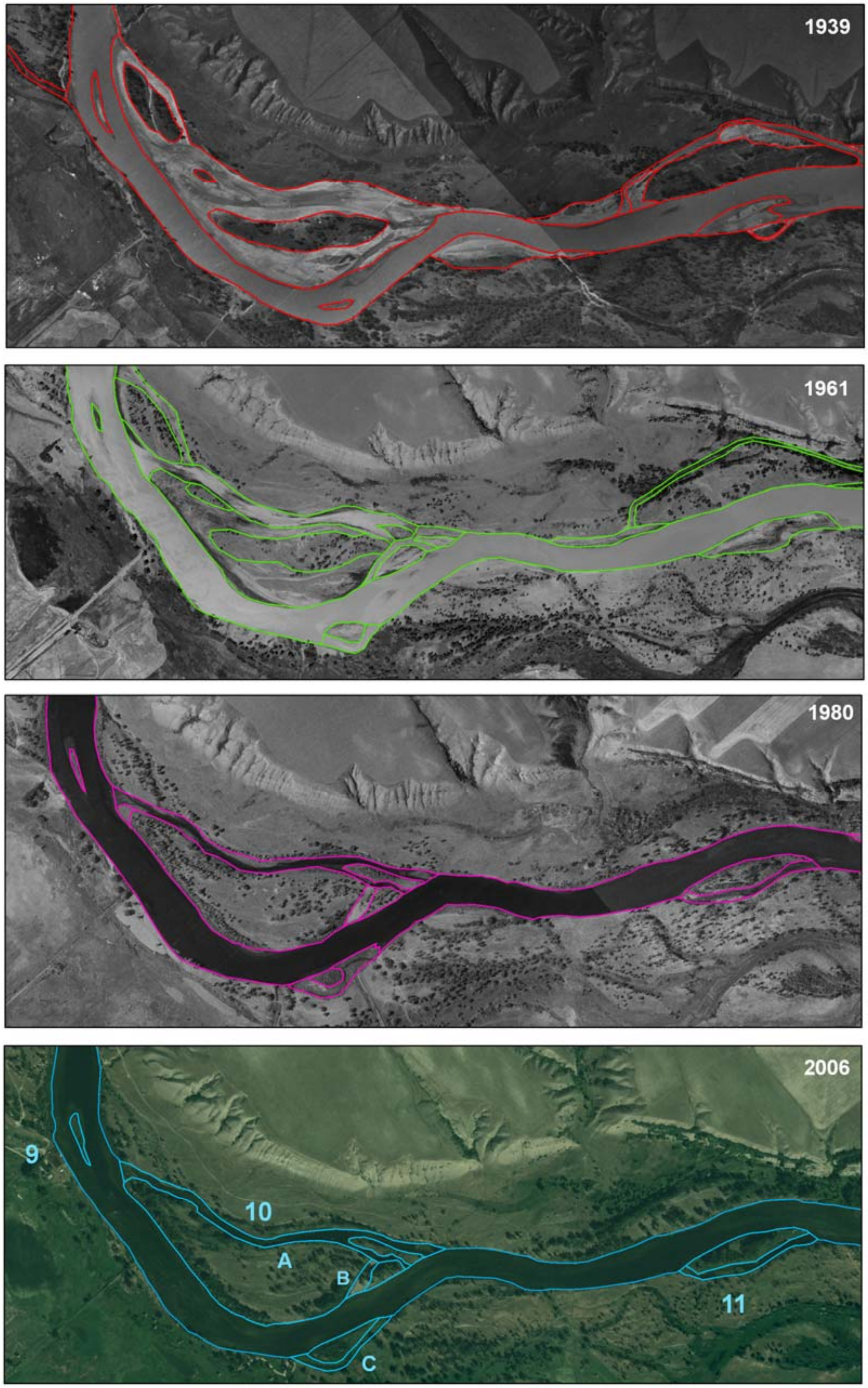


Figure 19. Historical channel mapping for complexes 9, 10 and 11.

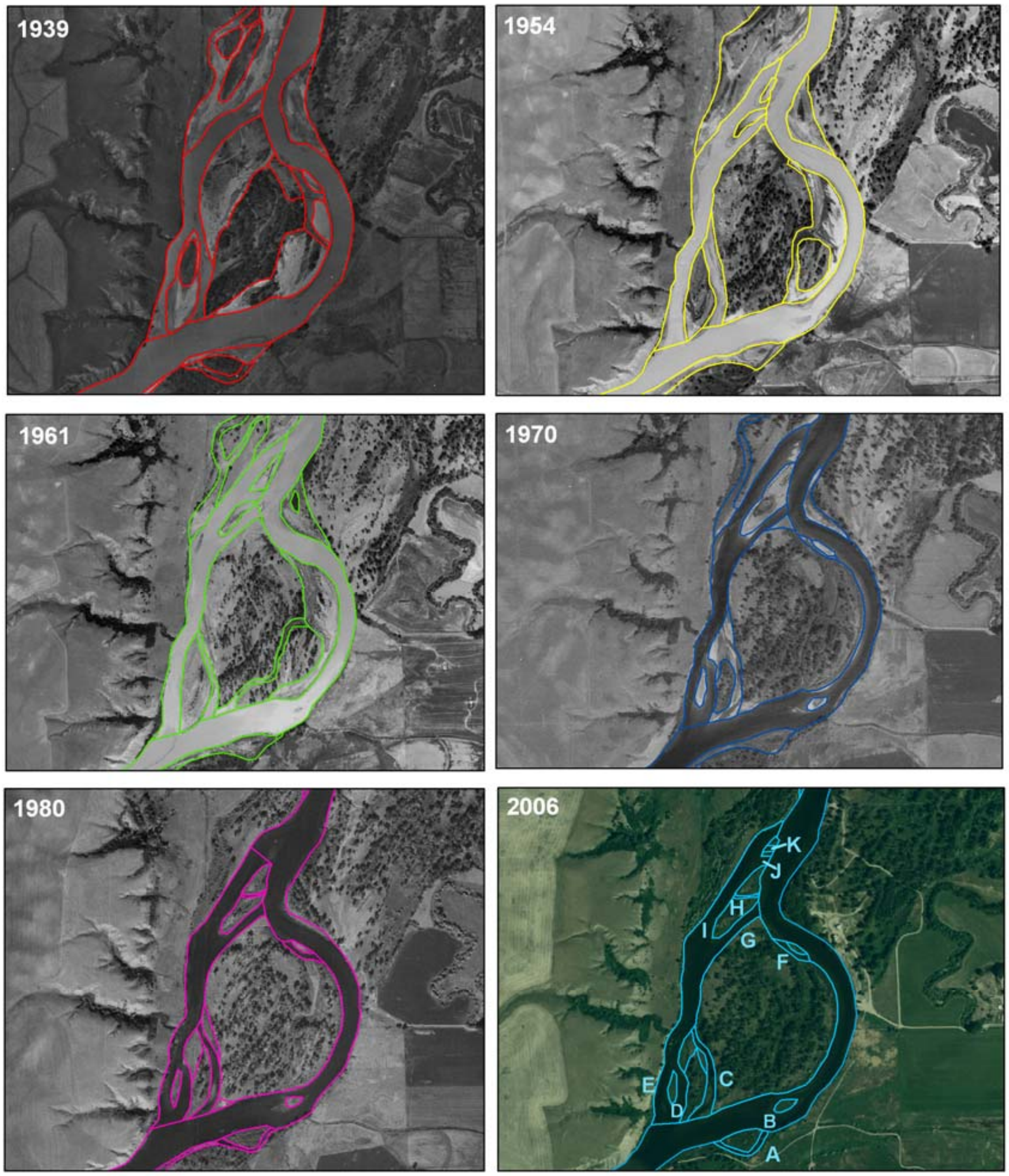


Figure 20. Historical channel mapping for complex 12.

<u>Channel complex 14</u>

The split flow pattern and channel locations in 2006 aerial photography for channel complex 14 had developed by 1980 (Figure 21). In 1939, the channel pattern consisted of a main channel along the left bank with an unvegetated lateral bar and overflow channel along the right bank. By 1954, the split flow pattern had developed with the right channel (14C) considerably narrower than the left channel. By 1970, bars were beginning to develop in their current locations, forming side channels 14B and 14D; erosion along the right bank created a channel of similar width to the 2006 channel. Vegetation density was also notable by 1970 and continued to increase through 2006. Side channel 14A appears to have developed prior to 1991 as shown on FWP channel mapping. However, it is not easily recognized in aerial photography prior to 2006. This side channel deepened after its sharp bend with low to moderate velocity flow during 2009 field work; other side channels in the complex were observed to have moderate velocities with cobble substrates. Soap Creek enters just downstream of this channel complex and has been located at this confluence point since 1939. This tributary contributes a sediment load of primarily sand, silt and clay to the Bighorn River.

<u>Channel complex 15</u>
The area of complex 15 had a very different configuration prior to dam construction (Figure 21). In 1939, the main channel was located in what is now a vegetated island. Several side channels were located on either side of the main channel with vegetated and unvegetated bars between the channels. By 1954, the side channel along the right bank was abandoned and a split flow pattern developed at the upstream and downstream ends of the complex. The 1970 aerial photography shows that the main channel had moved to the left side of the valley between 1961 and 1970 and that side channels 15A, 15B and 15E and overflow channels 15C and 15F had begun to develop in their current locations where the main channel had migrated laterally towards the right (east) bank. Vegetation was also beginning to emerge on islands in greater quantities than previously. By 1980, most of the side channels and overflow channels were in their 2006 positions. Side channel 15D was a very short-lived side channel that was visible in 1980 photography. This side channel has primarily served as an overflow channel. In 2009, most of the side channels in this channel complex, including 15A, 15C and15D, had dry entrances with vegetation obscuring the entrances and a backwater at the downstream connections. Side channel 15B had a cobble bed at its entrance and silt accumulations in secondary flow areas with moderate velocity flow. Observations made following the July 2009 high flow indicated that channel 15B had been scoured and widened and a larger volume and higher velocity flow was entering the side channel. This channel complex was also noted to have bedrock in its channel bed in side channel 15B and in the main channel between 15C and the confluence with side channel 13.

<u>Channel complex 16</u>
The channel configuration of complex 16 has been similar since 1939, with split flow around an unvegetated bar (Figure 22), and had developed its 2006 position by 1980. The bar became partially vegetated by 1954 and has maintained a similar coverage of vegetation since that time, with the upper end of the bar remaining unvegetated. Side channel 16 was noted to be long and deep with high flow velocities and a cobble substrate during 2009 field observations.

<u>Channel complex 17</u>
Channel complex 17 is located at the entrance of an unnamed gulch. The history for complex 17 is similar to complex 16. In 1939, the side channel was in its present location, but shorter in length (Figure 22). By 1954, the configuration was very close to the present configuration.

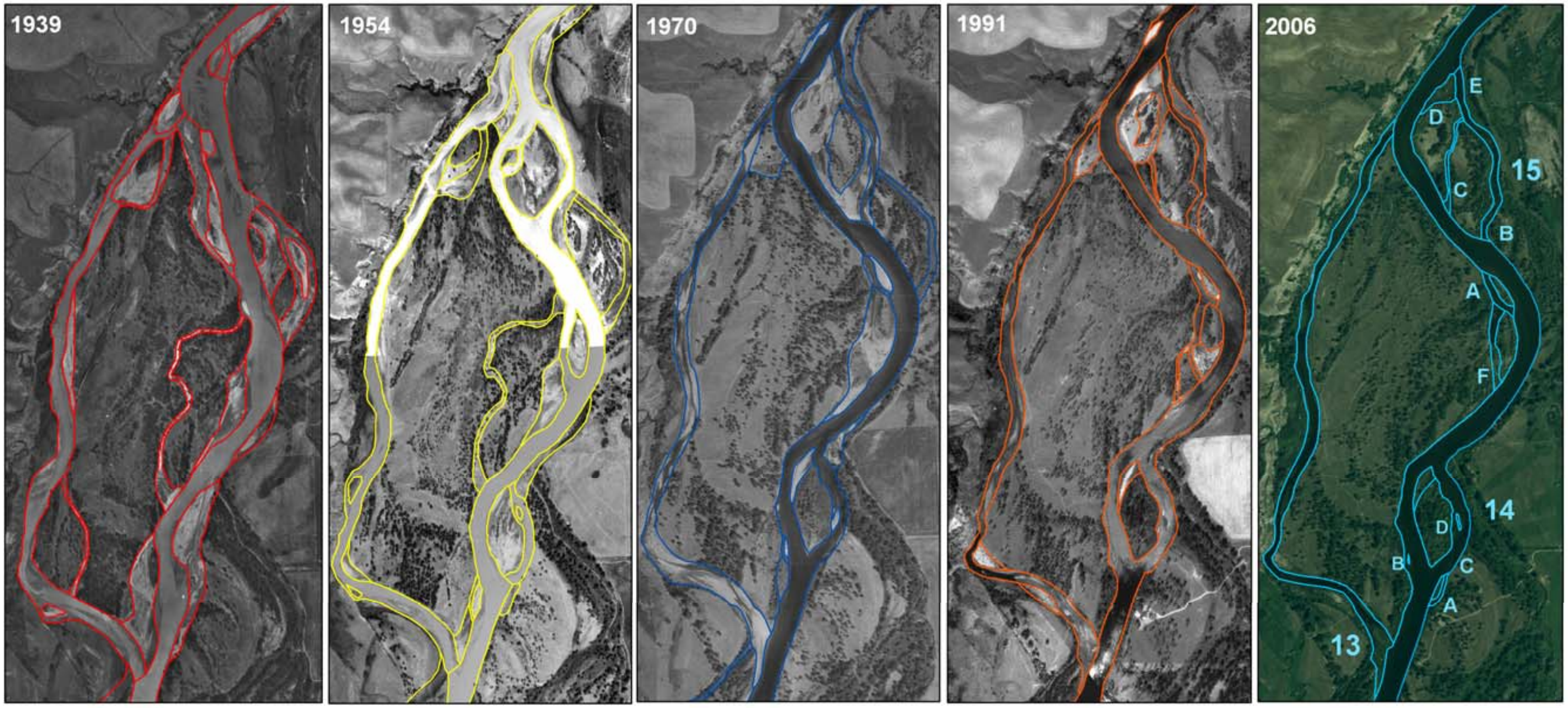


Figure 21. Historical channel mapping for complexes 13, 14 and 15.

By 1970, small mid-channel bars had developed and by 1980, had the same extent as 2006. Bars separating the side channel from the main channel have grassy vegetation and small shrubs, which suggest that they are frequently inundated. The channel substrate was observed to be cobbly and the channel itself is steep and narrow with swift velocities.

Channel complex 18

Channel complex 18 is mapped as a split flow channel through the historical period with exception of 1939 and 1961 where the difference in width between the two channels was great enough to define the left channel as a side channel (Figure 22). While the mid-channel bar has been in a similar location since 1939, it had established its 2006 location by 1970. This bar has larger trees and shrubs when compared to the bar at complex 17. The channels can be characterized as moderate to high velocity channels with cobble substrate.

Channel complex 19

From 1939 to 1970, channel complex 19 has existed as an unvegetated lateral bar (Figure 23). By 1980, a side channel had developed along the back edge of the bar that has persisted through 2006. Low vegetation developed in 1980 and has remained low and immature, probably due to frequent flooding over most of the bar's surface.

Complex 20

The 1939 channel configuration at channel complex 20 consisted of unvegetated lateral bars on the left bank and narrow overflow channels on the right bank floodplain (Figure 23). By 1954, the general bar configuration had developed into its present form. Progressive abandonment of the right bank overflow channels between complex 19 and 20 can be observed between 1939 and 1961, with some minor channel splays on the floodplain surfaces in 1961. By 1970, the upstream two side channels (20A, 20B and 20D) had developed with mid-channel bars beginning to vegetate and by 1980, all three side channels including 20C were in their 2006 locations. The continued growth and maturation of vegetation on the bars can be seen between 1990 and 2006.

Complex 21

At complex 21, a large side channel existed along the right bank in 1939 that evolved into an overflow channel by 1954 and was completely abandoned by 1980 (Figure 23). Multiple channels and unvegetated bars were present in 1939 photography and persisted in the same general locations until 1970, when the bars began to vegetate with small trees or large shrubs, eventually coalescing into larger vegetated islands with more mature vegetation between 1970 and 2006. The larger side channels along the right bank (21A and 21B) were established in their general locations by 1954; however, the smaller side channels in the vicinity of channel 21B developed as the smaller mid-channel bars and vegetation developed between 1961 and 2006.

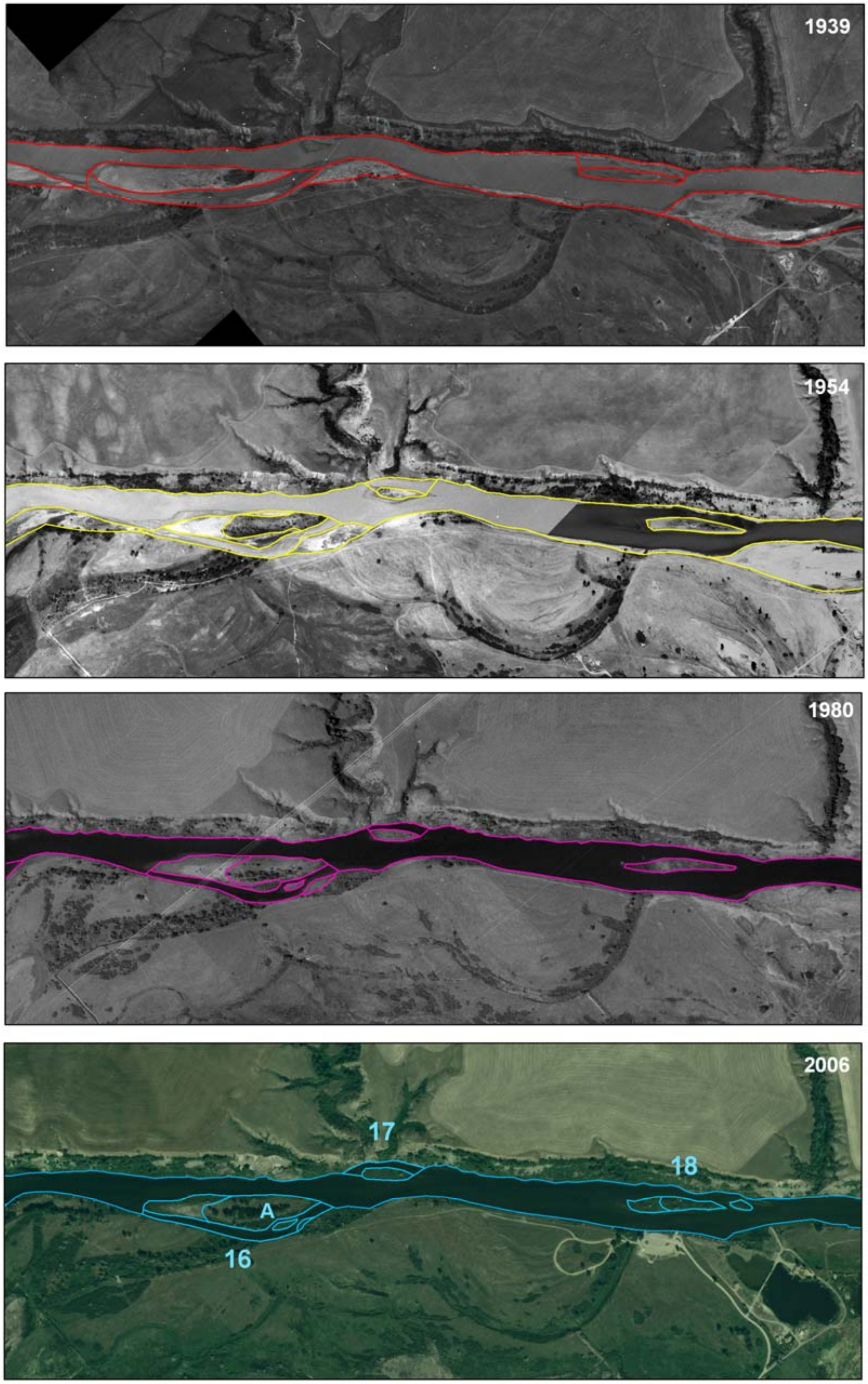


Figure 22. Historical channel mapping for complexes 16, 17 and 18.

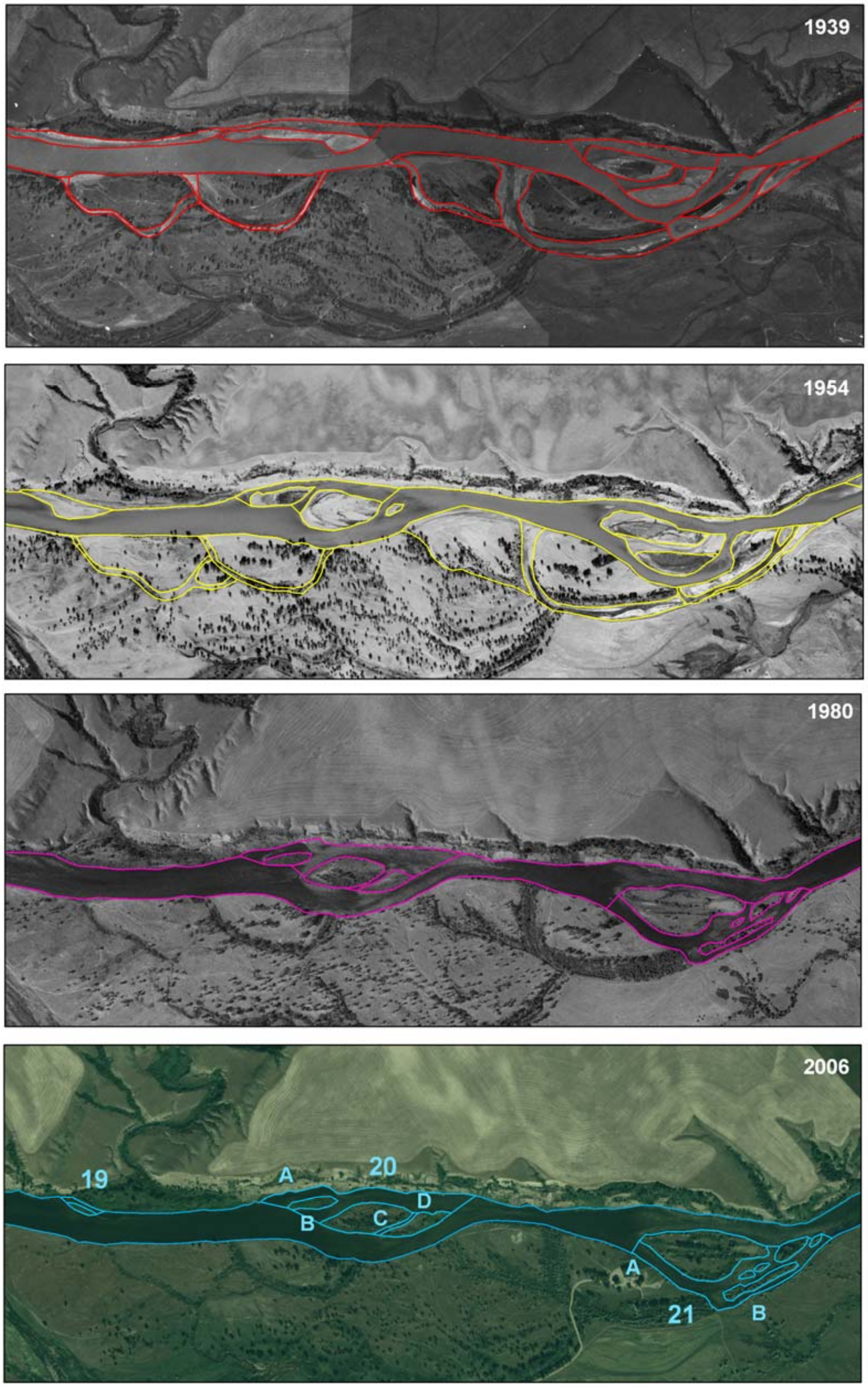


Figure 23. Historical channel mapping for complexes 19, 20 and 21.

Channel complexes 22 and 23

Channel complexes 22 and 23 in 1939 photography show split flow around a large unvegetated bar in the main channel and a side channel of considerable length along the right bank with a largely unvegetated bar in the middle of the complex (Figure 24). In 1954, side channel 22 is present at a slightly different location than 2006 with a mid-channel bar and lateral bar along the right bank. Side channel 23 is present at a very similar location to that of 2006. Between 1954 and 1961, side channel 22 is incorporated into the main channel while side channel 23 is located in essentially the same position. In 1970, a narrow side channel is formed at the location of 22 and persists through 2006; side channel 23 and its mid-channel bar are also in the same position as in 2006 with an additional narrow side channel that formed between 1991 and 2006. Changes from 1970 to 2006 are mainly related to vegetation establishment on lateral bars and mid-channel bars, which reduced the overall active channel area for these complexes and slight changes in the configuration of side channel 22. It should also be noted that the lengthy side channel along the right bank that existed in this area in 1939 had transitioned to an overflow channel by 1961.

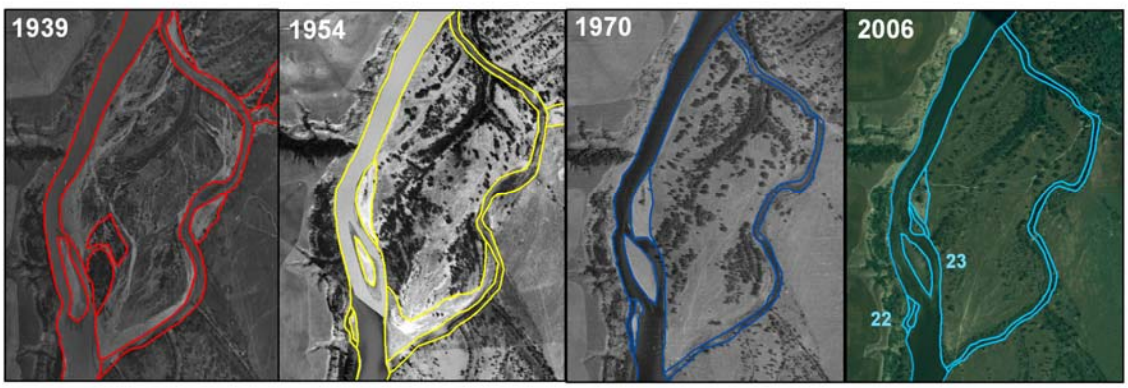


Figure 24. Historical channel mapping for complexes 22 and 23.

Channel complex 24

In the area of complex 24, a narrow lateral bar existed along the left bank in 1939, which was mostly underwater (Figure 25). Along the right bank, a lateral bar and large overflow channel existed that connected with an additional side channel/overflow channel to the east. The 1954 photography shows a similar channel configuration with lateral erosion of the right bank between 1939 and 1954. By 1961, the far eastern side channel had converted to an overflow channel. A major change in bar configuration can be observed along the left bank in which several unvegetated bars developed between 1961and 1970. This could be related at least in part to the construction of St. Xavier Bridge, which may have encouraged sediment deposition downstream of the bridge. By 1980, these bars had been stabilized by vegetation and vegetation growth continued across these surfaces so that by 2006 mature vegetation existed on the majority of islands along the left bank.

Channel complex 25

Channel complex 25 has had a similar channel configuration since 1939 with minor changes in the position of the left bank side channel, increasing area of the mid channel bar between 1939 and 1961, and right bank erosion between 1939 and 1970 (Figure 25).

Vegetation increases similar to other complexes can be observed between 1970 and 2006. Most of the vegetation on this bar has remained relatively immature, suggesting that it is inundated frequently.

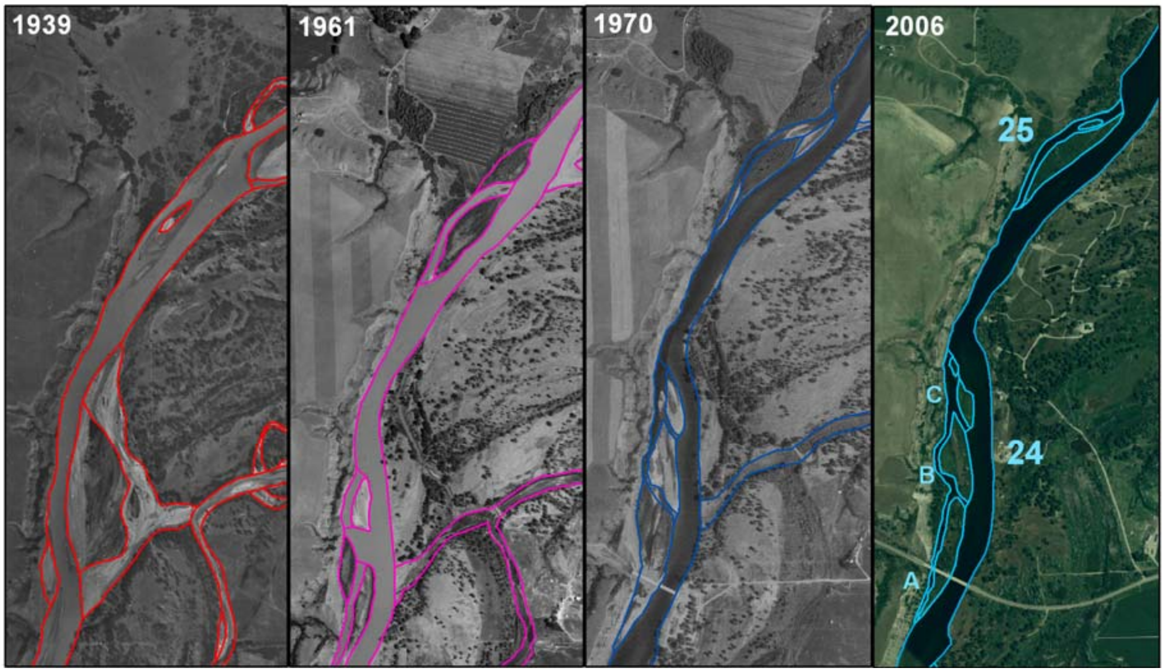


Figure 25. Historical channel mapping for complexes 24 and 25.

Channel complex 26

Channel morphology in 1939 in the vicinity of complex 26 consisted of a split flow channel pattern with extensive unvegetated bars (Figure 26). Between 1939 and 1954, the channel shifted toward the right bank with a more equal split in flow between the two channel branches. By 1961, a greater amount of flow appeared to be routed down the left channel, which had widened since 1954 while the right channel (26A) had narrowed in width. Between 1961 and 1970, the main channel migrated toward the right (east) bank and vegetation established on the large mid-channel bar between the two channels. The channel pattern in 1970 has remained relatively stable with the exception of development of side channel 26B. Additional vegetation on the banks and bars has developed through 2006. Side channel 26C was also a late development, appearing between 1980 and 1990 and partially filling by 2006.

Channel complex 27

At channel complex 27, multiple channels and bars existed in 1939, but in a slightly different configuration than present (Figure 26). Between 1939 and 1954, the main channel moved to the opposite bank. The channels mapped in 1961 had moved to similar locations to that of the 2006 overflow channel through erosion of the right bank to establish a split flow channel. The split flow channel had disappeared by 1970 and evolved into a single channel along the left bank that conveyed the majority of the flow and an overflow channel on the right bank. Vegetation appears to have progressively encroached on lateral bars and islands beginning in 1961 and continuing through 2006.

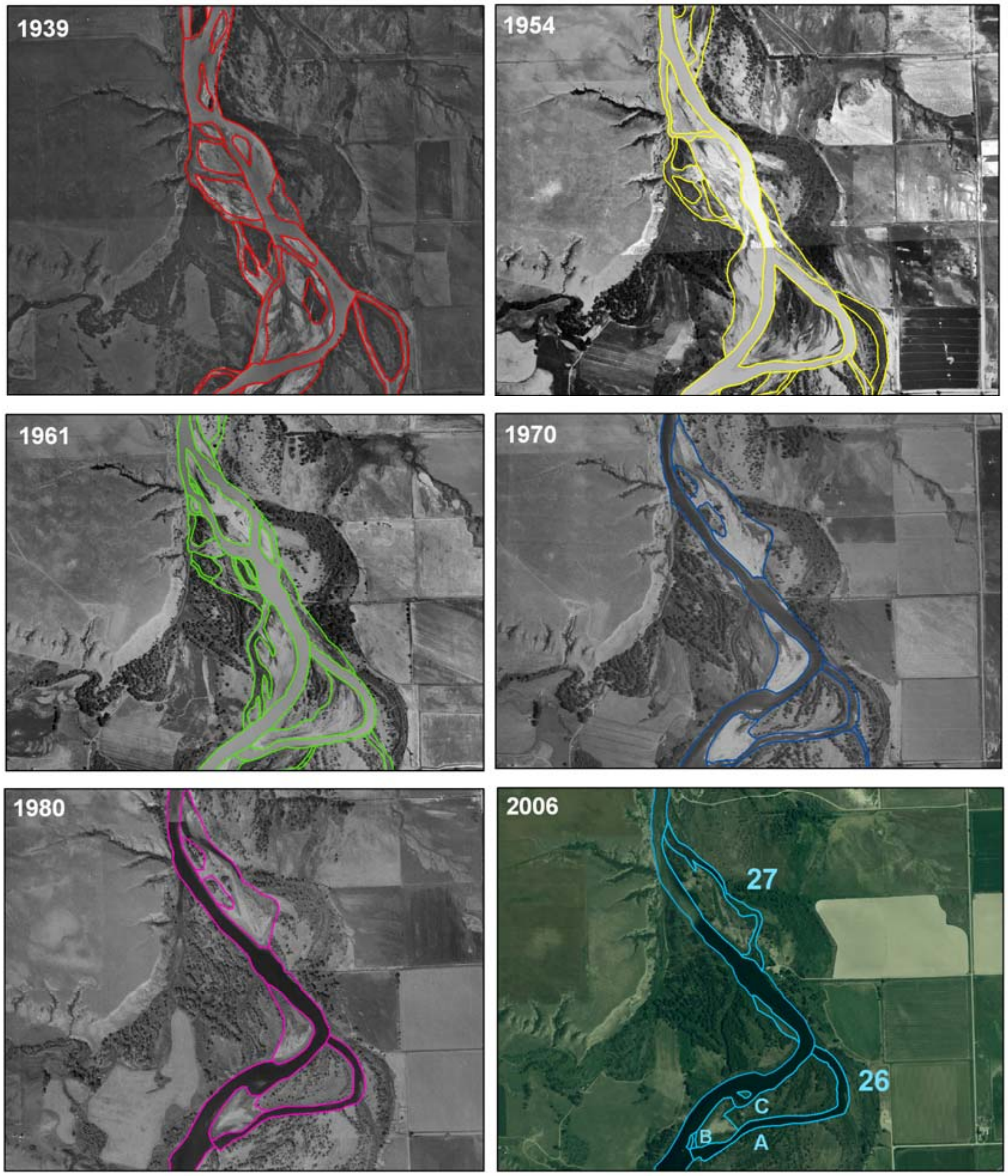


Figure 26. Historical channel mapping for complexes 26 and 27.

<u>Channel complex 28</u>

In 1939, the main channel in the vicinity of channel complex 28 was located along the left bank with a narrow lateral bar along the right bank and several overflow channels running through the right bank floodplain (Figure 27). Between 1939 and 1961, the main moved from the left bank into the overflow channel on the right bank. The main channel subsequently transitioned into a side channel, shown in 1961 aerial photography. Vegetation growth has helped to stabilize this channel pattern that has persisted through 2006.

Channel complex 29

The general configuration of side channel 29 was formed between 1939 and 1961. In 1939, the channel complex was composed of a single thread, straight channel with a narrow lateral bar and overflow channel along the left bank (Figure 27). Erosion along the right bank between 1939 and 1961 established a more extensive lateral bar and a side channel developed along the left bank. Slight changes in the channel geometry and bar morphology established side channel 29 in its 2006 position by 1980.

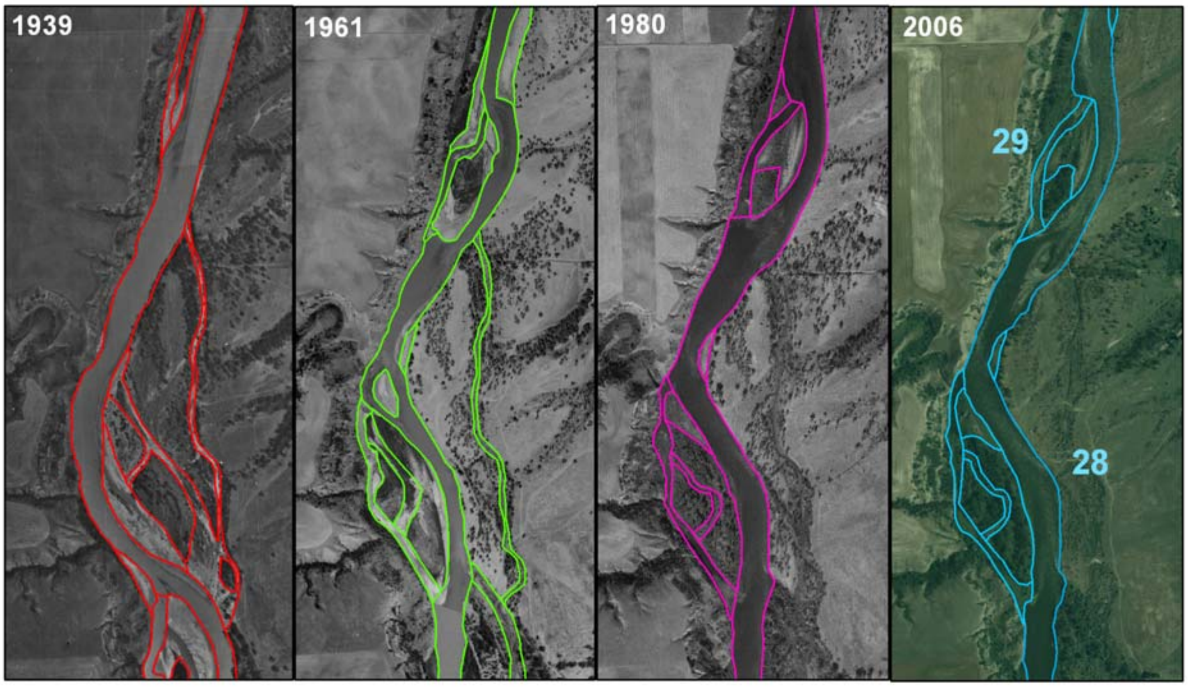


Figure 27. Historical channel mapping for complexes 28 and 29.

Channel complex 30

Side channel 30A has existed in its general location since 1939 and has alternated between a side channel and weakly visible overflow channel within an unvegetated lateral bar from 1939 to 1980 (Figure 28). Its present position was established in 1980 and it has remained in a similar position for the last 26 years. The 1939 photography shows that this complex was much more intricate with more overflow channels and lateral bars than exist currently. Overflow channel 30B is a good example of a large side channel that has subsequently transitioned to an overflow channel with the change in flow regime.

Channel complex 31

Side channel 31 formed between 1939 and 1954 during a period of lateral erosion of the right bank and has remained a side channel for the past 52 years (Figure 28). While the mid-channel bar between the main channel and side channel 31 has been stabilized by vegetation growth, very little has changed in the configuration of the side channel itself. Several overflow channels and lateral bars have reattached to the streambanks through vegetation encroachment between 1961 and 2006 and have thereby significantly reduced the active channel area near this complex.

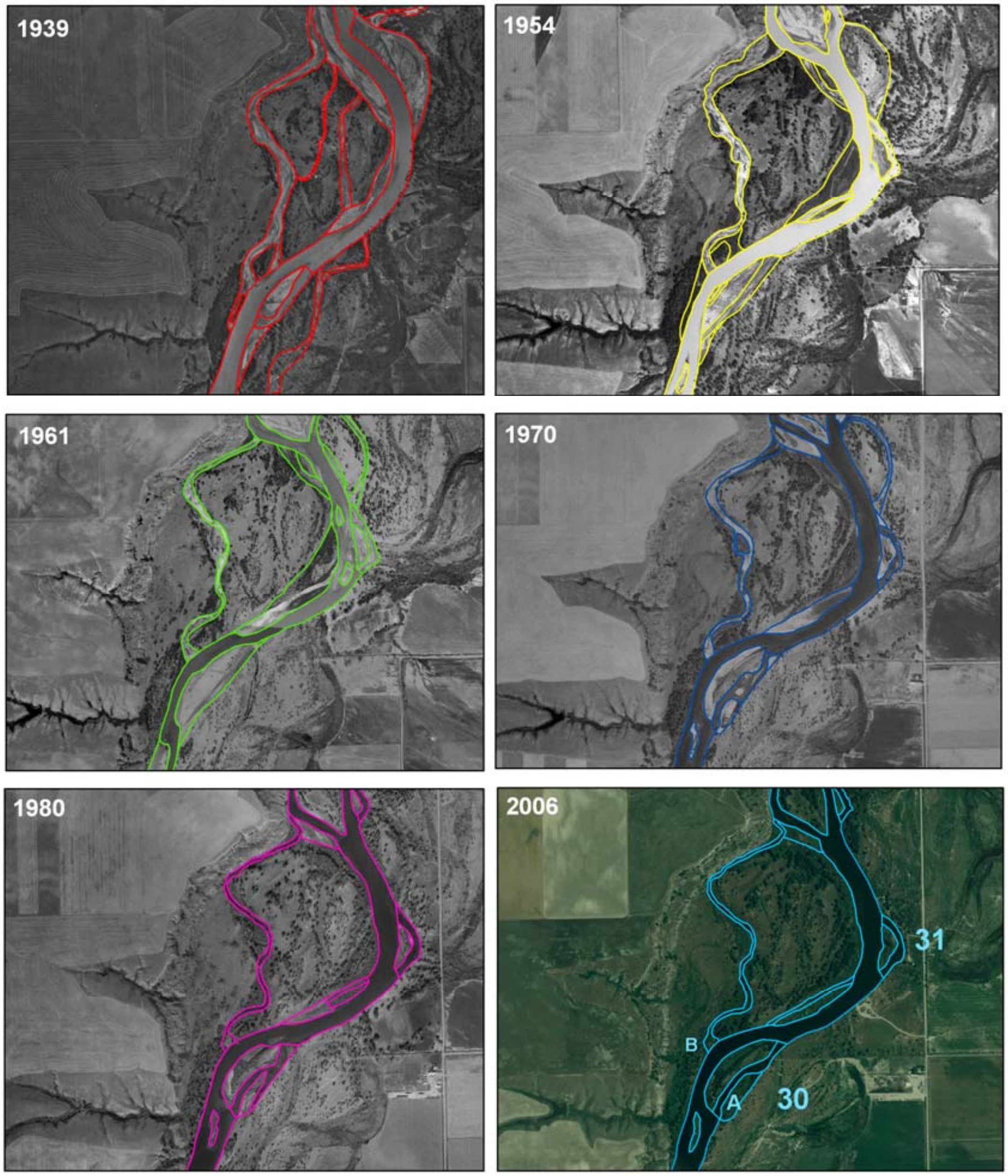


Figure 28. Historical channel mapping for complexes 30 and 31.

5.4 Trends/patterns in channel abandonment

Analysis of historical channel changes for each individual channel complex reveals that most complexes had established their 2006 channel position within the first decade following dam construction and at the latest, by 1980 (Table 5). The channel positions have essentially been "fixed" in place, or stable, for the last 28 years at a minimum and in some cases for much longer. For example, complexes 1, 5, 9, 13, 16, 18 and 19 have been functioning as side channels in the Bighorn River system since at least 1939. These are simple complexes, with essentially one side channel and associated island that splits from the main channel for a relatively short distance. In some cases, the complex can be better characterized for the majority of the historical period as one of split flow, with apparently equal volumes of flow routed around a stable island. Since dam construction, relatively few side channels have been gained in this reach; rather, the general pattern is one of loss or stability, where side channel and main channel area has shown an overall decrease. Some of the side channels have converted to overflow channels and only receive flow during the largest discharges in the post-dam flow regime. A few side channels have formed, however they are relatively small when compared to the side channels that have been lost. Examples include 15D, which was formed between 1970 and 1980 and abandoned by 1991 and two side channels that have branched from 12I through grassy islands sometime after 1970 and before 1980. These channels are still active in 2009 with more defined and vegetated islands.

Table 5. Timing of the formation and stabilization of side channels and complexes

Complex no.	2006 channel configuration established	2006 channel pattern stabilization
1	1939	1939
2	1961	1970
3	1954	1980
4	1954	1970
5	1939	1980
6	1954	1970
7	1970	1970
8	1970	1970
9	1939	1939
10	1954	1980
11	1954	1980
12	1939	1980
13	1939	1939
14	1970	1980
15	1970	1980
16	1939	1980
17	1939	1980
18	1939	1970
19	1939	1980
20	1970	1980
21	1939	1980
22	1954	1970
23	1954	1970
24	1970	1970
25	1961	1970
26	1961	1970
27	1954	1970
28	1961	1970
29	1961	1991
30	1939	1970
31	1954	1970

5.5 Effects of the June 2009 peak discharge (12,800 ft^3/s)

On June 23, 2009, a peak discharge of 12,800 ft^3/s was released from Yellowtail Afterbay, which had not been equaled in about 14 years (see Figure 2). The effects of this discharge on the channel downstream of Yellowtail Dam and Afterbay were observed during August 2009 field work. High water marks from the June 2009 peak discharge indicate that the stage of the flow was relatively consistent in the main channel along the length of the study reach. Most of the side channels that were not flowing during August field work had inundation depths at their channel entrances during the June peak ranging from 2-4 ft based on high water marks. The dense vegetation in channel entrances inhibited flow in some of the side channels downstream from the entrance. High water marks in these side channels were difficult to observe since most of the debris forming the high water marks had been trapped at the entrance.

Several side channels appeared to contain significantly less fine sediment when compared to April 2009 field observations. Remnant benches of sediment were noted along the sides of several channels as well as remnant sand bars that were significantly eroded and stood above the low water level during field work (Figure 29).

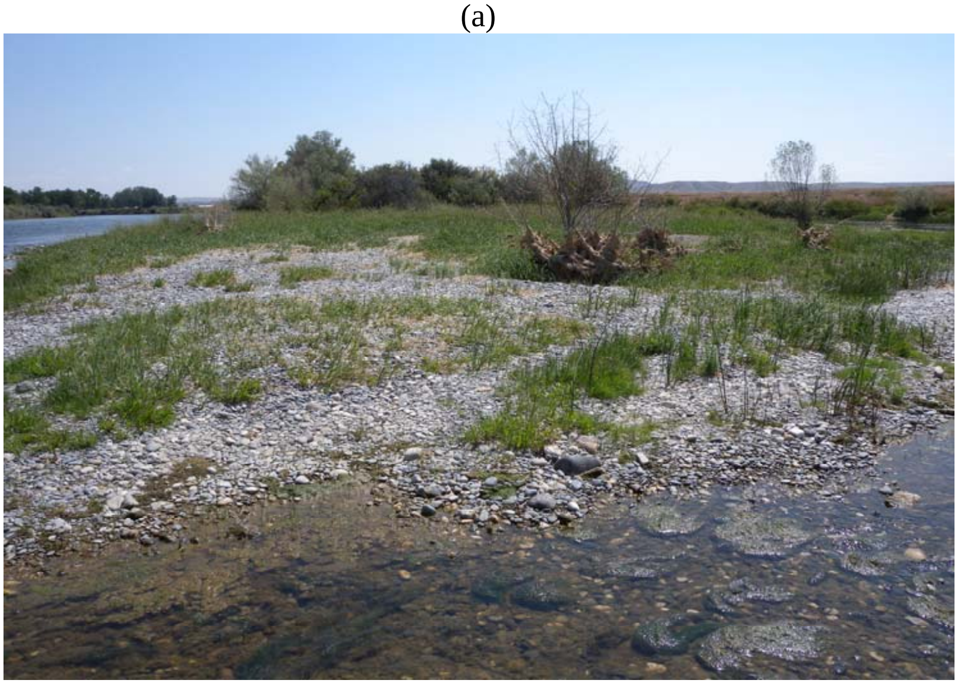
Figure 29. Erosion of sand bars in the study reach.

Gravel transported short distances into the side channels from their entrances was also apparent by the presence of isolated cobbles sitting on the surface of dry channels. Several new gravel deposits at the heads of mid-channel bars were also observed (Figure 30). Areas of scour were associated with points of high shear stress, such as downstream of woody obstructions. Preferential scour in some places left a patchy appearance to deposits in which fine-grained sediment had been stripped down to gravel in some places and not in others. A beaver dam located in channel complex 7 was also eroded along with much of the fine sediment that had accumulated behind it.

Channel 15B had widened significantly since April field work; it is likely that other side channels also experienced changes that were not noted during field observations.

These observations suggest that flows of 12,000 ft^3/s, while not affecting every channel, are capable of at least partially scouring side channels that are filling in with fine sediment and of transporting gravel onto the heads of islands and for short distances into vegetation choked side channels.

(a)



(b)

Figure 30. Changes observed from the flood of June 23, 2009; (a) gravel mobilization and debris at entrance to side channel; (b) gravel deposition at head of bar, side channel 8B.

6.0 Discussion

6.1 Areas of historical instability/lateral channel change

Areas of historical instability and lateral channel change were identified based on lateral migration of the main channel and major changes in the channel positions within anabranching sections using the aerial photography from 1935 to 2006. The areas identified meet at least one of two criteria:

- Lateral movement of more than one main channel width (200-300 ft)
- Major changes in channel configuration

While most locations along this section of the Bighorn River have been relatively stable during the historical period, a few channel complexes met at least one of the above criteria (Table 6).

Table 6. Areas of lateral channel change

Channel complex number	Description of changes
7	lateral erosion along left bank; changes in channel configuration
14	lateral erosion along right bank; changes in channel configuration from single channel to split flow
15	lateral erosion along right and left banks; changes in channel configuration from single channel to split flow and transition to side channel complex in right branch of split flow
26	lateral erosion along right bank; changes in channel configuration from split flow to main channel with large side channel
27	changes in channel configuration from split flow to main channel with overflow channel
28	main channel avulsion from left bank to right bank

6.2 Channels abandoned following dam construction

Several side channels formed prior to 1966 have been abandoned following the closure of the dams upstream. Since these channels still may receive flow during higher discharges, the abandonment is defined by side channels remaining dry during low flows, or at flows less than 4,000 ft^3/s. This value was chosen because this was the maximum discharge during the aerial photography flights and during field observations. The abandoned channels are located in complexes 8, 10 and 15 and with the exception of side channel 15D, were abandoned by 1970 (Table 7; Figure 31). Side channel 15D is a relatively small channel that was formed in 1980 and abandoned as a side channel by 1991. Side channels 8E and 8F have dry side channel entrances that are elevated above the main channel streambanks. However, they remain connected at their downstream ends, forming ponds and wetland environments. Side channel 10B is choked with vegetation that can withstand wet conditions. A small amount of water still enters at the upstream end of the side channel but flow goes subsurface within a short distance from the entrance. The fact that the channel contains vegetation that prefers wet conditions suggests that flow continues through the subsurface for some distance downstream. However, the downstream end of the channel is drier with less cattails suggesting that subsurface flow may be deeper in this area. Side channel 10C is much higher in elevation above the main channel and differs from many of the other channels in that it is relatively free of vegetation, suggesting that it has been modified recently, probably during the floods of June 18, 2008 (10,000 ft^3/s) and June 23, 2009.

Table 7. Channels abandoned following dam construction

Side channel	Description	August 2009 observations	Longevity
8F	2 ft of fines over gravel	wetland at downstream end	1939-1970
8E	2-3 inches of fines over gravel	ponded water at downstream end	1954-1970
10B	1 ft of fines over gravel at entrance	minimal flow along upstream end of channel; most of channel is choked with young willow and cattails	1954-1970
10C	gravelly deposits, vegetation free	no flow; acts as overflow channel during high flow	1954-1970
13	up to 1 ft of fines over gravel at entrance; further downstream, 2-4 inches of fines over gravel	vegetation established at entrance; no flow into channel	1939-1991
15D	did not measure	no flow observed	1980-1991

6.3 Channels at greatest risk of abandonment

Channels at the greatest risk of abandonment were identified based on their lack of observed flow or minimal flow at side channel entrances during field work (August 11-12, 2009), and the character of fine sediment and vegetation in the channel itself (Table 8; Figure 31). These channels generally had some amount of fine sediment at side channel entrances and had

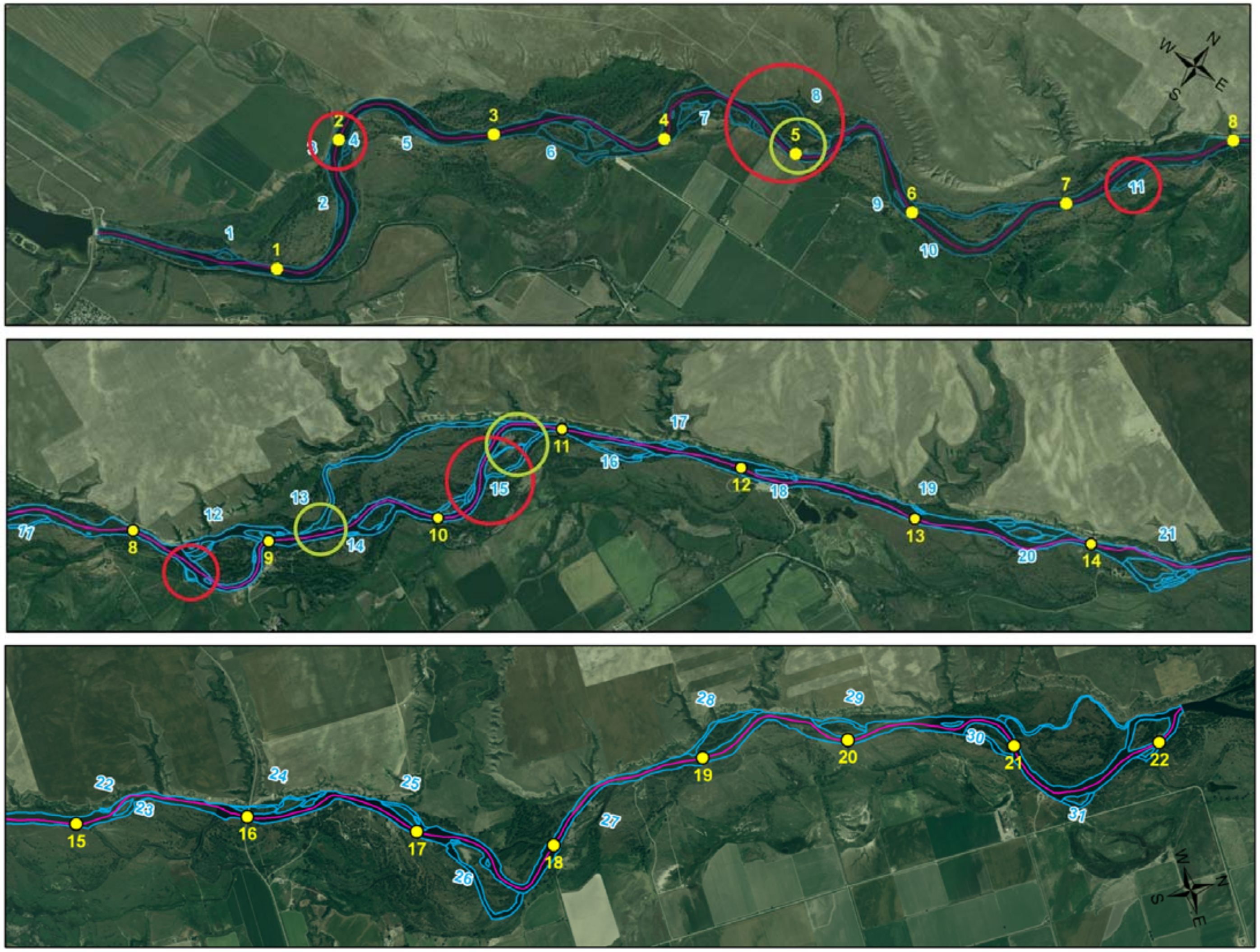


Figure 31. Locations of abandoned side channels (green circles) and side channels at risk (red circles).

shallow, low velocity flow (Figure 32). Some of the side channels have vegetation growing at their entrances as well and are characterized by discontinuous ponded water in scour holes along their lengths. Most of the downstream connections are ponded, wetland environments with thicker deposits of fine sediment than at channel entrances and sediment that is composed of greater fractions of clay and silt than those deposits at the channel entrances.

Figure 32. Examples of side channels at risk of abandonment; (a) entrance to side channel 4; (b) near mouth of side channel 10A.

Channels identified in Table 8 are mostly located on insides of channel bends where shear stress and stream power are lower, allowing for less scour from overbank flows. They are also located at the heads of channel complexes where flow splits into multiple channels and channel gradients and shear stresses are lower, allowing for higher probability of sediment deposition.

Table 8. Side channels at greatest risk of abandonment

Channel no.	Fine sediment deposition	Flow characteristics†	Year first observed	Location
4	8 inches of fines over gravel at entrance; thins downstream	shallow low velocity flow at entrance	1970	inside channel bend
8A	3 inches of fines over gravel; thickens downstream	ponded water in channel; no flow at entrance	1939	inside channel bend/ head of complex
10A	thin veneer of fines over gravel at entrance; low flow riffle at entrance is composed of pebbles and cobbles	moderate velocity riffle at entrance; low velocity flow downstream; ponded water or low flow at downstream end	1980	inside channel bend/ head of complex
11	4 inches of fines over gravel	ponded water; grass, willows and cattails in channel	1954	straight reach
12A	up to 1 ft of fines over gravel	low velocity shallow flow; channel is filled with cattails (or canary reed grass?)	1939	head of complex
12C	pebble-cobble bed material at entrance; some fines are filling in low areas	low velocity flow and water ponding at entrance; reed canary grass in channel	1939	head of complex
15A	2-4 inches of fines over gravel	no flow; ponded water in scour holes	1954	inside channel bend
15C	up to 1 ft of fines over gravel	entrance has thick vegetation; channel is filled with reeds downstream of entrance; shallow flow at entrance	1980	~inside channel bend

†Observations were made on August 11-12, 2009, with a mean daily discharge of ~3500 ft^3/s

6.4 Processes associated with side channel loss

River technicians and scientists as well as anglers have observed that several side channels appear to be dry in 2009 that were inundated at similar discharges several decades ago. This would lead to the conclusion that side channels in the study reach are becoming disconnected from the system and losing their functionality as aquatic habitat. Several processes could be responsible for this abandonment, three of which seem to be most likely: (1) degradation of the channel leading to greater flow conveyance in the main channel and larger discharges required to inundate side channels; (2) lateral migration of the channel or channel avulsion away from side channels, causing a transition from frequent low flow inundation to infrequent high flow floodplain sedimentation; or (3) reduction in peak flows, thereby reducing the erosive capability of flows to promote channel avulsion and channel scour, and allowing for deposition and filling of side channels with sediment. While all three explanations, individually or in combination, are plausible, this analysis has shown that there is no evidence to support channel degradation. Both USGS gage cross section data and repeat cross sections surveys indicate that channel degradation is not apparent in the study reach. Qualitative observations of mid-channel bars that have existed since 1939 (such as the mid-channel bar at complex 9) and are still being inundated frequently today and provide an indication that the channel is not undergoing reach-wide degradation. Geomorphic mapping and historical channel analysis illustrate that channel positions have remained relatively fixed since 1980 and very little channel migration or avulsion has occurred for the past 26 years. Even prior to 1980, many areas of the channel had a relatively stable channel pattern, existing since 1939. This suggests that lateral channel migration is not responsible for the majority of side channel shallowing and loss.

Based on data analysis, field observations and existing literature that documents similar response of rivers downstream from dams, the lack of large discharges that periodically mobilized large quantities of sediment prior to dam construction have limited new channel avulsions and the formation of new islands and bars. Lower magnitude flows that inundate side channels tend to deposit sediment in the channel; main channel flows that only marginally inundate side channels deposit sediment along channel entrances as natural levees or berms, which act to block flow further. Longer periods of dry channels promote vegetation encroachment and establishment at channel entrances and in channel beds, which act to further stabilize and inhibit side channels from being scoured during the higher flows that do occur. Examination of the record of monthly mean discharge shows that a period of low flow from 1999 to 2008 probably acted as a catalyst to further promote side channel loss as well as the stabilization of lateral and mid-channel bars, further inhibiting sediment supply in the reach and the ability of the river to create new active areas and channel complexity (Figure 33).

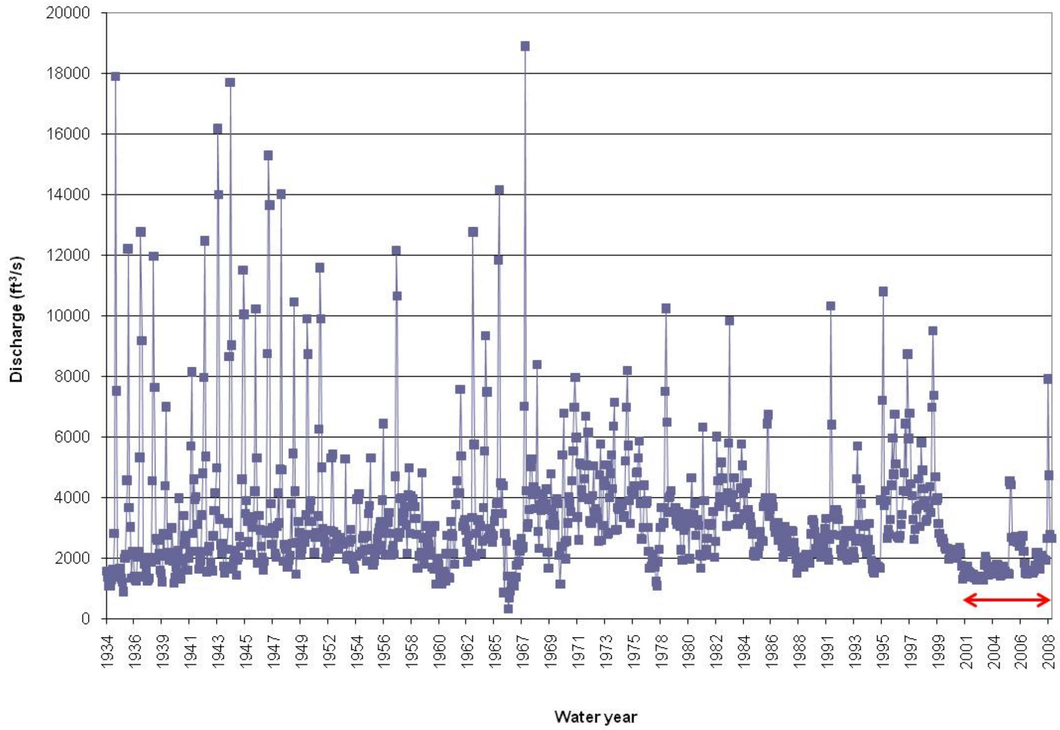


Figure 33. Mean monthly flow values, Bighorn River near St. Xavier, MT (USGS gaging station #06287000) showing a period of low mean monthly flows beginning in 1999 (shown by double red arrow).

Ligon et al. (1995) showed that similar processes were at work in the McKenzie River, which is also characterized as an anabranching or wandering gravel bed river. On the McKenzie River, channel morphology gradually transitioned from a multi-thread channel to a single-thread channel over several decades; smaller channels slowly filled in, removing the existing islands from the active system. On the Bighorn River, this process can be observed in many locations; at channel complex 10, side channels 10B and 10C present in 1961 have been lost and not replaced by other channels; the entrance to channel 10A is in the process of filling in with sediment, as shown by the accumulation of grasses, shrubs and small trees in 2006 photography (Figure 34). At side channel 13, the majority of change at the entrance appears to have occurred between 1991 and 2006, a period of overall low flows and few large flows, which allowed vegetation to become established at the side channel entrance.

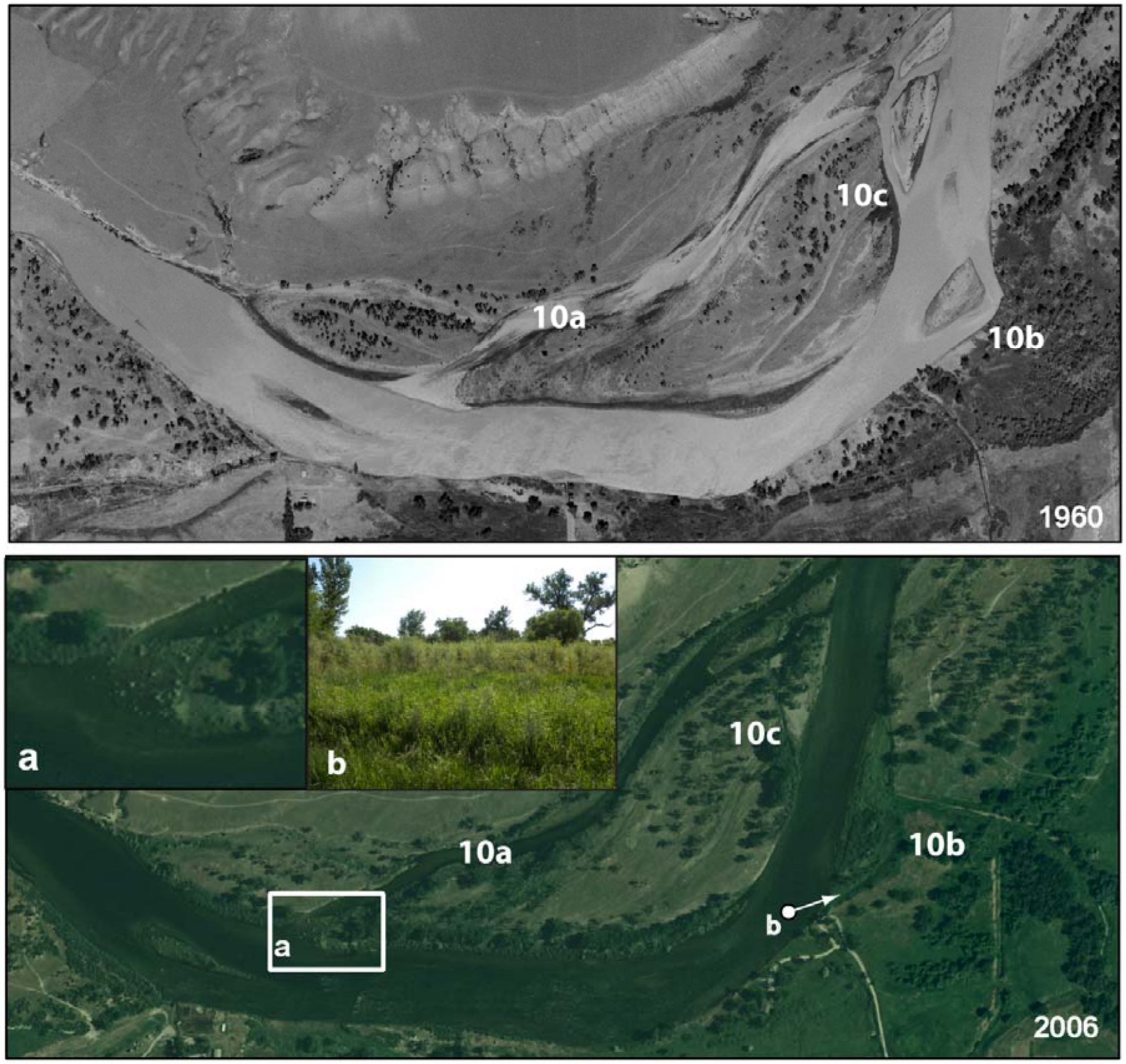


Figure 34. Channel changes at channel complex 10; (a) vegetation establishment and sediment deposition in side channel 10a entrance; (b) vegetation growth in side channel 10b entrance

7.0 Conclusions

Geomorphic analysis of vertical and lateral historical changes on the Bighorn River from Yellowtail Dam to St. Xavier Bridge was conducted in order to investigate the loss of side channels in recent decades. Vertical changes were investigated by examining bed elevation changes at the USGS gaging station no. 06287000, Bighorn River near St. Xavier, MT and by resurveying historical cross sections established during the FWP wetted perimeter study in 1997 (Frazer, 1997). Lateral changes were investigated through detailed geomorphic mapping on seven sets of historical aerial photography from 1939 to 2006. Results show that the mean bed elevation of the channel fluctuated up to 3.3 ft from 1935 to 1965 prior to the construction of Yellowtail Dam and Afterbay and remained relatively stable throughout the post-dam period from 1967 to 2009, fluctuating up to 1.2 ft. The channel positions of the main stem and side channels have been in similar positions since 1980 and reflect a stable river system in which large-scale lateral movement in the channel was been halted about a decade following dam construction. Analysis of geomorphic mapping indicates that many channels have filled in with sediment and vegetation and that the geomorphic complexity, reflected in active channel area, has been decreasing since 1961 as side channels are abandoned and unvegetated channel bars are covered with vegetation. This reflects the reduction in peak flows and sediment supply that are required to scour channels and modify bars as well as deposit sediment in new areas, facilitating the formation of new bars and channels. The reduction in active channel area from 1939 to 1961 reflects the recovery of the channel from the 1935 flood, and possibly the effects of reduced peak discharges from the construction of Boysen Dam in 1952. Observations of channel conditions during 2009 indicate that several critical side channels are becoming disconnected with the main channel. This conclusion is based on the presence of fine sediment accumulations at side channel entrances and mouths that suggests that the channels are filling in with sediment and the establishment of vegetation in side channel mouths as well as along their lengths. This information is confirmed by mapping historical channel change, in which side channels inundated in 1939 are not inundated in 2009 even with larger discharges in the channel. These side channels are not being replaced by new channels through channel avulsion, but rather are being lost. This has serious implications for the creation and maintenance of aquatic habitat for rainbow and brown trout populations and will continue to be of concern on the Bighorn River.

8.0 Recommendations

The geomorphic analysis can be used to explore how habitat conditions are related to the physical features along the river and how they may have changed following dam construction. Hydraulic modeling, the second component of the Bighorn River Side Channel Investigation, has been proposed to continue in Fiscal Year 2010. This analysis will identify the flows needed to inundate the side channels and the depth of inundation associated with specific discharges. Modeling could also be performed to determine the potential of various discharges to scour the channel bed in critical side channels. This would require additional field data collection of sediment in the channel bed.

9.0 References

Agard, S.S., 1989, Map showing Quaternary and Late Tertiary terraces of the lower Bighorn River, Montana: U.S. Geological Survey Miscellaneous Field Studies Map MF-2094.

Alden, W.C., 1932, Physiography and glacial geology of eastern Montana and adjacent areas: U.S. Geological Survey Professional Paper 174, 133 p.

Burge, L.M., 2005, Wandering Miramichi rivers, New Brunswick, Canada: Geomorphology, v. 69, p. 253-274.

Church, M., 1983, Pattern of instability in a wandering gravel bed channel, in: Collinson, J.D. and Lewin, J., eds., Modern and Ancient Alluvial Systems, International Association of Sedimentologists Special Publication 6, p. 169-180.

Collier, M., Webb, R.H., and Schmidt, J.C., 1996, Dams and Rivers: A Primer on the Downstream Effects of Dams: U.S. Geological Survey Circular 1126, 94 p.

Frazer, K., 1997, Bighorn River wetted perimeter analysis: Montana FWP, 11 p.

Frazer, K., 1999, Upper Bighorn River Investigations, Montana Department of Fish, Wildlife and Parks Job Progress Report, April 1, 1993-March 31, 1998, Project no. F-78-R-3, 41 p.

Fredenburg, W., 1984, Bighorn Lake and Bighorn River Post-Impoundment Study, Job Progress Report, April 1, 1982 through March 31, 1983: Montana Department of Fish, Wildlife and Parks, Fisheries Division, Project no. F-20-R-27, 46 p.

Fredenburg, W., 1986, Bighorn Lake and Bighorn River Post-Impoundment Study, Job Progress Report, April 1, 1985 through March 31, 1986: Montana Department of Fish, Wildlife and Parks, Fisheries Division, Project no. F-20-R-30, 60 p.

Fredenburg, W., 1987, Bighorn Lake and Bighorn River Post-Impoundment Study, Job Progress Report, April 1, 1986 through March 31, 1987: Montana Department of Fish, Wildlife and Parks, Fisheries Division, Project no. F-20-R-31, 39 p.

Graf, W.L., 1999, Dam nation: A geographic census of American dams and their large-scale hydrologic impacts: Water Resources Research, v. 35, no. 4, p. 1305-1311.

Graf, W.L., 2006, Downstream hydrologic and geomorphic effects of large dams on American rivers: Geomorphology, v. 79, p. 336-360.

Grant, G.E., Schmidt, J.C., and Lewis, S.L., 2003, A geological framework for interpreting downstream effects of dams on rivers: A Unique River, Water Science and Application 7, American Geophysical Union, p. 209-225

Hamilton, L.J. and Paulson, Q.F., 1968, Geology and ground-water resources of the lower Bighorn valley, Montana: U.S. Geological Survey Water-Supply Paper 1876, 39 p.

Hirschboeck, K.K., 1991, Climate and Floods, Hydrology of floods and droughts, National Water Summary 1988-89: U.S. Geological Survey Water Supply Paper 2375, p. 67-88.

Inbar, M., 1990, Effect of dams on mountainous bedrock rivers: Physical Geography, v. 11, no. 4, p. 305-319.

Jacobsen, R.B., 1995, Spatial controls on patterns of land-use induced stream disturbance at the drainage basin scale—an example from gravel bed streams of the Ozark Plateau, Missouri, In Natural and Anthropogenic Influences in Fluvial Geomorphology, American Geophysical Union Geophysical Monograph 89, p. 219-239.

Klumpp, C., 1997, Literature review of the hydraulic and geomorphic relationships of the Bighorn River Fisheries Study, Montana: Bureau of Reclamation, Technical Services Center, Denver, CO, 24 p.

Klumpp, C., 2005, Bighorn River, Montana flushing flows analysis, Bureau of Reclamation, Technical Services Center, Denver, CO, 13 p.

Knighton, A.D. and Nanson, G.C., 1996, Anabranching rivers: their cause, character and classification: Earth Surface Processes and Landforms, v. 21, p. 217-239.

Koch, R., Curry, R. and Weber, M., 1977, The effect of altered streamflow on the hydrology and geomorphology of the Yellowstone River Basin, Montana: Yellowstone Impact Study Technical Report No. 2, Montana Department of Natural Resources and Conservation, 163 p.

Ligon, F.K., Dietrich, W.E., and Trush, W.J., 1995, Downstream ecological effects of dams: a geomorphic perspective: BioScience, v. 45, no. 3, p. 183-192.

Mullen, W.E., 1916, Cases decided in the Supreme Court of Wyoming from February 13, 1915 to January 25, 1916: Woming Reports v. 23, The Laramie Republican Company Printers and Binders, Laramie Wyoming, 623 p.

Paulson, R.W., Chase, E.B., Roberts, R.S., and Moody, D.W., compilers, 1991, National Water Summary 1988-89—Hydrologic Events and Floods and Droughts: U.S. Geological Survey Water Supply Paper 2375, 591 p.

Reheis, M.C., 1983, Glaciofluvial origin and drainage history revealed by terraces in the northern Bighorn Basin, Montana: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 431.

Reheis, M.C., 1985, Evidence for Quaternary tectonism in the northern Bighorn Basin, Wyoming and Montana: Geology, v. 13, no. 5, p. 364-367.

Richards, P.W., 1955, Geology of the Bighorn Canyon-Hardin area, Montana and Wyoming: U.S. Geological Survey Bulletin 1026, 93 p.

Willams, G.P. and M.G. Wolman, 1984. Downstream effects of dams on alluvial rivers: U.S. Geological Survey Professional Paper 1286, 83 p.

Appendix A: Map Atlas