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Managing Water in the West

Technical Report No. SRH-2012-26

Bighorn River Side Channel Investigation: Hydraulic and Sediment Transport Analysis

U.S. Department of the Interior
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Technical Services Center
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Mission Statements

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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.

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Bighorn River Side Channel Investigation: Hydraulic and Sediment Transport Analysis

Report Prepared for:

Montana Area Office

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_______________________ DATE: 9/25/2012

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

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1 Executive Summary

The Bureau of Reclamation has been asked to perform a thorough evaluation of the Bighorn River from Yellowtail Dam to the St. Xavier Bridge near Ft. Smith, MT. The investigation was divided into two parts, a geomorphic investigation (companion document), completed by Godaire in 2010, and a hydraulics and sediment transport investigation (this document). The primary focus of the overall investigation was the loss of side channel connectivity at frequent discharges. Over the past decade, and perhaps a bit longer, the entrance to many side channels have begun to aggrade due to the infrequency of high discharges capable of transporting sediment through the side channels and preventing the encroachment of vegetation. A significant finding of Godaire (2010) was that the Bighorn River within the study reach was not incising.

This report details the hydraulics of the Bighorn River within the study reach and evaluates potential solutions to stop, or reverse, the aggradational trend occurring in the entrances of many side channels. Sediment transport was evaluated with a two dimensional (2D) hydraulic model in a static condition, whereby the bed did not undergo deformation and discharges were steady. Conditions of sediment transport was evaluated across the spectrum of bed motion, from zero transport to vigorous transport. The numerical modeling of sediment motion was coupled with observation of sediment transport using particle tracers, resulting in a validation of sediment results provided by the model.

Repeat surveys were performed, beginning in April 2009 when the three WAPA cross sections were re-surveyed for the first time in approximately a decade. Additional surveys were performed in August 2009, February 2012, and April 2012. Bed material data were collected in October 2011 to populate the numerical model with representative sediment size distributions.

The primary conclusion of the hydraulic study is that releases from Yellowtail Dam alone are not likely to provide conditions to reverse the trend of side channel aggradation. At best, planned high flow releases will stop the aggradational trend. This conclusion begs the question of whether or not the side channel entrances should be mechanically excavated to once again provide a surface connection at frequent discharges. Mechanical removal, while not an ideal solution, may be the only option. While this is not a sustainable solution, and regular maintenance of the side channels is anticipated, planned releases of high flows from Yellowtail Dam are expected to minimize the required maintenance on excavated channels, limit the encroachment of vegetation, and provide greater diversity in the study reach. Another conclusion of this study is that sediment inflow to the side channels is occurring, replacing any sediment that may be eroded during higher discharges. In some cases, the main channel is aggrading in the vicinity of the entrance to a side channel, further complicating the use of mechanical means to restore the frequent surface connection.

Recommended release strategies have been recommended in this report, however no specific strategies for mechanical removal of sediment are suggested. Designs for excavations should be evaluated separately, where priorities can be laid out, access determined, and funding mechanisms are in place.

Side channels in natural and controlled rivers are very dynamic. Their creation, progression, and senescence are not well understood, demonstrated by little coverage in the literature. Some side channels can remain functional for many decades, while others exist for only a few flood cycles. Furthermore, naturally occurring side channels exist throughout a range of connectivity to the main channel, with some connected at base flow and others only connected at discharges that may only occur every few years.

2 Introduction

The Bureau of Reclamation's (Reclamation) Technical Service Center (TSC) has been asked to perform a comprehensive study regarding the past, present, and future condition of side channels on the Bighorn River downstream of Yellowtail Dam (Figure 1 and Figure 2). The primary concern is the potential loss of critical habitat for introduced Rainbow (*Oncorhynchus mykiss*) and Brown (*Salmo trutta*) trout that now inhabit the Bighorn River following the closure of Yellowtail Dam in 1966. In February, 2010, Godaire (2010) completed a geomorphic analysis on the Bighorn River from the afterbay dam to the St. Xavier Bridge, which serves as the first half of a two-part study. The primary focus of the geomorphic investigation was to document vertical and lateral changes to the Bighorn River (1939 – 2006) to investigate the morphodynamics related to vertical isolation of several side channels in the study reach. This report is part two of the study, including a hydraulic and sediment transport analysis to identify potential corrective actions that might be taken by Reclamation to stop, or perhaps even reverse, the trend of side channel loss that had been anecdotally observed over the past decade and subsequently documented by Godaire (2010).

Godaire (2010) concluded the following: 1) bed elevations in the main channel have remained relatively stable throughout the post-dam period; 2) channel positions of the main stem and side channels have maintained a similar location since 1980; 3) geomorphic complexity has been decreasing since 1961; 4) several critical side channels are becoming disconnected from the main channel, and: 5) several side channels were abandoned between 1961 and 2009. Field observations have identified several side channels that are at risk of abandonment, showing sediment and vegetation accumulating in the channels. These findings are consistent with the conclusions of many researchers regarding the changing morphology of river channels downstream of dams (e.g. Kondolf and Wilcock, 1996; Power et al., 1996; Trush et al., 2000; Wilcock et al., 1996, Kondolf and Williams, 1996).

Based on these findings, it was determined that a lack of high discharges, replicating natural floods, is causing some side channels to become vertically isolated. What has typically occurred is an accumulation of sediment at the entrances to side channels. These accumulations contain sediment distributions that are finer than those found in the main channel. Moderate discharges are capable of transporting the finer gravel in the main channel, which accumulates at the side channel entrances, forming a berm. This berm elevation increases enough to create a condition whereby it takes an increasingly larger, and less frequent, main channel discharge to inundate the side channels such that sediment transport capacities are exceeded to sufficiently to carry sediment through the side channel. As a result, vegetation has established in some of the side channels, inducing further deposition of sediment.

High flows released from Yellowtail Dam may be able to restore the connectivity of side channels, but it is necessary to specify these releases from dams as accurately as possible because the released water will not be available for irrigation and power generation. Therefore, financial costs of environmental releases can be very large (Wilcock et al., 1996). To complicate the specification of high flow releases, there is now also the realization that the full range of flow variability is ecologically important(Kondolf and Williams, 1999). It is not possible to specific a single flow rate that, if attained, would fully restore the natural processes that existed prior to the construction of the dam.

“Responses of rivers and river ecosystems to dams are complex and varied, as they depend on local sediment supplies, geomorphic constraints, climate, dam structure and operation, and key attributes of the biota. Therefore, "one-size-fits-all" prescriptions cannot substitute for local knowledge in developing prescriptions for [reservoir] operation to protect local biodiversity. One general principle is self-evident: that biodiversity is best protected in rivers where physical regimes are the most natural. A sufficiently natural regime of flow variation is particularly crucial for river biota and food webs” (Power et al., 1996). Periodic disturbance to river systems that includes sediment mobilization occurring with a frequency on the order of every 1.5 to 2 years, is generally a necessary component for maintaining channel complexity typically associated with aquatic habitat. These disturbances provide a myriad of benefits, some of which are; the prevention of vegetation encroachment (Trush et al, 2000), periodic flushing of spawning gravels (Wilcock et al., 1996; Kondolf and Wilcock, 1996), erosion of banks to provide contributions of sediment and woody debris, maintaining a variety of mesohabitat conditions such as pools, glides, and riffles, which in turn provides diversity in available flow velocity, appropriate conditions for benthic invertebrates (Kondolf and Williams, 1999) and other food web interactions (Power et al., 1996). Because river ecosystems persist through a complex interacting array of physical and biological processes (Trush et al., 2000), caution is warranted such that a delicate balance is not further degraded. Rarely is a single imposition on a river system associated with a single response (Trush et al., 2000).

2.1 Previous Bighorn River studies

Previous studies on the Bighorn River include those by Koch et al., 1977; Frazer, 1997; Klumpp, 1997, Klumpp, 2005, Wiley at al., 1995; and Godaire, 2010. Godaire (2010) is of primary significance to this study, specifically detailing historical changes in channel geomorphology and addressing the direct causes of the loss of side channel habitat. The results and conclusions of Godaire (2010) are referenced heavily throughout this report. The Frazer (1997) report details minimum in-stream discharges to maintain the trout fishery and a wetted perimeter analysis of the Bighorn River. The wetted perimeter analysis was used to determine whether or not flow levels requested under an informal agreement between Reclamation and MT-FWP in 1986 were still valid for three important side channels. Koch (1977) examined geomorphic changes to the Bighorn River downstream of Yellowtail Dam to the Yellowstone River. The results and conclusions of Koch (1977) have been incorporated into Godaire (2010). Koch (1977) also evaluated sediment size distributions in the Bighorn River however the sample locations are outside the current study reach. The two studies by Klumpp (1997 and 2005) were focused on the current study reach and were the first to mention periodic high flows for maintaining habitat conditions. Klumpp (2005) addresses flushing flows for the purpose of removing fine sediment from spawning gravels. Wiley et al. (1995) provides a detailed analysis of sediment and habitat conditions on the Bighorn River in Wyoming near Thermopolis. This site is downstream of Boysen Dam and well upstream of Yellowtail Dam.

2.2 Study goals and objectives

The current study investigates hydraulic conditions under a wide range of main channel discharges within the study reach, which extends from the Yellowtail afterbay dam to the Bighorn Boat launch, approximately 12 river miles (Figure 2). The goal of the hydraulic analysis is to determine the feasibility of improving the habitat conditions of the study reach through recommended release strategies from Yellowtail Dam and afterbay. The hypothesis is that properly planned releases will inundate the side channels to such an extent that sediment transport conditions in some side channels will be sufficient to erode the berms at the side channel entrances. Ideally, these discharges will eventually carry sediment through the entire length of the side channels, however there is no expectation that sediment will travel such a distance in a single event. A secondary benefit to planned releases is a more frequent wetting of gravel bars and other off channel areas, which is expected to limit vegetation encroachment into the active channel. A significant concern related to this study is that an increase in main channel discharge would significantly increase sediment transport within the main channel and eventually cause incision within the main channel. Incision within the main channel has largely been avoided to date because the magnitude of the high flows has been significantly reduced since dam closure and are not sufficient to mobilize the now armored bed of the Bighorn River. Incision would have negative consequences including further separating the side channels from the main channel and potentially creating infrastructure concerns.

A thorough review of pre- and post-dam hydrology, channel morphology and local geology is included in Godaire (2010). Also included in the report is a detailed description of the side channel complexes within the study reach. The current hydraulic analysis will use the same annotation with respect to river miles and side channel complexes found in Godaire (2010).

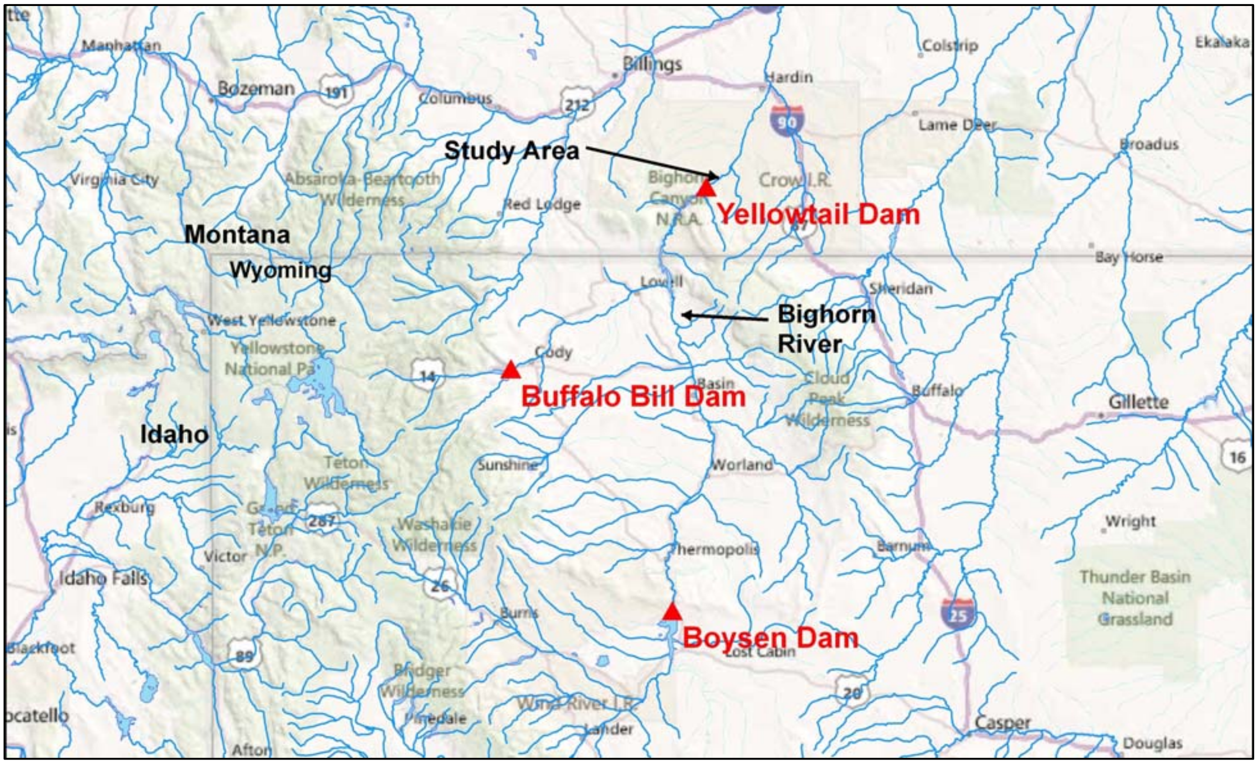

Figure 1: Location map of the Bighorn River Basin and study area.

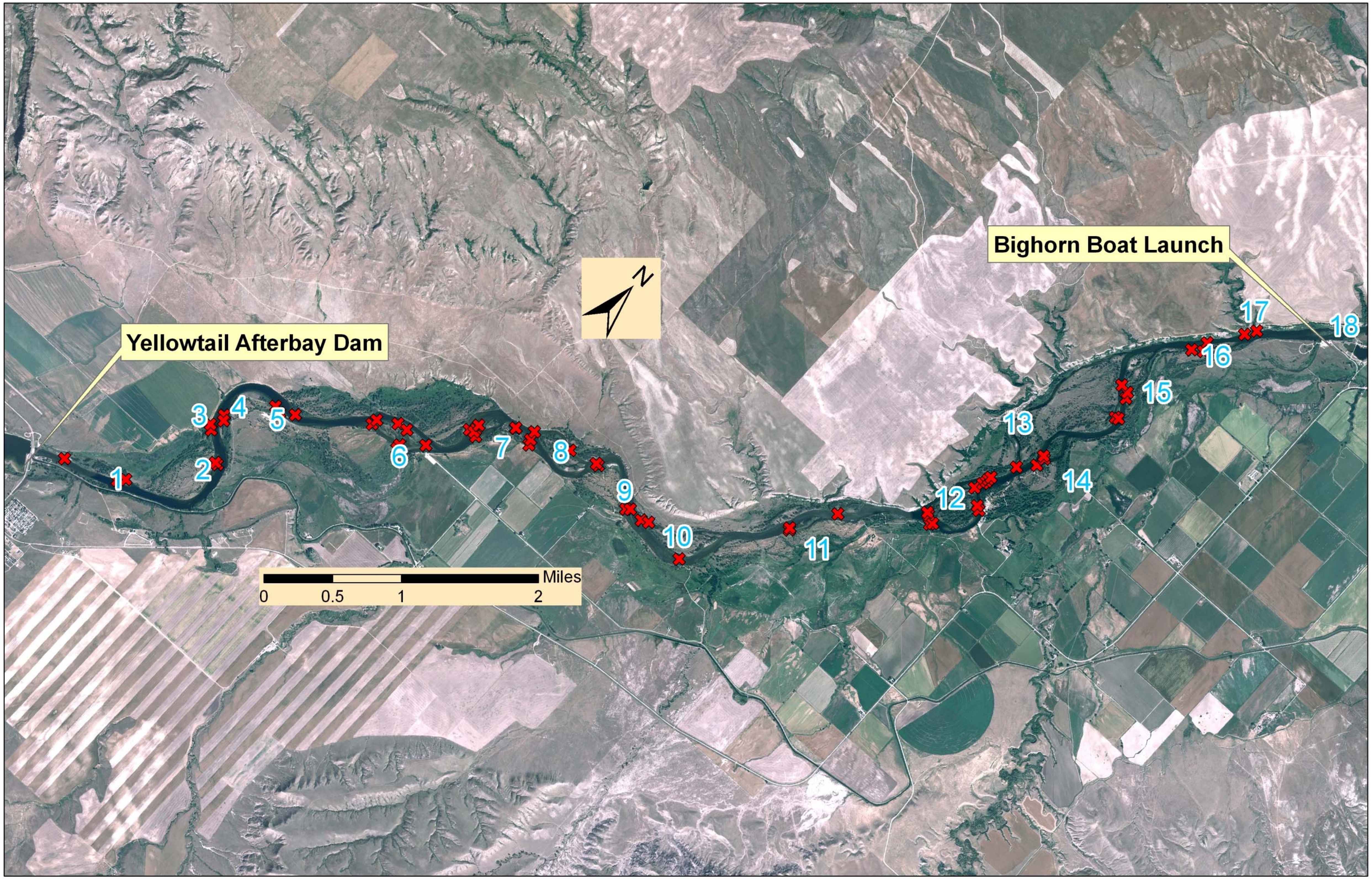

Figure 2 Location map showing the study reach. Red X's indicate the location of pebble counts collected in October 2011. Numbers indicate side channel complexes (designations are consistent with Godaire (2010)).

2.3 Recent observations

During the annual runoff in 2011, sustained high flows (Figure 3) were released from Yellowtail Dam as a result of record reservoir inflows (Tim Felchle, per. Comm.). The resulting geomorphic change was documented during a site visit in October, 2011. Some of this change was significant. Side channels that were previously choked with vegetation and fine sediment were visibly eroded. Alternatively, at least one side channel completely aggraded with gravel. These observations indicate that flow releases from Yellowtail Dam cause observable geomorphic change in the study reach, although there is significant uncertainty in predicting specific changes at specific locations (Figure 4 and Figure 5).

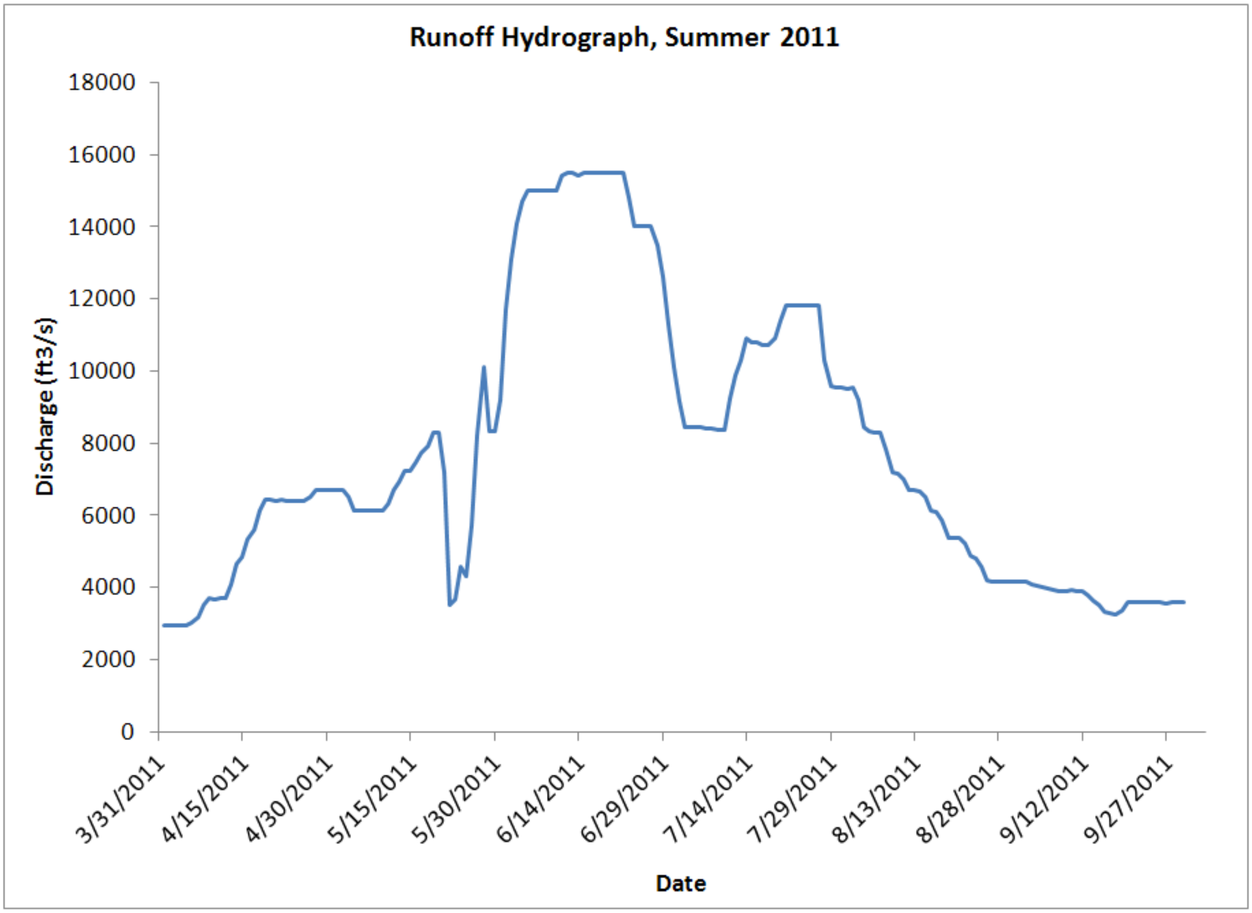

Figure 3: Hydrograph of the Bighorn River downstream of Yellowtail Dam during the 2011 runoff period (USGS # 06287000 Bighorn River near St. Xavier, MT).

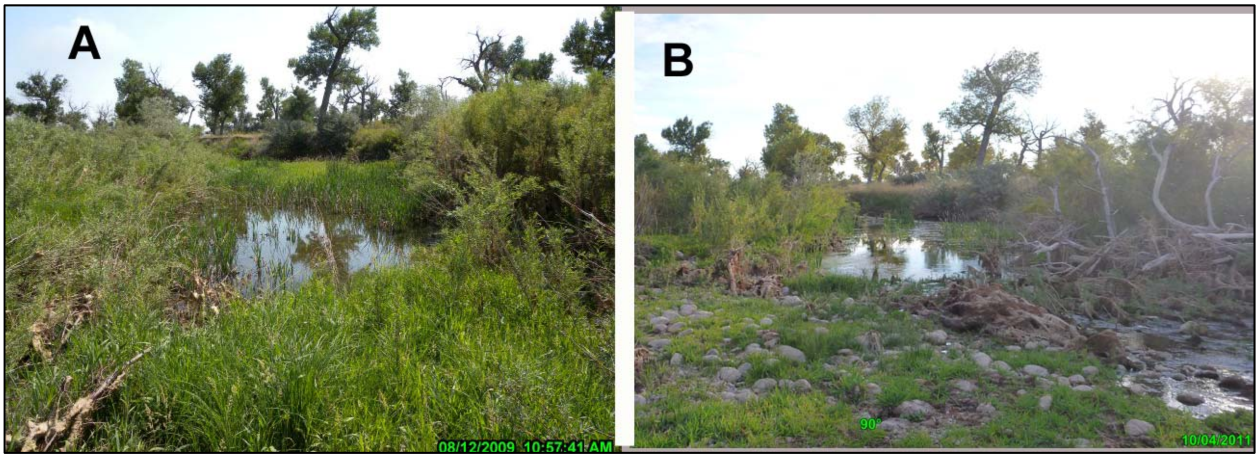

Figure 4: Photos of the entrance to side channel #11. A = August 2009 (3,115 ft^3/s), B = October, 2011(3,250 ft^3/s). Note the vegetation removal that took place during the summer 2011 high flows.

Figure 5: Photographs of a side channel in complex 12 that completely aggraded during the summer 2011 high flows. A = May 2009 (3,574 ft^3/s), B = October, 2011(3,250 ft^3/s).

2.3.1 Excavation of Side Channel 13 (Cline's channel)

In February 2012 the entrance to side channel 13 was excavated to provide a surface connection between the main channel and the downstream portion of the side channel. Approximately 125 feet of the entrance was excavated to a maximum depth of 1.2 feet. This was a cooperative effort among the Bighorn River Alliance, MT Fish, Wildlife, and Parks, the Crow Tribe, the Bureau of Reclamation, the Natural Resources Conservation Service, the Bighorn County Conservation District Council and a local land owner. Funding was provided through a grant from the Great Plains Fish Habitat Partnership. Before and after photos of the entrance to side channel #13 (Clines channel) are shown in Figure 6. It is expected that this channel will be monitored into the future to determine the effectiveness of this mechanical excavation.

Although the entrance was excavated to a width of 30 feet, it was recommended by Reclamation that the excavation width be 15 feet. This entrance was not intended to create habitat in the near future in this short section of channel, rather to provide a surface connection to the downstream portion of the side channel that does not appear to be aggraded to the same extent as the entrance. As the excavated channel evolves over multiple flood cycles, assuming it does not significantly aggrade again, channel complexity will increase to the benefit of aquatic habitat.

Figure 6: Side channel #13 (Clines channel) before and after the excavation of the channel entrance.

3 Bighorn River Hydrology

The headwaters of the Bighorn River are in the Wind River Range in Wyoming. The river flows northward into Montana through alluvial valleys and bedrock-controlled Bighorn Canyon in southern Montana (Godaire, 2010). The Bighorn River is impounded by Boysen Dam (1952, Figure 1) at the Wind River Canyon in Wyoming and by Yellowtail Dam (1966) in the Bighorn Canyon near Ft. Smith, Montana. The primary gage used for analysis is USGS Gage # 06287000, Bighorn River near St. Xavier, MT. Hydrographs of average daily discharge are shown in Appendix A. These plots are broken down by decade to retain resolution, beginning in the first year of the gage record, 1934.

In order to investigate a discharge hydrograph that might be responsible for doing geomorphic work to stop and perhaps reverse the declining trend of available side channel habitat, it is necessary to investigate the hydraulic conditions under which the idealized or desired planform was established. Godaire (2010) points out that side channel complexes within the study reach were established by 1980. This determination was made using aerial photography dated 1939, 1954, 1961, 1970, 1980, 1991, and 2006. Examining peak flow data, typically responsible for adjustments to channel planform, reveals a couple of notable changes after 1980, aside from the typical reduction in peak value (Figure 7, and Table 1). It is noted that prior to 1980 a period of more than four years had not passed without a peak over 10,000 ft^3/s, a discharge considered significant enough to mobilize sediment in the side channels, discussed later in the report. After 1980, seven year and a nine year periods in the 1980’s and 2000’s pass without a discharge over 10,000 ft^3/s. During these periods, vegetation encroached on the side channels and exposed gravel bars, creating a decrease in active channel area noted in Godaire (2010). Concomitant with the decrease in discharge and frequency of the annual peaks is a decrease in the frequency of flow peaks that occur outside of the June run-off period, typically late winter and fall (Table 1).

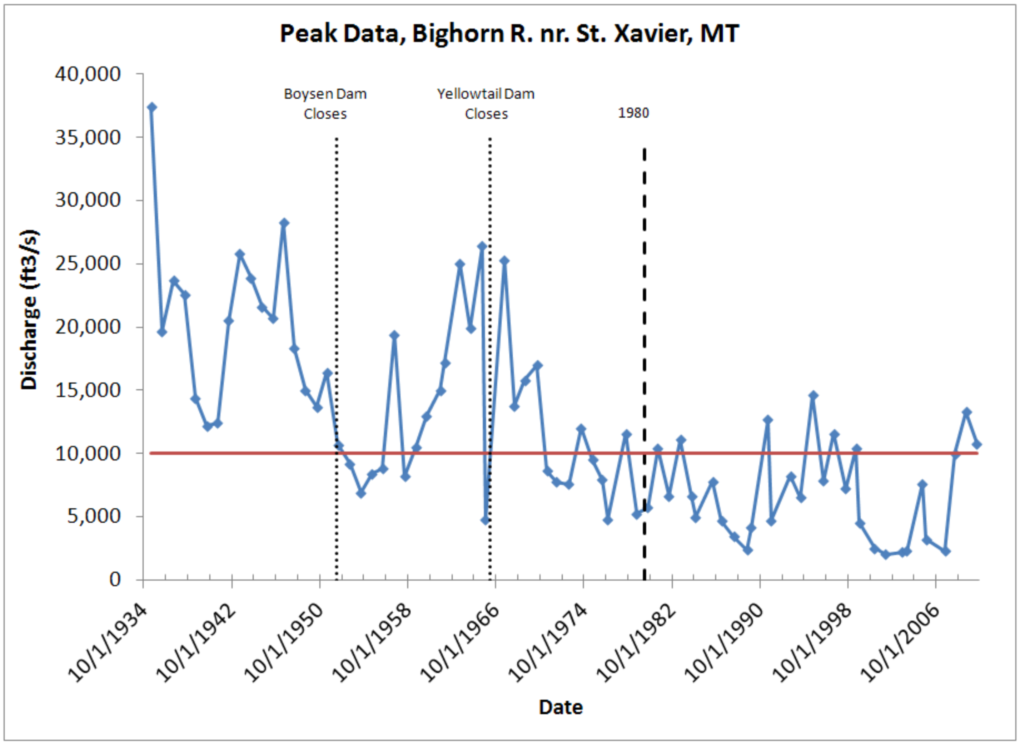

Figure 7: Plot of annual peak data from the beginning of the record to water year 2010. Data taken from historical records at USGS gage # 06287000, Bighorn R. nr. St. Xavier.

The post-impoundment hydrology of recent decades has halted lateral erosion and contributed to the decrease in side channel habitat and overall active channel area (Godaire, 2010), however the lack of sediment contribution from upstream cannot be overlooked. A lack of sediment input to the study reach, along with reduced peak discharges, has significantly reduced the rate at geomorphic change occurs and has created a condition whereby all measures of channel complexity are not expected to recover significantly under current conditions. A decrease in the sediment supply reduces the rate at which channel bars (e.g. point bars, mid-channel bars etc..) are built. If no channel bars (point, mid-channel, etc..) are being built then there is less hydraulic force put upon the channel banks and therefore less bank erosion takes places. Without active bank erosion taking place, floodplain surfaces are not reworked and the riparian vegetation becomes more established and further reduces the erodibility of floodplain and side channel surfaces.

Table 1: Table showing peaks greater than 5,000 ft^3/s occurring in months outside of the annual June run-off period.

Year	**Month**	**Peak Daily Discharge (ft^3/s)**
1939	March	5,450
1940	October	9,070
1942	March	7,900
1943	March	11,000
1946	September	9,630
1947	March	5,550
1948	February	7,270
1949	March	7,400
1950	September	5,680
Boysen Dam Closes, 1952		
1961	September	10,500
1962	February	11,500
1965	April	7,420
Yellowtail Dam Closes		
1968	January	6,680
1971	October	7,040
1972	November	5,180
1973	November	7,380
1982	October	5,630
1993	November	5,600
1997	April	6,800
1999	March	5,590

4 Surveys

4.1 Bathymetric survey

Key to the hydraulic analysis is the bathymetric survey conducted in April, 2009. A supplemental survey was performed in August, 2009 to survey some areas missed in the April survey. Channel bathymetry was obtained using a combination of wading in the side channels and shallow areas of the main channel, and boat mounted SONAR for the main channel and deeper portions of the side channels. Both surveys utilized survey grade Real Time Kinematic (RTK) Global Positioning System (GPS) equipment. Survey control for the site was provided by Charles Hardes (MT Area Office) using the Montana State Plane projection (NAD 83). All units presented in this report are in international feet for horizontal positioning and U.S. survey feet for vertical positioning (NAVD 88).

The SONAR data were collected using a Rio Grande Workhorse acoustic Doppler current profiler (ADCP), manufactured by T-RDI. The boat mounted SONAR set up is shown in Figure 8. Horizontal and vertical positioning was provided with RTK GPS survey equipment. The depth data provided by the ADCP was post processed in such a way that each of the four beams emanating from the transducers (angled at 20 degrees from the vertical) provided an individual depth and horizontal position. This is a significant improvement over using the depth calculated from an average of all four beams.

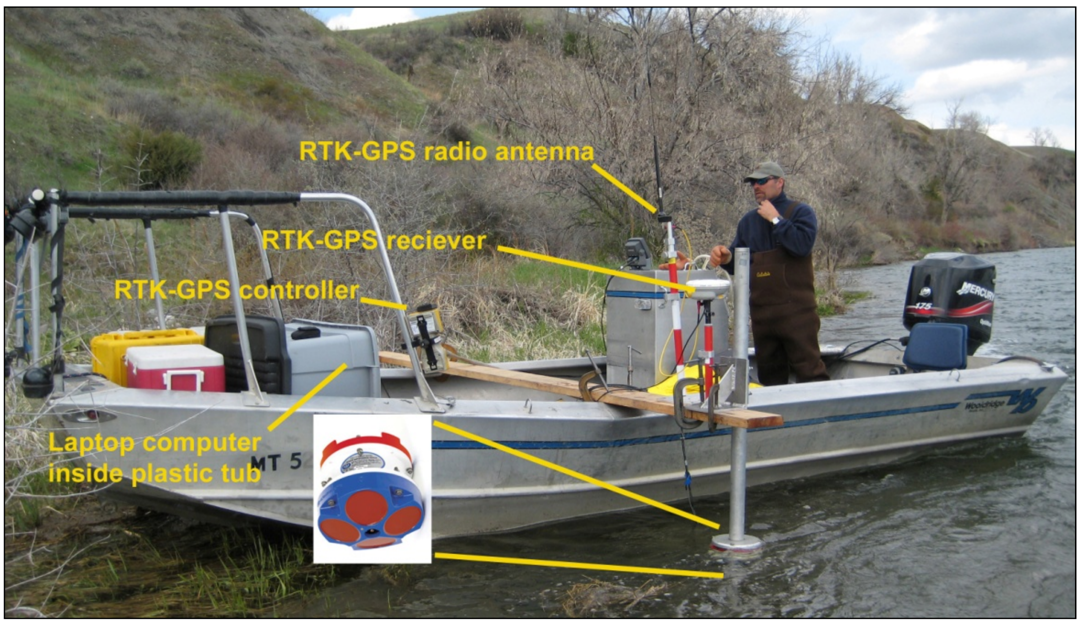

Figure 8: Photograph of the survey boat set showing the survey and SONAR gear.

4.2 Terrestrial survey

The out-of-channel topography has been represented with interferometric synthetic aperture radar (IFSAR) data, collected with airborne methods. The data were delivered in the form of a digital elevation model (DEM) with ± 8.2 feet (2.5 meter) horizontal accuracy. Vertical accuracies for these data are on the order of ± 3.2 feet (1 meter), which is better than that of a 10-meter USGS map but not as accurate as is typically obtained with bare earth LiDAR. The decision to use IFSAR data was based on its cost effectiveness, approximately 1/20th the cost of LiDAR. The IFSAR DEM was processed to remove most vegetation, although accounting for low growing shrubs and grasses is more difficult.

Because the hydraulic model is evaluating in-channel flows, the lack of vertical accuracy for out-of-channel areas is not considered a significant shortcoming. There are a few instances where modeled discharges exceed the bank height, primarily limited to island inundation. Accounting for this inundation was aided significantly with aerial photography flown in July 2011, at which time the Bighorn River discharge was 14,000 ft^3/s. The procedure used to adjust out-of-channel areas is discussed later in the report. The lack of horizontal accuracy is of less concern considering that it represents much less than 10% of the channel width.

5 Bed material data

To quantify bed material size distributions throughout the study reach, pebble count data were collected in October, 2011. The methodology of Wolman (1954) was followed, where the intermediate axis of 100 particles was measured with a template during a random walk over the river bed. Bed material size distributions were determined at all side channel entrances and select main channel locations throughout the reach. In some side channels, a second pebble count was performed some distance downstream of the entrance. A total of 64 pebble counts were collected and their locations are shown in Figure 1. Complete pebble count data are shown in Appendix B

5.1 Tracer particles

The placement of tracer particles in four side channels of the study reach was done for two purposes: 1) track the movement of coarse gravel through the side channels, determining the travel distances with each high flow event and potentially travel time through the side channels; and 2) use the tracer gravels to indicate incipient motion conditions. Three size classes ranging from very coarse gravel to small cobbles were selected. Size classes and seeding locations are shown in Table 2 and

Table 3.

Table 2: Description of the tracer particles seeded in channels of the Bighorn River.

Size Class (mm)	Number of Particles	Color	Serial No. Range
32 – 45	137	Orange	141565271 - 141565410
45 – 64	136	Light green	141565411 - 141565553
64 - 90	66	Yellow	141565554 - 141565623
56 – 84*	59	Dark green	16-530 – 16-588
***These particles were derived from an alternative source, creating a unique size class with a median size of 68mm.			

Table 3: Locations and numbers of particles seeded in various side channels of the Bighorn River.

Location	32 – 45mm	45 – 64mm	64 – 90mm	56 – 84mm
Side Channel 8b	34	34	17	15
Side Channel 10	34	34	16	14
Side Channel 11	34	34	16	15
Side Channel 13	35	34	17	15

The particles were sourced from a gravel supplier in Denver, CO, except for the 56 – 84 mm size class, which originated from the Trinity River in California. Because the particles were not native to the Bighorn River, specific gravity testing was performed to insure that the foreign particles matched the density of the native materials. The testing indicated that no significant density difference existed between the native and foreign source particles. Sphericity of the foreign particles matched that of the native material. Specific gravity testing was also performed comparing particles with and without the RFID tags. There was a slight (negligible) decrease in specific gravity with an RFID tag installed. The decrease is greater for smaller particles and less for larger particles. The test results are shown in Appendix C.

The gravel particles were drilled or a longitudinal groove was cut in the case of some of the 32 – 45mm particles and a 32mm RFID tag was placed inside. Flexible silicone was used to fill the hole prior to inserting the RFID tag into the particle (Figure 9). The flexible silicone helps to prevent breakage of the glass tag resulting from expansion and contraction of the particle during temperature changes when deployed. After the particles were drilled and the RFID tags were inserted, each size class was painted a separate color (Table 2, Figure 10). Serial numbers were recorded such that each size class can be identified by the serial number, which is displayed in the device used to relocate the particles.

The tracer particles were placed on top of the native gravel, which was loosely packed and readily mobile in the side channel entrances. The tracers were seeded in a line across the deepest and swiftest portion of the channel. This seeding methodology has been utilized by other researchers (e.g. Leopold et al, 1966; Hassan et al., 1984; Hassan et al., 1999). Hassan and Ergenzinger (2003) recommend that tagged particles be introduced in a way that reduces the effects of artificial seeding and matches the natural sediment transport conditions. For this reason, the tracer particles were walked on to embed them into the native material to reduce the likelihood that the tracer particles are artificially mobilized prior to the mobilization of the native material. The native material was loosely packed enough to accommodate this methodology. In spite of the apparently successful efforts to embed the particles into the native material, Hassan and Ergenzinger (2003) recommend treating the initial movement with caution.

Figure 9: Photograph of the three size classes of particles with RFID tags inserted. Ruler is in inches.

Figure 10: Painted particles prior to seeding.

6 Modeling methodology

6.1 Representation of the terrain

The single most important factor in determining 2D model prediction accuracy is accurate representation of the modeling surface (Pasternack, 2006), particularly bathymetry. The DEM provided by the IFSAR data was converted to point data, spaced at 16.4 feet (5 meters). The points coinciding with the wetted portions of the channel were removed from the IFSAR data using a digitized waterline and replaced with data from the bathymetry survey (Figure 11). In portions of the channel that were poorly represented by survey data were augmented to maintain channel characteristics. This is especially critical in narrow side channels, where interpolation between points creates artificial obstructions.

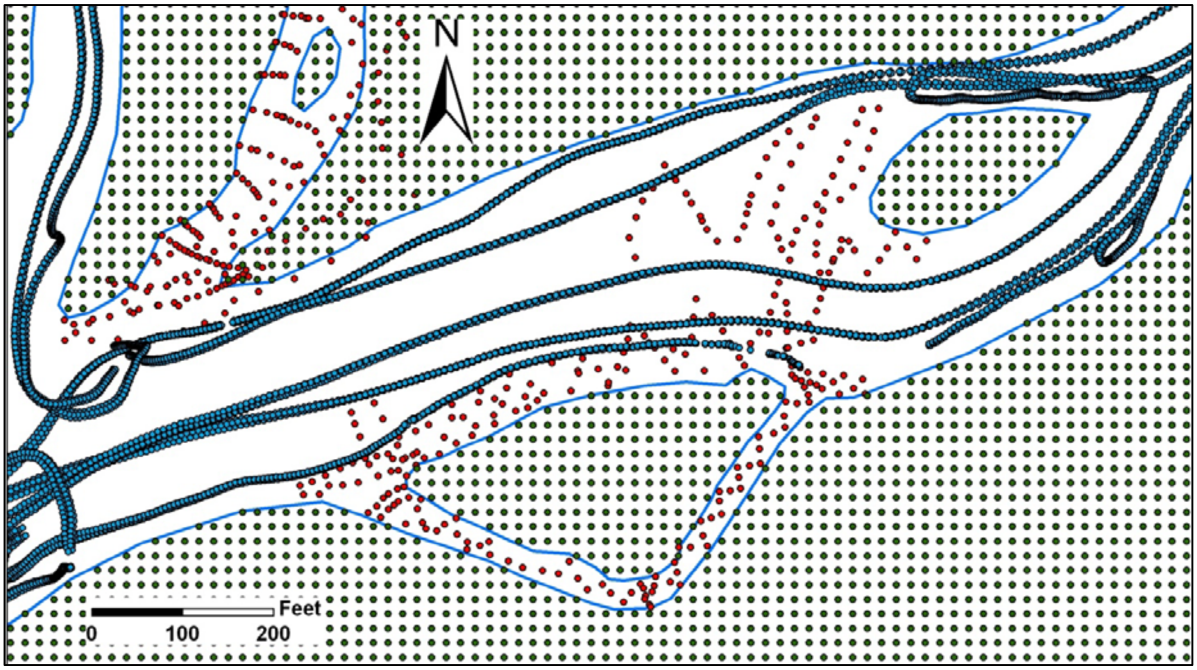

Figure 11: Example of the survey data used to represent topography and bathymetry. The green, evenly spaced floodplain points are IFSAR data, the red points were obtained by wading side channels and shallow portions of the main channel, and the blue points are boat-mounted SONAR data. The waterline used to crop the IFSAR data is shown as a blue line.

During model calibration at a flow of 14,000 ft^3/s, it was noted at many locations within the study reach that the simulated inundation did not match the observed. The error occurred because in some cases, islands in the river were lower than the adjacent channel elevations. The misrepresentation was caused by errors in the IFSAR data, under representing bank height. To correct the bank elevations, artificial levees were constructed in the terrain to match observed wetted widths in the aerial photography. The levees were constructed using a polyline with individually assigned elevations and incorporating these data into the surface model. An example of the added levees is shown in Figure 12.

Using all point and line data a terrain was created in Arc GIS to represent the modeling surface. A terrain is a linear interpolator very similar to a Triangulated Irregular Network (TIN). The terrain was then converted to a 15 foot Cartesian grid that provided the surface input to the hydraulic model using the Surface-water Modeling System (SMS, ver. 10.0.11, Aquaveo 2008). Details regarding the model input are discussed later.

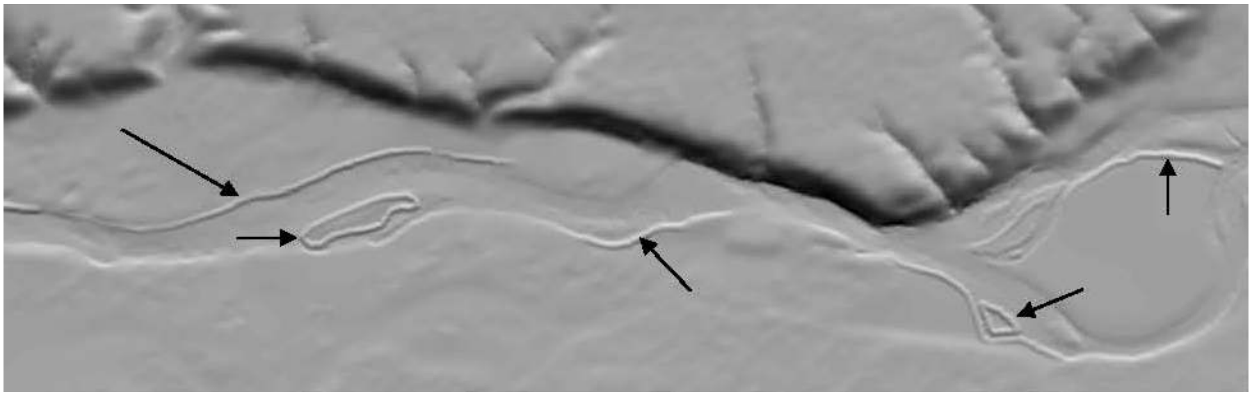

Figure 12: Surface representation of a portion of the study reach showing artificial levees (indicated with arrows).

6.2 Hydraulic model

Because of the complex nature of the interaction of the main channel with side channels, the depth averaged, two-dimensional (2D) model SRH-2D (Lai, 2008) was chosen for the hydraulic and sediment transport study. SRH-2D is a two-dimensional (2D) hydraulic, sediment, temperature, and vegetation model for river systems under development at the Bureau of Reclamation, applying a finite volume discretization of the 2D dynamic wave equations, i.e. the depth-averaged St. Venant equations. SRH-2D utilizes a flexible, unstructured hybrid mesh containing both quadrilateral and triangular cells, following the method of Lai (2010). The mesh is constructed and output evaluated in SMS.

6.2.1 Model input

6.2.1.1 Mesh generation

The primary input to the 2D model is the model mesh and representation of the terrain. The mesh is constructed in SMS and contains all spatial data such as ground/bed elevations, channel roughness, and bed material (Figure 13). Elevation values are stored at each node of the mesh, while bed material and channel roughness values are stored within each element. Typical mesh cell dimensions in the main channel are approximately 20 feet in the lateral direction and 30 feet in the longitudinal direction. Cell size was decreased significantly in the side channels and varies based on channel width. Cell size increases with increasing distance away from the area of interest. The entire mesh contains just over 197,000 mesh cells.

When the mesh construction is completed elevation, bed material, and channel roughness data are added to the mesh. Elevation data are imported from Arc GIS and interpolated to each mesh node. Channel roughness and bed material size distributions are assigned to polygons created to construct the mesh.

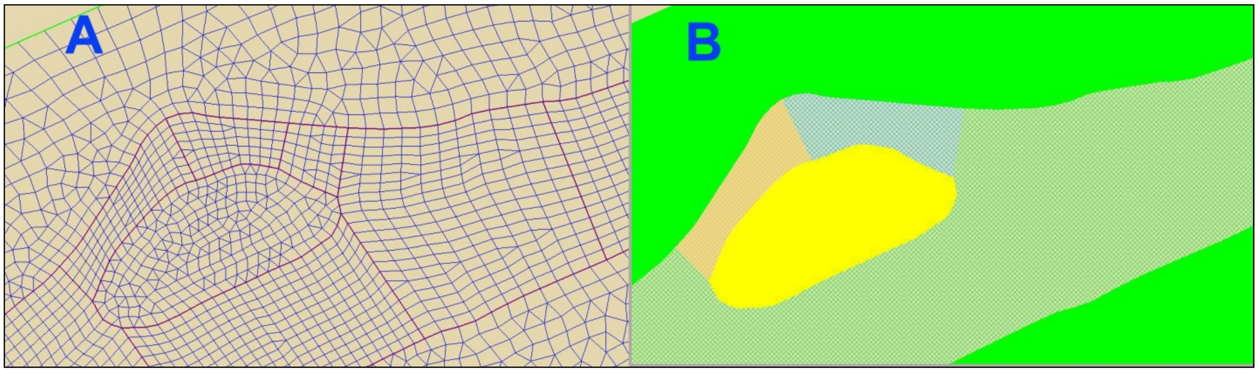

Figure 13: A – Model mesh showing quadrilateral and triangular elements the main channel, overbanks, and an island (Complex #1). B – Material properties of the model mesh indicating various bed material size distributions assigned to each polygon outlined in red in 'A'.

6.2.1.2 Boundary conditions

Certain conditions along the model boundary must be provided as input to a numerical model. Primary boundary conditions are at the inlet and outlet of the model. At the inlet of the model, a discharge is specified. At the outlet, a water surface elevation is given for each discharge. In the case of modeling unsteady flow, a hydrograph (text file containing time – discharge values) is specified at the inlet and a stage-discharge relationship is provided at the outlet. When an unsteady flow is simulated, discharge is calculated locally near the outlet to impose an appropriate water surface elevation at the outlet boundary.

Along the model boundary that does not include the inlet and outlet, a wall of infinite height is constructed to provide containment for any flow that may reach the edge of the model. The wall is assigned a roughness equal to that of the boundary cells. Under no conditions does water flow against the wall boundary in this model.

6.2.1.2.1 Downstream boundary

The rating curve used for the downstream boundary condition was derived with a one-dimensional HEC-RAS model constructed from the same surface used for the 2D model. Results of the 1D model were validated with measured water surface elevations collected during the survey.

6.2.1.2.2 Steady state discharge input

A series of steady state discharges provides input at the upstream boundary for evaluation across a wide range of discharges. Each discharge input at the upstream boundary has a corresponding water surface elevation at the downstream boundary, or outlet, of the model. The steady state discharges evaluated for this study are shown in Table 4. The highest discharge evaluated, 15,500 ft^3/s, represents a limit imposed by the operations group at Reclamation's MT Area Office.

Table 4: Steady state discharges evaluated in this study.

Discharge in ft^3/s								
2,500	3,475	5,500	6,800	8,000	10,000	12,000	14,000	15,500

6.2.1.2.3 Unsteady discharge input

Two hydrographs were run in the model, primarily to test for attenuation throughout the reach and examine changes in flow depth over time at specific locations throughout the model. An antecedent discharge of 3,500 ft^3/s was assumed. Hydrograph 1 imposes a ramp rate of 200 $ft^3/s/hr$ with a peak duration of 24 hours and a total duration of 128 hours. Hydrograph 2 simulates a double peak often seen in the gage record (Figure 14). It also assumes flow operation with increases of 1000 ft^3/s.

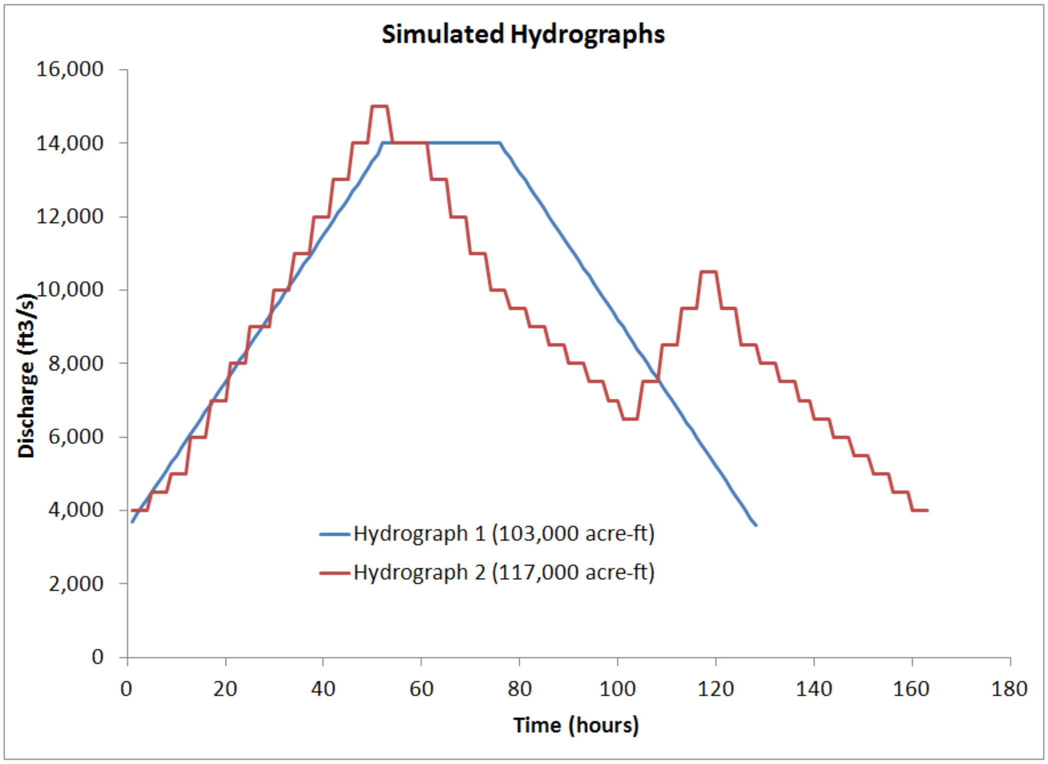

Figure 14: Two hydrographs simulated in the model.

6.2.2 Model calibration

6.2.2.1 Moderate discharge calibration to water surface elevation

The primary adjustment factor in the model is channel roughness that can be optimized to match measured water surface elevations. Channel roughness is specified using the Manning's *n* value (Table 5). In side channels, a low roughness value is assigned when there's no vegetation growth, however the roughness is typically somewhat greater than the main channel due to shallower depth. A high side channel roughness is assigned to side channels that have significant vegetation growth and/or debris. Islands with sparse vegetation growth are given a lower roughness value than those islands where vegetation is dense. The choice for roughness on the islands is also related to the type of vegetation present. Low growing, shrub vegetation provides a greater resistance to flow than the growth of large trees, where the only interruption to flow is the stem or trunk. Because the floodplain is not significantly inundated at modeled discharges, one roughness is provided, representing the low growing shrub and willow growth along the banks. This calibration was performed at a discharge of 3,574 ft^3/s, matching the average discharge during the April 2009 surveys. Discharge varied between 3,560 and 3,630 ft^3/s (less than 2%) over the 5 days of the survey.

Table 5: Table of channel roughness values (Manning's 'n'*) used in the model.*

Main Channel	**Side Channel Low '*n*'**	**Side Channel High '*n*'**	**Island Low '*n*'**	**Island High '*n*'**	**Floodplain '*n*'**
0.03	0.035	0.04	0.06	0.075	0.075

A comparison between predicted (modeled) and observed (measured) water surface elevations by subtracting the measured from the predicted value. Minimum criteria indicating an acceptable water surface calibration is a raw mean error less than 0.25 ft and a standard deviation less than 0.5 ft. There are over 8,000 observations spanning the entire study reach used in the statistical comparison, shown in Table 6. Examination of these values indicates a satisfactory agreement between predicted and observed water surface elevations.

Table 6: Statistics regarding the comparison of predicted minus observed water surface elevations.

Residual Mean (ft)	-0.006
Residual Standard Deviation (ft)	0.25
Predicted values within ± 0.1 ft of measured	35.6%
Predicted values within ±0.2 ft of measured	62.4%
Predicted values within ±0.5 ft of measured	94.5%
Root-Mean-Square Error (RMSE) (ft)	0.08
Mean Average Error (MAE) (ft)	0.19

6.2.2.2 High discharge calibration to wetted width

A second calibration compared wetted width and areas of inundation using aerial photography flown in 2011 when the river discharge was 14,000 ft^3/s. In many instances, artificial berms had to be constructed in the modeling surface to keep flow in the channel and match observed wetted areas. Vertical error in the IFSAR data has been discussed previously. Upon completion of the high flow calibration, a qualitative check was made to insure that observed inundation matched the modeled inundation.

Because the bank heights were artificially adjusted in the modeling surface for a discharge of 14,000 ft^3/s, confidence in model results for higher discharges decreases significantly. A maximum modeled discharge of 15,500 ft^3/s was requested by the client, which is the peak discharge evaluated for this project. It is not possible to quantify the level of uncertainty in model results for discharges greater than 14,000 ft^3/s due to unknown bank heights. Model results at 15,500 ft^3/s should be considered less reliable than lower discharges.

6.2.3 Model validation for hydraulics

After the calibration process was completed, the model was validated using measured depth-averaged-velocity. These velocities were collected concurrent with the survey in April 2009 using the ADCP. Because the primary focus of the ADCP work performed during the survey was to collect bathymetry data, there is a wider variability in velocity values due to flow disturbance around the ADCP. Velocity data measured with the ADCP is more sensitive to near-field flow disturbance caused by inconsistent boat motion. Although every effort was made to operate the boat to minimize disturbance, ideal conditions for collecting velocity data were not always met, causing a greater variability in measured data. It is also important to point out that the ADCP collects an instantaneous velocity measurement at a single point, which is subject to fluctuations due to turbulence. To account for turbulence in the flow field, a time averaged measurement would be required. Velocity data were not collected in this manner due to time constraints during the survey. Modeled velocity values represent a spatial and temporal average not reflected in the observed data. Nonetheless, it remains appropriate to compare observed and predicted velocities as a method of model validation.

Using Arc GIS to spatially locate coincident values of predicted and observed velocities, a comparison of the two data sets was performed using 1,611 samples. Sampled velocity data were used throughout the study reach. The ADCP is limited to collecting velocity at a depth of 3 feet or greater. Residuals are calculated by subtracting the observed data from the predicted data. Using similar statistics that were applied to water surface elevation comparisons, raw mean and standard deviation were calculated as well as MAE (Equation 1) and RMSE (Equation 2) (Table 7). These errors fall within bounds considered acceptable in the literature (Lacey and Millar, 2004; Pasternack et al., 2006; Barker, 2010; Pasternack, 2011). Definitions of the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) are shown in Equations 1 and 2:

$$RMSE = \sqrt{\frac{1}{n}\sum_j^n \left(M_j - P_j\right)^2} \qquad \text{(Equation 1)}$$

$$MAE = \frac{1}{n}\sum_j^n \left|M_j - P_j\right| \qquad \text{(Equation 2)}$$

where n = number of samples, M_j and P_j are measured and predicted values, respectively.

Table 7: Statistics describing velocity validation at 3,475 ft^3/s using 1,611 samples.

Residual mean (ft/s)	-0.14
Residual standard deviation (ft/s)	1.04
Percent predicted values within ± 1 ft/s of observed	73.9
Percent predicted values within ± 1.5 ft/s of observed	86.5
Percent predicted values within ± 2 ft/s of observed	93.9
Mean Absolute Error (ft/s)	0.77
Mean Absolute Error (%)	26.9
Root-Mean-Square Error (ft/s)	1.05

An appropriate validation will include a sampling of velocities in reasonable proportion to those that exist in the river. Figure 15 A and B shows the frequency of predicted and observed velocities used in the comparison. Figure 5A is a histogram of all wetted areas that are inundated during the 3,475 ft^3/s discharge. Observed velocities throughout the domain would be more appropriate however it is impossible to know this distribution. Low velocities (0 – 2 ft/s) are seen to be undersampled in the observed data. Many lower velocity values exist in shallow portions of the side channels and near the margins of the main channel. These locations are notoriously difficult to access during a survey, and depths less than 3 feet cannot be sampled for velocity due to equipment limitations.

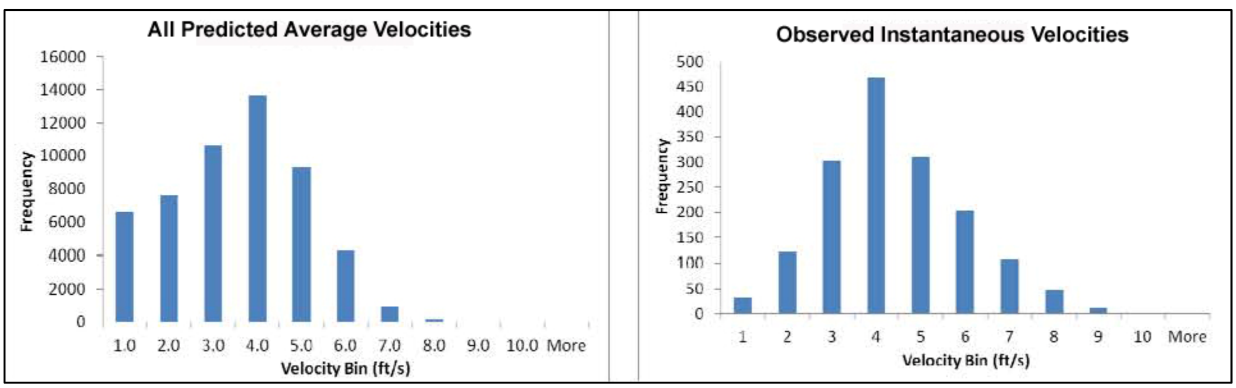

Figure 15: Histograms of predicted vs. observed velocities. Predicted velocities are model results from the entire wetted domain of the 3,475 ft^3/s discharge.

Examining the percent mean absolute error will indicate which velocities present the greatest error (Figure 16) shows a plot of the percent absolute velocity error with observed velocities, indicating that large percentage errors are limited to low velocities, typical for 2D modeling

(Pasternack, 2011). A total of 19 points from the entire data set are beyond 200% error, a very small portion of the 1,611 samples.

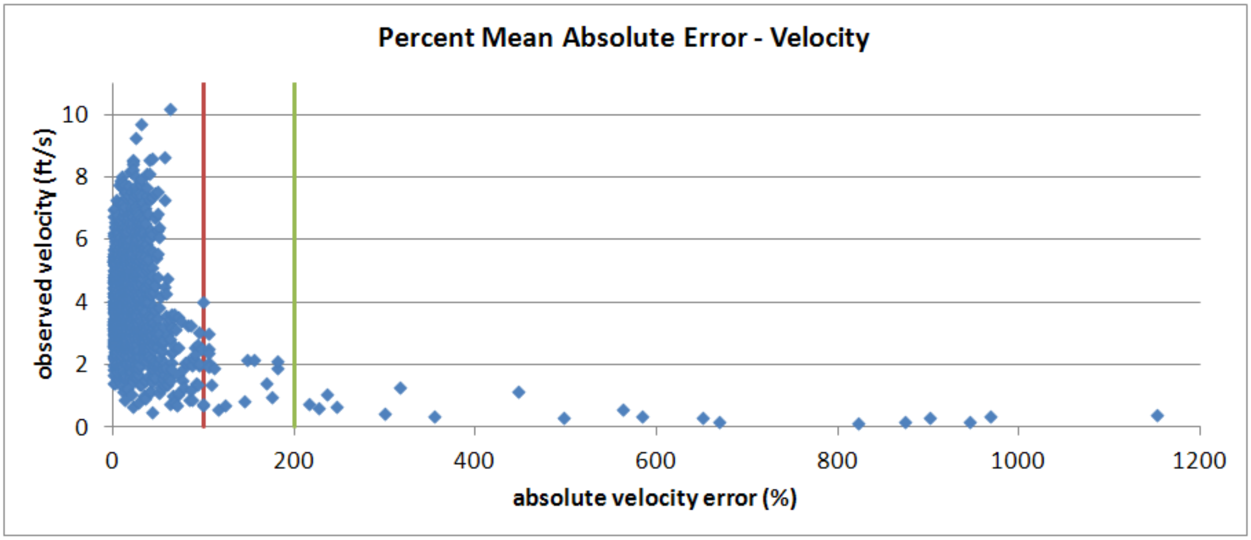

Figure 16: Plot of percent mean absolute velocity error.

Below is a velocity data comparison showing a plot of predicted versus observed velocities (Figure 17). The coefficient of determination (R^2) indicates how well values are predicted by a model (Devore, 1995). The linearity (0.9075 in this case) and y-intercept (0.487) are a measure of a models tendency to predict high velocities too low and low velocities too high (Pasternack, 2011). Values of these metrics are within acceptable criteria for 2D modeling (Pasternack, 2011). Much of the scatter, and lower correlation, shown in these results is related to the variability in the observed value, due to both the collection method and a comparison of instantaneous versus time averaged velocities.

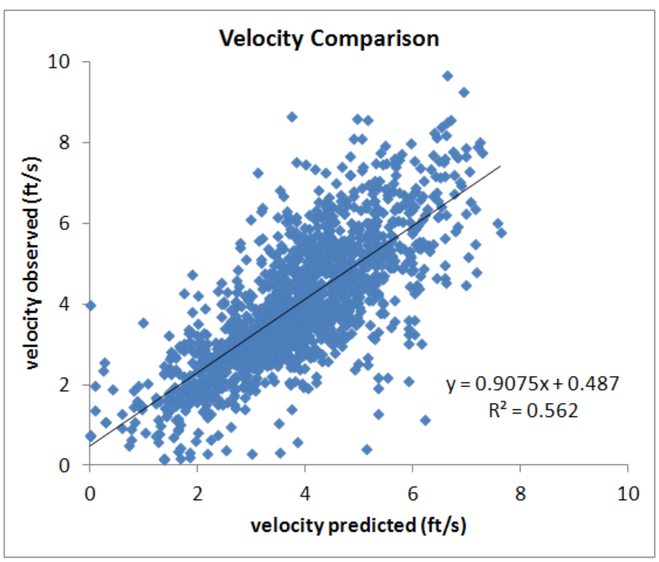

Figure 17: Plot of predicted versus observed velocity. Scatter in these data can be largely explained with the method of data collection for the observed velocities.

Depth values were also used to validate predicted quantities, using methods similar to velocity validation. A sample size of 18, 472 spatially coincident depth values is used for the analysis. The ADCP is limited to a flow depth of 1 foot for collecting depth data. Typically, 2D models are better at predicting depth than velocity (Pasternack, 2011), therefore relative error values are expected to be less for depth comparisons. This is the case here, as can be seen in Table 8, Figure 18, and Figure 19. All metrics to measure the reliability of the model results fall within acceptable criteria set up by Pasternack (2011).

Table 8: Statistics describing depth validation at 3,475 ft^3/s using 18,472 samples.

Residual mean (ft)	-0.04
Residual standard deviation (ft)	0.45
Percent values within ± 0.5ft	81.2
Percent values within ± 1ft	95.9
Mean Absolute Error (ft)	0.32
Mean Absolute Error (%)	12.1
Root-Mean-Square Error (ft)	0.45

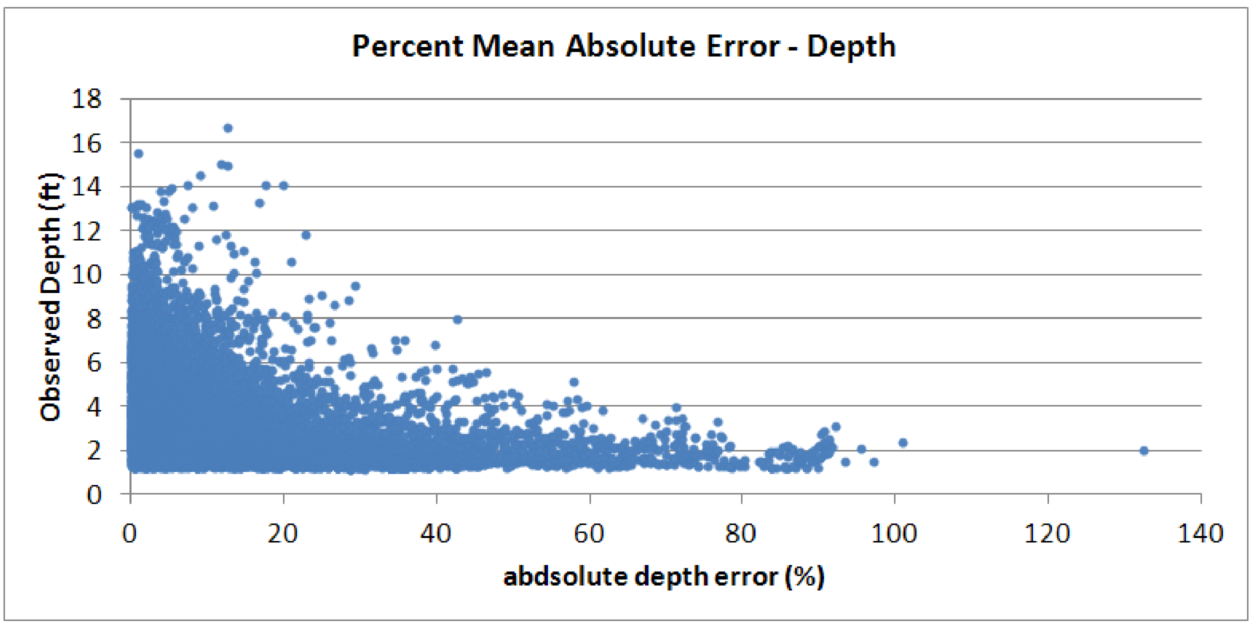

Figure 18: Plot of percent mean absolute depth error.

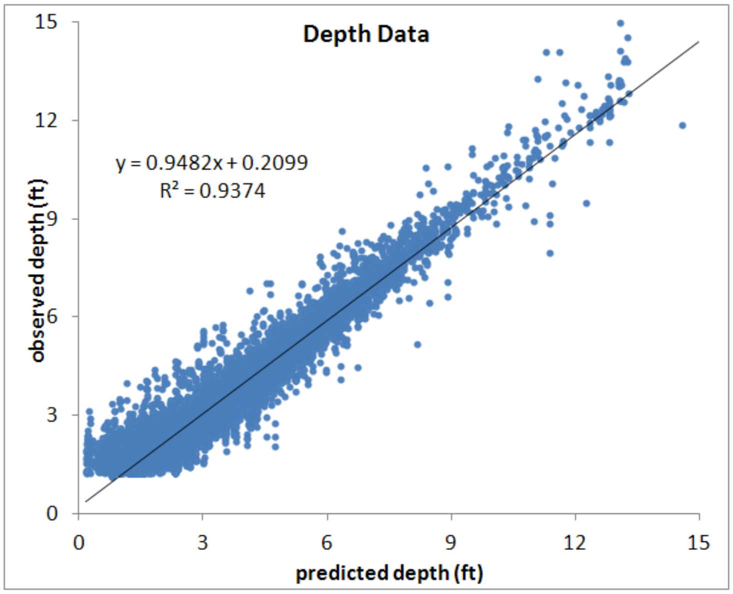

Figure 19: Plot of predicted versus observed depth. Observed depths do not include values less than 1 foot due to instrument limitations.

6.2.4 Sensitivity

Testing was performed to determine the sensitivity of the model to time step. The time step chosen for the model output was 5 seconds. Choosing a 5 second time step improves run time without compromising computational stability. The sensitivity testing was performed at 2, 5, and 10 seconds by comparing the residuals of depth and velocity (Table 9).

Table 9: Table of residual values comparing depth and velocity at three time steps, 2, 5, and 10 seconds.

	Depth Residual, 5sec-2sec (ft)	Depth Residual, 10sec-2sec (ft)	Velocity Residual, 5sec-2sec (ft/sec)	Velocity Residual, 10sec-2sec (ft/sec)
Mean	-0.00008	0.0007	0.0016	0.0020
Std. Dev.	0.003	0.005	0.02	0.03
Min.	-0.60	-0.60	-1.42	-1.7
Max.	0.17	0.18	1.35	1.38

Sensitivity to the roughness parameter, Manning's *n*, was not specifically evaluated. However, it has been documented in similar modeling efforts (e.g. Hilldale and Lai, 2007,Sutton et al., 2010) that the sensitivity to water surface elevations when roughness is evaluated over a reasonable range (Maning's *n* +/- 0.005) is on the order of 0.2 ft.

7 Limitations of the current study

Prior to discussion of numerical modeling and results, a discussion of the limitations of the current study is warranted. All numerical analyses are subject to certain assumptions and limitations. This study is no exception. Of particular relevance to the results and conclusions in this report are the assumptions and limitations that have gone into the sediment transport analysis. Two primary limitations are discussed here. 1) Although every effort was made to classify the spatial distribution of sediment size distributions throughout the study reach, it is not possible to account for all the natural variability throughout the model domain. It is likely that localized areas of sediment transport conditions are misrepresented due to the lack of complete sediment distribution information at all locations within the channel. These areas have been identified and have been eliminated from the analysis. 2) Sediment transport dynamics have been simplified in this report and are limited to rigid boundary, steady flow conditions. That is to say, the current study analyzes the steady state hydraulic conditions under which sediment motion is expected to occur and calculates the ability of the river to transport sediment, but does not simulate sediment motion and the resulting bed deformation. For example, calculations that indicate sediment motion near a side channel entrance do not consider the sediment load and size distribution of sediment that may be transported into the side channel entrance. Assumptions of channel degradation based on sediment motion are uncertain because the incoming sediment load to each side channel is unknown.

However, the calculation of incipient motion based on the sediment distribution as defined in this study is a reasonable predictor of geomorphic work, and as such, conclusions predicting sediment motion within the main and side channels are considered reasonable and prudent. A 2D, mobile bed, sediment transport model is within the capability of the Sedimentation and River Hydraulics Group, however that type of analysis is limited to site-scale conditions due to its computational intensity. Considering budgetary and time constraints placed on the project, the current level of analysis is appropriate given the scope and scale of the study. If further detail is needed to quantify sediment motion, such a study is recommended. Much of the necessary data are in hand, with the possible exception of greater definition of bed composition for a given site.

Incipient motion calculations are also subject to significant uncertainty when no observational data are available. However, the introduction and subsequent tracking of tracer gravels has provided a validation, albeit minimal, of the incipient motion criteria used in this report. Incipient motion values have been documented to vary between Shields numbers of 0.02 and 0.06 (Parker et al., 1982; Andrews, 1994; Buffington and Montgomery, 1997; Pitlick and Van Steeter, 1998) and it is difficult to predict their value in a particular river with certainty without specific field data providing knowledge on incipient motion thresholds. Further compounding the prediction of incipient motion is the intergranular geometry controlled by grain shape, sorting, and packing in the bed (Buffington and Montgomery, 1997). The looseness of intergranular sediment packing can significantly change the threshold of sediment motion, and no satisfactory method of measuring and quantifying this property of gravel deposits has been developed (Kondolf and Wilcock, 1998).

8 Model results

8.1 Hydraulics and side channel inundation

One of the goals of the hydraulic modeling is to determine which side channels become connected at the upstream and downstream ends at a given discharge. Examining the results of the steady state discharges indicates that several side channels and overflow channels are not inundated at 2,500 ft^3/s, the lowest discharge evaluated. A complete list of these observations is shown in Table 10. One should consider the resolution of the discharges evaluated (Table 4), as a particular channel may become connected somewhere between the discharge indicated in Table 10 and the next lower modeled discharge.

As with uncontrolled rivers, not all side channels in the study reach of the Bighorn River are inundated at the most commonly occurring discharges. Free-flowing rivers often exhibit a variety of off channel habitat conditions that are available over a wide range of inundation frequencies. The condition, or state, of off channel habitat is typically dynamic, varying from newly created conditions to those in their senescence. The longevity of specific off channel features depends on a fickle combination of hydrology, local hydraulics, sediment availability, and in some cases woody debris.

Table 10: Table of approximate discharge at which specific side channels become connected at the upstream and downstream end. Discharges below 2,500 ft^3/s were not evaluated.

Channel Identification	Approximate minimum discharge required for connection (ft^3/s)
Complex #4, river right, upstream channel	2,500
Complex #8, center island channel	3,475
Complex # 8, far left channel	8,000
Complex #10, Picture channel	2,500
Complex #10, far right channel	15,500
Complex #11 (Pipeline channel)	3,475
Complex #12, island channel at upstream end	5,500
Complex #13 (Clines channel, prior to excavation)	5,500
Overflow channel, river left, upstr. of Complex #15	8,000 – 10,000
Complex #15, center island channel	10,000

8.2 Unsteady flow results

The results of imposing an unsteady hydrograph in the model indicated that significant attenuation through the study reach is of little concern. Results indicate that there is a lag of 3 hours from Yellowtail afterbay dam to the Bighorn boat launch imposing a hydrograph with a 14,000 ft^3/s peak discharge (hydrograph 1, Figure 14). There is no appreciable attenuation in the discharge peak. These results indicate that imposing a specific discharge released from the afterbay dam will result in approximately the same peak discharge throughout the reach.

Model results from hydrograph 1 (Figure 14) were used to determine the rate of change in flow depth near the downstream end of side channel 13 (Clines channel, Figure 20). This information can be used to evaluate the possibility of stranding fish during the falling limb of a hydrograph. Evaluating flow depth over time (Figure 21) indicates a decreasing rate of approximately 1 ft/hr on the falling limb of the hydrograph. The model assumes dry conditions throughout the channel at the beginning of the hydrograph, as side channel #13 is not inundated until a main channel discharge of approximately 5,500 ft^3/s is exceeded (under modeled conditions).

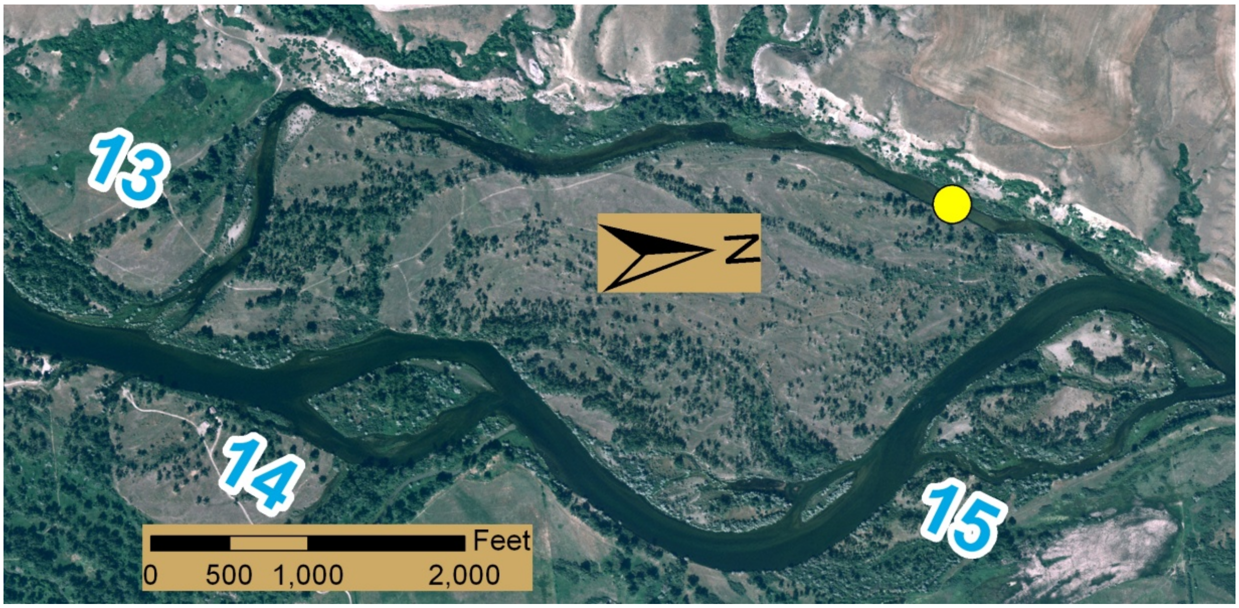

Figure 20: Yellow dot indicates the location of one of the monitoring points in the hydraulic model in side channel #13 (Clines channel) at the top of the photograph. A monitoring point provides output data over time at a specific location and can be used to monitor the change in flow depth with time over a hydrograph.

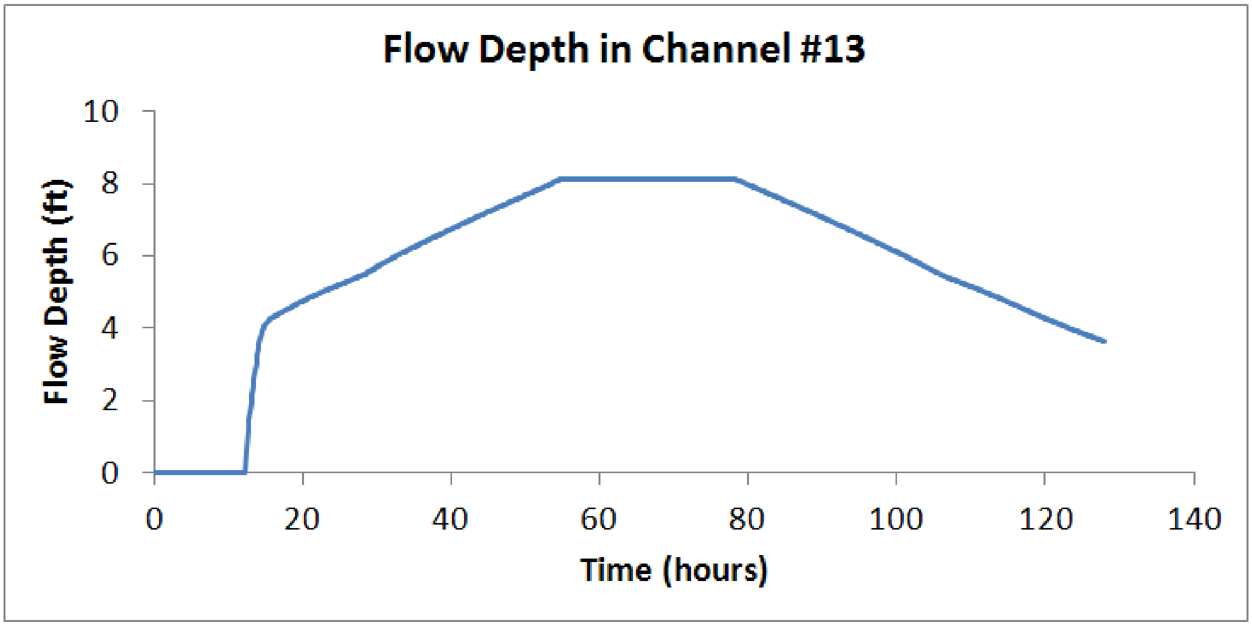

Figure 21: Plot of flow depth changing over Hydrograph 1 (Figure 14) at a monitoring point in side channel #13 (Clines channel Figure 20). This information can be used to determine the probability of stranding fish during the falling limb of a hydrograph. The rate of change in flow depth beyond hour 80 is approximately -1 ft/day.

8.3 Sediment Transport

This analysis of sediment transport uses static conditions, regarding both discharge and bed configuration. The goal of the sediment analysis is to evaluate when sediment begins to move (incipient motion) in the side channels to better understand channel dynamics and so flow prescriptions can be wisely evaluated. Defining incipient motion is difficult because the movement, or transport, of fluvial sediment occurs across a continuum, from just a few particles moving a short distance in only one or two locations at some intermediate discharge to the entire bed being vigorously transported nearly everywhere in the study reach at some higher discharge. By the strictest definition the former example would be considered incipient motion. However this very minimal amount of sediment transport is not worth considering because it does not change the channel form. What is of interest in this study is when a significant amount of sediment is set in motion in many locations, resulting in some potential channel change, or geomorphic work. This is the purpose of the various thresholds of incipient motion shown in Table 11.

Table 11: Table of incipient motion criteria used in this study.

No Sediment Transport	**Marginal Sediment Transport**	**Significant Sediment Transport**	**Vigorous Sediment Transport**
$0 < \tau_c^* \leq 0.03$	$0.03 < \tau_c^* \leq 0.047$	$0.047 < \tau_c^* \leq 0.06$	$\tau_c^* > 0.06$

An example showing progressively increasing values of the Shields parameter with discharge is shown in Figure 22. This is a side channel in Complex # 12 (Figure 2). The feature is hydraulically connected at approximately 5,500 ft^3/s and indicates an increasing area and intensity of sediment transport with increasing discharge.

Analysis of incipient motion with SRH-2D begins with a determination of the applied boundary shear stress in two dimensions:

$$\tau_x, \tau_y = \rho u_*^2 \frac{(U,V)}{\sqrt{U^2+V^2}} \qquad \textit{Equation 3}$$

where ρ is the density of water, u_* is shear velocity $\left(\sqrt{\frac{\tau}{\rho}}\right)$, U and V are the horizontal components of depth-averaged velocity (longitudinal and lateral, respectively). Applying the resultant magnitude velocity in Equation 3, the critical Shields parameter is:

$$\tau_c^* = \frac{\tau_c}{(\rho_s-\rho)gd} \qquad \textit{Equation 4}$$

where τ_c^* is the critical dimensionless shear stress, τ_c is the critical boundary shear stress for incipient motion, ρ_s is the density of sediment, and d is the particle diameter. For all analyses in this report, the sediment diameter used to evaluate initiation of sediment motion is d_{50}, the sediment size for which 50% of the sample is larger and 50% is smaller. Each sediment sample represents the surface distribution, determined with a pebble count. Applying the Shields criteria to the surface d_{50} to determine meaningful bed motion is a common procedure (Parker et al., 1982; Andrews, 1994; Buffington and Montgomery, 1997, Pitlick and Van Steeter, 1998). Many investigators use the Shields parameter to define incipient motion of a grain size of interest (Buffington and Montgomery, 1997). In fact, Pitlick and Van Steeter (1998) state that the Shields parameter is the only practical means for estimating the onset of particle motion in the absence of direct observation. Following methodology in Pitlick and Van Steeter (1998) and Andrews (1994), incipient motion criteria for the Bighorn River has been matched to the values shown in Table 11.

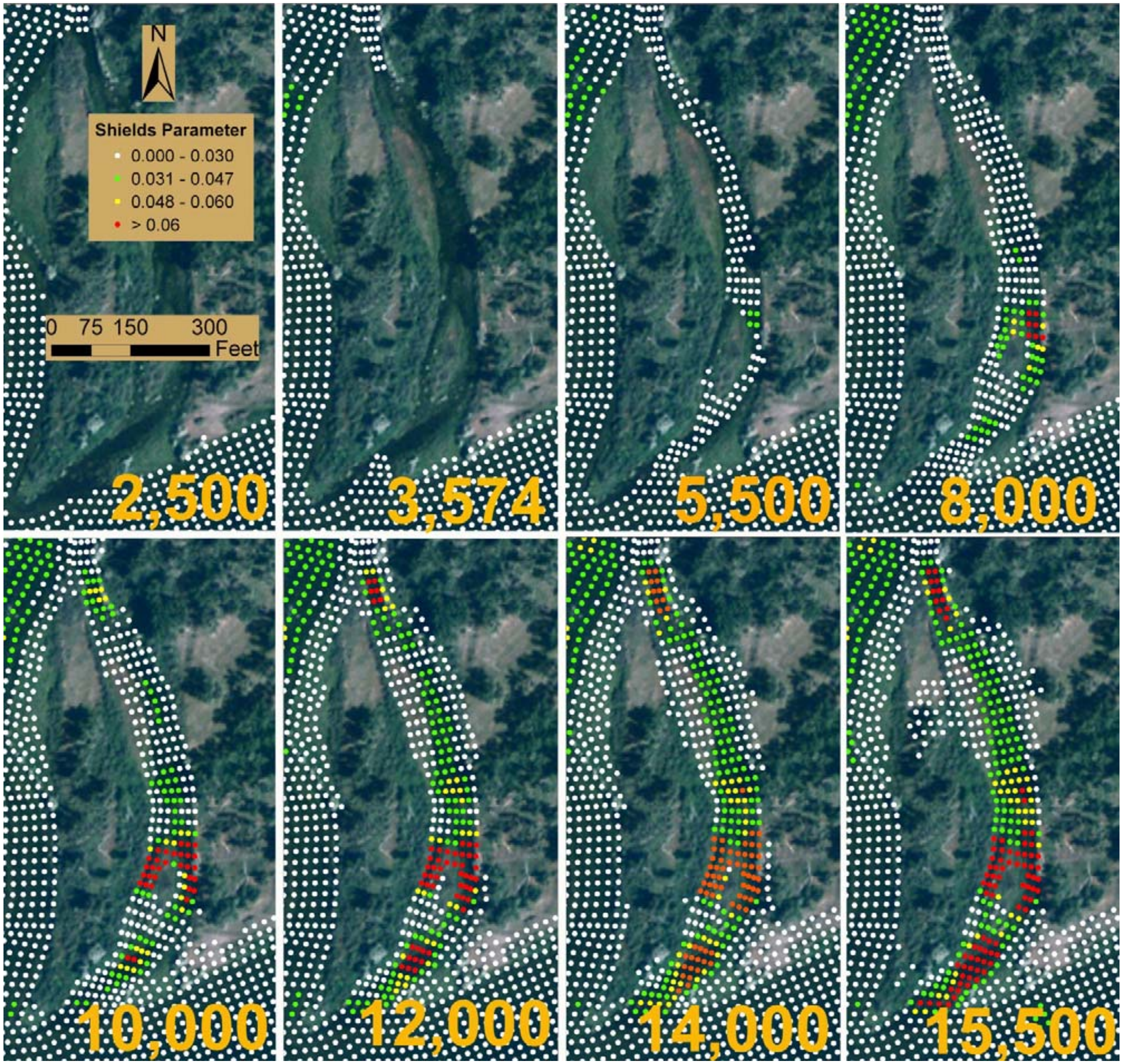

Figure 22: Shields parameters for the range of modeled discharges, indicated at the bottom right of each frame. The selected side channel is part of Complex #12 at head of island. Flow does not enter the channel until a discharge of 5,500 ft^3/s is exceeded; therefore the channel is dry for discharges of 2,500 and 3,574 ft^3/s. Discharges are indicated on each panel, in ft^3/s.

8.3.1 Sediment transport in the newly excavated entrance to side channel 13 (Clines channel)

Because the entrance to side channel 13 was not excavated until well after the modeling was completed, sediment transport is not evaluated in the new excavation with the hydraulic model. However, tracer particles were placed in the new excavation so that transport in this channel can be evaluated now and into the future.

The sediment transport observed in this channel using the tracers following the April 2012 release of 6,800 ft^3/s is considered significant. All the particles were transported from their seeding location and distributed throughout the channel, with the farthest particles being transported over 180 feet. Many particles were buried by native sediment, another indication of significant sediment transport. This transport occurred at a flow that marginally transports sediment in other channels, indicating the possibility of some degradation with higher discharges. It is not certain if significant volumes of sediment will be transported into this channel from the main channel.

8.3.2 Validation of Predicted Incipient Motion

8.3.2.1 Observed tracer particle motion

Although tracer particles were seeded in four side channel entrances, only three locations can be used for validation of incipient motion, 8b, 10, and 11, because the entrance to side channel 13 was excavated after the numerical modeling was completed. The particles were seeded in February 2012 with the anticipation of relocating the particles following a planned release of moderate magnitude in April 2012 and high flows from spring runoff. Due to the dry conditions only the planned release in April 2012 occurred, with a peak discharge of 6,800 ft^3/s (Figure 23).

Following the release in April 2012, the particles were located in side channels 8b, 10, and 11. The peak discharge of 6,800 ft^3/s was predicted to provide marginal transport of the sediment, and therefore the tracer particles, in the side channel entrances. The following discussion will show that the model predicted the observed marginal transport, although a higher discharge in early summer would have improved the validation and further reduced the uncertainty.

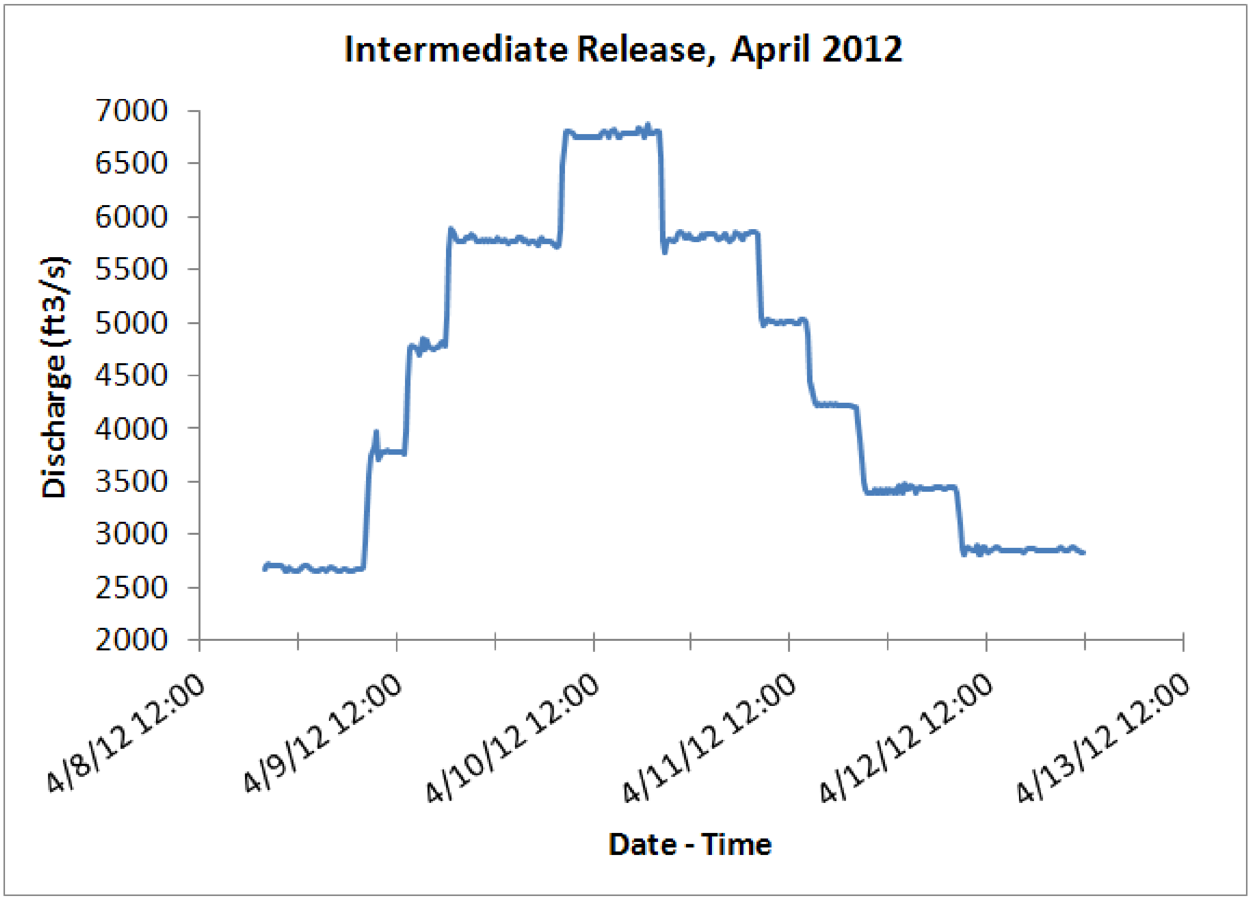

Figure 23: Graph of the planned intermediate release in April 2012. The purpose of this release was to observe sediment transport activity in selected side channels.

Tracer particles in side channel 8b were mobilized more so than tracer particles in side channels 10, and 11. Two particles between 64 and 90 mm moved approximately 90 feet, roughly two side channel widths. Six particles of all sizes moved approximately 55 feet. Another 7 particles of all sizes moved approximately 45 feet. 12 particles of all size ranges moved approximately 35 feet. The remaining particles either remained in their seeded location or moved a short distance from the seeding location. Overall, approximately half of the seeded particles moved from their seeded position. This level of sediment movement is considered marginal sediment transport (Figure 24).

Tracer particles in side channel 10 were much less mobile. One particle in the 32 – 45 mm size class moved 18 feet. Fifteen particles of all size ranges moved approximately six feet. All other particles remained in the seeded location. This level of sediment transport is considered weakly marginal (Figure 25).

Tracer particles in side channel 11 were the least mobile of the three channels used for model validation. One particle in the 32 – 45 mm size class moved 21 feet. Three particles, one of each size range 32 – 45, 45 – 65, and 64 – 90 mm, moved 10 feet. One other particle in the 45 –

64 mm size class moved five feet. This level of sediment transport is considered weakly marginal (Figure 26).

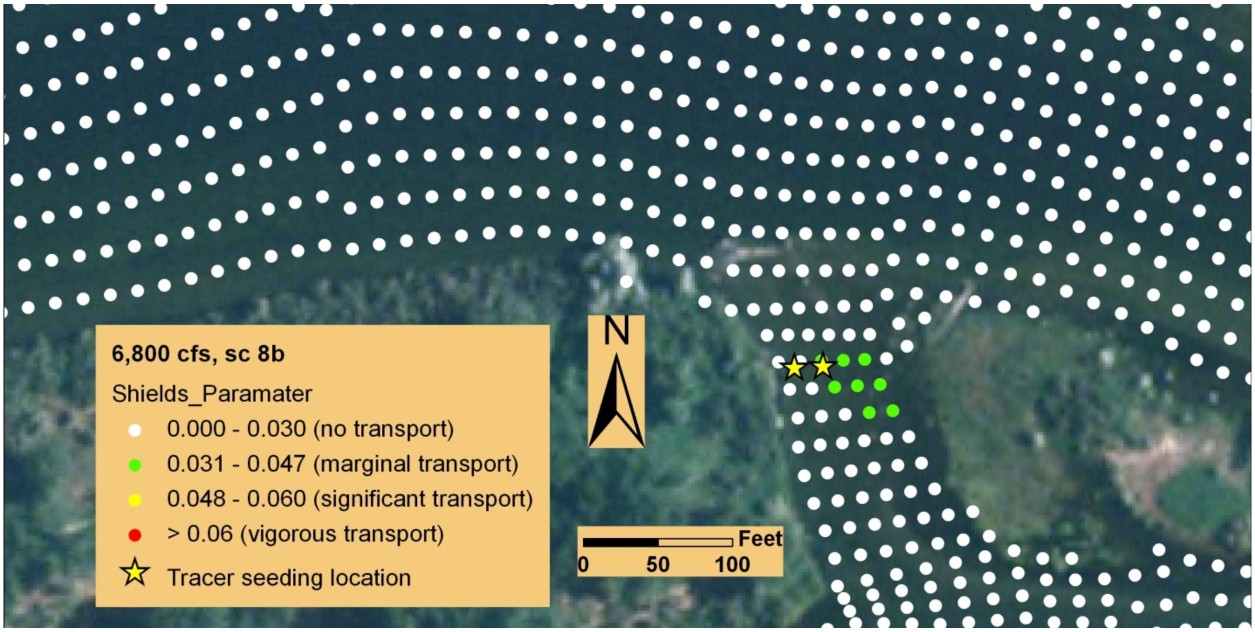

Figure 24: Diagram showing predicted initiation of sediment transport in side channel 8b at 6,800 ft^3/s. Tracer seeding location is shown with yellow stars, model results indicate marginal transport, verified by limited tracer motion following the release in April 2012.

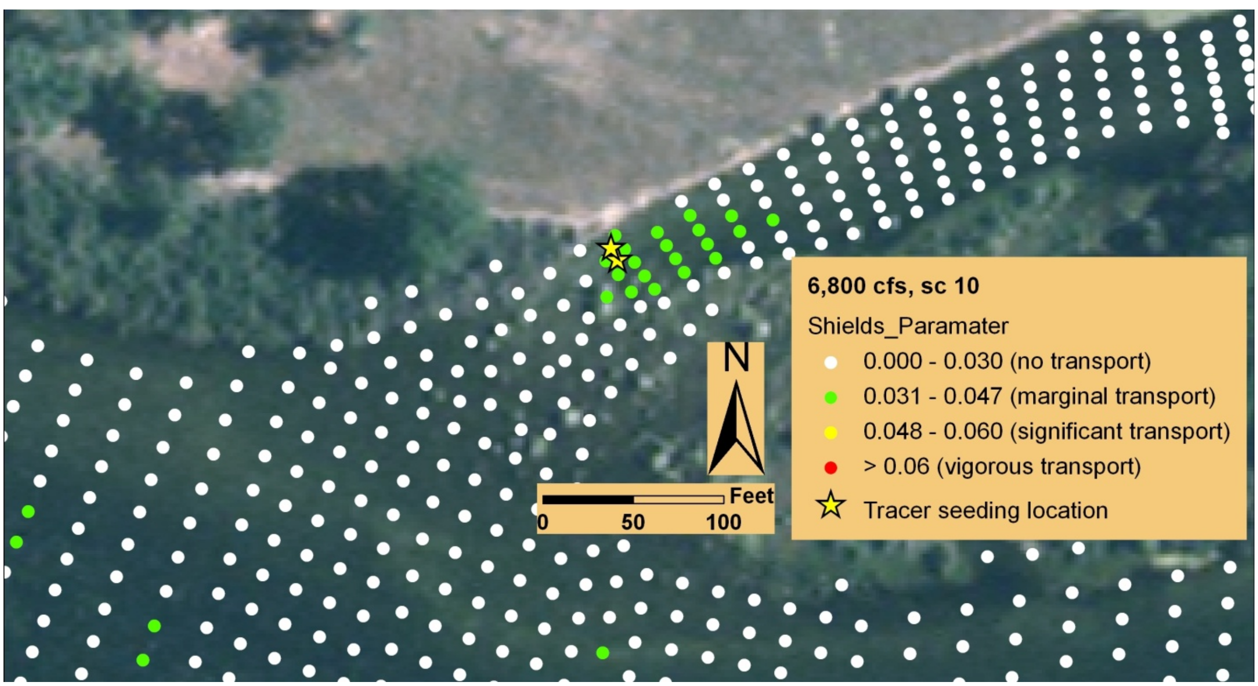

Figure 25: Diagram showing predicted initiation of sediment motion in side channel 10 (picture channel) at 6,800 ft^3/s. Tracer seeding location is indicated with two yellow stars, model results indicate marginal transport, verified by tracer motion following the release in April 2012.

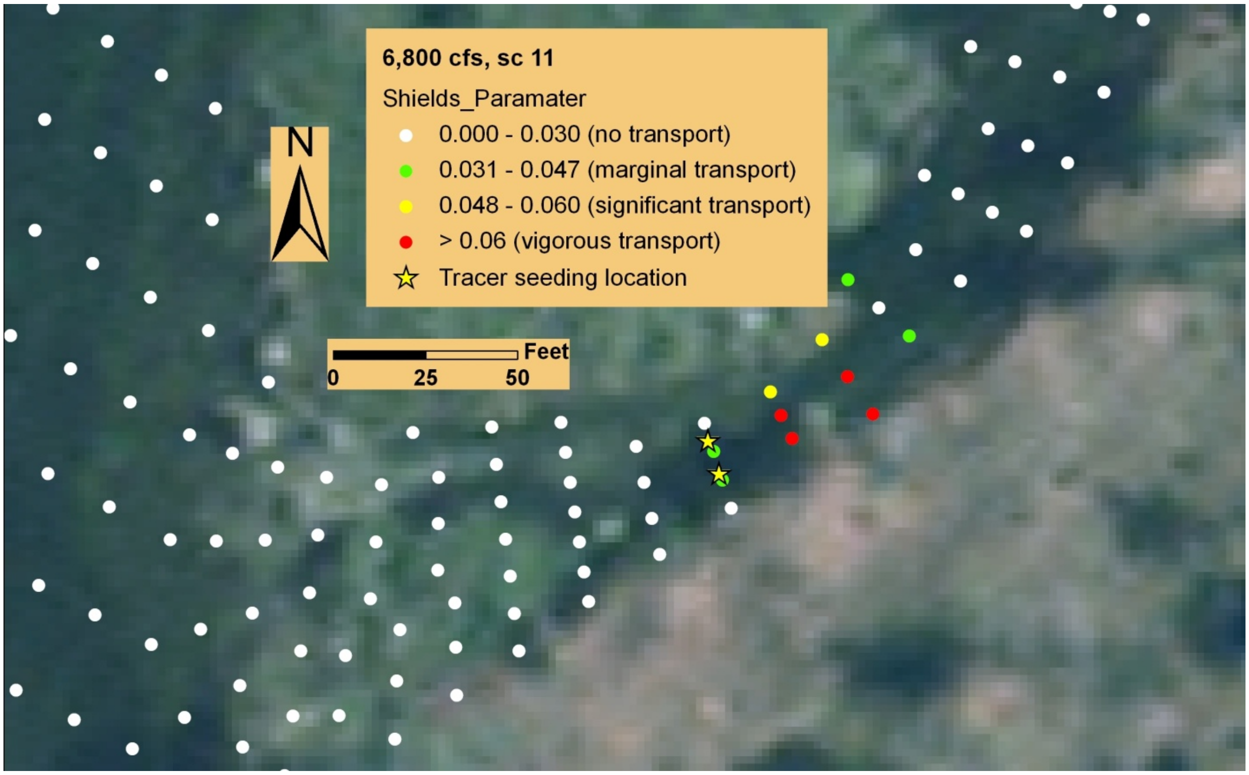

Figure 26: Diagram showing predicted initiation of sediment motion in side channel 11 (pipeline/juniper channel) at 6,800 ft^3/s. Tracer seeding location is indicated with two yellow stars, model results indicate marginal transport, verified by tracer motion following the release in April 2012. The vigorous transport indicated downstream of the tracer location is in a deep pool, as opposed to the riffle where the tracers were placed.

9 Discussion and recommendations

The primary goal of this portion of the side channel study is to determine what action can be taken, if any, to halt annd possibly reverse the trend of loss of side channel habitat. The results of the hydraulic model, predictions and observations of sediment transport, and conclusions made by Godaire (2010) and other researchers will guide this discussion.

9.1 Consequences of our actions

It is important to precede any recommended release strategies or flow prescriptions with a discussion on the consequences of such efforts, both predictable and unforseen. Rarely is a single change imposed on a river ecosystem that can be associated with a single response (Trush et al., 2000). Similarly, no combination of release magnitude and frequency will optimize all objectives (Wilcock et al., 1996). Increasing the frequency and magnitude of flooding will prompt a geomorphic response that is only somewhat predictable and should be approached with caution, however imposing any post-dam hydrologic regime on a river system will have both geomorphic and ecological consequences. Godaire (2010) concluded that vertical bed fluctuations (measured annually) following the closure of Yellowtail Dam and afterbay has been approximately1.2 feet compared to a pre-dam fluctuation of up to 3.3 feet. Indications from this observation and the WAPA cross section measurements, reach wide channel incision has not occurred since dam construction. It must be a primary goal of any effort to maintain healthy off channel habitat that widespread channel incision over the long term does not occur as a result.

A second conclusion by Godaire (2010) is that the study reach of the Bighorn River has been in a state of lateral stability since approximately 1980, with infilling of some side channels ocurring in the interim. It is reasonable to expect that imposing increased flood frequency and magnitude in the study reach will decrease the lateral stability realized over the past decades. Downstream portions of the study reach realize sediment contributions not seen in the first few miles downstream of the Yellowtail afterbay. This is due to stored sediment in the channel, primarily islands that could contribute sediment to the system. Erosion of high bluffs has been observed (Godaire, 2010) and can further contribute sediment to the study reach. Increased sediment supply in the lower reaches, coupled with increased frequency and magnitude of high discharges is likely to create geomorphic change.

Riparian vegetation will respond to a change in hydrology. As observed in Godaire (2010), vegetation encroachment has caused a loss of unvegetated bars and has accelerated the loss of side channels, decreasing the amount of available habitat. Vegetation encroachment can also reduce the hydraulic capacity of the channel, increasing the flood hazard (Kondolf and Wilcock, 1996). Vegetation encroachment is one factor that can be controlled with a release strategy.

The timing of high flows can provide an advantage or disadvantage for specific pieces of a river's ecosystem. For example, necessary moisture and substrate conditions can be created for successful seedling establishment and stand development (Trush et al., 2000). This may be a positive outcome for releases on the Bighorn River regarding native species but could also advantage undseirable invasive species such as Tamarisk (*Tamarix* spp) and Russian Olive (*Elaeagnus angustifolia*). Timing of high flows may also impact macroinvertebrate populations and other food sources as well as spawning and incubation periods for trout. This is in no way an exhaustive list of possible outcomes from changing the hydrologic regime. Experts in ecology should be consulted for other potential consequences.

9.2 Recommendations for maintaining side channel connectivity

The hypothesis at the onset of this investigation was that the side channel aggradation problem could be stopped, or even reversed, using only well conceived releases from Yellowtail Dam. Observations over the past three years of this study and numerical modeling results indicate that an increased frequency of high discharges coupled with mechanical action in selected side channels is likely necessary to reverse the trend of side channel aggradation. While it is likely that well planned releases from Yellowtail Dam can likely retard or stop the side channel aggradation, it is not likely that releases alone can reverse the aggradational trend in a timely manner.

The most telling evidence pointing to the inability of only reservoir releases reversing the trend of aggradation in the side channels is repeat surveys of several side channels between 2009 and 2012. In the recent past discharges have exceeded 10,000 ft^3/s each year from 2008 through 2011, with the largest and longest peak occurring during spring runoff in 2011 when the peak discharge reached 15,700 ft^3/s (as measured by the USGS gage near St. Xavier #06287000)

(Figure 3). These recent releases from Yellowtail Dam of this magnitude are as large and frequent as can be reasonably expected to occur in the future and have had little effect on degrading side channel entrances. If four large discharges in consecutive years are not able to affect a significant positive change on the bed elevation of side channel entrances, it is unlikely that future releases alone will obtain the desired result in less than a decade or longer, making mechanical removal of accumulated sediment in side channels a likely step toward reversing the trend of aggradation. The following paragraphs and figures demonstrate the lack of significant change in bed elevation of selected side channel entrances observed over the past few years. Alternatively, the recent high flows have benefitted the Bighorn by clearing significant amounts of vegetation and creating gravel bars, some newly built, others cleared of vegetation.

Side channel 8a has seen the greatest benefit from the recent high discharges on the Bighorn River. Note the clearing of aquatic vegetation in this channel over the recent past (Figure 27). Side channel 8a has undergone as much as 0.8 feet of degradation since 2009. Although the entrance to this side channel has degraded less than 0.5 feet (Figure 28).

Portions of side channel 8b have degraded since 2009, including the entrance. However, the magnitudes of the degradation are slight (< 0.5 ft. at the entrance, Figure 29). This is the shortest of the side channels monitored and represents little side channel habitat compared to many others in the study reach, but it can still provide information on sediment transport in side channels.

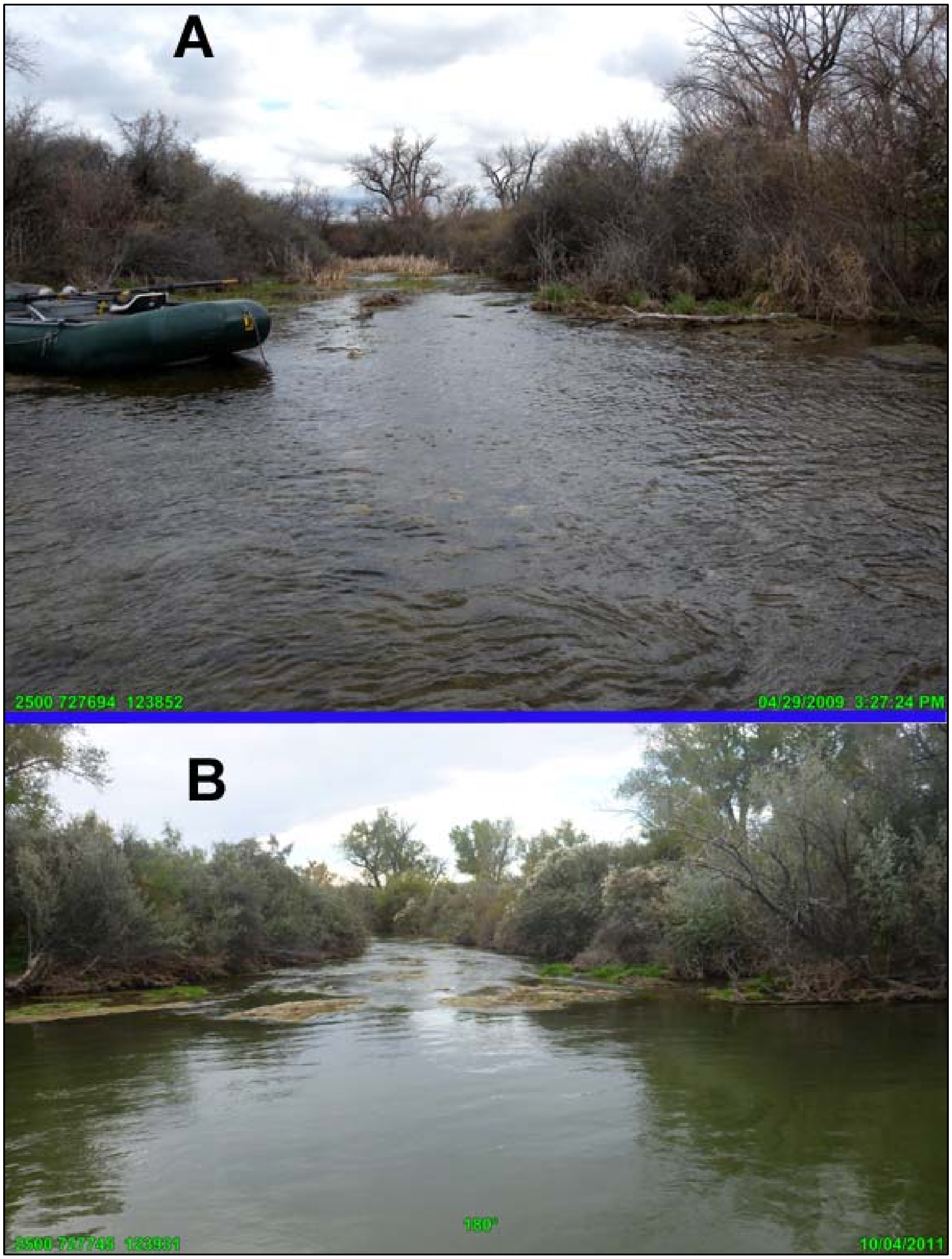

Figure 27: Photographs of side channel 8a showing cleared vegetation following high flows. (A. photo taken in April 2009, Q = 3,574 ft^3/s; B.) photograph taken in October 2011, Q = 3,250 ft^3/s.

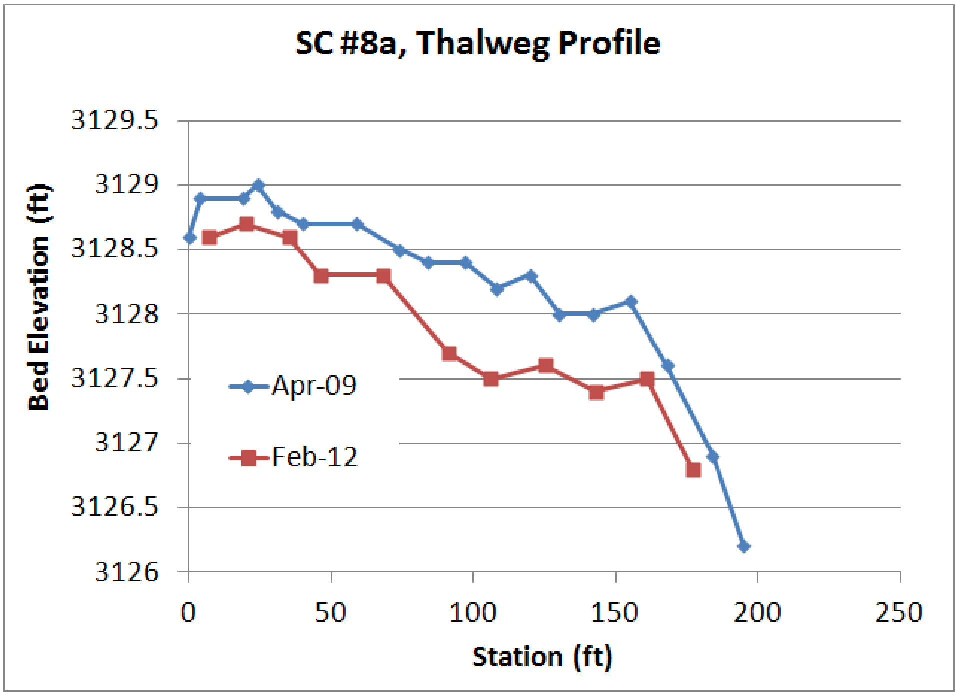

Figure 28: Thalweg profile of side channel 8a repeated surveyed in 2009 and 2012.

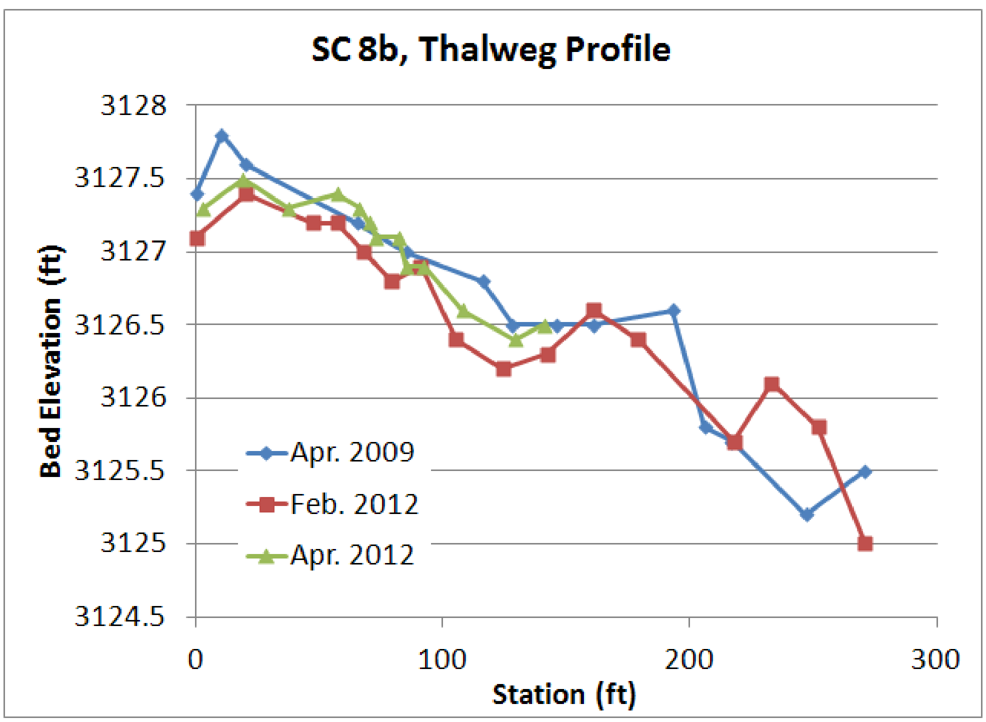

Figure 29: Thalweg profile of side channel 8b, surveyed in 2009 and twice in 2012.

Side channel 10 (Picture channel) showed some erosion of the side channel entrance, primarily toward the main channel (< 0.5 ft., Figure 30). It also appears that a riffle eroded at about station 240. The recent high water in 2011 visibly eroded aquatic and terrestrial vegetation and widened the entrance to this side channel. Even though the bed elevation of the entrance did not change significantly, the widened channel following high flows is allowing more discharge into the channel (Figure 31). The main channel of the Bighorn River has been aggrading on river left in the vicinity of the entrance to side channel 10 for several years (Earl Radonski, pers. communication, 2011). It is likely that even after excavation of the side channel entrance aggradation is expected to continue in this vicinity, requiring frequent excavation.

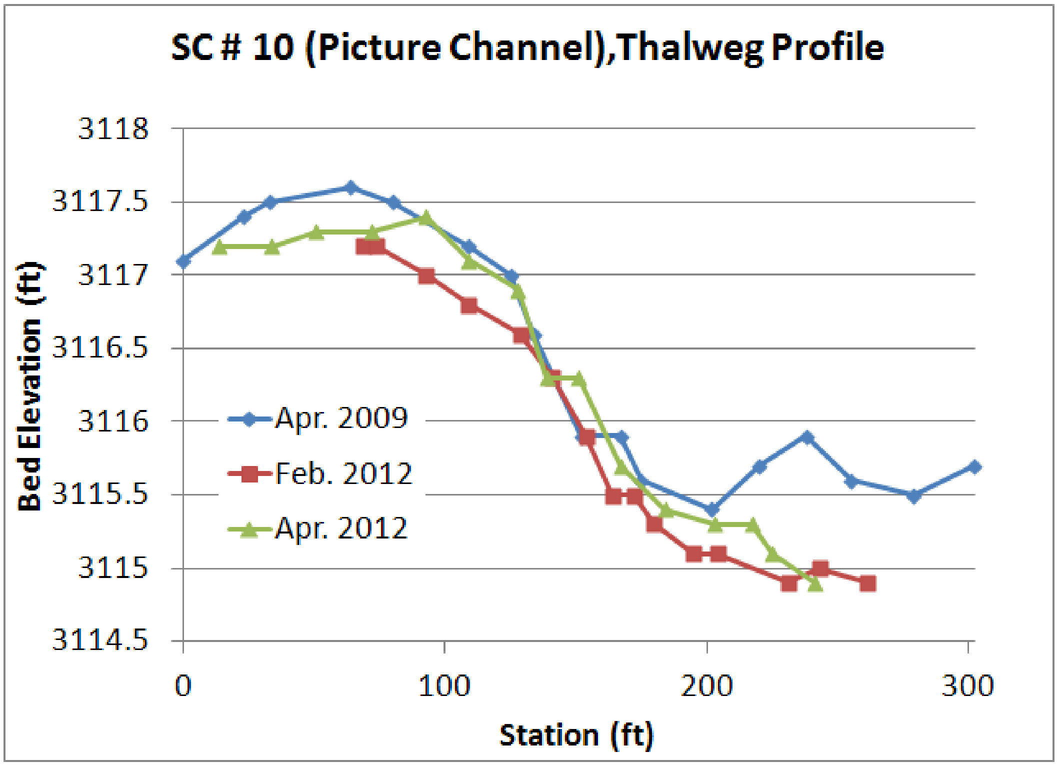

Figure 30: Thalweg profile of side channel 10, surveyed in 2009 and twice in 2012.

Figure 31: Photographs of side channel 10 (picture channel) showing channel widening after high flows; A.) Aug. 2009, Q = 3,115 ft^3/s; B.) Oct. 2011, Q = 3,250 ft^3/s.

Side channel 11 (Pipeline/Juniper channel) showed little to no degradation of the channel since 2009. The variation seen in the surveys (Figure 32) is likely a result of the specific location representing the thalweg rather than real channel change. This channel experienced significant clearing of aquatic and terrestrial vegetation during the high flow in 2011.

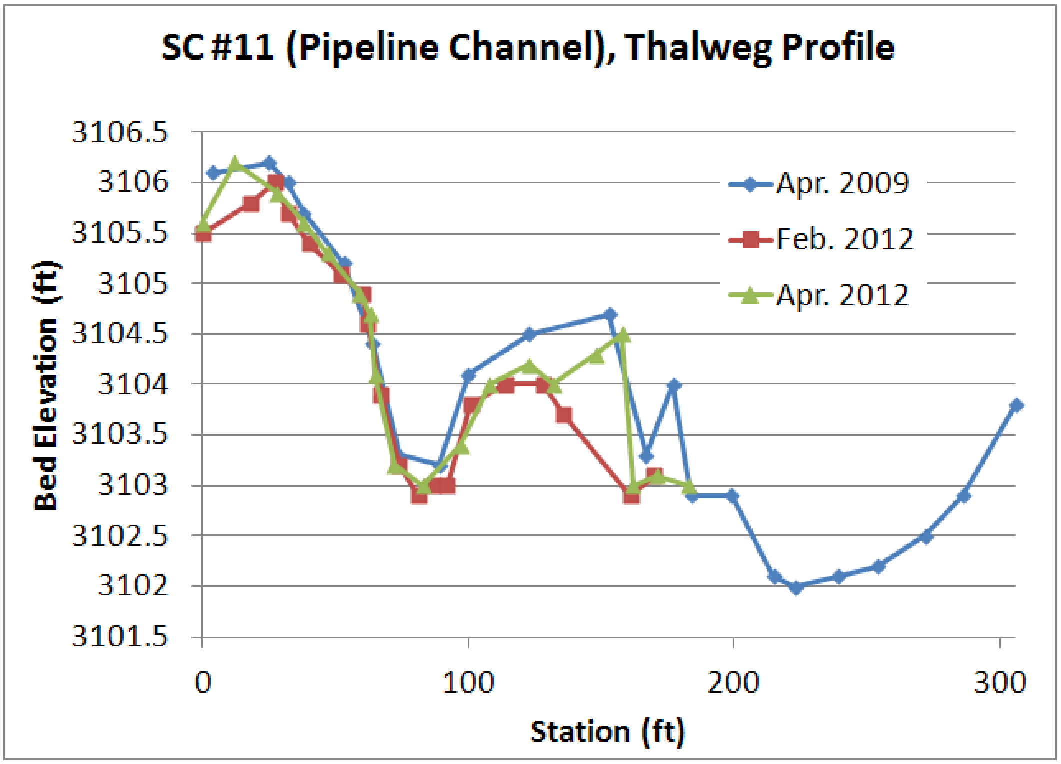

Figure 32: Thalweg profile of side channel 11 (Pipeline/Juniper channel), surveyed in 2009 and twice in 2012.

Side channel 12c shows no significant change between the two surveys (Figure 33). As noted in Godaire (2010), this channel is not likely to become frequently active and will remain a flood channel. This channel runs across a well established mid-channel island.

Side channel 13 (Clines channel) was excavated in early 2012 and the changes are shown in the thalweg profile (Figure 34). This channel entrance should be monitored into the future to determine success or failure of the mechanical removal of aggraded sediment.

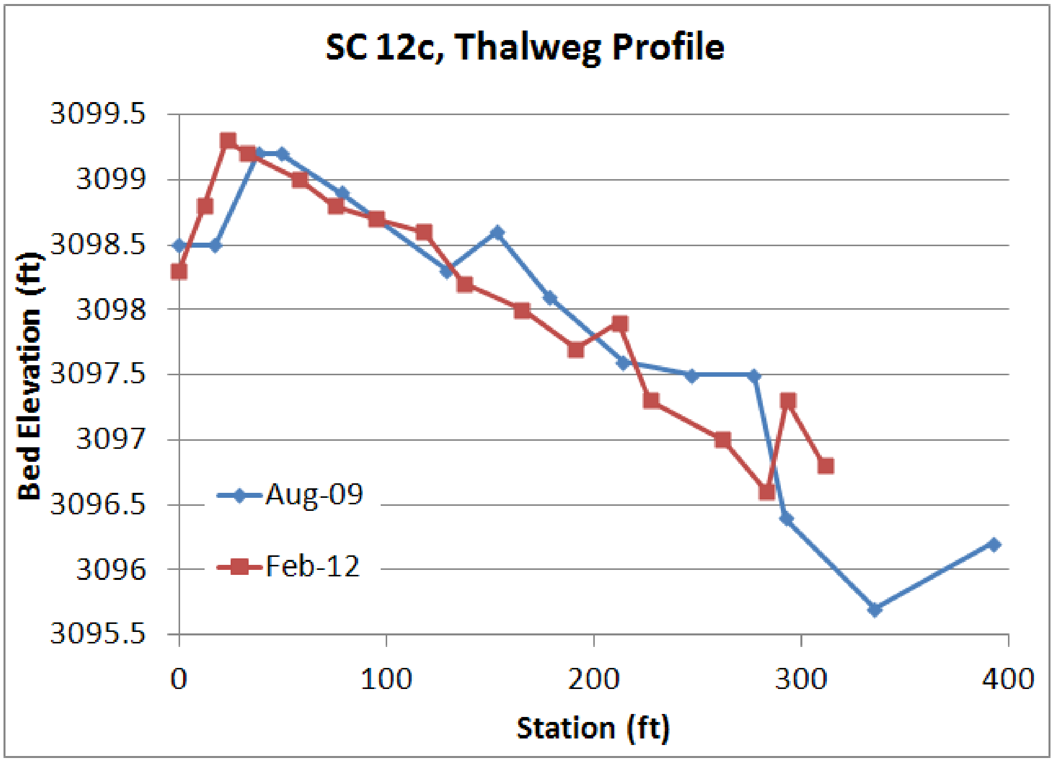

Figure 33: Thalweg profile of side channel 12c, surveyed in 2009 and 2012.

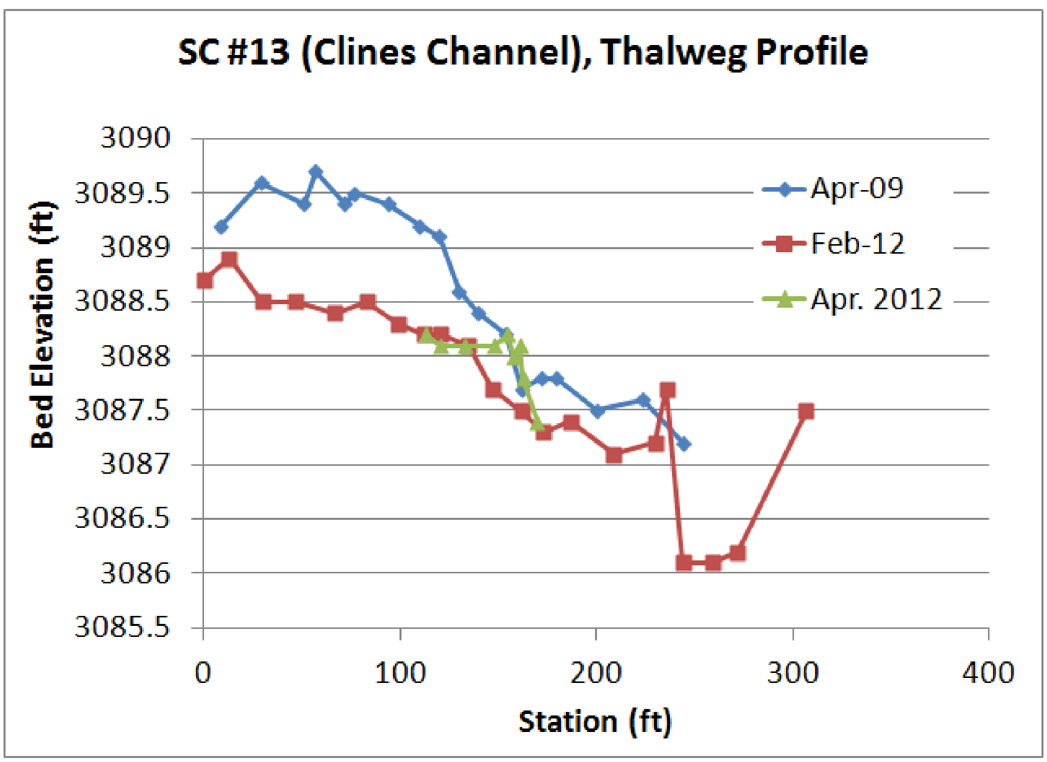

Figure 34: Thalweg profile of side channel 13 (Clines channel), surveyed in 2009 and twice in 2012). The entrance to this side channel was excavated in February 2012, prior to the survey.

Although the recent high flows have provided some erosion in the side channels, it is apparent that high flows alone will not reverse the trend of aggradation in the near term, stopping it at best. Mechanical manipulation is likely required to restore side channel connectivity. It is also likely that regular maintenance will be required into the foreseeable future, although the frequency of the maintenance is uncertain. Efforts to revitalize the side channels in the Bighorn River through mechanical means will be aided by an increase in the frequency and magnitude of reservoir releases compared to past releases prior to 2008. Increasing the magnitude and frequency of reservoir releases will not guarantee that the side channels will not once again aggrade with sediment, however it is likely to reduce the level of maintenance required to maintain a desirable condition of surface connectivity in the side channels and limit vegetation encroachment.

Based on the numerical model results and observations during the study, it is likely that a nontrivial amount of sediment is being transported into the side channels from the main channel. The contributions of sediment to the side channels from the main channel complicate the analysis and solution to reversing the trend of aggradation at the side channel entrances. Continued sediment contributions to the side channels points to the shortcomings of the fixed bed sediment analysis performed in this study, however live bed sediment models are computationally intensive and cannot simulate the entire study domain. Continued sediment contributions to the side channels also indicate a continuing effort to maintain side channel connectivity should there be mechanical manipulation. If mechanical removal is utilized as an option for reconnecting some side channels within the study reach, it may be beneficial to design these connections to meet the main channel at 90 degrees or greater. Such a design feature may limit the influx of coarse sediment, increasing the potential for a functioning side channel. Designing the invert elevation to be well above the bed of the main channel also aids in preventing main channel sediment from entering the side channel. These strategies may not work for all side channels, especially if the main channel is aggrading near the entrance of the side channel as in side channel 10, however they are worth considering in future designs. Regardless of the design, the priority must be on sediment transport at the entrance.

9.3 Recommended releases for the Bighorn River

Two primary parameters were considered to determine a discharge recommendation: hydraulic conditions for sediment transport, and inundation for vegetation encroachment. Special consideration is provided in this analysis to side channels that have been specifically mentioned by stakeholders and where a positive effect is anticipated in the event of mechanical removal of accumulated sediment in the side channel entrances. The channels considered are not necessarily expected to undergo geomorphic change as a result of only increasing the magnitude and frequency of flood flows, however some changes as discussed previously may occur. These side channels are considered the ones of greatest interest in the study reach based on stakeholder input (Figure 35 and Figure 36).

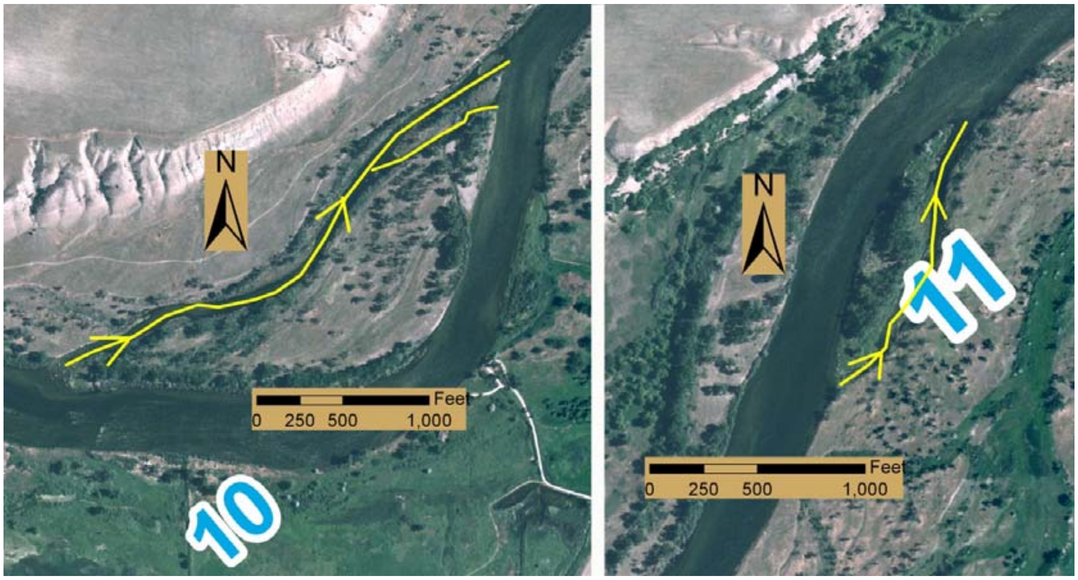

Figure 35: Side channels 10 (Picture channel) and 11 (Pipeline/Juniper channel).

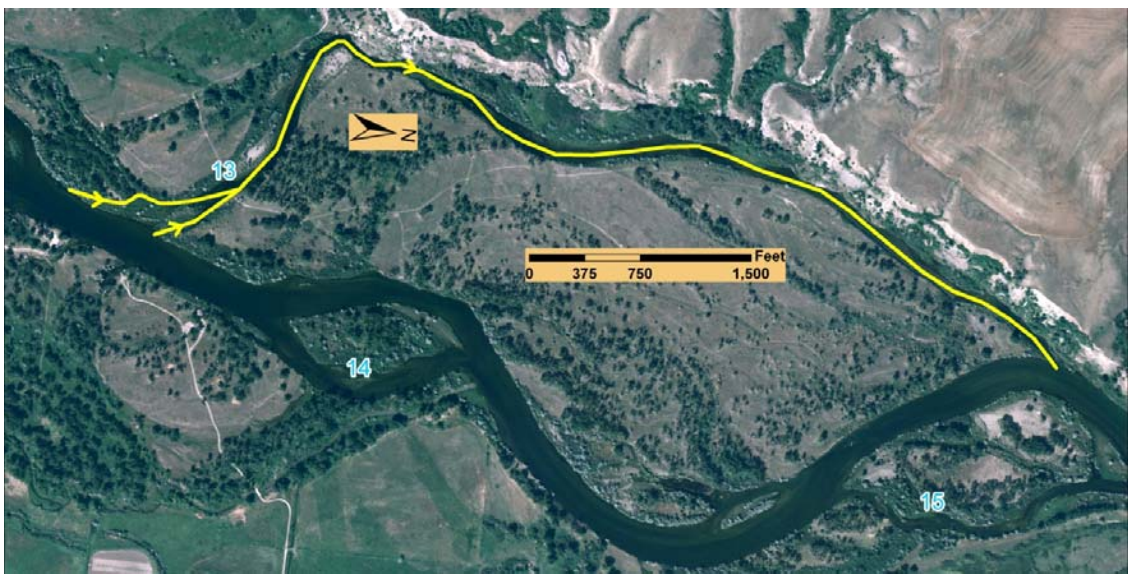

Figure 36: Side channel 13 (Clines).

Determining a specific hydrograph or a series of hydrographs for planned releases to improve habitat conditions on the Bighorn River will require a balancing act among the following concerns: available water volume, a logistical schedule tolerable to Reclamation's reservoir operations group, river and reservoir conditions palatable to stakeholders, biological and ecological impacts, and sediment transport conditions. Considering the many factors that go into determining and recommending specific hydrographs, this report will only recommend peak values, peak duration, and peak frequency. These recommendations will provide guidance for reservoir operations when a sufficient volume of water exists to implement suggested discharges. It is hoped that the flexibility offered in these recommendations will aid in their implementation, easing the burden on reservoir operators and the myriad of considerations that go into setting release discharges. A variation of reservoir releases is encouraged, as it will increase the geomorphic diversity, benefitting the ecology of the Bighorn River.

9.3.1 Peak discharge

Under current conditions, side channels #10 and #11 have a surface connection at the upstream end at approximately 2,500 and 3,574 ft^3/s, respectively. Recent excavation to side channel #13 provides a surface connection at approximately 2,000 ft^3/s (Dennis Fischer, pers. comm.), as opposed to 5,500 ft^3/s previously. To evaluate the effectiveness of given discharges at moving sediment in side channels, two metrics are tracked with discharge; 1) the Shields parameter spatially averaged over a specified area, and 2) the proportion of the specified area that is subject to a Shields parameter greater than 0.047, the value considered to be a threshold for significant sediment motion. The area chosen for this evaluation is a polygon near each side channel entrance with dimensions of one channel width in the lateral direction and four channel widths in the longitudinal direction. The results of this evaluation can be seen in Figure 37.

The same approach was taken to evaluate the ability of a given discharge to move sediment in the main channel. Significant sediment transport in the main channel is not desired, such that channel incision is avoided over the long term. The dimensions of the main channel polygons is the same as the side channel polygons, 1 x 4 channel widths (lateral and longitudinal, respectively). The locations of each main channel polygon is chosen a bit more arbitrarily that the location of side channel polygons. Model results indicate that there are some locations within the main channel where significant sediment transport is anticipated for some of the modeled discharges. These locations are primarily localized and not widespread. Much of the main channel is not predicted to undergo significant sediment transport under the conditions modeled. Based on experience and familiarity with numerical modeling, sediment transport, and the river itself, four polygons were chosen in the vicinity of channel complex numbers 2, 5, 10, and 16. The results of this evaluation can be seen in Figure 38.

Assessing the sediment transport results, a discharge in the range of 10,000 to 15,000 ft^3/s is predicted to initiate sediment motion in the side channels without significantly disturbing sediment in the main channel. These results may seem to be in contradiction with the repeat surveys, showing little or no change to the side channel entrances following high discharges. However, this modeling does not account for sediment contributions to the side channels from the main channel, which is apparently occurring. Based on the model validation using the tracer results, the initiation of sediment motion is well predicted in the side channel entrances by SRH-2D.

Should the planned high flow releases be implemented, it is recommended that the first release is no bigger than 12,000 ft^3/s. The monitoring plan should be implemented following the first release, focusing on areas of concern such as; newly excavated side channel entrances, main channel habitat such as popular spawning locations, and signs of systemic incision of the main channel. The negative impacts, if any, should be weighed against positive outcomes. At this point a decision can be made regarding the next high flow release and if increasing the peak will provide a net benefit to the ecology of the study reach.

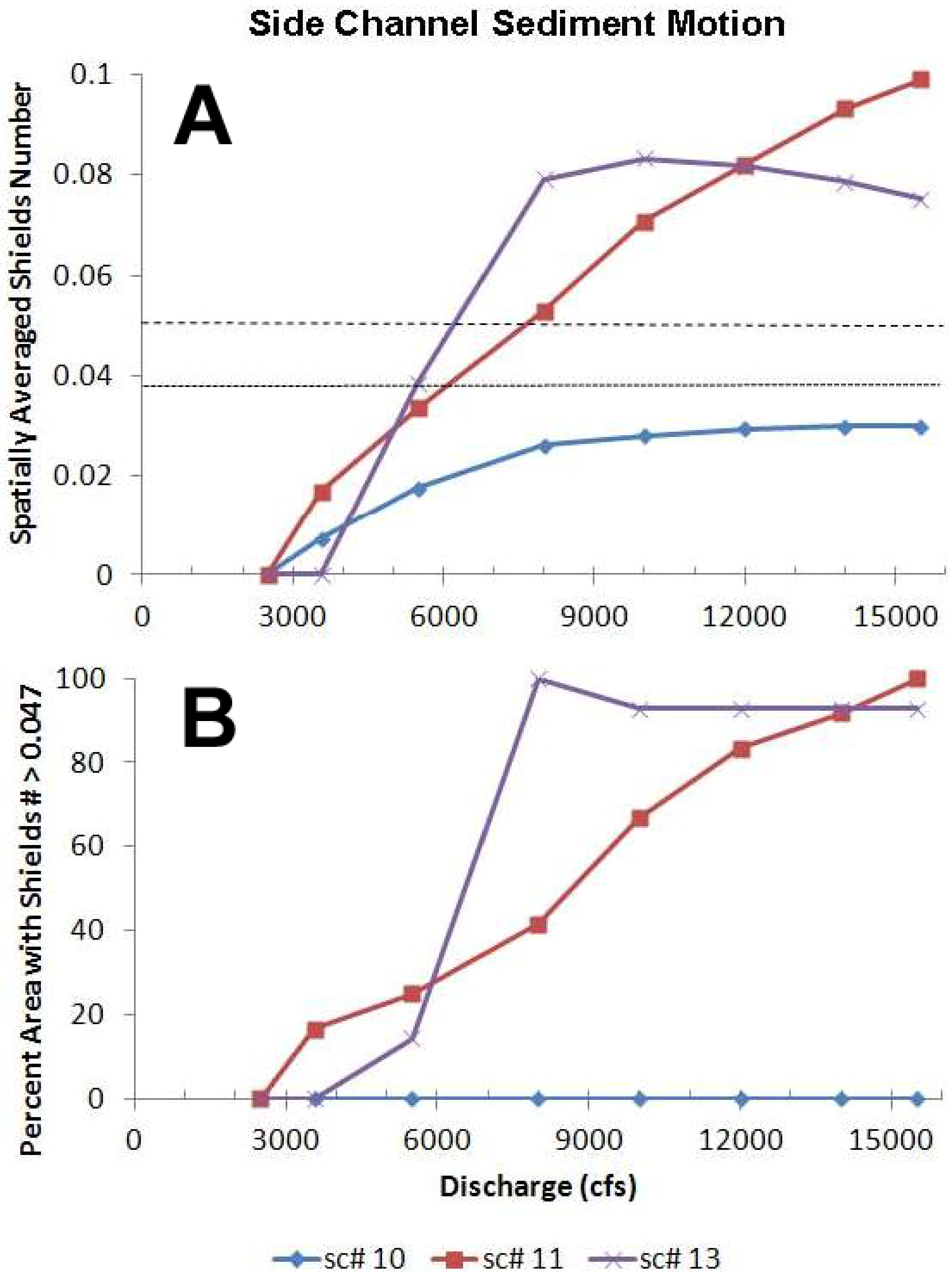

Figure 37: Plots indicating initiation of sediment motion in selected side channels. A – Spatially averaged values of the Shields parameter. Dashed horizontal lines indicate Shields parameter values of 0.03 and 0.047. B – The portion (in %) of the side channel entrance where the Shields parameter indicates significant sediment motion (> 0,047). Results for SC 13 are for an unexcavated condition.

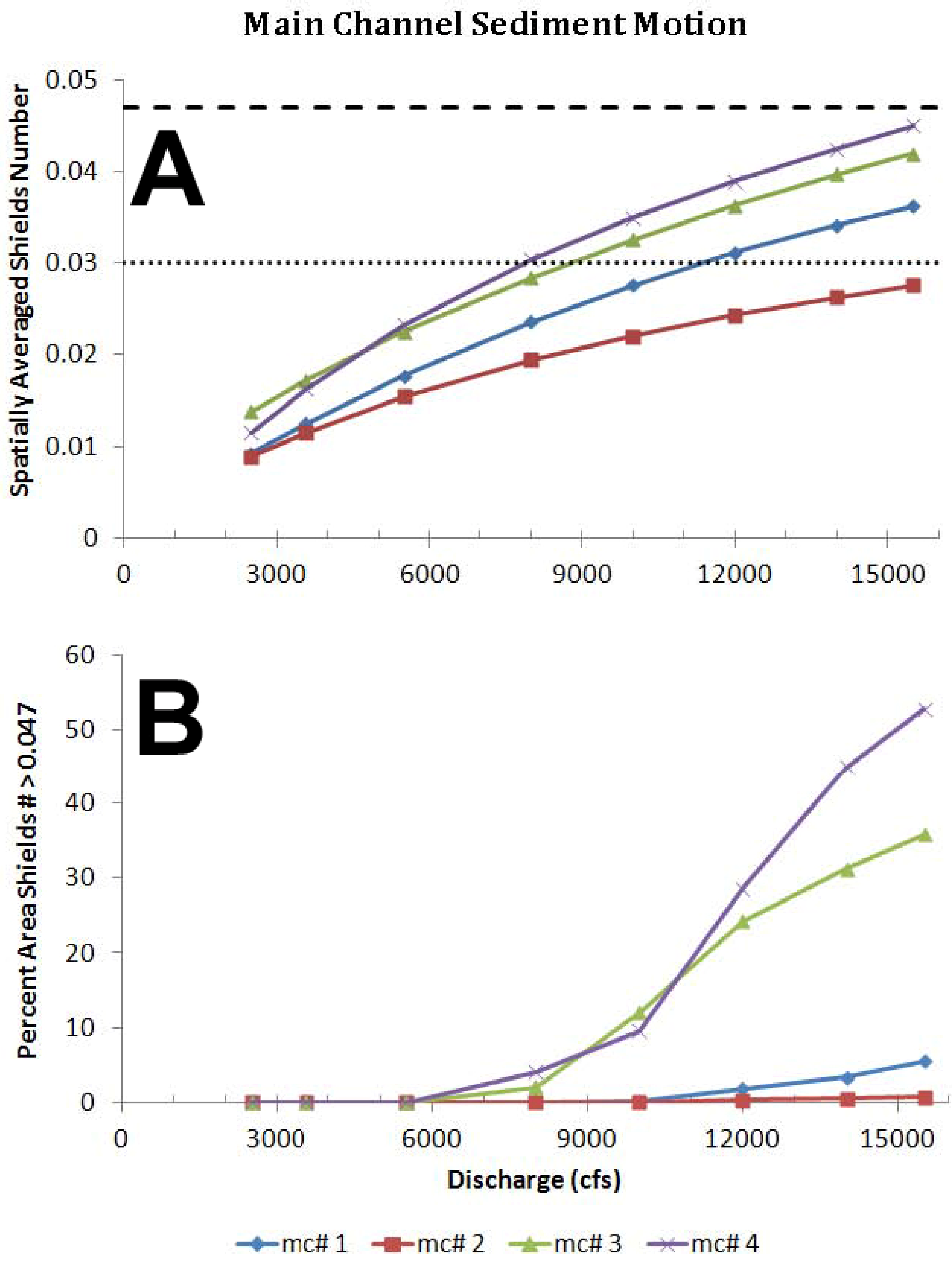

Figure 38: Plots indicating initiation of sediment motion in selected main channel polygons. A – Spatially averaged values of the Shields parameter. Dashed horizontal lines indicate Shields parameter values of 0.03 and 0.047. B – The portion (in %) of the main channel polygon where the Shields parameter indicates significant sediment motion (> 0,047).

Assessing the hydraulic modeling results for inundation, a discharge between 6,000 and 10,000 ft^3/s is predicted to inundate a significant amount of bars and side channels to prevent significant vegetation encroachment. However, discharges of this magnitude can potentially cause side channel aggradation over several seasons if not coupled with occasional higher flows greater than 10,000 ft^3/s.

9.3.2 Frequency

The frequency of discharges that are predicted to inundate side channels for the prevention of vegetation encroachment should be based on the ability of the discharge to do one of two things; 1.) scour bar sediment to such an extent that the seedling is not able to colonize, or 2.) inundate the vegetation frequently enough or long enough to drown the seedling such that it cannot establish. A scour discharge, considered to be 10,000 to 15,000 ft^3/s, is recommended to occur biannually (Kondolf and Wilcock, 1998), with no more than 5 years passing between high flow discharges. Typically, vegetation becomes difficult to scour beyond a three year period. An intermediate discharge, considered to be 6,000 to 10,000 ft^3/s, is recommended to occur annually, with n o more than 2 – 3 years passing between intermediate discharges. The intermediate discharges are necessary to;1-) flush fine sediment from the side channels, and 2-) limit the encroachment of vegetation into the active channel.

If possible, a high discharge during runoff can occasionally be coupled with an intermediate discharge in the same year. This is based on the historical record, where partial peak discharges occurred with high regularity (Table 1), most often in the fall and late winter. These partial peak discharges sometimes occurred in the same year as a high runoff. The magnitudes shown in Table 1 are similar in magnitude to the recommended inundation discharges indicated above, mimicking the natural diversity in the historical record.

9.3.3 Duration

Along with magnitude and frequency, duration of the peak discharge needs to be recommended as well. This topic has received little attention in the literature, probably reflecting the amount of thought that has gone into the subject (Kondolf and Williams, 1999). The intended purpose of the release must be considered, as well as secondary purposes (e.g. preventing vegetation encroachment). Of course water availability and stakeholder concerns are additional considerations.

Releases intended to limit vegetation encroachment can cause mortality via inundation or scour, and durations will be different depending on the intended mechanism. The minimum duration for mortality via inundation is approximately 2 weeks for Fremont Cottonwood (Auchincloss et al., 2012). If the mechanism for mortality is scour, the duration is much shorter, perhaps 24-hours. Observation may be the best method of determining the mechanism to limit vegetation encroachment. The maximum duration can be set by water demand and other concerns regarding releases previously discussed. If there is a need to spill water at the end of the irrigation season, it will be more ecologically beneficial to shape that available volume into a hydrograph, rather than a slow release over a longer time period, which could encourage vegetation growth. With an annual or near annual frequency of 6,000 ft^3/s to 10,000 ft^3/s there is a reduced concern for vegetation encroachment and mortality via inundation will not be necessary.

As coarse sediment rolls and saltates along the river bed, it travels in pulses when critical conditions for bed load transport are exceeded (Humphries et al., 2012; Venditti et al., 2010). Over the course of a hydrograph with a peak large enough to transport bed load, it is common for the majority of the bed material load to be transported during the rising limb. This is referred to as clockwise hysteresis (Humphries et al., 2012). Because much of the sediment transport occurs during the rising limb, it makes little sense to sustain a prolonged peak discharge. There is likely little to no benefit to maintaining a hydrograph peak for a duration greater than 24 hours. This is especially true when one considers the high cost of water and potential benefits to habitat by holding back some water to sustain minimum releases during the dry summer months. More specific information regarding the movement of sediment during high and low duration events can be gained by following up on the sediment tracers placed in February 2012.

Ramp rates have not been addressed in this report, however conversations have taken place with Tim Felchle (Reclamation, MT Area Office Reservoir Operations Group). During those conversations, it became evident that ramp rates greater than 2,000 ft^3/s/day, occurring at 1,000 ft^3/s increments twice per day, are likely to be implemented. The result of a slower ramp rate is a greater cost in terms of water volume.

9.3.4 Bank erosion

Rapid drawdown rates may induce bank erosion, which has been anecdotally observed within the study reach by stakeholders. It is possible that by reducing the change in discharge during drawdown (e.g 500 ft^3/s increments as opposed to 1,000 or 2,000 ft^3/s) may reduce the bank erosion induced by a more rapid drawdown. This specific issue is beyond the scope of this study but is worth mentioning here, as this concern has been raised by stakeholders.

A much more significant cause of bank erosion on the Bighorn River is induced by cattle allowed to access the river for water (Figure 39). Cattle trampling a river bank is a known cause of accelerated bank erosion and these effects are apparent within the study reach. Cattle remove stabilizing vegetation along the bank and also actively destabilize terraces by trampling.

Figure 39: Cattle accessing the main channel of the Bighorn River, a concern regarding bank erosion.

9.4 Sample hydrographs

Two sample hydrographs are provided in this section, one representing the moderate peak and one representing the high peak discussed in Chapter 9.2.1. The specific durations of peak discharges in both proposed hydrographs are not critical, however they should last for a minimum of 12 - 24 hours. Peak discharges imposed for greater than 24 hours for the purpose of transporting side channel sediment will have a diminishing return. The ramp up and ramp down rates are the same as Hydrograph 1 in Figure 14 and will have the same rate of change in depth shown in Figure 21. The assumed beginning and ending discharge is 2,500 ft^3/s.

The high discharge hydrograph is shown in Figure 40 and has a peak discharge of 12,000 ft^3/s. This hydrograph is expected to coincide with annual run-off typically occurring in June, assuming sufficient availability. Total duration for this hydrograph is 118 hours, with a total volume of 79,735 acre-ft.

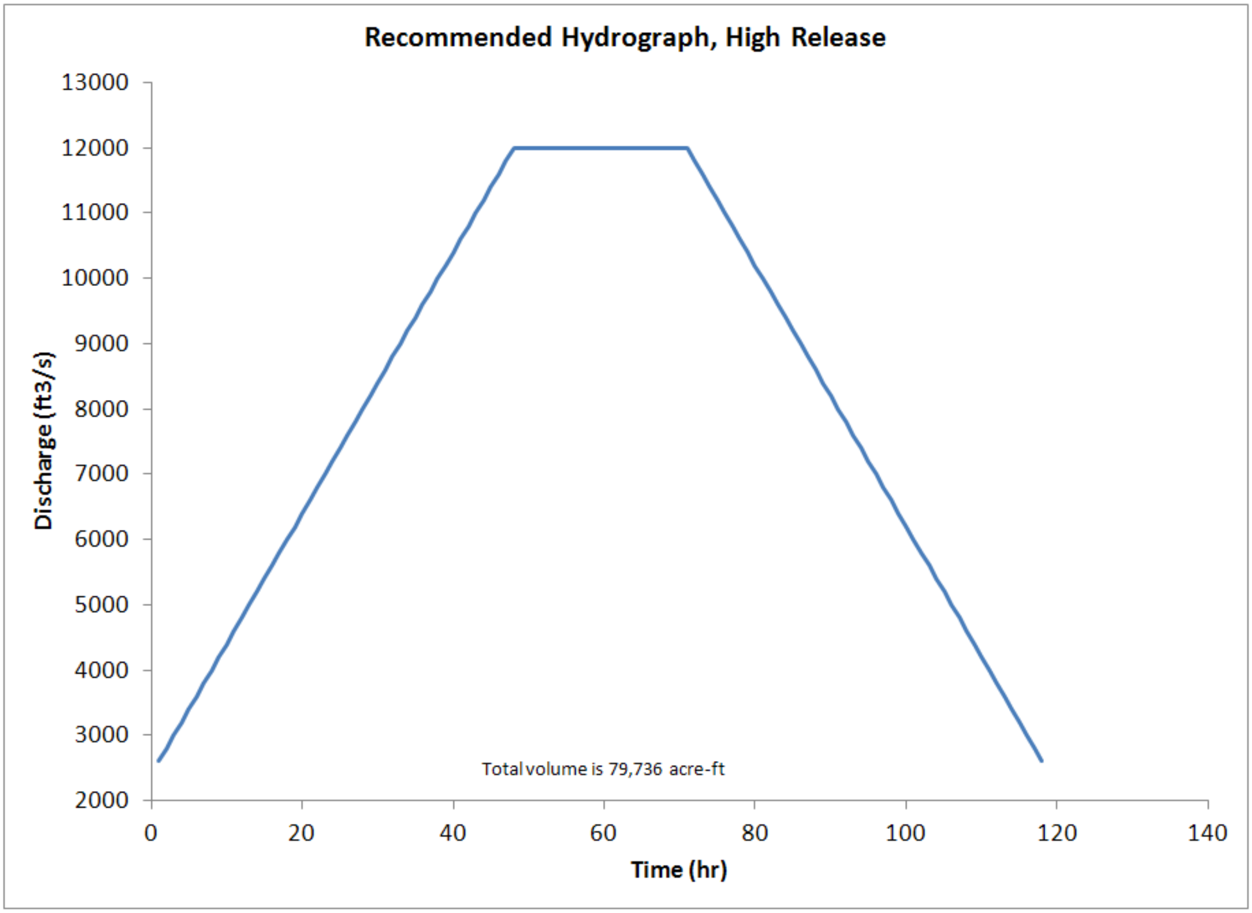

Figure 40: Proposed high release hydrograph recommended to occur biannually, no less frequent than once every five years assuming water availability.

The intermediate discharge hydrograph is shown in Figure 41 and has a peak discharge of 7,500 ft^3/s. This hydrograph is planned for early spring and/or fall releases, assuming sufficient water availability. Total duration of this hydrograph is 74 hours with a total volume of 35,124 acre-ft.

The ramp rates in the sample hydrographs are a compromise between competing interests. Although rapid ramp rates conserve water they may pose a risk to downstream fishermen on the rising limb and strand fish and accelerate bank erosion on the falling limb. A ramp down rate that decreases the water surface elevation on the order of 1 ft/day poses no risk of bank erosion due to rapid draw down and is not likely to strand fish.

Variability in river discharges, both intra- and interannually, will provide conditions favorable for the creation of channel diversity and complexity. Not all habitat types will benefit equally from a single discharge value. The lack of channel complexity within the study reach have been discussed in Godaire (2010), and providing greater channel complexity will improve overall ecological function on the Bighorn River. Should a practice of ecological releases from Yellowtail Dam be implemented, variability of intra- and interannual discharges will be more beneficial to the ecology of the Bighorn River.

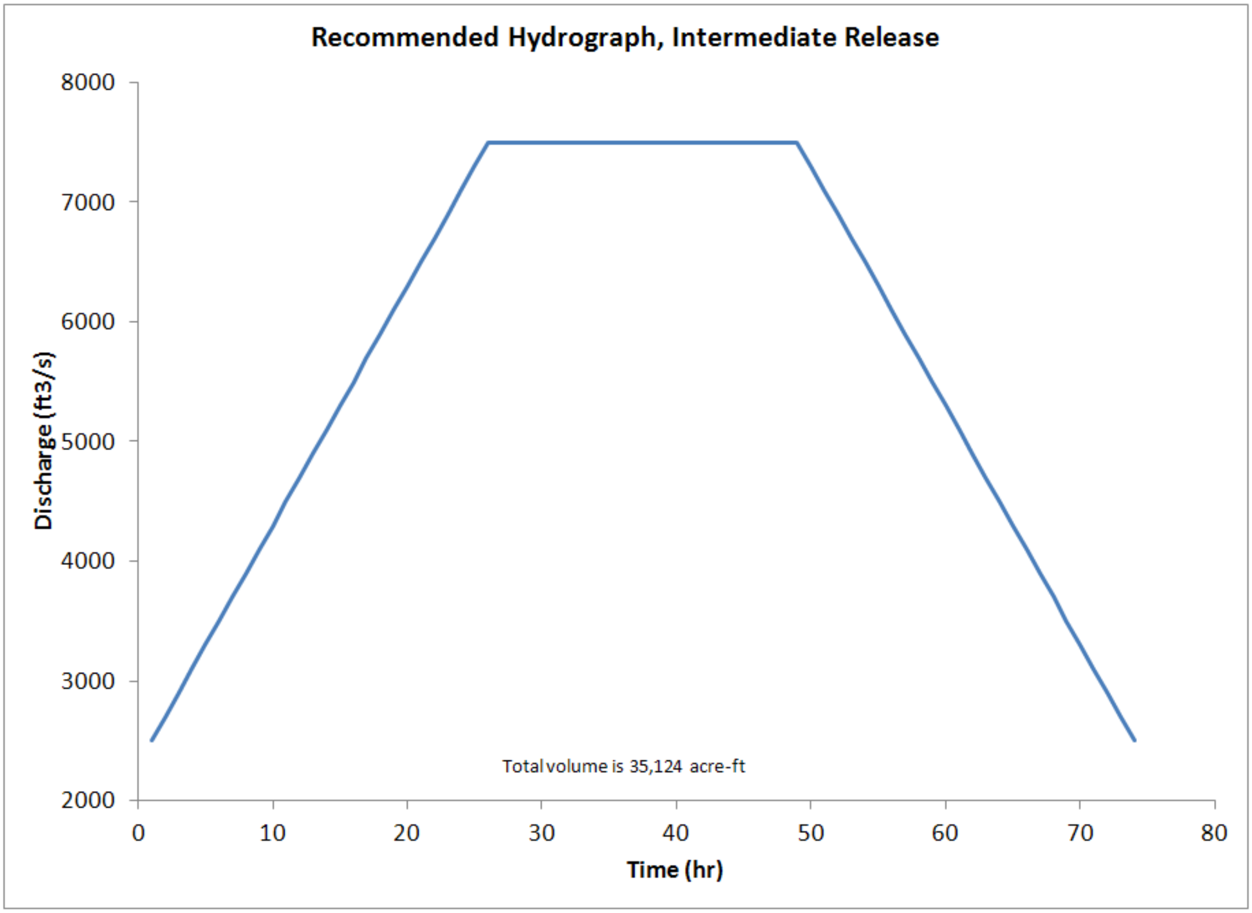

Figure 41: Proposed intermediate hydrograph recommended to occur annually, no less than once biannually, in the spring and/or fall assuming water availability.

10 Project monitoring

Accurate specification of releases to enhance habitat is hampered by the complexity of the flow and transport system and often very limited data (Wilcock et al., 1996). As such, the recommendations in this report are best regarded as starting points (Kondolf and Williams, 1999). Future monitoring of the Bighorn River should take place to insure that project objectives and desired outcomes are met within the study reach, and that channel incision is not being induced by ecological releases. Monitoring efforts should be implemented with a frequency that captures the changes induced by discharges greater than 6,000 ft^3/s to 7,000 ft^3/s, whether the release is intended for ecological purposes or part of normal releases following spring runoff. The Bighorn River downstream of Yellowtail Dam and afterbay exists in a fragile state of quasi-equilibrium, where large scale lateral movement of the channel was halted approximately a decade after dam construction (Godaire, 2010). However, the term 'fragile' was used to describe subtle changes to the channel morphology that continue to evolve, potentially impacting habitat conditions for introduced trout species. Godaire (2010) has documented some of these trends over several decades, dating back to 1939, including area measurements of the main channel, vegetated islands, unvegetated gravel bars, overflow channels, and side channels. Also tracked were vertical changes at specific locations and lateral migration throughout the study reach.

Some of these measurements should continue into the future for project monitoring. The frequency of this monitoring can be on the order of every 5 years or whenever new aerial photography is acquired.

10.1 Sediment Mobility

Complexities related to estimating sediment movement with appropriate prescribed releases requires an experimental approach (Kondolf and Williams, 1999). This approach should take the form of adaptive management, linking the prescribed releases with specific objectives and adequate monitoring to test the hypotheses (Walters, 1986; Healey et al., 1998). The movement of sediment in the side channels and main channel of the study reach of the Bighorn River at various discharge conditions should be monitored. Tracer particles have been used at select side channels to obtain information on the fluvial transport of sediment (Hassan and Ergenzinger, 2003) and can be monitored into the future. Gravel and cobble particles marked with a combination of paint and embedded passive interference tags have been seeded at strategic locations to provide information on sediment entrainment, flow competence, distance of movement, and depositional areas (Hassan and Ergenzinger, 2003). The tracer particles have been placed in strategic locations of the main channel and key side channels and then monitored for movement following one intermediate release thought to be of significance to sediment entrainment. Future monitoring of the tracer particles is dependent on priorities and future funding.

The results of the tracer particle experiment have provided some information on sediment entrainment specific to concerns in the study reach of the Bighorn River. Further tracking of these particles can provide more detailed information regarding sediment movement in side channels. Thus far, the tracers have provided valuable feedback to modeling results, which were based on generalized conclusions of sediment entrainment thresholds. Continuing to observe sediment movement in specific areas of interest on the Bighorn River can provide feedback on environmental releases from Yellowtail Dam. Knowledge gained from future tracer movement may also inform future efforts of mechanical manipulation of the side channels, insuring project objectives are met.

The lifespan of the passive interference tags is indefinite, however recovery of these particles is limited by the ability to detect their position. Detection distances are typically limited to 3 – 6 feet or less depending on sensor orientation within the particle, making recovery of their position difficult in deep water or when buried to a significant depth.

10.2 Channel morphology

Because the project seeks to make subtle changes to the channel morphology, specific monitoring plans should be made to quantify these changes. Regular surveys of key main channel and side channel locations should be performed. At a minimum, the three WAPA cross sections referenced in Godaire (2010) should be surveyed annually and no less frequently than once every two years. The existing three WAPA cross sections should be monumented with a semi-permanent marker on at least one end of the cross section, with perhaps a less permanent monument on the opposite side. The monuments will provide a consistent starting and ending location as well as a stationary point to which elevations can be tied. It is recommended that more cross sections are established further downstream.

Key side channels at complexes 8, 10, 11, and 13 should also be regularly surveyed. Based on additional input, other locations can be added to this list, perhaps side channels deemed significant to habitat but do not appear to be threatened by aggradation. The survey should be most detailed at the entrance, mimicking the survey performed in 2009. If possible, the thalweg of the channel should be surveyed throughout the side channel length. Discharge and wetted width at various locations throughout the channel should be noted during the survey.

Photo points should be established at several locations of interest, in addition to the four side channels to be surveyed. Photos taken from a consistent viewpoint will provide qualitative information about the site, including changes to vegetation, locations of gravel bars, etc. These photos should be taken at a nearly consistent low flow, documenting the date and the 15 minute discharge recorded at USGS gage #06287000, Bighorn River near St. Xavier, MT.

11 Conclusions

This report has shown that releases from Yellowtail Dam have a limited but important effect on the channel morphology. The entrances to selected side channels have been shown to remain mostly stable with respect to vertical changes throughout 4 consecutive years of high discharges, which is not expected to occur again in the near future. The vertical stability is largely due to the contribution of sediment to the side channels from the main channel and because sediment is not being transported through the entire side channel. It has been observed that sediment availability in the study reach of the Bighorn River increases with increasing distance from Yellowtail Afterbay Dam. The source of sediment is primarily contained in the banks, gravel bars, and high bluffs to the west. The many islands in the main channel at and downstream of the Lind boat launch (3 Mile) provide an appreciable and important volume of sediment, considering the deficit of sediment supply created by Yellowtail Dam.

In the event of mechanical removal of sediment in selected side channel entrances, excavations should be designed to maximize the transport sediment, not for creating habitat or aesthetics. Ecological releases from Yellowtail Dam may not be reliable considering periodic draught, increasing water demand, and shifting priorities. However, implementing the recommended releases to the extent possible will improve the ecological function of the Bighorn River into the future.

Future monitoring of the Bighorn River between Yellowtail Afterbay Dam and the Bighorn Boat Launch is strongly recommended if ecological releases are implemented. It is necessary to quantify the effect of such releases on side channel habitat and the main channel. If side channels entrances are excavated, repeat surveys are also recommended in these locations.

12 References

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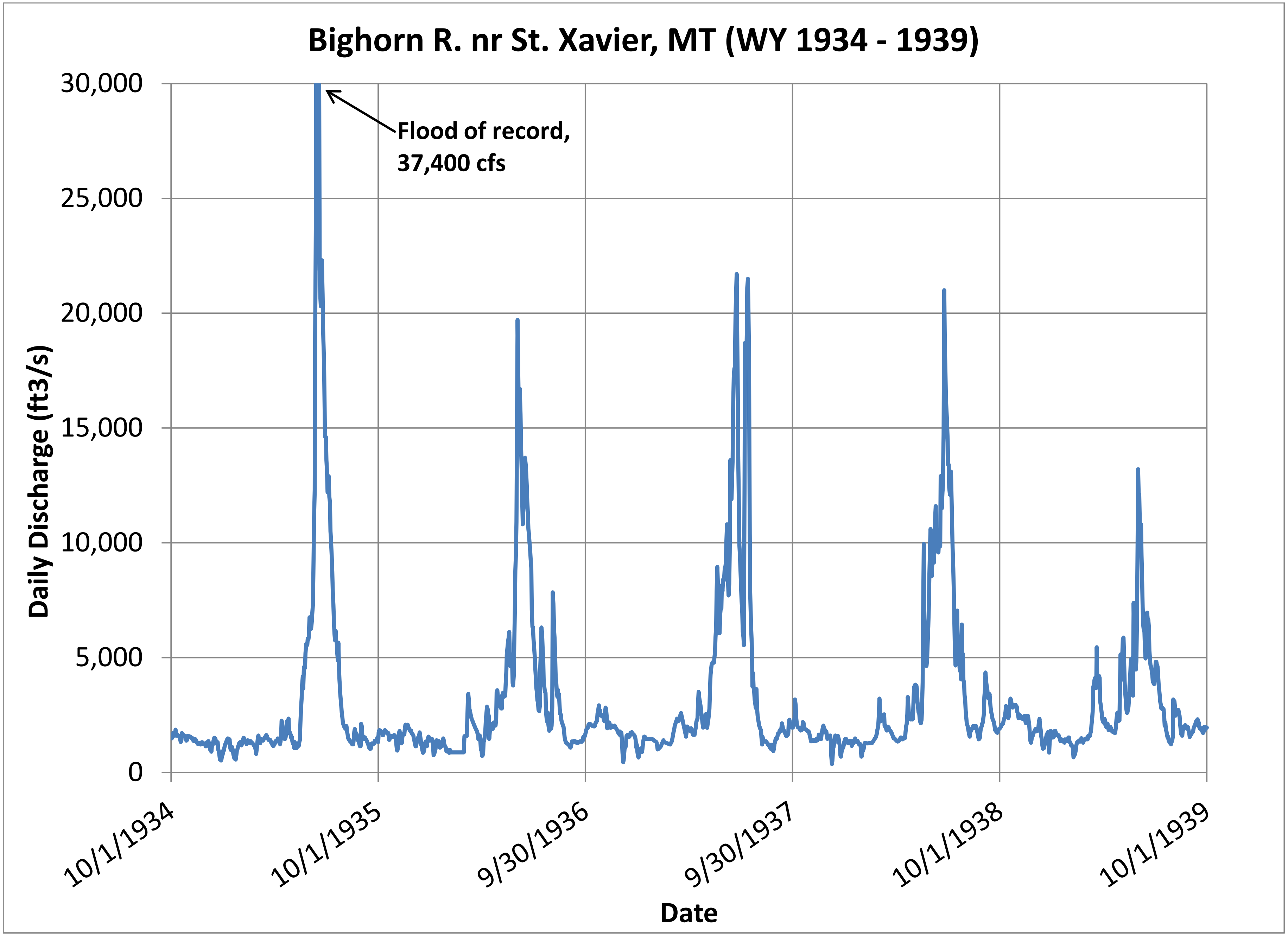
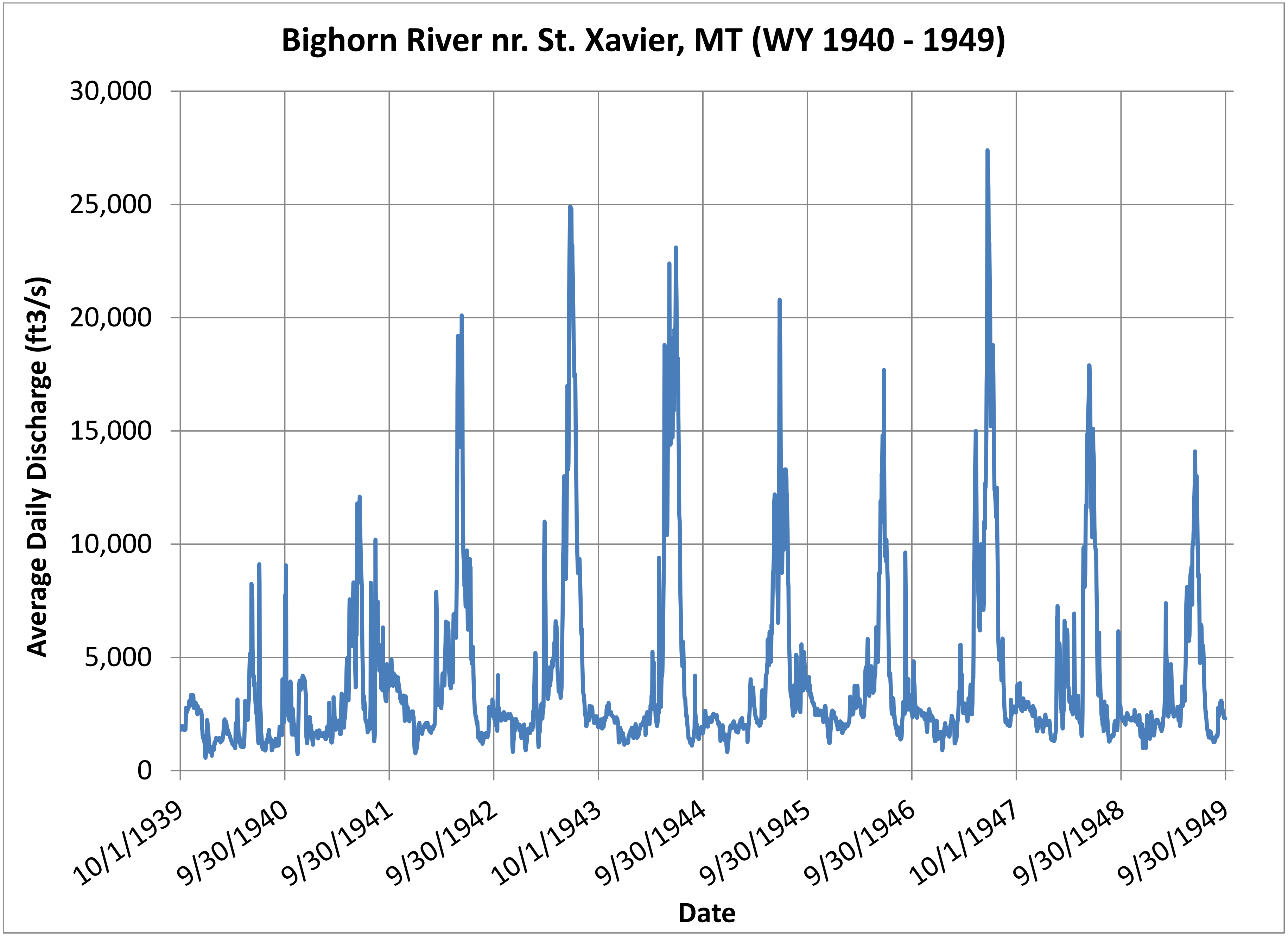
Appendix A

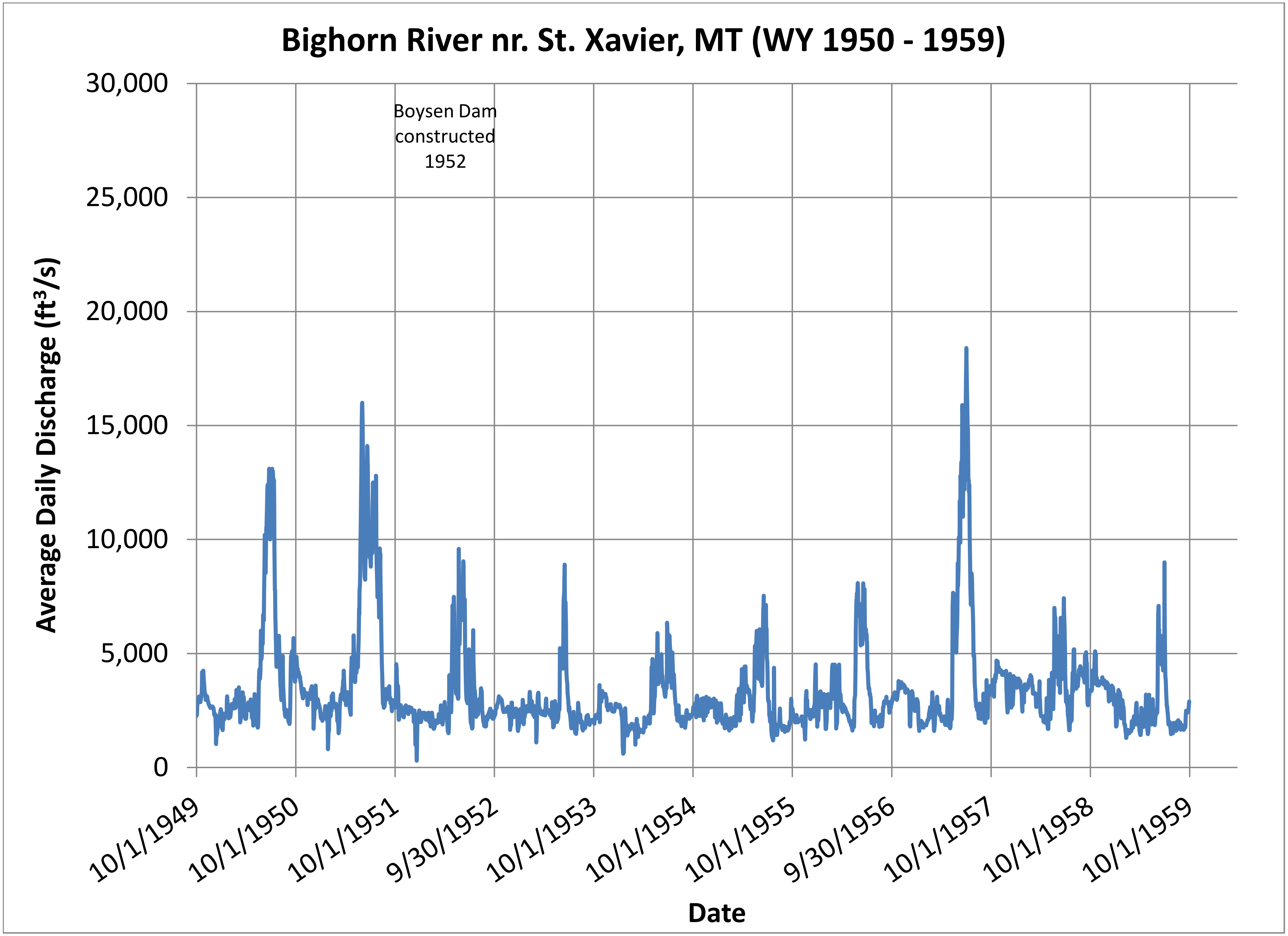
Past Hydrology



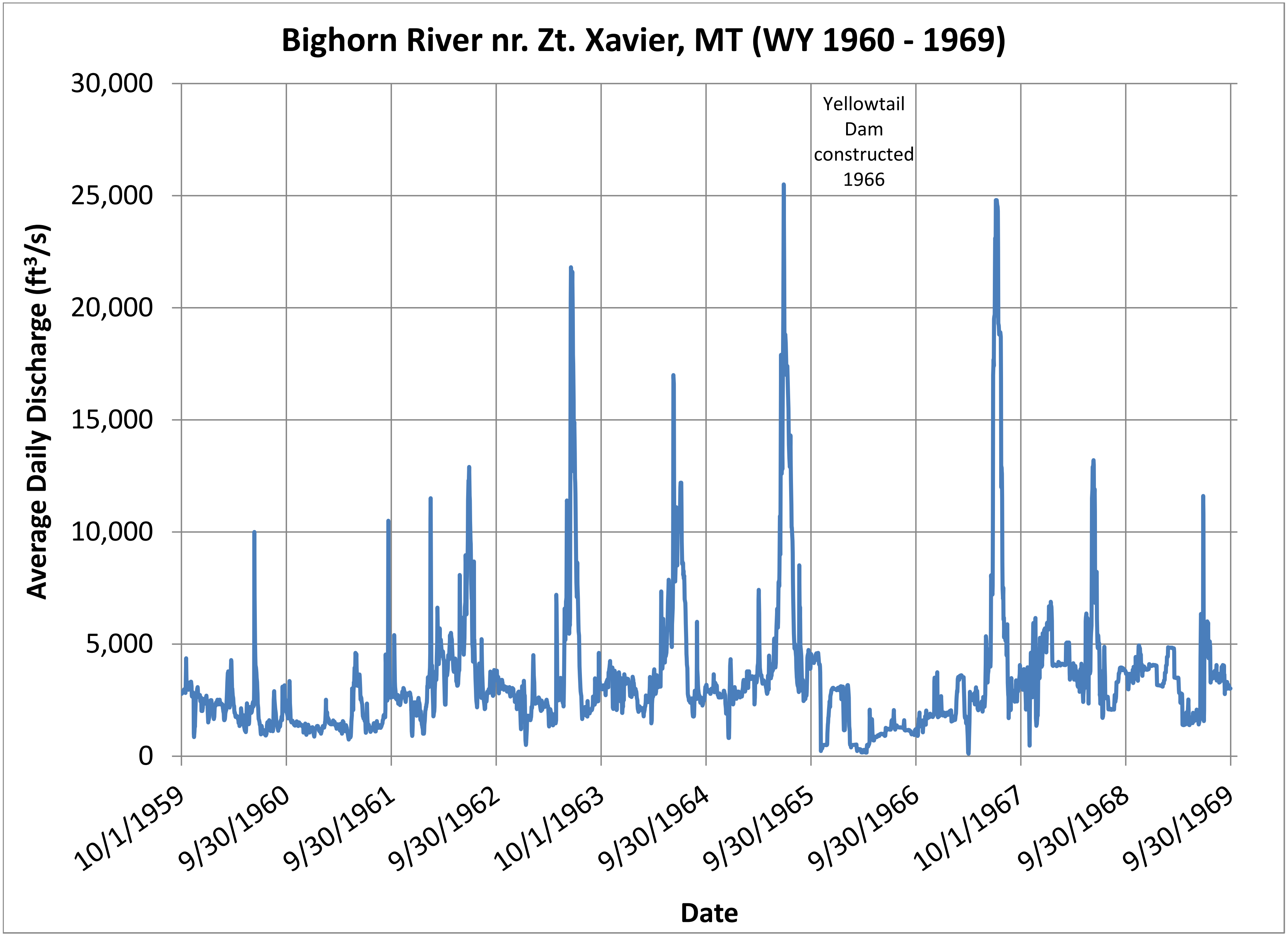
Bighorn R. nr St. Xavier, MT (WY 1934 - 1939)
Daily Discharge (ft3/s)
30,000
25,000
20,000
15,000
10,000
5,000
0
Flood of record,
37,400 cfs
10/1/1934
10/1/1935
9/30/1936
9/30/1937
10/1/1938
10/1/1939
Date

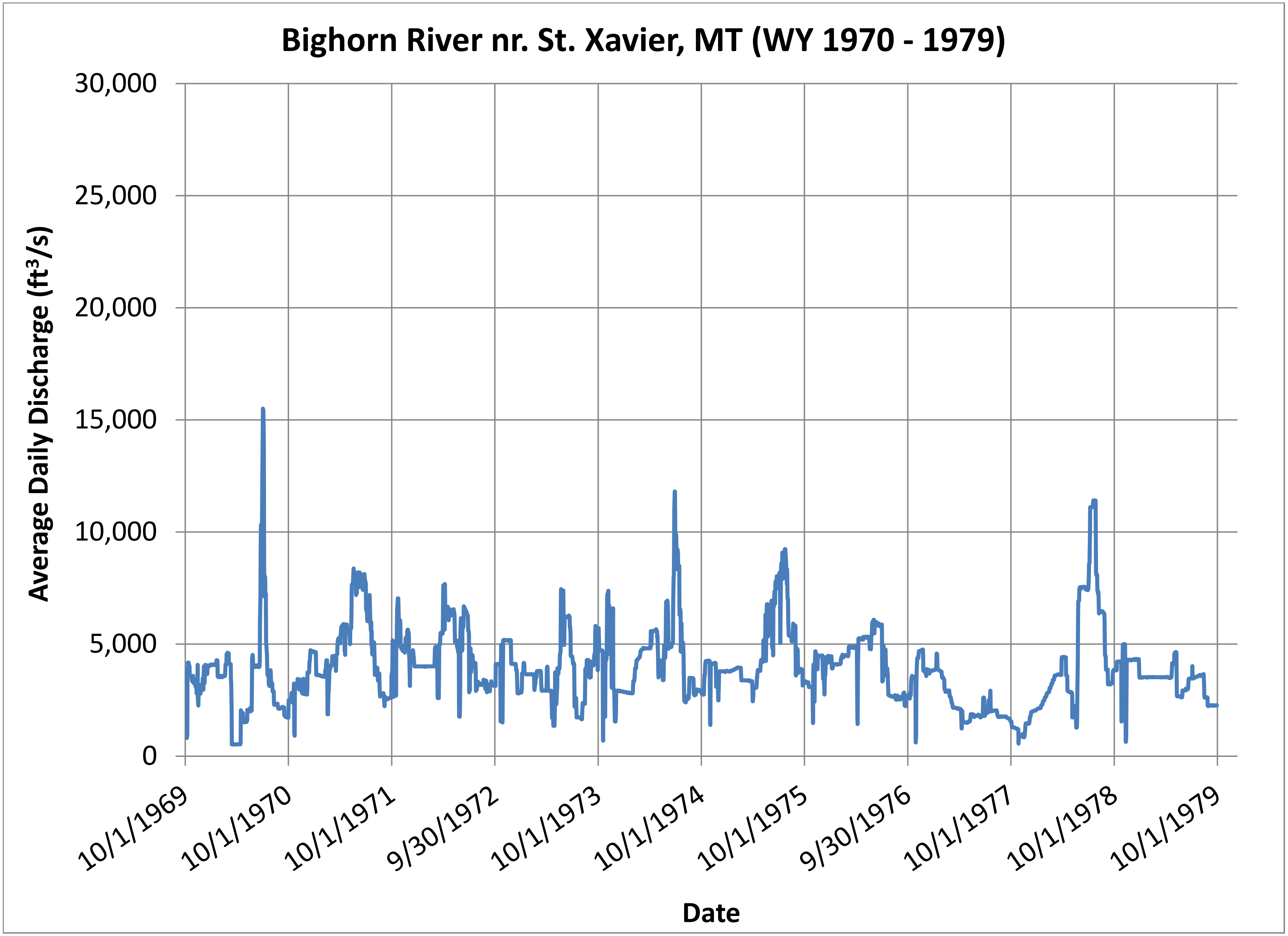


Bighorn River nr. St. Xavier, MT (WY 1940 - 1949)
Average Daily Discharge (ft3/s)
30,000
25,000
20,000
15,000
10,000
5,000
0
10/1/1939
9/30/1940
9/30/1941
9/30/1942
10/1/1943
9/30/1944
9/30/1945
9/30/1946
10/1/1947
9/30/1948
9/30/1949
Date

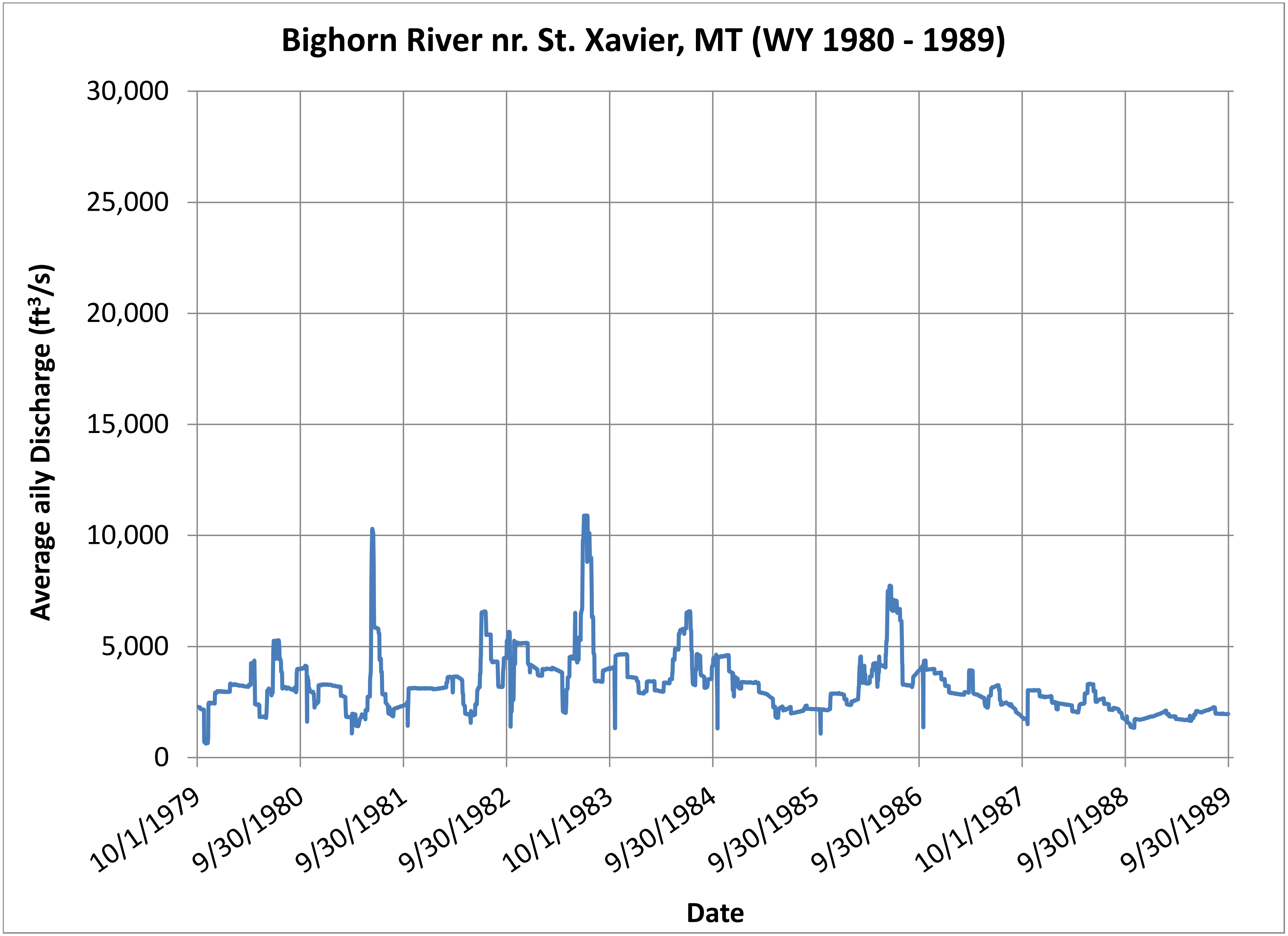


Bighorn River nr. St. Xavier, MT (WY 1950 - 1959)
Average Daily Discharge (ft^3/s)
30,000
25,000
20,000
15,000
10,000
5,000
0
Boysen Dam constructed 1952
10/1/1949
10/1/1950
10/1/1951
9/30/1952
10/1/1953
10/1/1954
10/1/1955
9/30/1956
10/1/1957
10/1/1958
10/1/1959
Date

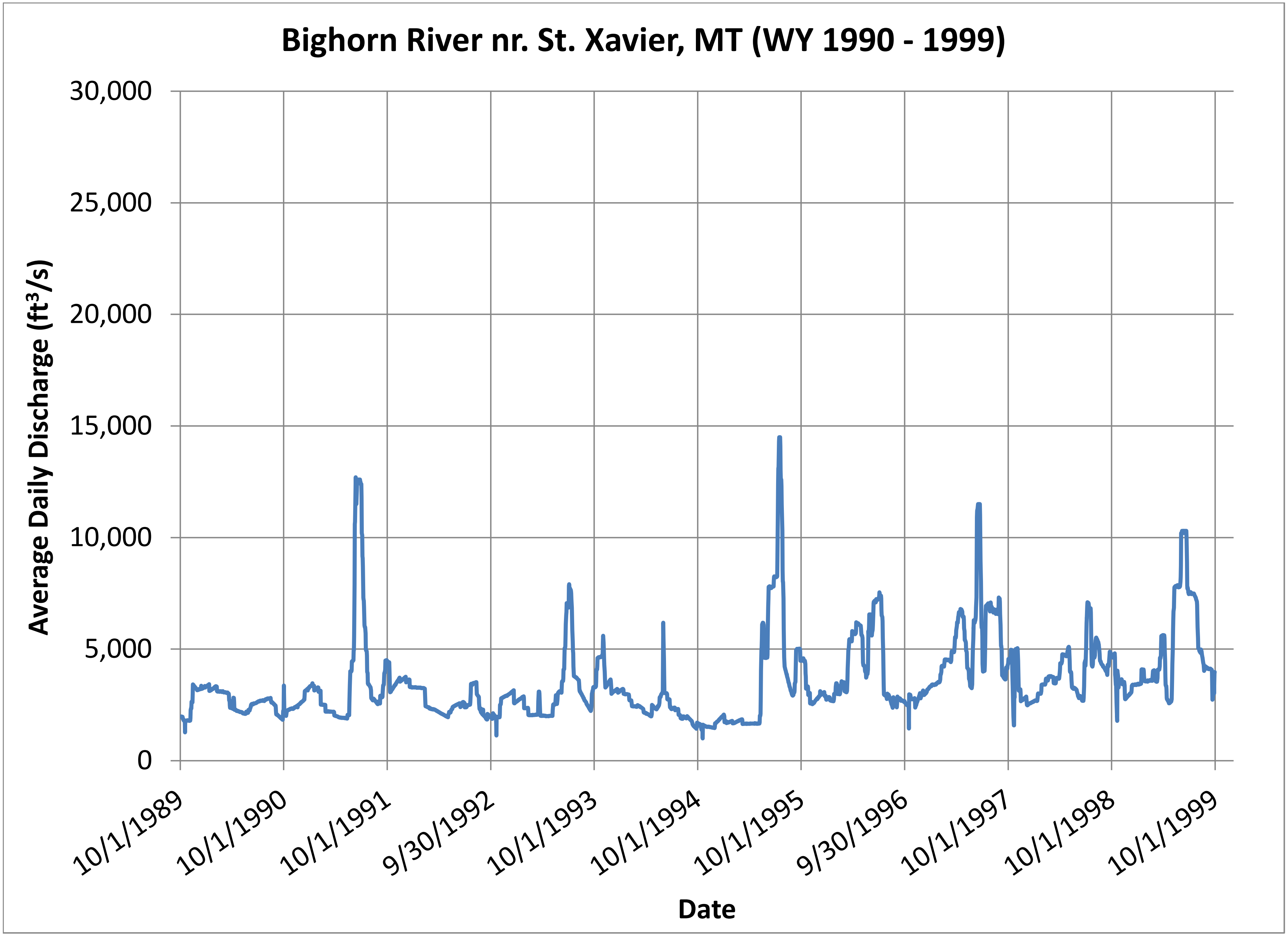

Bighorn River nr. Zt. Xavier, MT (WY 1960 - 1969)
30,000
25,000
20,000
15,000
10,000
5,000
0
Average Daily Discharge (ft³/s)
Yellowtail Dam constructed 1966
10/1/1959
9/30/1960
9/30/1961
9/30/1962
10/1/1963
9/30/1964
9/30/1965
9/30/1966
10/1/1967
9/30/1968
9/30/1969
Date



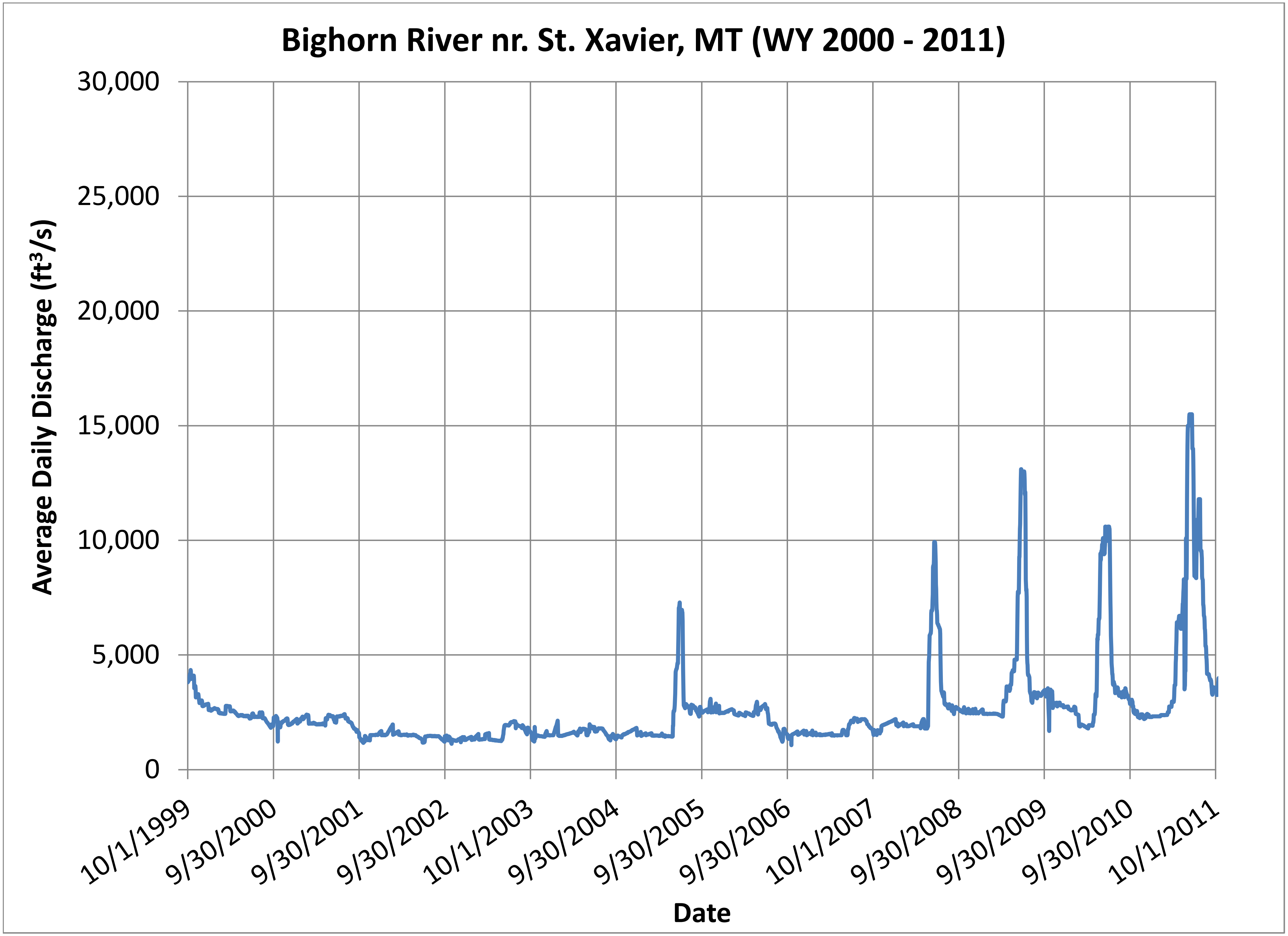
Bighorn River nr. St. Xavier, MT (WY 1970 - 1979)
Average Daily Discharge (ft³/s)
30,000
25,000
20,000
15,000
10,000
5,000
0
10/1/1969
10/1/1970
10/1/1971
9/30/1972
10/1/1973
10/1/1974
10/1/1975
9/30/1976
10/1/1977
10/1/1978
10/1/1979
Date



Bighorn River nr. St. Xavier, MT (WY 1980 - 1989)
30,000
25,000
20,000
15,000
10,000
5,000
0
Average aily Discharge (ft³/s)
10/1/1979
9/30/1980
9/30/1981
9/30/1982
10/1/1983
9/30/1984
9/30/1985
9/30/1986
10/1/1987
9/30/1988
9/30/1989
Date



Bighorn River nr. St. Xavier, MT (WY 1990 - 1999)
Average Daily Discharge (ft³/s)
30,000
25,000
20,000
15,000
10,000
5,000
0
10/1/1989
10/1/1990
10/1/1991
9/30/1992
10/1/1993
10/1/1994
10/1/1995
9/30/1996
10/1/1997
10/1/1998
10/1/1999
Date


Bighorn River nr. St. Xavier, MT (WY 2000 - 2011)
Average Daily Discharge (ft³/s)
30,000
25,000
20,000
15,000
10,000
5,000
0
10/1/1999
9/30/2000
9/30/2001
9/30/2002
10/1/2003
9/30/2004
9/30/2005
9/30/2006
10/1/2007
9/30/2008
9/30/2009
9/30/2010
10/1/2011
Date

Appendix B

Pebble Count Data: Size Distribution and Location

All counts indicate particles passing the given size in mm

Site # 64

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		93.2
4	0	0	2.0	
5.6	0	0		D84
8	2	2	5.9	80.4
11	1	3		
16	5	8	21.6	D65
22.6	6	14		57.4
32	16	29	44.1	
45	17	46		D50
64	28	74	23.5	47.3
90	16	89		
128	8	97	2.9	D35
180	3	100		35.9
256	0	100	0	
360	0	100		D16
512	0	100		23.8
sum	102		100.0	
				D10
				18.2

All counts indicate particles passing the given size in mm

Site # 63

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		79.0
4	0	0	0.0	
5.6	0	0		D84
8	0	0	1.0	71.7
11	0	0		
16	1	1	14.0	D65
22.6	5	6		57.4
32	9	15	62.0	
45	23	38		D50
64	39	77	23.0	50.2
90	21	98		
128	2	100	0.0	D35
180	0	100		43.0
256	0	100	0	
360	0	100		D16
512	0	100		32.5
sum	100		100.0	
				D10
				26.4

All counts indicate particles passing the given size in mm

Site # 62

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		124.6
4	0	0	5.0	
5.6	1	1		D84
8	4	5	21.0	114.9
11	7	12		
16	14	26	17.0	D65
22.6	10	36		87.7
32	7	43	10.0	
45	7	50		D50
64	3	53	39.0	45.0
90	13	66		
128	26	92	8.0	D35
180	8	100		21.8
256	0	100	0	
360	0	100		D16
512	0	100		12.2
sum	100		100.0	
				D10
				10.0

All counts indicate particles passing the given size in mm

Site # 61

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		57.9
4	0	0	1.0	
5.6	0	0		D84
8	1	1	16.0	52.3
11	2	3		
16	14	17	41.0	D65
22.6	14	31		36.8
32	27	58	38.0	
45	17	75		D50
64	21	96	4.0	28.9
90	3	99		
128	1	100	0.0	D35
180	0	100		24.9
256	0	100	0	
360	0	100		D16
512	0	100		15.6
sum	100		100.0	
				D10
				13.3

All counts indicate particles passing the given size in mm

Site # 60

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		57.9
4	0	0	4.0	
5.6	0	0		D84
8	4	4	25.0	43.8
11	9	13		
16	16	29	43.0	D65
22.6	20	49		28.8
32	23	72	20.0	
45	13	85		D50
64	7	92	8.0	22.9
90	6	98		
128	2	100	0.0	D35
180	0	100		17.7
256	0	100	0	
360	0	100		D16
512	0	100		11.8
sum	100		100.0	
				D10
				9.9

All counts indicate particles passing the given size in mm

Site # 59

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0.0	0.0	D90
2.8	0	0.0		93.2
4	0	0.0	2.0	
5.6	0	0.0		D84
8	2	2.0	5.9	80.4
11	1	2.9		
16	5	7.8	21.6	D65
22.6	6	13.7		57.4
32	16	29.4	44.1	
45	17	46.1		D50
64	28	73.5	23.5	47.3
90	16	89.2		
128	8	97.1	2.9	D35
180	3	100.0		35.9
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		23.8
sum	102		100.0	
				D10
				18.2

All counts indicate particles passing the given size in mm

Site # 58

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		109.7
4	0	0	0.0	
5.6	0	0		D84
8	0	0	0.0	96.1
11	0	0		
16	0	0	14.0	D65
22.6	6	6		71.0
32	8	14	44.0	
45	19	33		D50
64	25	58	39.0	57.2
90	23	81		
128	16	97	3.0	D35
180	3	100		46.3
256	0	100	0	
360	0	100		D16
512	0	100		33.2
sum	100		100.0	
				D10
				26.9

All counts indicate particles passing the given size in mm

Site # 57

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		121.7
4	0	0	0.0	
5.6	0	0		D84
8	0	0	2.0	110.1
11	1	1		
16	1	2	7.0	D65
22.6	1	3		84.5
32	6	9	25.0	
45	7	16		D50
64	18	34	59.0	73.9
90	38	72		
128	21	93	7.0	D35
180	7	100		64.6
256	0	100	0	
360	0	100		D16
512	0	100		45.0
sum	100		100.0	
				D10
				33.6

All counts indicate particles passing the given size in mm

Site # 56

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		107.3
4	0	0	0.0	
5.6	0	0		D84
8	0	0	1.0	94.1
11	0	0		
16	1	1	9.0	D65
22.6	2	3		77.6
32	7	10	33.0	
45	14	24		D50
64	19	43	55.0	68.0
90	39	82		
128	16	98	2.0	D35
180	2	100		55.2
256	0	100	0	
360	0	100		D16
512	0	100		37.0
sum	100		100.0	
				D10
				32.0

All counts indicate particles passing the given size in mm

Site # 55

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		122.3
4	0	0	0.0	
5.6	0	0		D84
8	0	0	3.0	111.5
11	0	0		
16	3	3	13.0	D65
22.6	9	12		85.5
32	4	16	21.0	
45	14	30		D50
64	7	37	56.0	73.2
90	33	70		
128	23	93	7.0	D35
180	7	100		62.7
256	0	100	0	
360	0	100		D16
512	0	100		32.0
sum	100		100.0	
				D10
				20.9

All counts indicate particles passing the given size in mm

Site # 54

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0.0	0.0	D90
2.8	0	0.0		123.4
4	0	0.0	0.0	
5.6	0	0.0		D84
8	0	0.0	0.0	112.1
11	0	0.0		
16	0	0.0	3.8	D65
22.6	3	2.9		85.4
32	1	3.8	32.7	
45	16	19.2		D50
64	18	36.5	55.8	73.4
90	35	70.2		
128	23	92.3	7.7	D35
180	8	100.0		62.0
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		41.9
sum	104		100.0	
				D10
				36.7

All counts indicate particles passing the given size in mm

Site # 53

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
date/time	Easting-UTM	Northing-UTM	0.0	
2	0	0	0.0	D90
2.8	0	0		126.1
4	0	0	0.0	
5.6	0	0		D84
8	0	0	1.0	115.0
11	1	1		
16	0	1	11.0	D65
22.6	1	2		85.3
32	10	12	37.0	
45	13	25		D50
64	24	49	42.0	65.2
90	19	68		
128	23	91	9.0	D35
180	9	100		52.1
256	0	100	0	
360	0	100		D16
512	0	100		35.5
sum	100		100.0	
				D10
				29.8

All counts indicate particles passing the given size in mm

Site # 52

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		1.0	
2	1	1	0.0	D90
2.8	0	1		100.6
4	0	1	1.0	
5.6	0	1		D84
8	1	2	7.8	86.7
11	3	5		
16	5	10	16.7	D65
22.6	3	13		63.3
32	14	26	39.2	
45	16	42		D50
64	24	66	32.4	50.6
90	21	86		
128	12	98	2.0	D35
180	2	100		38.5
256	0	100	0	
360	0	100		D16
512	0	100		24.5
sum	102		100.0	
				D10
				16.4

All counts indicate particles passing the given size in mm

Site # 51

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		25.0	
2	25	25	0.0	D90
2.8	0	25		75.9
4	0	25	5.0	
5.6	3	28		D84
8	2	30	27.0	64.0
11	9	39		
16	18	57	23.0	D65
22.6	14	71		19.5
32	9	80	4.0	
45	2	82		D50
64	2	84	16.0	13.8
90	12	96		
128	4	100	0.0	D35
180	0	100		9.5
256	0	100	0	
360	0	100		D16
512	0	100		--
sum	100		100.0	
				D10
				--

All counts indicate particles passing the given size in mm

Site # 50

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		70.0
4	0	0	0.0	
5.6	0	0		D84
8	0	0	4.0	61.4
11	0	0		
16	4	4	31.7	D65
22.6	11	15		47.8
32	21	36	51.5	
45	25	60		D50
64	27	87	12.9	39.0
90	11	98		
128	2	100	0.0	D35
180	0	100		31.7
256	0	100	0	
360	0	100		D16
512	0	100		23.0
sum	101		100.0	
				D10
				19.4

All counts indicate particles passing the given size in mm

Site # 49

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
			0.0	
2	0	0	0.0	D90
2.8	0	0		58.8
4	0	0	0.0	
5.6	0	0		D84
8	0	0	7.0	54.2
11	3	3		
16	4	7	44.0	D65
22.6	22	29		39.0
32	22	51	41.0	
45	24	75		D50
64	17	92	8.0	31.5
90	8	100		
128	0	100	0.0	D35
180	0	100		24.8
256	0	100	0	
360	0	100		D16
512	0	100		18.4
sum	100		100.0	
				D10
				16.8

All counts indicate particles passing the given size in mm

Site # 48

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	2.0	D90
2.8	0	0		90.0
4	2	2	2.0	
5.6	1	3		D84
8	1	4	2.0	82.3
11	1	5		
16	1	6	27.0	D65
22.6	10	16		62.1
32	17	33	34.0	
45	11	44		D50
64	23	67	33.0	49.3
90	23	90		
128	10	100	0.0	D35
180	0	100		34.0
256	0	100	0	
360	0	100		D16
512	0	100		22.6
sum	100		100.0	
				D10
				18.4

This site was noted more for model verification rather than model input
The sediment composition here is all sand and is a backwater
    deposition area that should be reflected in the model.
No pebble count was taken here

Waypoint	sand
Site # 47	

All counts indicate particles passing the given size in mm

Site # 46

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		119.8
4	0	0	0.0	
5.6	0	0		D84
8	0	0	1.0	112.2
11	0	0		
16	1	1	10.8	D65
22.6	4	5		91.3
32	7	12	29.4	
45	14	25		D50
64	16	41	54.9	73.1
90	23	64		
128	33	96	3.9	D35
180	4	100		55.7
256	0	100	0	
360	0	100		D16
512	0	100		35.5
sum	102		100.0	
				D10
				29.3

All counts indicate particles passing the given size in mm

Site # 45

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	2.0	D90
2.8	0	0		34.0
4	2	2	11.0	
5.6	2	4		D84
8	9	13	33.0	29.8
11	21	34		
16	12	46	42.0	D65
22.6	22	68		21.6
32	20	88	12.0	
45	11	99		D50
64	1	100	0.0	17.0
90	0	100		
128	0	100	0.0	D35
180	0	100		11.3
256	0	100	0	
360	0	100		D16
512	0	100		8.4
sum	100		100.0	
				D10
				7.1

All counts indicate particles passing the given size in mm

Site # 44

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		55.6
4	0	0	0.0	
5.6	0	0		D84
8	0	0	18.0	36.4
11	3	3		
16	15	18	55.0	D65
22.6	27	45		29.0
32	28	73	19.0	
45	14	87		D50
64	5	92	8.0	24.0
90	8	100		
128	0	100	0.0	D35
180	0	100		19.9
256	0	100	0	
360	0	100		D16
512	0	100		15.2
sum	100		100.0	
				D10
				13.1

All counts indicate particles passing the given size in mm

Site # 43

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		114.5
4	0	0	4.0	
5.6	0	0		D84
8	4	4	6.0	102.5
11	2	6		
16	4	10	22.0	D65
22.6	11	21		70.8
32	11	32	28.0	
45	16	48		D50
64	12	60	36.0	47.7
90	17	77		
128	19	96	4.0	D35
180	4	100		34.1
256	0	100	0	
360	0	100		D16
512	0	100		19.3
sum	100		100.0	
				D10
				16.0

All counts indicate particles passing the given size in mm

Site # 42

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		10.0	
2	10	10	0.0	D90
2.8	0	10		83.7
4	0	10	9.0	
5.6	4	14		D84
8	5	19	18.0	72.3
11	6	25		
16	12	37	25.0	D65
22.6	13	50		39.3
32	12	62	17.0	
45	5	67		D50
64	12	79	19.0	22.6
90	14	93		
128	5	98	2.0	D35
180	2	100		15.0
256	0	100	0	
360	0	100		D16
512	0	100		6.5
sum	100		100.0	
				D10
				4.0

All counts indicate particles passing the given size in mm

Site # 41

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		7.0	
2	7	7	0.0	D90
2.8	0	7		37.5
4	0	7	8.0	
5.6	3	10		D84
8	5	15	26.0	32.7
11	8	23		
16	18	41	42.0	D65
22.6	20	61		24.1
32	22	83	17.0	
45	15	98		D50
64	2	100	0.0	18.7
90	0	100		
128	0	100	0.0	D35
180	0	100		14.1
256	0	100	0	
360	0	100		D16
512	0	100		8.3
sum	100		100.0	
				D10
				5.6

All counts indicate particles passing the given size in mm

Site # 40

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		126.1
4	0	0	0.0	
5.6	0	0		D84
8	0	0	0.0	114.1
11	0	0		
16	0	0	8.1	D65
22.6	3	3		83.7
32	5	8	39.4	
45	17	25		D50
64	22	47	43.4	66.5
90	22	70		
128	21	91	9.1	D35
180	8	99		52.5
256	1	100	0	
360	0	100		D16
512	0	100		37.4
sum	99		100.0	
				D10
				33.2

All counts indicate particles passing the given size in mm

Site # 39

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		139.4
4	0	0	0.0	
5.6	0	0		D84
8	0	0	0.0	124.0
11	0	0		
16	0	0	3.0	D65
22.6	2	2		101.2
32	1	3	24.0	
45	10	13		D50
64	14	27	60.0	85.6
90	27	54		
128	33	87	13.0	D35
180	12	99		70.8
256	1	100	0	
360	0	100		D16
512	0	100		48.5
sum	100		100.0	
				D10
				40.6

All counts indicate particles passing the given size in mm

Site # 38

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		144.2
4	0	0	5.0	
5.6	1	1		D84
8	4	5	6.9	126.1
11	3	8		
16	4	12	10.9	D65
22.6	3	15		99.1
32	8	23	17.8	
45	8	31		D50
64	10	41	44.6	77.4
90	17	57		
128	28	85	14.9	D35
180	14	99		52.5
256	1	100	0	
360	0	100		D16
512	0	100		23.8
sum	101		100.0	
				D10
				13.4

All counts indicate particles passing the given size in mm

Site # 37

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		14.0	
2	14	14	0.0	D90
2.8	0	14		148.9
4	0	14	4.0	
5.6	0	14		D84
8	4	18	6.0	93.6
11	2	20		
16	4	24	24.0	D65
22.6	12	36		98.7
32	12	48	6.0	
45	2	50		D50
64	4	54	28.0	45.0
90	5	59		
128	23	82	18.0	D35
180	18	100		22.0
256	0	100	0	
360	0	100		D16
512	0	100		6.7
sum	100		100.0	
				D10

All counts indicate particles passing the given size in mm

Site # 36

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		88.7
4	0	0	1.0	
5.6	1	1		D84
8	0	1	12.0	81.1
11	4	5		
16	8	13	28.0	D65
22.6	16	29		59.6
32	12	41	27.0	
45	12	53		D50
64	15	68	30.0	41.3
90	23	91		
128	7	98	2.0	D35
180	2	100		26.9
256	0	100	0	
360	0	100		D16
512	0	100		17.1
sum	100		100.0	
				D10
				13.9

All counts indicate particles passing the given size in mm

Site # 35

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		3.0	
2	3	3	0.0	D90
2.8	0	3		105.0
4	0	3	2.0	
5.6	0	3		D84
8	2	5	7.0	92.0
11	0	5		
16	7	12	16.0	D65
22.6	6	18		70.4
32	10	28	30.0	
45	15	43		D50
64	15	58	41.0	53.0
90	25	83		
128	16	99	1.0	D35
180	1	100		37.5
256	0	100	0	
360	0	100		D16
512	0	100		20.1
sum	100		100.0	
				D10
				14.4

All counts indicate particles passing the given size in mm

Site # 34

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		97.4
4	0	0	0.0	
5.6	0	0		D84
8	0	0	5.9	86.0
11	2	2		
16	4	6	24.8	D65
22.6	13	19		65.5
32	12	31	32.7	
45	11	42		D50
64	22	63	36.6	51.6
90	24	87		
128	13	100	0.0	D35
180	0	100		36.6
256	0	100	0	
360	0	100		D16
512	0	100		21.0
sum	101		100.0	
				D10
				17.8

All counts indicate particles passing the given size in mm

Site # 33

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		74.5
4	0	0	0.0	
5.6	0	0		D84
8	0	0	5.0	62.9
11	1	1		
16	4	5	21.8	D65
22.6	6	11		47.5
32	16	27	58.4	
45	35	61		D50
64	24	85	12.9	40.2
90	11	96		
128	2	98	2.0	D35
180	2	100		34.7
256	0	100	0	
360	0	100		D16
512	0	100		25.3
sum	101		100.0	
				D10
				21.5

All counts indicate particles passing the given size in mm

Site # 32

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		90.0
4	0	0	0.0	
5.6	0	0		D84
8	0	0	0.0	69.7
11	0	0		
16	0	0	14.0	D65
22.6	1	1		54.2
32	13	14	68.0	
45	32	46		D50
64	36	82	13.0	46.8
90	8	90		
128	5	95	5.0	D35
180	5	100		40.0
256	0	100	0	
360	0	100		D16
512	0	100		32.7
sum	100		100.0	
				D10
				28.8

All counts indicate particles passing the given size in mm

Site # 31

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		120.1
4	0	0	0.0	
5.6	0	0		D84
8	0	0	0.0	109.1
11	0	0		
16	0	0	8.0	D65
22.6	2	2		83.1
32	6	8	34.0	
45	11	19		D50
64	23	42	52.0	70.1
90	30	72		
128	22	94	6.0	D35
180	5	99		57.5
256	1	100	0	
360	0	100		D16
512	0	100		41.0
sum	100		100.0	
				D10
				34.0

All counts indicate particles passing the given size in mm

Site # 30

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		113.8
4	0	0	0.0	
5.6	0	0		D84
8	0	0	5.0	97.4
11	1	1		
16	4	5	13.0	D65
22.6	7	12		78.8
32	6	18	34.0	
45	12	30		D50
64	22	52	44.0	62.0
90	26	78		
128	18	96	4.0	D35
180	4	100		51.9
256	0	100	0	
360	0	100		D16
512	0	100		28.5
sum	100		100.0	
				D10
				20.5

All counts indicate particles passing the given size in mm

Site # 29

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		119.6
4	0	0	0.0	
5.6	0	0		D84
8	0	0	3.0	110.3
11	1	1		
16	2	3	11.0	D65
22.6	7	10		83.8
32	4	14	36.0	
45	17	31		D50
64	19	50	45.0	64.0
90	19	69		
128	26	95	5.0	D35
180	5	100		48.5
256	0	100	0	
360	0	100		D16
512	0	100		33.3
sum	100		100.0	
				D10
				22.6

All counts indicate particles passing the given size in mm

Site # 28

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		120.4
4	0	0	0.0	
5.6	0	0		D84
8	0	0	5.0	109.8
11	1	1		
16	4	5	6.0	D65
22.6	2	7		84.7
32	4	11	26.0	
45	8	19		D50
64	18	37	57.0	72.9
90	34	71		
128	23	94	6.0	D35
180	5	99		61.5
256	1	100	0	
360	0	100		D16
512	0	100		39.6
sum	100		100.0	
				D10
				29.3

All counts indicate particles passing the given size in mm

Site # 27

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		2.0	
2	2	2	1.0	D90
2.8	0	2		30.8
4	1	3	17.0	
5.6	5	8		D84
8	12	20	40.0	27.4
11	15	35		
16	25	60	32.0	D65
22.6	14	74		18.1
32	18	92	8.0	
45	7	99		D50
64	1	100	0.0	13.8
90	0	100		
128	0	100	0.0	D35
180	0	100		11.0
256	0	100	0	
360	0	100		D16
512	0	100		7.1
sum	100		100.0	
				D10
				5.9

All counts indicate particles passing the given size in mm

Site # 26

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0.0	0.0	D90
2.8	0	0.0		103.1
4	0	0.0	0.0	
5.6	0	0.0		D84
8	0	0.0	1.0	89.6
11	1	1.0		
16	0	1.0	16.7	D65
22.6	3	3.9		69.5
32	14	17.6	41.2	
45	20	37.3		D50
64	22	58.8	40.2	55.4
90	26	84.3		
128	15	99.0	1.0	D35
180	1	100.0		43.3
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		30.7
sum	102		100.0	
				D10
				26.4

All counts indicate particles passing the given size in mm

Site # 25

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		16.0	
2	16	16.0	0.0	D90
2.8	0	16.0		87.7
4	0	16.0	7.0	
5.6	1	17.0		D84
8	6	23.0	18.0	74.9
11	9	32.0		
16	9	41.0	20.0	D65
22.6	12	53.0		37.9
32	8	61.0	17.0	
45	8	69.0		D50
64	9	78.0	21.0	20.7
90	13	91.0		
128	8	99.0	1.0	D35
180	1	100.0		12.5
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		4.0
sum	100		100.0	
				D10

All counts indicate particles passing the given size in mm

Site # 24

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0.0	0.0	D90
2.8	0	0.0		127.5
4	0	0.0	0.0	
5.6	0	0.0		D84
8	0	0.0	3.9	114.5
11	2	2.0		
16	2	3.9	11.8	D65
22.6	3	6.9		84.5
32	9	15.7	24.5	
45	6	21.6		D50
64	19	40.2	50.0	71.4
90	31	70.6		
128	20	90.2	9.8	D35
180	8	98.0		58.0
256	2	100.0	0	
360	0	100.0		D16
512	0	100.0		32.6
sum	102		100.0	
				D10
				25.6

All counts indicate particles passing the given size in mm

Site # 23

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0.0	0.0	D90
2.8	0	0.0		125.7
4	0	0.0	1.0	
5.6	0	0.0		D84
8	1	1.0	2.0	113.5
11	1	2.0		
16	1	3.0	17.8	D65
22.6	2	5.0		83.4
32	16	20.8	25.7	
45	9	29.7		D50
64	17	46.5	44.6	67.3
90	24	70.3		
128	21	91.1	8.9	D35
180	9	100.0		50.3
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		28.8
sum	101		100.0	
				D10
				25.2

All counts indicate particles passing the given size in mm

Site # 22

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0.0	0.0	D90
2.8	0	0.0		125.9
4	0	0.0	0.0	
5.6	0	0.0		D84
8	0	0.0	1.0	114.7
11	0	0.0		
16	1	1.0	6.9	D65
22.6	1	2.0		86.9
32	6	7.9	27.7	
45	8	15.8		D50
64	20	35.6	55.4	74.3
90	33	68.3		
128	23	91.1	8.9	D35
180	9	100.0		63.3
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		45.1
sum	101		100.0	
				D10
				35.0

All counts indicate particles passing the given size in mm

Site # 21

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		153.5
4	0	0	0.0	
5.6	0	0		D84
8	0	0	0.0	134.0
11	0	0		
16	0	0	3.0	D65
22.6	0	0		112.7
32	3	3	13.0	
45	4	7		D50
64	9	16	66.0	100.7
90	19	35		
128	47	82	18.0	D35
180	15	97		90.0
256	3	100	0	
360	0	100		D16
512	0	100		64.0
sum	100		100.0	
				D10
				50.6

All counts indicate particles passing the given size in mm

Site # 20

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		139.4
4	0	0	3.0	
5.6	0	0		D84
8	3	3	4.0	120.7
11	3	6		
16	1	7	11.0	D65
22.6	3	10		84.3
32	8	18	30.0	
45	11	29		D50
64	19	48	39.0	66.1
90	21	69		
128	18	87	13.0	D35
180	12	99		50.3
256	1	100	0	
360	0	100		D16
512	0	100		29.3
sum	100		100.0	
				D10
				22.6

All counts indicate particles passing the given size in mm

Site # 19

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		10.2	
2	11	10.2	0.0	D90
2.8	0	10.2		39.3
4	0	10.2	8.3	
5.6	0	10.2		D84
8	9	18.5	35.2	32.7
11	12	29.6		
16	26	53.7	29.6	D65
22.6	24	75.9		19.1
32	8	83.3	14.8	
45	12	94.4		D50
64	4	98.1	1.9	11.0
90	2	100.0		
128	0	100.0	0.0	D35
180	0	100.0		12.0
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		7.2
sum	108		100.0	
				D10

All counts indicate particles passing the given size in mm

Site # 18

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0.0	0.0	D90
2.8	0	0.0		60.1
4	0	0.0	1.0	
5.6	0	0.0		D84
8	1	1.0	13.0	53.1
11	4	5.0		
16	9	14.0	40.0	D65
22.6	14	28.0		37.9
32	26	54.0	39.0	
45	22	76.0		D50
64	17	93.0	7.0	30.3
90	5	98.0		
128	2	100.0	0.0	D35
180	0	100.0		24.8
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		16.8
sum	100		100.0	
				D10
				13.5

All counts indicate particles passing the given size in mm

Site # 17

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		117.2
4	0	0	0.0	
5.6	0	0		D84
8	0	0	4.0	105.5
11	0	0		
16	4	4	12.0	D65
22.6	3	7		78.5
32	9	16	34.0	
45	9	25		D50
64	25	50	45.0	64.0
90	25	75		
128	20	95	5.0	D35
180	5	100		51.8
256	0	100	0	
360	0	100		D16
512	0	100		32.0
sum	100		100.0	
				D10
				25.4

All counts indicate particles passing the given size in mm

Site # 16

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		97.6
4	0	0	1.0	
5.6	1	1		D84
8	0	1	7.0	84.1
11	1	2		
16	6	8	41.0	D65
22.6	16	24		52.1
32	25	49	23.0	
45	11	60		D50
64	12	72	28.0	33.0
90	15	87		
128	13	100	0.0	D35
180	0	100		26.3
256	0	100	0	
360	0	100		D16
512	0	100		19.0
sum	100		100.0	
				D10
				16.7

All counts indicate particles passing the given size in mm

Site # 15

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		73.4
4	0	0	2.0	
5.6	0	0		D84
8	2	2	9.0	62.2
11	2	4		
16	7	11	33.0	D65
22.6	14	25		47.6
32	19	44	42.0	
45	17	61		D50
64	25	86	13.0	36.1
90	10	96		
128	3	99	1.0	D35
180	1	100		27.1
256	0	100	0	
360	0	100		D16
512	0	100		18.1
sum	100		100.0	
				D10
				15.2

All counts indicate particles passing the given size in mm

Site # 14

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0.0	0.0	D90
2.8	0	0.0		109.4
4	0	0.0	0.0	
5.6	0	0.0		D84
8	0	0.0	6.6	95.9
11	4	3.8		
16	3	6.6	12.3	D65
22.6	2	8.5		74.1
32	11	18.9	34.0	
45	17	34.9		D50
64	19	52.8	44.3	60.5
90	30	81.1		
128	17	97.2	2.8	D35
180	3	100.0		45.1
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		29.1
sum	106		100.0	
				D10
				23.8

All counts indicate particles passing the given size in mm

Site # 13

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	1.0	D90
2.8	0	0		123.3
4	1	1	0.0	
5.6	0	1		D84
8	0	1	0.0	114.3
11	0	1		
16	0	1	6.0	D65
22.6	1	2		90.0
32	5	7	32.0	
45	13	20		D50
64	19	39	54.0	73.9
90	26	65		
128	28	93	7.0	D35
180	7	100		59.4
256	0	100	0	
360	0	100		D16
512	0	100		40.5
sum	100		100.0	
				D10
				34.6

All counts indicate particles passing the given size in mm

Site # 12

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0.0	0.0	D90
2.8	0	0.0		140.0
4	0	0.0	0.0	
5.6	0	0.0		D84
8	0	0.0	5.0	123.8
11	2	2.0		
16	3	5.0	2.0	D65
22.6	0	5.0		100.8
32	2	6.9	28.7	
45	17	23.8		D50
64	12	35.6	51.5	83.0
90	19	54.5		
128	33	87.1	12.9	D35
180	11	98.0		62.8
256	2	100.0	0	
360	0	100.0		D16
512	0	100.0		38.5
sum	101		100.0	
				D10
				34.1

All counts indicate particles passing the given size in mm

Site # 11

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0.0	0.0	D90
2.8	0	0.0		70.7
4	0	0.0	0.0	
5.6	0	0.0		D84
8	0	0.0	8.9	61.4
11	3	3.0		
16	6	8.9	40.6	D65
22.6	20	28.7		47.8
32	21	49.5	37.6	
45	11	60.4		D50
64	27	87.1	12.9	32.5
90	10	97.0		
128	3	100.0	0.0	D35
180	0	100.0		25.1
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		18.1
sum	101		100.0	
				D10
				16.3

All counts indicate particles passing the given size in mm

Site # 10

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		62.1
4	0	0	0.0	
5.6	0	0		D84
8	0	0	3.0	56.9
11	0	0		
16	3	3	41.0	D65
22.6	13	16		43.1
32	28	44	48.0	
45	24	68		D50
64	24	92	8.0	34.8
90	8	100		
128	0	100	0.0	D35
180	0	100		28.6
256	0	100	0	
360	0	100		D16
512	0	100		22.6
sum	100		100.0	
				D10
				19.3

All counts indicate particles passing the given size in mm

Site # 9

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		1.0	
2	1	1	0.0	D90
2.8	0	1		75.9
4	0	1	2.0	
5.6	0	1		D84
8	2	3	10.0	62.9
11	3	6		
16	7	13	35.0	D65
22.6	13	26		45.0
32	22	48	37.0	
45	17	65		D50
64	20	85	15.0	33.3
90	10	95		
128	5	100	0.0	D35
180	0	100		26.1
256	0	100	0	
360	0	100		D16
512	0	100		17.3
sum	100		100.0	
				D10
				13.6

All counts indicate particles passing the given size in mm

Site # 8

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		13.1	
2	13	13.1	0.0	D90
2.8	0	13.1		49.4
4	0	13.1	9.1	
5.6	2	15.2		D84
8	7	22.2	31.3	32.4
11	16	38.4		
16	15	53.5	30.3	D65
22.6	17	70.7		20.1
32	13	83.8	12.1	
45	4	87.9		D50
64	8	96.0	4.0	14.7
90	4	100.0		
128	0	100.0	0.0	D35
180	0	100.0		10.3
256	0	100.0	0	
360	0	100.0		D16
512	0	100.0		5.8
sum	99		100.0	
				D10

All counts indicate particles passing the given size in mm

Site # 7

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		52.0
4	0	0	3.0	
5.6	0	0		D84
8	3	3	8.0	45.9
11	1	4		
16	7	11	42.0	D65
22.6	15	26		36.7
32	27	53	47.0	
45	30	83		D50
64	17	100	0.0	30.8
90	0	100		
128	0	100	0.0	D35
180	0	100		25.4
256	0	100	0	
360	0	100		D16
512	0	100		18.0
sum	100		100.0	
				D10
				15.2

All counts indicate particles passing the given size in mm

Site # 6

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		69.0
4	0	0	0.0	
5.6	0	0		D84
8	0	0	5.0	60.2
11	1	1		
16	4	5	29.0	D65
22.6	9	14		45.0
32	20	34	54.0	
45	31	65		D50
64	23	88	12.0	38.2
90	9	97		
128	3	100	0.0	D35
180	0	100		32.4
256	0	100	0	
360	0	100		D16
512	0	100		23.4
sum	100		100.0	
				D10
				19.4

All counts indicate particles passing the given size in mm

Site # 5

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		80.8
4	0	0	0.0	
5.6	0	0		D84
8	0	0	7.0	72.6
11	2	2		
16	5	7	21.0	D65
22.6	11	18		55.3
32	10	28	49.0	
45	20	48		D50
64	29	77	22.0	46.1
90	19	96		
128	3	99	1.0	D35
180	1	100		36.1
256	0	100	0	
360	0	100		D16
512	0	100		21.2
sum	100		100.0	
				D10
				17.6

All counts indicate particles passing the given size in mm

Site # 4

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		88.7
4	0	0	0.0	
5.6	0	0		D84
8	0	0	1.0	81.1
11	0	0		
16	1	1	20.0	D65
22.6	7	8		61.9
32	13	21	47.0	
45	16	37		D50
64	31	68	32.0	52.2
90	23	91		
128	9	100	0.0	D35
180	0	100		43.1
256	0	100	0	
360	0	100		D16
512	0	100		28.0
sum	100		100.0	
				D10
				23.8

All counts indicate particles passing the given size in mm

Site # 3

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		83.4
4	0	0	2.0	
5.6	0	0		D84
8	2	2	9.0	74.5
11	2	4		
16	7	11	28.0	D65
22.6	14	25		54.1
32	14	39	37.0	
45	14	53		D50
64	23	76	22.0	41.8
90	18	94		
128	4	98	2.0	D35
180	2	100		29.0
256	0	100	0	
360	0	100		D16
512	0	100		18.1
sum	100		100.0	
				D10
				15.2

All counts indicate particles passing the given size in mm

Site # 2

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		145.2
4	0	0	0.0	
5.6	0	0		D84
8	0	0	2.8	127.9
11	0	0		
16	3	3	6.5	D65
22.6	3	6		107.8
32	4	9	14.0	
45	6	15		D50
64	9	23	60.7	94.2
90	23	45		
128	42	84	15.9	D35
180	17	100		77.0
256	0	100	0	
360	0	100		D16
512	0	100		47.0
sum	107		100.0	
				D10
				33.3

All counts indicate particles passing the given size in mm

Site # 1

size (mm)	count (passing)	cum. % passing	% retained	D_{xx}
1	---		0.0	
2	0	0	0.0	D90
2.8	0	0		168.1
4	0	0	0.0	
5.6	0	0		D84
8	0	0	2.0	146.7
11	0	0		
16	2	2	12.0	D65
22.6	6	8		78.5
32	6	14	36.0	
45	12	26		D50
64	24	50	28.0	64.0
90	25	75		
128	3	78	22.0	D35
180	15	93		51.4
256	7	100	0	
360	0	100		D16
512	0	100		33.9
sum	100		100.0	
				D10
				25.4

Point #	Date	comment	POINT_X	POINT_Y	Waypoint
1	10/5/2011 0:00	mc	2375644.371	393525.0497	1Z
2	10/5/2011 0:00	sc entrance	2377681.815	394305.2243	2Z
3	10/5/2011 0:00	sc	2377914.613	394558.5524	3Z
4	10/5/2011 0:00	mc	2380074.318	397399.213	5Z
5	10/5/2011 0:00	sc	2379964.721	397411.1855	4Z
6	10/5/2011 0:00	sc entrance	2378980.656	398213.5194	6Z
9	10/5/2011 0:00	mc	2378959.46	398972.9912	D
11	10/5/2011 0:00	sc	2380440.66	400503.0955	11Z
10	10/5/2011 0:00	sc entrance	2380159.68	400570.092	10Z
12	10/5/2011 0:00	mc	2380931.828	400855.8361	E
15	10/5/2011 0:00	sc	2384668.906	402607.7358	15Z
13	10/5/2011 0:00	sc entrance	2383318.647	402632.4027	13Z
16	10/5/2011 0:00	sc	2384644.585	402780.0241	14Z
14	10/5/2011 0:00	mc	2383340.114	402867.4867	12Z
17	10/5/2011 0:00	sc entrance	2384029.814	403324.7372	16Z
18	10/5/2011 0:00	sc	2384440.046	403387.9941	17Z
19	10/5/2011 0:00	sc	2385386.969	403466.3409	18Z
22	10/4/2011 0:00	mc	2386536.739	405023.5674	21Z
20	10/4/2011 0:00	mc	2386180.051	405050.3136	19Z
21	10/4/2011 0:00	mc	2386364.471	405110.8786	20Z
23	10/4/2011 0:00	sc entrance	2386333.204	405426.5617	22Z
27	10/4/2011 0:00	sc	2388247.227	406201.4759	27Z
25	10/6/2011 0:00	sc entrance	2387436.061	406307.9062	24Z
24	10/6/2011 0:00	mc	2387435.527	406334.2194	GRAVY5
26	10/4/2011 0:00	sc entrance	2388153.557	406394.2171	26Z
36	10/6/2011 0:00	mc	2395464.944	406988.9011	GRAVY4
33	10/4/2011 0:00	sc	2392654.367	406970.536	36Z
28	10/4/2011 0:00	sc entrance	2388055.278	406716.1811	28Z
34	10/4/2011 0:00	sc entrance	2393377.225	407070.7548	37Z
32	10/4/2011 0:00	mc	2392783.745	407086.3119	B
35	10/4/2011 0:00	sc	2393644.401	407202.1715	38Z
29	10/4/2011 0:00	sc	2389547.458	407140.4294	30Z
31	10/4/2011 0:00	sc	2390730.301	407456.3074	35Z
30	10/4/2011 0:00	mc	2390628.155	407469.5189	34Z
37	10/4/2011 0:00	sc entrance	2397768.157	410723.9123	41Z
38	10/4/2011 0:00	mc	2397721.334	410786.927	43Z
39	10/6/2011 0:00	mc	2398699.969	412458.6596	GRAVY3
42	10/3/2011 0:00	sc entrance	2401523.15	414600.9273	44Z
43	10/3/2011 0:00	mc	2401599.288	414704.3674	46Z
41	10/3/2011 0:00	sc entrance	2401255.737	414821.65	47Z
40	10/3/2011 0:00	mc	2401156.669	414875.0745	49Z
44	10/4/2011 0:00	mc	2402542.544	416294.5241	C
45	10/4/2011 0:00	sc	2402375.672	416374.2018	53AZ
46	10/3/2011 0:00	sc	2401825.673	416807.4286	53Z
47	10/3/2011 0:00	backwater	2401943.17	417144.849	SAND
48	10/3/2011 0:00	sc	2401985.269	417286.1753	50Z

Continued…

Point #	Date	comment	POINT_X	POINT_Y	Waypoint
49	10/3/2011 0:00	sc	2401986.146	417402.5053	51Z
50	10/3/2011 0:00	mc	2402008.414	417527.9943	52Z
51	10/3/2011 0:00	sc entrance	2402443.828	418485.8862	54Z
52	10/4/2011 0:00	sc entrance	2402962.463	419078.1301	55Z
53	10/3/2011 0:00	sc entrance	2403007.422	419449.3868	57Z
54	10/3/2011 0:00	mc	2402915.358	419514.8672	56Z
56	10/3/2011 0:00	sc entrance	2403894.804	422496.689	59Z
55	10/3/2011 0:00	mc	2404015.486	422544.2799	60Z
57	10/3/2011 0:00	sc entrance	2403676.578	423303.5595	61Z
58	10/3/2011 0:00	sc	2403570.342	423513.2915	62Z
59	10/6/2011 0:00	mc	2403220.392	423571.2441	GRAVY2
60	10/3/2011 0:00	sc entrance	2404222.336	426398.8017	64Z
62	10/6/2011 0:00	mc	2404481.073	427011.328	GRAVY1
63	10/3/2011 0:00	sc entrance	2405302.538	428238.2745	66Z
64	10/3/2011 0:00	sc	2405542.032	428649.2127	AZ
7	10/5/2011 0:00	sc	2378824.509	398347.6344	7z
61	10/3/2011 0:00	sc	2404592.173	426665.7724	65Z
8	10/5/2011 0:00	sc entrance	2379089.159	398788.8995	8z

Appendix C

Specific Gravity Testing

7-2336 (1-86)
Bureau of Reclamation

BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION

Designation USBR 5320-

SAMPLE NO.	PROJECT	FEATURE
Rob's Gravel Green Rock batch #2		

HOLE NO.	DEPTH ft ☐ m ☐

TESTED BY	DATE	COMPUTED BY	DATE	CHECKED	DATE
Baca	3/12/12	B. Baca	3/15/12	Strauss	3/26/12

SUSPENSION METHOD

		TRIAL NO. 1	TRIAL NO. 2
1. Mass of basket in water	(g)	308	308
2. Mass of basket in air	(g)	349	349
3. Mass of SSD* specimen + basket in air	(g)	901	900
4. Mass of SSD specimen + basket in water	(g)	649	648
5. Mass of ovendry specimen	(g)	547	545
6. Mass of SSD specimen in air (3) - (2)	(g)	552	551
7. Mass of SSD specimen in water (4) - (1)	(g)	341	340
8. Apparent specific gravity (5)/[(5) - (7)]		2.655	2.659
9. Average apparent specific gravity		2.66	
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]		2.616	2.611
11. Average bulk specific gravity (SSD)		2.61	
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]		2.592	2.583
13. Average bulk specific gravity (ovendry)		2.59	
14. Absorption [[(6) - (5)] /(5)] x 100	(%)	0.91	1.10
15. Average absorption	(%)	1.0	

SIPHON METHOD

1. Mass of specimen (SSD)	(g)		
2. Volume of water displaced	(mL)		
3. Mass of ovendry specimen	(g)		
4. Mass of water (1) - (3)	(g)		
5. Bulk specific gravity (SSD) (1)/(2)			
6. Average bulk specific gravity (SSD)			
7. Bulk specific gravity (ovendry) (3)/(2)			
8. Average bulk specific gravity (ovendry)			
9. Absorption [(4)/(3)] x 100	(%)		
10. Average absorption	(%)		

*SSD (Saturated surface-dry) One gravel partical painted green. #589.
Dish CL-226 Tare mass = 206

GPO 849-606

7-2336 (1-86) Bureau of Reclamation	BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION	Designation USBR 5320- __

SAMPLE NO.	PROJECT	FEATURE
Rob's Gravel	w/o RFID Locators	

HOLE NO.	DEPTH ft☐ m☐

TESTED BY	DATE	COMPUTED BY	DATE	CHECKED	DATE
BACA	2/25/12	B. Baca	3/1/12	S MASS	3-21/2017

SUSPENSION METHOD

		TRIAL NO. 1	TRIAL NO. 2
1. Mass of basket in water	(g)	1187	1188
2. Mass of basket in air	(g)	1339	1339
3. Mass of SSD* specimen + basket in air	(g)	2433	2432
4. Mass of SSD specimen + basket in water	(g)	1870	1872
5. Mass of ovendry specimen	(g)	1088	1087
6. Mass of SSD specimen in air (3) - (2)	(g)	1094 ✓	1093 ✓
7. Mass of SSD specimen in water (4) - (1)	(g)	683 ✓	684 ✓
8. Apparent specific gravity (5)/[(5) - (7)]		2.686 ✓	2.697 ✓
9. Average apparent specific gravity		2.69 ✓	
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]		2.662 ✓	2.672 ✓
11. Average bulk specific gravity (SSD)		2.67 ✓	
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]		2.647 ✓	2.658 ✓
13. Average bulk specific gravity (ovendry)		2.65 ✓	
14. Absorption [[(6) - (5)] /(5)] x 100	(%)	0.55 ✓	0.55 ✓
15. Average absorption	(%)	0.6 ✓	

SIPHON METHOD

		1	2
1. Mass of specimen (SSD)	(g)		
2. Volume of water displaced	(mL)		
3. Mass of ovendry specimen	(g)		
4. Mass of water (1) - (3)	(g)		
5. Bulk specific gravity (SSD) (1)/(2)			
6. Average bulk specific gravity (SSD)			
7. Bulk specific gravity (ovendry) (3)/(2)			
8. Average bulk specific gravity (ovendry)			
9. Absorption [(4)/(3)] x 100	(%)		
10. Average absorption	(%)		

How many particles? Combined

*SSD (Saturated surface-dry) Container mass for oven dry = 921 gms.

*This test is with unmolested gravel

GPO 849-606

7-2336 (1-86)
Bureau of Reclamation

BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION

Designation USBR 5320-

SAMPLE NO. RF1	PROJECT	FEATURE
HOLE NO.	DEPTH ft ☐ m ☐	
TESTED BY / DATE	COMPUTED BY / DATE	CHECKED STRAUSS / DATE 3/24/2012

SUSPENSION METHOD

		TRIAL NO. 1	2
1. Mass of basket in water	(g)	308	
2. Mass of basket in air	(g)	350	
3. Mass of SSD* specimen + basket in air	(g)	776	
4. Mass of SSD specimen + basket in water	(g)	572	
5. Mass of ovendry specimen	(g)	424	
6. Mass of SSD specimen in air (3) - (2)	(g)	426	
7. Mass of SSD specimen in water (4) - (1)	(g)	264	
8. Apparent specific gravity (5)/[(5) - (7)]		2.650	
9. Average apparent specific gravity			
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]		2.630	
11. Average bulk specific gravity (SSD)			
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]		2.617	
13. Average bulk specific gravity (ovendry)			
14. Absorption [[(6) - (5)]/(5)] x 100	(%)	0.47	
15. Average absorption	(%)		

SIPHON METHOD

	(g)		
	(mL)		
	(g)		
	(g)		
	(%)		
	(%)		

with Sensors.

Apparent SPG AVG - 2.62

Bulk SPG AVG - 2.57 (ovendry)

Absorption Avg - 0.7

*SSD (Saturated surface-dry) CL-119 = 168.2 RFID

RF1

7-2336 (1-86)
Bureau of Reclamation

BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION

Designation USBR 5320-___

SAMPLE NO. RF2	PROJECT	FEATURE
HOLE NO.	DEPTH ft☐ m☐	
TESTED BY / DATE	COMPUTED BY / DATE	CHECKED STRAUSS DATE 3/26/2012

SUSPENSION METHOD

	TRIAL NO. 1	2
1. Mass of basket in water (g)	308	
2. Mass of basket in air (g)	350	
3. Mass of SSD* specimen + basket in air (g)	606	
4. Mass of SSD specimen + basket in water (g)	466	
5. Mass of ovendry specimen (g)	254	
6. Mass of SSD specimen in air (3) - (2) (g)	256 ✓	
7. Mass of SSD specimen in water (4) - (1) (g)	158 ✓	
8. Apparent specific gravity (5)/[(5) - (7)]	2.646 ✓	
9. Average apparent specific gravity		
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]	2.612 ✓	
11. Average bulk specific gravity (SSD)	✓	
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]	2.592	
13. Average bulk specific gravity (ovendry)		
14. Absorption [[(6) - (5)]/(5)] x 100 (%)	0.79 ✓	
15. Average absorption (%)		

SIPHON METHOD

	1	2
1. Mass of specimen (SSD) (g)		
2. Volume of water displaced (mL)		
3. Mass of ovendry specimen (g)		
4. Mass of water (1) - (3) (g)		
5. Bulk specific gravity (SSD) (1)/(2)		
6. Average bulk specific gravity (SSD)		
7. Bulk specific gravity (ovendry) (3)/(2)		
8. Average bulk specific gravity (ovendry)		
9. Absorption [(4)/(3)] x 100 (%)		
10. Average absorption (%)		

*SSD (Saturated surface-dry) CL154 - 172.5 RFID

RF2

GPO 849-606

7-2336 (1-86)
Bureau of Reclamation

BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION

Designation USBR 5320-__

SAMPLE NO. RF3	PROJECT	FEATURE
HOLE NO.	DEPTH	ft ☐ m ☐
TESTED BY / DATE	COMPUTED BY / DATE	CHECKED SM/NSS DATE 3/26/2012

SUSPENSION METHOD

		TRIAL NO. 1	2
1. Mass of basket in water	(g)	308	
2. Mass of basket in air	(g)	350	
3. Mass of SSD* specimen + basket in air	(g)	501	
4. Mass of SSD specimen + basket in water	(g)	400	
5. Mass of ovendry specimen	(g)	150 ✓	
6. Mass of SSD specimen in air (3) - (2)	(g)	151 ✓	
7. Mass of SSD specimen in water (4) - (1)	(g)	92 ✓	
8. Apparent specific gravity (5)/[(5) - (7)]		2.586 ✓	
9. Average apparent specific gravity			
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]		2.559 ✓	~~2.88~~
11. Average bulk specific gravity (SSD)			
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]		2.542 ✓	
13. Average bulk specific gravity (ovendry)			
14. Absorption [[(6) - (5)]/(5)] x 100	(%)	0.67 ✓	
15. Average absorption	(%)		

SIPHON METHOD

		1	2
1. Mass of specimen (SSD)	(g)		
2. Volume of water displaced	(mL)		
3. Mass of ovendry specimen	(g)		
4. Mass of water (1) - (3)	(g)		
5. Bulk specific gravity (SSD) (1)/(2)			
6. Average bulk specific gravity (SSD)			
7. Bulk specific gravity (ovendry) (3)/(2)			
8. Average bulk specific gravity (ovendry)			
9. Absorption [(4)/(3)] x 100	(%)		
10. Average absorption	(%)		

*SSD (Saturated surface-dry) CL125 = 211.5 RFID

RF3

7-2336 (1-86) Bureau of Reclamation	BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION	Designation USBR 5320-__

SAMPLE NO. RF4	PROJECT	FEATURE
HOLE NO.	DEPTH ft ☐ m ☐	
TESTED BY / DATE	COMPUTED BY / DATE	CHECKED Strauss / DATE 3/24/2012

SUSPENSION METHOD

		TRIAL NO. 1	2
1. Mass of basket in water	(g)	308	
2. Mass of basket in air	(g)	350	
3. Mass of SSD* specimen + basket in air	(g)	867	
4. Mass of SSD specimen + basket in water	(g)	623	
5. Mass of ovendry specimen	(g)	513	
6. Mass of SSD specimen in air (3) - (2)	(g)	517 ✓	
7. Mass of SSD specimen in water (4) - (1)	(g)	315 ✓	
8. Apparent specific gravity (5)/[(5) - (7)]		2.591 ✓	
9. Average apparent specific gravity			
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]		2.559 ✓	
11. Average bulk specific gravity (SSD)			
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]		2.540 ✓	
13. Average bulk specific gravity (ovendry)			
14. Absorption [[(6) - (5)]/(5)] x 100	(%)	0.78 ✓	
15. Average absorption	(%)		

SIPHON METHOD

		1	2
1. Mass of specimen (SSD)	(g)		
2. Volume of water displaced	(mL)		
3. Mass of ovendry specimen	(g)		
4. Mass of water (1) - (3)	(g)		
5. Bulk specific gravity (SSD) (1)/(2)			
6. Average bulk specific gravity (SSD)			
7. Bulk specific gravity (ovendry) (3)/(2)			
8. Average bulk specific gravity (ovendry)			
9. Absorption [(4)/(3)] x 100	(%)		
10. Average absorption	(%)		

*SSD (Saturated surface-dry) Dish - 89-11 = 209.0 RFID

RF4

7-2336 (1-86) Bureau of Reclamation	BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION	Designation USBR 5320-

SAMPLE NO. Rob Hilldale	PROJECT RFID Samples.	FEATURE
HOLE NO.	DEPTH ft☐ m☐	
TESTED BY Billy Baca DATE 2/24/12	COMPUTED BY Baca DATE 3/1/12	CHECKED Strauss DATE 3/26/2011

SUSPENSION METHOD

		Trial No. 1	Trial No. 2
1. Mass of basket in water	(g)	1187	1188
2. Mass of basket in air	(g)	1339	1339
3. Mass of SSD* specimen + basket in air	(g)	2689	2688
4. Mass of SSD specimen + basket in water	(g)	2014	2017
5. Mass of ovendry specimen	(g)	1342	1342
6. Mass of SSD specimen in air (3) - (2)	(g)	1350 ✓	1349 ✓
7. Mass of SSD specimen in water (4) - (1)	(g)	829 ✓	829 ✓
8. Apparent specific gravity (5)/[(5) - (7)]		2.616 ✓	2.616 ✓
9. Average apparent specific gravity		2.62 ✓	
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]		2.591 ✓	2.594 ✓
11. Average bulk specific gravity (SSD)		2.59 ✓	
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]		2.576 ✓	2.581 ✓
13. Average bulk specific gravity (ovendry)		2.58 ✓	
14. Absorption [[(6) - (5)]/(5)] x 100	(%)	0.60 ✓	0.52 ✓
15. Average absorption	(%)	0.6 ✓	

SIPHON METHOD

1. Mass of specimen (SSD)	(g)		
2. Volume of water displaced	(mL)		
3. Mass of ovendry specimen	(g)		
4. Mass of water (1) - (3)	(g)		
5. Bulk specific gravity (SSD) (1)/(2)			
6. Average bulk specific gravity (SSD)			
7. Bulk specific gravity (ovendry) (3)/(2)			
8. Average bulk specific gravity (ovendry)			
9. Absorption [(4)/(3)] x 100	(%)		
10. Average absorption	(%)		

How many particles?

All 4 combined

*SSD (Saturated surface-dry)

This test on gravel containing RFID locators.

GPO 849-606

7-2336 (1-86)
Bureau of Reclamation

BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION

Designation USBR 5320- __

SAMPLE NO.	PROJECT	FEATURE
Rob's Gravel batch #2		

HOLE NO.	DEPTH ft ☐ m ☐

TESTED BY	DATE	COMPUTED BY	DATE	CHECKED	DATE
B. Baca	3/12/12	B. Baca	3/19/12	SMANSS	3/26/2011

SUSPENSION METHOD

		TRIAL NO. 1	TRIAL NO. 2
1. Mass of basket in water	(g)	308	308
2. Mass of basket in air	(g)	349	349
3. Mass of SSD* specimen + basket in air	(g)	2414	2412
4. Mass of SSD specimen + basket in water	(g)	1604	1602
5. Mass of ovendry specimen	(g)	2052	2051
6. Mass of SSD specimen in air (3) - (2)	(g)	2065 ✓	2063 ✓
7. Mass of SSD specimen in water (4) - (1)	(g)	1296 ✓	1294 ✓
8. Apparent specific gravity (5)/[(5) - (7)]		2.714 ✓	2.709 ✓
9. Average apparent specific gravity		2.71 ✓	
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]		2.685 ✓	2.683 ✓
11. Average bulk specific gravity (SSD)		2.68 ✓	
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]		2.668 ✓	2.667 ✓
13. Average bulk specific gravity (ovendry)		2.67 ✓	
14. Absorption [[(6) - (5)] /(5)] x 100	(%)	0.63 ✓	0.59 ✓
15. Average absorption	(%)	0.61 ✓	

SIPHON METHOD

1. Mass of specimen (SSD)	(g)		
2. Volume of water displaced	(mL)		
3. Mass of ovendry specimen	(g)		
4. Mass of water (1) - (3)	(g)		
5. Bulk specific gravity (SSD) (1)/(2)			
6. Average bulk specific gravity (SSD)			
7. Bulk specific gravity (ovendry) (3)/(2)			
8. Average bulk specific gravity (ovendry)			
9. Absorption [(4)/(3)] x 100	(%)		
10. Average absorption	(%)		

How many particles?
All Rocks (9)

*SSD (Saturated surface-dry) Material Tested are Particals marked "Native" unmolested Gravel.

7-2336 (1-86) Bureau of Reclamation	BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION	Designation USBR 5320- __

SAMPLE NO. UN2	PROJECT	FEATURE

HOLE NO.	DEPTH ft ☐ m ☐

TESTED BY	DATE	COMPUTED BY	DATE	CHECKED SPEARSS	DATE 3/26/2012

SUSPENSION METHOD

		TRIAL NO. 1	2
1. Mass of basket in water	(g)	308	
2. Mass of basket in air	(g)	350	
3. Mass of SSD* specimen + basket in air	(g)	807	
4. Mass of SSD specimen + basket in water	(g)	594	
5. Mass of ovendry specimen	(g)	455	
6. Mass of SSD specimen in air (3) - (2)	(g)	457 ✓	
7. Mass of SSD specimen in water (4) - (1)	(g)	286 ✓	
8. Apparent specific gravity (5)/[(5) - (7)]		2.692 ✓	
9. Average apparent specific gravity			
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]		2.673 ✓	
11. Average bulk specific gravity (SSD)			
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]		2.661 ✓	
13. Average bulk specific gravity (ovendry)			
14. Absorption [[(6) - (5)] /(5)] x 100	(%)	0.44 ✓	
15. Average absorption	(%)		

ETHOD

	(g)		
	(mL)		
	(g)		
	(g)		
	(%)		
	(%)		

Apparent SpG. 2.66

Bulk SpG. 2.64

No Sensor

*SSD (Saturated surface-dry) CL136 = 202.3 unmolde

UN2

7-2336 (1-86)
Bureau of Reclamation

BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION

Designation USBR 5320-

SAMPLE NO. UN 3.	PROJECT	FEATURE
HOLE NO.	DEPTH ft ☐ m ☐	
TESTED BY / DATE	COMPUTED BY / DATE	CHECKED SNWSS DATE 3/24/2011

SUSPENSION METHOD

	TRIAL NO. 1	2
1. Mass of basket in water (g)	308	
2. Mass of basket in air (g)	350	
3. Mass of SSD* specimen + basket in air (g)	664	
4. Mass of SSD specimen + basket in water (g)	503	
5. Mass of ovendry specimen (g)	313	
6. Mass of SSD specimen in air (3) - (2) (g)	314 ✓	
7. Mass of SSD specimen in water (4) - (1) (g)	195 ✓	
8. Apparent specific gravity (5)/[(5) - (7)]	2.653 ✓	
9. Average apparent specific gravity		
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]	2.639 ✓	
11. Average bulk specific gravity (SSD)		
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]	2.630 ✓	
13. Average bulk specific gravity (ovendry)		
14. Absorption [[(6) - (5)] /(5)] x 100 (%)	0.32 ✓	
15. Average absorption (%)		

SIPHON METHOD

	1	2
1. Mass of specimen (SSD) (g)		
2. Volume of water displaced (mL)		
3. Mass of ovendry specimen (g)		
4. Mass of water (1) - (3) (g)		
5. Bulk specific gravity (SSD) (1)/(2)		
6. Average bulk specific gravity (SSD)		
7. Bulk specific gravity (ovendry) (3)/(2)		
8. Average bulk specific gravity (ovendry)		
9. Absorption [(4)/(3)] x 100 (%)		
10. Average absorption (%)		

*SSD (Saturated surface-dry) CL216 = 248.5 unmole

UN3

7-2336 (1-86)
Bureau of Reclamation

BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION

Designation USBR 5320-

SAMPLE NO. UN 4	PROJECT	FEATURE
HOLE NO.	DEPTH	ft ☐ m ☐
TESTED BY / DATE	COMPUTED BY / DATE	CHECKED Sprague DATE 3/21/2012

SUSPENSION METHOD

		TRIAL NO. 1	2
1. Mass of basket in water	(g)	308	
2. Mass of basket in air	(g)	350	
3. Mass of SSD* specimen + basket in air	(g)	554	
4. Mass of SSD specimen + basket in water	(g)	434	
5. Mass of ovendry specimen	(g)	203	
6. Mass of SSD specimen in air (3) - (2)	(g)	204	
7. Mass of SSD specimen in water (4) - (1)	(g)	126.0	
8. Apparent specific gravity (5)/[(5) - (7)]		2.636	
9. Average apparent specific gravity			
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]		2.615	
11. Average bulk specific gravity (SSD)			
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]		2.603	
13. Average bulk specific gravity (ovendry)			
14. Absorption [[(6) - (5)] /(5)] x 100	(%)	0.49	
15. Average absorption	(%)		

SIPHON METHOD

		1	2
1. Mass of specimen (SSD)	(g)		
2. Volume of water displaced	(mL)		
3. Mass of ovendry specimen	(g)		
4. Mass of water (1) - (3)	(g)		
5. Bulk specific gravity (SSD) (1)/(2)			
6. Average bulk specific gravity (SSD)			
7. Bulk specific gravity (ovendry) (3)/(2)			
8. Average bulk specific gravity (ovendry)			
9. Absorption [(4)/(3)] x 100	(%)		
10. Average absorption	(%)		

*SSD (Saturated surface-dry) CL102 = 172.9 unmold.

UN 4

7-2336 (1-86)
Bureau of Reclamation

BULK SPECIFIC GRAVITY AND PERCENT ABSORPTION OF THE PLUS NO. 4 FRACTION

Designation USBR 5320-

SAMPLE NO. UN1	PROJECT	FEATURE
HOLE NO.	DEPTH ft ☐ m ☐	
TESTED BY / DATE	COMPUTED BY / DATE	CHECKED / DATE

SUSPENSION METHOD

BAD TEST

		TRIAL NO. 1	2
1. Mass of basket in water	(g)	308	
2. Mass of basket in air	(g)	350	
3. Mass of SSD* specimen + basket in air	(g)	467	
4. Mass of SSD specimen + basket in water	(g)	388	
5. Mass of ovendry specimen	(g)	118	
6. Mass of SSD specimen in air (3) - (2)	(g)	117 ✓	
7. Mass of SSD specimen in water (4) - (1)	(g)	80 ✓	
8. Apparent specific gravity (5)/[(5) - (7)]		3.105 ✓	
9. Average apparent specific gravity			
10. Bulk specific gravity (SSD) (6)/[(6) - (7)]		3.162 ✓	
11. Average bulk specific gravity (SSD)			
12. Bulk specific gravity (ovendry) (5)/[(6) - (7)]		3.189 ✓	
13. Average bulk specific gravity (ovendry)			
14. Absorption [[(6) - (5)] /(5)] x 100	(%)	-0.85 ✓	
15. Average absorption	(%)		

? →

SIPHON METHOD

		1	2
1. Mass of spe[...]	(g)		
2. Volume of [...]	(mL)		
3. Mass of ov[...]	(g)		
4. Mass of w[...]	(g)		
5. Bulk spec[...]			
6. Average [...]			
7. Bulk spe[...]			
8. Average [...]			
9. Absorp[...]	(%)		
10. Avera[...]	(%)		

w/o Sensors.
Apparent Spg. Avg - 2.77
Bulk spg (Oven) Avg - 2.77
Absorption - 0.4

*SSD (Saturated surface-dry) CL226 = 206.0 unmole

UN 1