# Development and Evaluation of Flushing Flow Recommendations for the Bighorn River

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## ABSTRACT

The Big Horn River near Thermopolis, Wyoming is rated as a Class 1 fishery from Wedding of the Waters to Kirby Creek. The Wyoming Game and Fish Department and the Bureau of Reclamation are concerned about the flow regime in this stretch of river as controlled by the operation of Boysen Reservoir. The goal of this study was to assess the need for flushing flows to enhance the natural recruitment of rainbow trout and brown trout in the Bighorn River. I have assessed the effects of a March 1994 flushing flow on substrate and spawning habitat in the Bighorn River. Data from this test flushing flow provided insight about the magnitude, duration, and timing of flushing flow regimes needed to scour pools, clean spawning gravel, maintain side channels, and remove fine sediment from the reach of the Bighorn River managed as a "blue ribbon" trout fishery.

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# CHAPTER I

# INTRODUCTION

The natural streamflow regime of the Rocky Mountain region is characterized by high runoff during the spring, followed by a recession of flows throughout summer and fall. In late fall a baseflow is reached that continues through the winter. Most streams in North America are no longer in their natural condition. Water withdrawal, flow augmentation, channelization, water storage, and upland watershed activities have had their impact and forced streams to initiate adjustment processes (Heede 1986).

Construction of dams can have dramatic effects on natural river channels (Graf 1988). Reservoir storage tends to flatten the hydrograph by increasing flows during what was the low flow time of the year and decreasing them during former high flow periods (Leopold *et al.* 1964). Storage projects can also increase the base levels of a river channel immediately above the dam. Other effects include degradation of the channel below the dam and a change in the downstream hydrograph (Simons and Senturk 1977).

The North Platte River in Wyoming has been regulated since the early 1900's (U.S. Bureau of Reclamation 1990). Historic high flow periods have been moderated while low flow conditions have been enhanced. The timing of peak flows has also been altered by upstream water storage. Following the installation of dams and diversion structures on the North Platte River, a 40 percent reduction in average annual peak flow occurred (Wenzel 1993).

Water storage and flow regime modifications can affect stream channel morphology. Bankfull channel characteristics (mean width, mean depth, width/depth ratio, mean cross-section area, and conveyance capacity) all decreased below diversion structures on 15 low gradient streams in Wyoming (Wesche 1991). The average channel width, length, sinuosity, number of islands and braided sections, and length of secondary channels in the North Platte River have decreased downstream from Gray Reef Reservoir over the period 1947 to 1989 (Wenzel 1993). Channel width decreased on the average by 43 ft. while the length of the main channel decreased by 6.9-mi. Length of secondary channels decreased by 4.7-mi, while the number of islands decreased from 34 to 25 and the number of braided sections from 6 to 5 (Wenzel 1993).

Another related effect of dams on natural river channels is the reduction in sediment load. Large reservoirs trap nearly all inflowing sediments (Simons 1979). The trapping of sediments results in clear, or sediment hungry, water discharge below dams which can erode the stream channel and accelerate channel degradation (Leopold *et al.* 1964). Since downcutting is probable, secondary channels are likely to be dewatered in time. The loss of secondary channels can result in a loss of cover for age-0 trout and spawning habitat (Harris 1991; Lanning 1992; Mullner 1992). Armoring of the channel bed may also result.

Flow regulation in streams can result in long-term sediment deposition problems (Reiser *et al.* 1989). The movement of sediment in streams is dependent on the availability of sediment in the drainage and the sediment transporting ability of the stream. Either factor can affect sediment transport rates depending on flow regulation.

In general, most water developments tend to lessen the natural peak flow of the stream, reducing its ability to transport sediment. The overall effect can be the accumulation of sediment transported into the mainstem by tributary channels (Reiser *et al.* 1989). Surficial flushing of fines may occur, but as bedload transport is diminished and bed mobilization occurs less frequently, fine sediments in the intergravel environment increase. If sufficiently high flows are not released to mobilize bed material, fines can accumulate and impact aquatic ecosystems.

Salmonids deposit their eggs in gravels to incubate (Kondolf *et al.* 1989). The availability of suitably sized gravels can inhibit spawning success (Allen 1969). To be suitable for spawning, gravels must be small enough to be moved by spawning females and free of interstitial fine sediment (Allen 1969; Reiser and Bjornn 1979). Salmonids, in the reproductive phase of their lives, rely heavily on erosional (characterized by rocks and gravel) and intermediate (characterized by sand and gravel) areas of the stream continuum (White 1973). An increase of fine sediment in spawning areas can reduce the survival of salmonid alevins by: (1) reducing the exchange of oxygen rich surface water with oxygen deficient water in the gravel bed, (2) trapping fry in the substrate by blocking emergence routes caused by the formation of a sand seal, and (3) reducing the capacity of rearing areas by covering or filling voids in the stream bottom with sand (Phillips *et al.* 1975; Hausle and Coble 1976; Beschta and Jackson 1979; Witzel and MacCrimmon 1981; Tappel and Bjornn 1983; Alexander and Hansen 1986; Reiser and White 1988; Crisp 1989). In particular, fines (< 2.0 mm median particle diameter) have been determined detrimental to salmonid embryo development (Hausle and Coble 1976;

Witzel and MacCrimmon 1983). Emergence of salmonid embryos is likely to be reduced when spawning gravels contain more than 20% fines (Hausle and Coble 1976). However, the use of the percentage of fines in spawning area substrate to estimate gravel quality has a major disadvantage, it does not take into account the textural composition of the remaining particles that can have a mitigating effect on survival (Platts *et al.* 1983). The use of fines as a single measure may be inadequate to describe potential survival to emergence of fry from substrate (Young *et al.* 1991).

The fredle index ($f_i$) is an index of spawning substrate quality (Lotspeich and Everest 1981) and appears to overcome limitations of the use of the percentage of fines to estimate gravel quality (Platts *et al.* 1983). This index incorporates elements that combine gravel permeability and pore size. Chapman (1988) used data from Tappel and Bjornn (1983), Koski (1966), Cooper (1965), and Lotspeich and Everest (1981) to compare survival to emergence of fry relative to the fredle index for several salmonids. At high fredle indices (5.0-7.0), survival for chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*, anadromous rainbow trout) exceeded 90%. Other factors that influence survival and spawning success include; dissolved oxygen concentration, pH, water depth, water velocity and water chemistry (Crisp 1989).

In regulated streams a solution to the problem of sediment deposition can be the programmed release of high-magnitude, short-duration flow events, termed flushing flows. Flushing flows can simulate flow peaks of the natural hydrograph, initiate bedload transport, flush fine sediments accumulated in the interstitial environment, and enhance natural recruitment of salmonids. Field observations indicated that fines deposited on gravels were removed by a controlled release in Huntington Creek, Utah (Beschta *et al* 1981.)

O'brien (1987) summarized a flushing flow case study on the Yampa River, Colorado, and found that sand could be scoured from the bed to an approximate depth of one median cobble diameter below the cobble surface without cobble movement. The author suggested that flows approaching the natural peak of the hydrograph for a short period (24-48 hours) might be necessary for long-term maintenance of a relatively sand-free cobble bed.

Wesche (1994) investigated flushing flow requirements on the Henry's Fork of the Snake River, Idaho, and concluded that flushing flows appear to be a viable management option to improve survival-to-emergence of rainbow trout (*Oncorhynchus mykiss*). He suggested a discharge in the range of 2,600 cfs for at least 9 hours. A flow of this magnitude has a return period of 14 years on the Henry's Fork, and has been equalled or exceeded less than 1% of the time since regulating the river (Wesche 1994).

A flushing flow on the North Platte River downstream from Gray Reef Dam, Wyoming, should be in the range of 4,000 cfs (Leonard 1995). At this magnitude, peak bedload and suspended sediment transport occurred. Flows in the range of 4,000 cfs have a recurrence interval of about 4 years and were estimated to be close to bankfull (Wenzel 1993).

Prior to Boysen Dam, the cutthroat trout (*Oncorhynchus clarki*) was the only trout species native to the Bighorn River (Baxter and Simon 1970). The completion of Boysen

Dam in 1952 created a tailwater, the reach of river downstream from a reservoir that is strongly influenced by fluctuations in reservoir releases. Stocking of other trout species occurred at this time. Releases from Boysen Reservoir are characterized by cool, clear, highly oxygenated water that have created the existing blue ribbon fishery in the Bighorn River near Thermopolis, Wyoming.

Recent estimates of trout populations in the Bighorn River indicate that the survival of hatchery plants is poor. The Wyoming Game and Fish Department (WGFD) Fisheries Management Crew in Cody, Wyoming, has documented large fluctuations in the wild brown trout (*Salmo trutta*) and rainbow trout populations of the Bighorn River (Vogt 1991).

The WGFD would like to focus more upon natural reproduction in the Bighorn River and emphasize wild trout management in this fishery. Since the completion of Boysen Dam, the water and sediment regimes of the river have been severely altered, channel downcutting has likely occurred, and important salmonid habitat for spawning and rearing appears to be affected. As the channel degrades, bed armoring occurs and secondary channels are gradually cut off. Therefore, enhancement of suitable habitat for spawning and rearing through an improved streamflow regime, in cooperation with the Bureau of Reclamation (BOR), is a critical management goal.

To assist the WGFD and BOR in their management of the Bighorn River, the goals of this study were to:

(1) assess the need for a flushing flow to enhance the natural recruitment of rainbow and brown trout and

(2) determine the magnitude, duration, and timing of such flow releases from Boysen Reservoir that would scour pools of concern, clean spawning gravel, maintain side channels, and flush fine sediment from the Bighorn River.

To achieve these goals, my specific objectives were to:

(1) Describe historic changes in hydrology of the Bighorn River channel in response to flow regulation;

(2) Identify and quantify sources of sediment entering the Bighorn River from Wedding of the Waters to Kirby Creek;

(3) Identify important spawning areas of brown and rainbow trout and characterize the bed material composition, mean velocity, nose velocity and water depth at each spawning site to develop habitat suitability curves;

(4) Evaluate temporal changes in intergravel fine sediment concentrations within important spawning locations over the water year;

(5) Quantify the relation between discharge and available trout spawning habitat, using the Physical Habitat Simulation Model (PHABSIM), to determine if fluctuations in brown and rainbow trout populations are related to flows which occurred during spawning, incubation, and emergence periods;

(6) Describe bedload and suspended sediment transport characteristics relative to the Bighorn River hydrograph;

(7) Develop and evaluate test flow releases from Boysen Reservoir; and

(8) Integrate the previous objectives to develop insight concerning the flushing flow needed to maintain and enhance the integrity of the fishery (scour pools, clean spawning gravel, and flush fine sediment from the Bighorn River).

## CHAPTER II

# DESCRIPTION OF STUDY AREA

The Wind/Bighorn River has its headwaters in the Wind River and Absaroka mountain ranges of west-central Wyoming. The river runs southeast, then north and flows through two additional mountain ranges before it joins the Yellowstone River at Big Horn, Montana, approximately 170-mi. northeast of Thermopolis, Wyoming (Figure 1). The waters eventually reach the Gulf of Mexico via the Missouri and Mississippi Rivers.

The river enjoys a dual name status as a result of exploration and mapping activities of two different parties. Mappers from the south adopted the name Wind River for that portion of the river. Mappers from the north adopted the name Bighorn River from French explorers who noted the large numbers of bighorn sheep in the area. Apparently, the different parties never realized they were mapping the same river (Hot Springs County Historical Museum 1993). The Wind/Bighorn River name change occurs at the Wedding of the Waters near the northern boundary of the Wind River Indian Reservation.

One mainstem dam (Boysen) is located 13.7-mi. upstream from Thermopolis, Wyoming. The construction of Boysen Dam was completed in December 1952. Regulation of stream flow generates power and provides for irrigation, municipal and industrial supplies, flood control, sediment retention, fish propagation, and recreation.

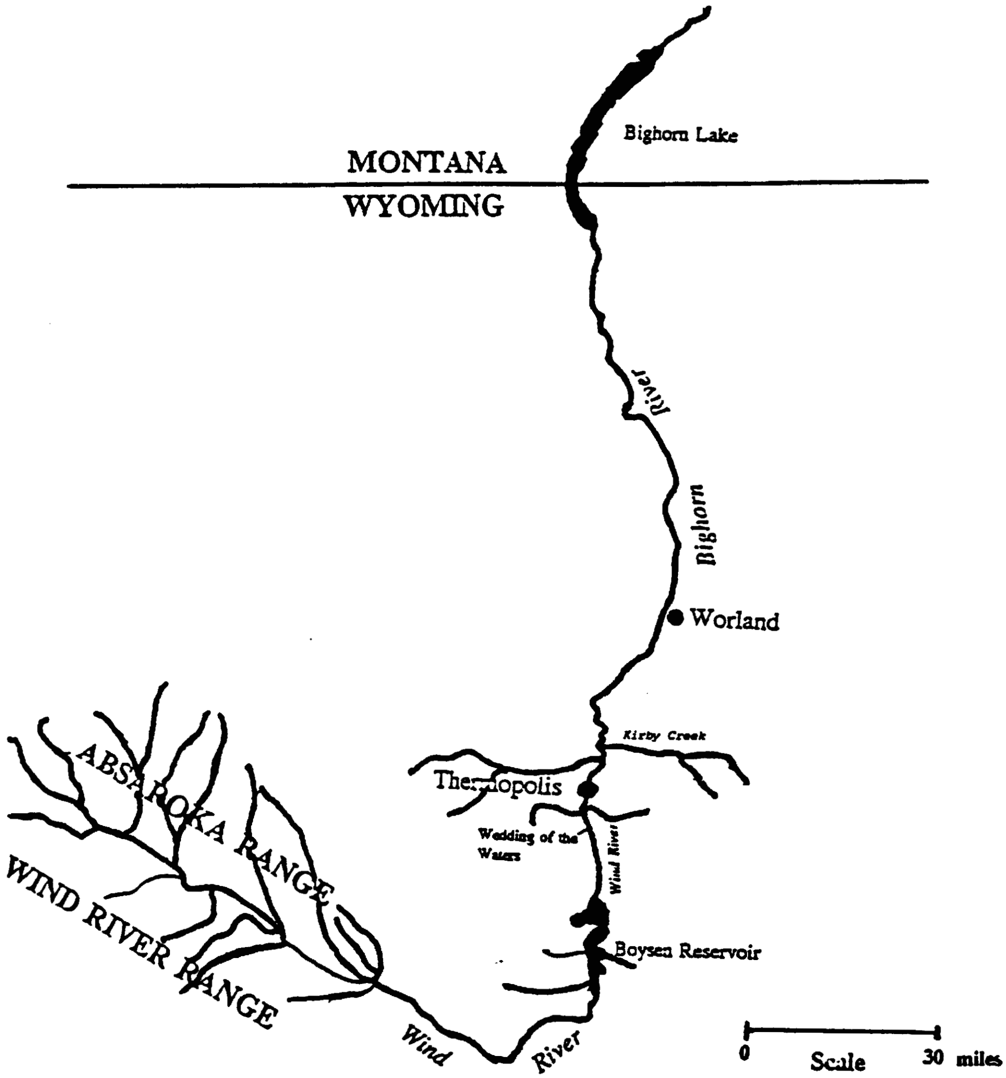



Figure 1. Map of Bighorn River, Wyoming.

The study reach (Wedding of the Waters downstream to Kirby Creek) is characterized by low gradient (Figure 2). The Wind River flows about 14-mi. through the Wind River Canyon before it reaches the Wedding of the Waters. As the river leaves the canyon the channel slope averages 0.39 percent. The lowest gradient occurs near Kirby Creek having a slope of 0.09 percent.

The WGFD classifies the Bighorn River from the northern boundary of the Wind River Reservation downstream to the mouth of Kirby Creek as a Class 1 - blue ribbon fishery (fishery of national importance). Less than 2% of all stream miles in Wyoming are classified as blue ribbon waters (Wolff and Wesche 1992).

Prior to Boysen Dam, the cutthroat trout was the only trout species native to the Bighorn River (Baxter and Simon 1970). Other salmonids were first stocked into the Bighorn River in 1953, one year following the construction of Boysen Dam. Recent estimates of rainbow trout and brown trout populations indicate large fluctuations (Table 1). Game species currently found include brown trout, several strains of rainbow trout and cutthroat trout, as well as mountain whitefish (*Prosopium williamsoni*), yellow perch (*Perca flavescens*), burbot (*Lota lota*), largemouth bass (*Micropterus salmoides*), walleye (*Stizostedion vitreum*) and sauger (*Stizostedion canadense*). Non game species include white sucker (*Catostomus commersoni*), mountain sucker (*Catostomus platyrhynchus*), longnose sucker (*Catostomus catostomus*), common carp (*Cyprinus carpio*), stonecat (*Noturus flavus*), northern redhorse (*Moxostoma macrolepidotum*), longnose dace (*Rhinichthys cataractae*), and emerald shiner (*Notropis atherinoides*, Steve Yekel WGFD, personal communication).

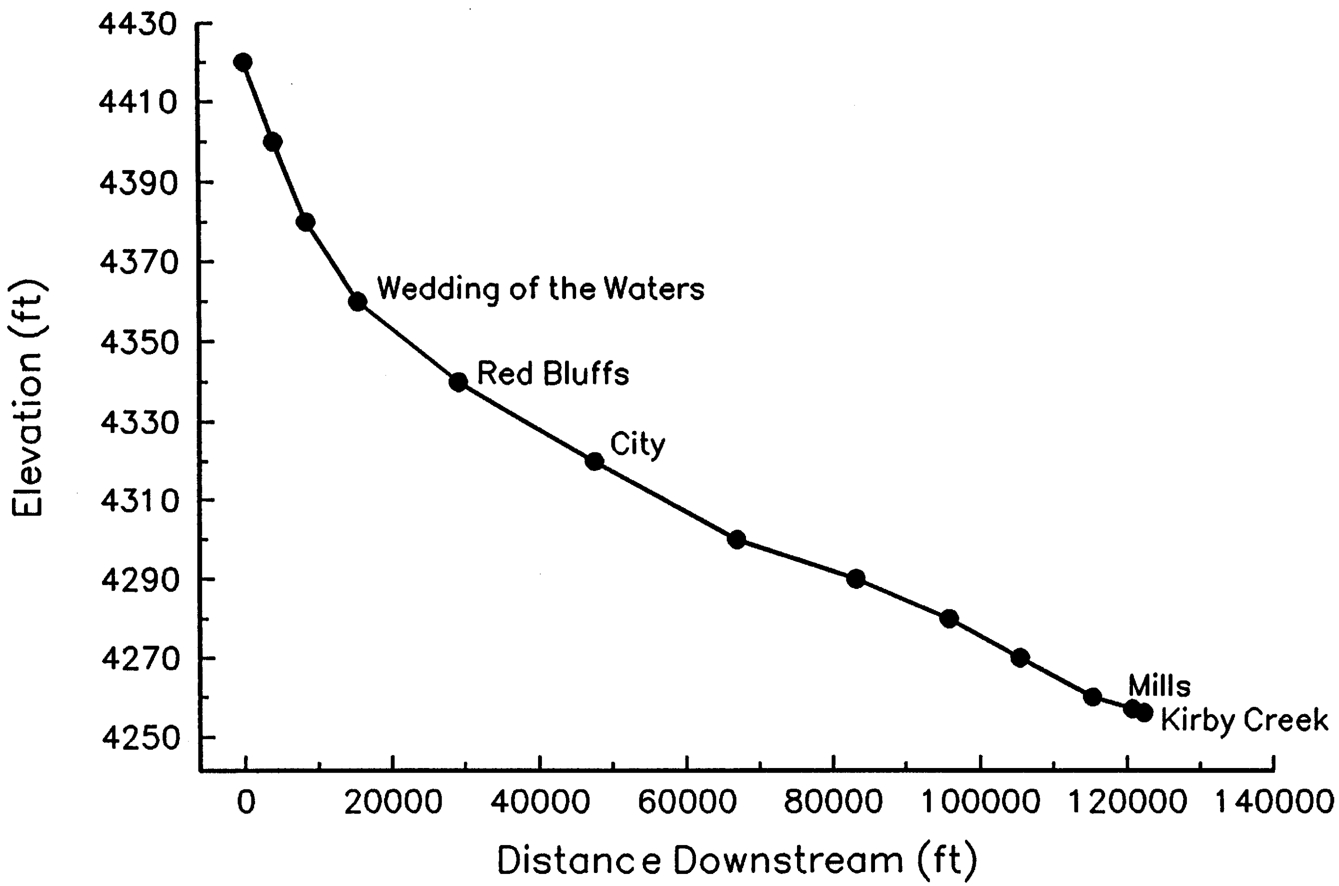



Figure 2. Channel profile of the Bighorn River from approximately three miles upstream of Wedding of the Waters to Kirby Creek.

Table 1. Population estimates in number of trout per mile, Bighorn River at Thermopolis, Wyoming 1980 - 1992. RBT = rainbow trout, BNT = brown trout, CTT = cutthroat trout.

| Sampling Date | RBT | BNT | CTT | Total |
|---|---|---|---|---|
| Nov. 1980 | 531 | 6 | | 537 |
| May 1984 | 318 | 39 | | 357 |
| Nov. 1984 | 2197 | 149 | | 2346 |
| May 1987 | 731 | 404 | 5 | 1140 |
| Oct. 1987 | 564 | 231 | 7 | 802 |
| Oct. 1988 | 1244 | 246 | 39 | 1529 |
| Oct. 1989 | 590 | 205 | 63 | 858 |
| Oct. 1990 | 638 | 98 | 57 | 793 |
| Oct. 1991 | 803 | 154 | 803 | 1760 |
| Oct. 1992 | 998 | 331 | 59 | 1388 |
| Oct. 1993 | 174 | 143 | 18 | 335 |
| Oct. 1994 | 728 | 442 | 126 | 1296 |

# CHAPTER III

# METHODS

This study concentrated on the section of river from the Wedding of the Waters downstream to Kirby Creek (Figure 3). Three primary study sites were selected in the fall of 1993, each representing the best potential spawning habitat for that section of river. The upstream most site was located at the Red Bluff secondary channel, 2.7-mi. downstream of the Wedding of the Waters and 0.6-mi. below the confluence of Buffalo Creek (NE 1/4 S13 T42N R95W). The middle site was the spawning area located in the City section of south Thermopolis, Wyoming, 5.3-mi. downstream of the Wedding of the Waters (SW 1/4 S1 T42N R95W and SE 1/4 S2 T42N R95W). The lower site was located north of Thermopolis, 20.3-mi. downstream of Wedding of the Waters and 0.3-mi. downstream of Black Mountain Bridge. Site selection was based upon the presence of spawning activity by brown trout and rainbow trout, relative quality of available spawning habitat, bed material characteristics, longitudinal coverage of the study reach, and hydraulic modelling criteria.

Secondary study sites were selected in the fall of 1993 and spring of 1994. One secondary study site was selected based upon the presence of brown trout redds and was located 0.8-mi. downstream of the Red Bluff Channel (NW 1/4 S13 T42N R95W). This secondary site was analyzed to develop suitability curves for brown trout. A second

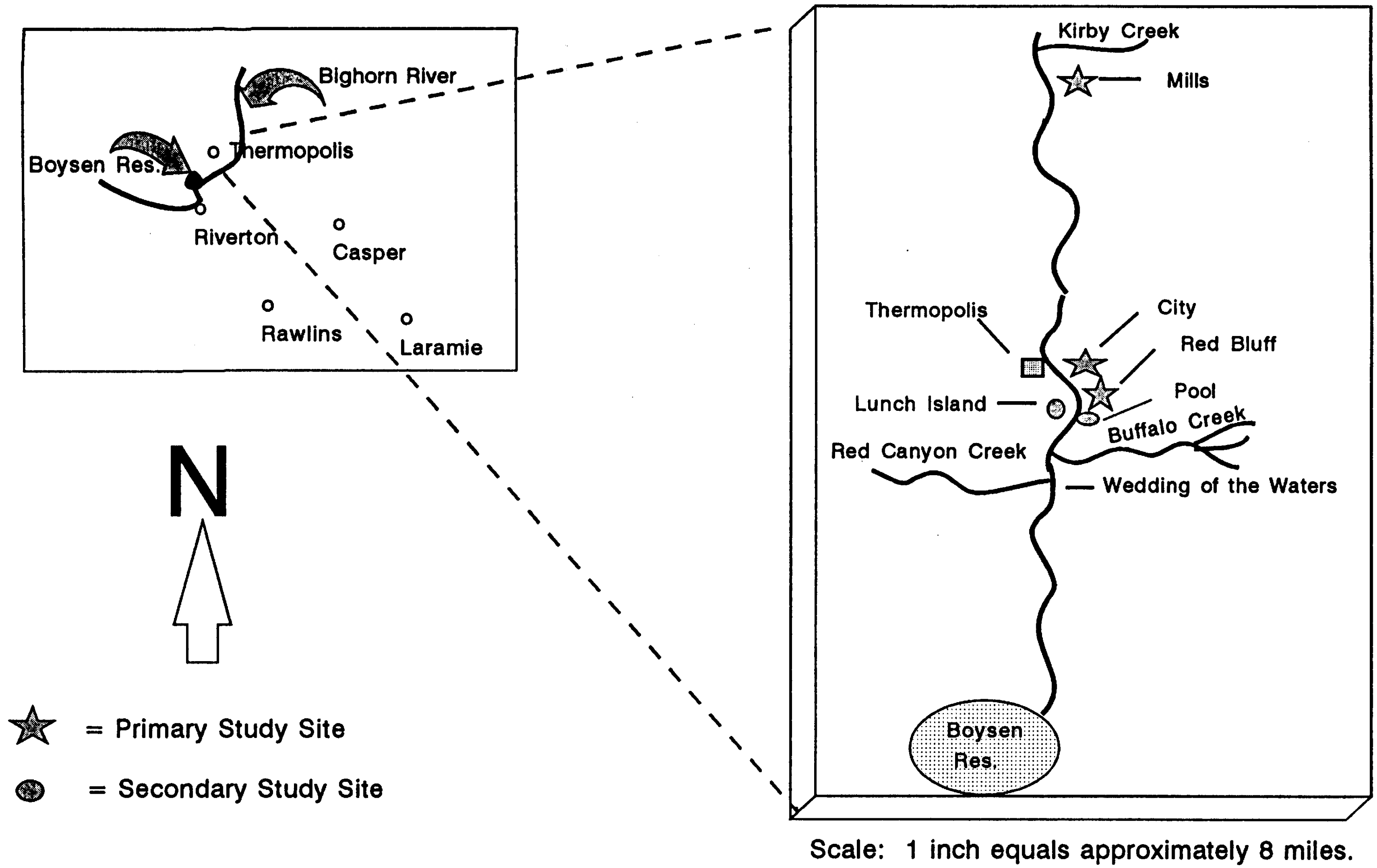



Figure 3. Map of the Bighorn River study reach, Wedding of the Waters to Kirby Creek.

secondary site was the large, deep pool located 0.3-mi. downstream of the confluence of Buffalo Creek and the Bighorn River (NE 1/4 S32 T44N R94W). This site was monitored to evaluate test flushing flow releases.

## Surface Hydrology

An analysis of the hydrology of the Bighorn River was undertaken to determine historic trends. The U.S. Geological Survey operates a recording stream gaging station just below Boysen Dam. Seasonal Steven's Model 'F' continuous stage recorders were installed at the three primary study sites to determine stage - discharge relations. Mean monthly flows, mean daily peak flows, seven-day low flows, and duration of mean daily flows from U.S. Geological Survey streamflow records obtained from the Wyoming Water Resources Center's Water Resource Data System (WRDS) were analyzed to determine hydrologic trends.

## Sediment Transport

Sediment transport was measured in the secondary channel at the City primary study site to evaluate the effectiveness of test flow releases for mobilizing bed material. This site was selected because it provides important spawning habitat for salmonids. Three permanent cross-channel transects were established to monitor both bedload and suspended load sediment transport on both the rising and falling limbs of the hydrograph. Because of limited manpower and equipment, sampling was confined to the lower transect. At that transect a tag line was stretched across the river to determine its width.

The width of the river was divided by 21 to determine 20 equally spaced sampling points. Water depth, velocity, suspended sediment and bedload samples were collected at each transect.

At wadeable flows a Marsh-McBirney meter mounted on a topsetting rod was used for velocity measurements. Hand held USDH-48 suspended sediment samplers and Helley-Smith bedload samplers were also used at wadeable flows.

For unwadeable conditions a jon boat was fitted with a boom and crosspiece apparatus that attached to a cross-channel cable. The cable was anchored by a 4 in. steel post at both left and right banks. A cable and reel with a sounding weight attached was used to measure depth and a Marsh-McBirney Model 201 portable velocity meter was used for velocity measurements. Cross-sectional suspended sediment samples were collected using a USD-74 cable and reel sampler using the Equal Width Increment (EWI) technique (Edwards and Glysson 1988). A Helley-Smith sampler, requiring the use of a cable and reel (Emmett 1980), was used to collect bedload samples.

Suspended sediment samples were analyzed by the filtration method (U.S. Geological Survey 1977) with results reported in milligrams per liter (mg/l). Suspended load discharge ($Q_{sl}$) in tons/day was calculated using the equation developed by Edwards and Glysson 1988:

$$Q_{sl} = (0.0027)(Cs)(Qw)$$

where, Cs = sediment concentration (mg/l)

Qw = water discharge (cfs)

0.0027 = a conversion constant

Bedload discharge (tons/day) was also calculated. Calculations of bedload discharge was based upon the weight of the sample, the width of the sample orifice, the top width of the transect at the time of sampling, the number of subsamples across the transect, and the total sampling time.

To quantify variation in daily suspended sediment transport, an ISCO Model 1680 automatic suspended sediment sampler was installed in the spring of 1994 at each of the three primary study sites as well as the Wedding of the Waters. The orifice of the ISCO suspended sediment samplers was placed approximately 3 in. from the stream bottom. This allowed for samples to be taken at a wide variety of discharges. Samplers were programmed to take hourly samples during the flushing flow and daily samples (at 1600 hours) the remainder of the season.

## Bed Material Dynamics

Twenty McNeil core samples (McNeil and Ahnell 1964) were collected before and after each test flow to evaluate temporal changes in intergravel fine sediment concentrations within important spawning locations (primary study sites). This is the most accurate device for assessing overall substrate composition (Young 1989). Sampling was limited to water depths less than 2 ft. due to the height of the McNeil sampler. Once samples were collected they were transferred to a 5-quart plastic bucket, labelled, and taken to the Watershed Laboratory in the College of Agriculture, University of Wyoming for further analysis.

Ten freeze core samples (Walkotten 1976), the only type of sample that allows the vertical stratification of a substrate sample and an assessment of changes in substrate composition with depth (Young 1989), were collected before and after each test flow. Freeze cores were collected at the primary study sites and analyzed in the same way as McNeil substrate samples.

At each primary study site, three transects were established in the secondary channel and one in the main channel. Bed elevations at each transect were plotted to monitor aggradation or degradation during the study. This was accomplished by measuring channel elevations using an engineer's level and stadia rod before and after test flows. Changes in channel geometry were also evaluated before and after test flows using an engineer's level and stadia rod.

Finally, the WGFD requested that a deep pool below the confluence of the Bighorn River and Buffalo Creek be monitored for any aggradation or degradation during the study. This was accomplished by measuring channel elevations before and after test flows. Changes in channel geometry were also evaluated before and after test flows.

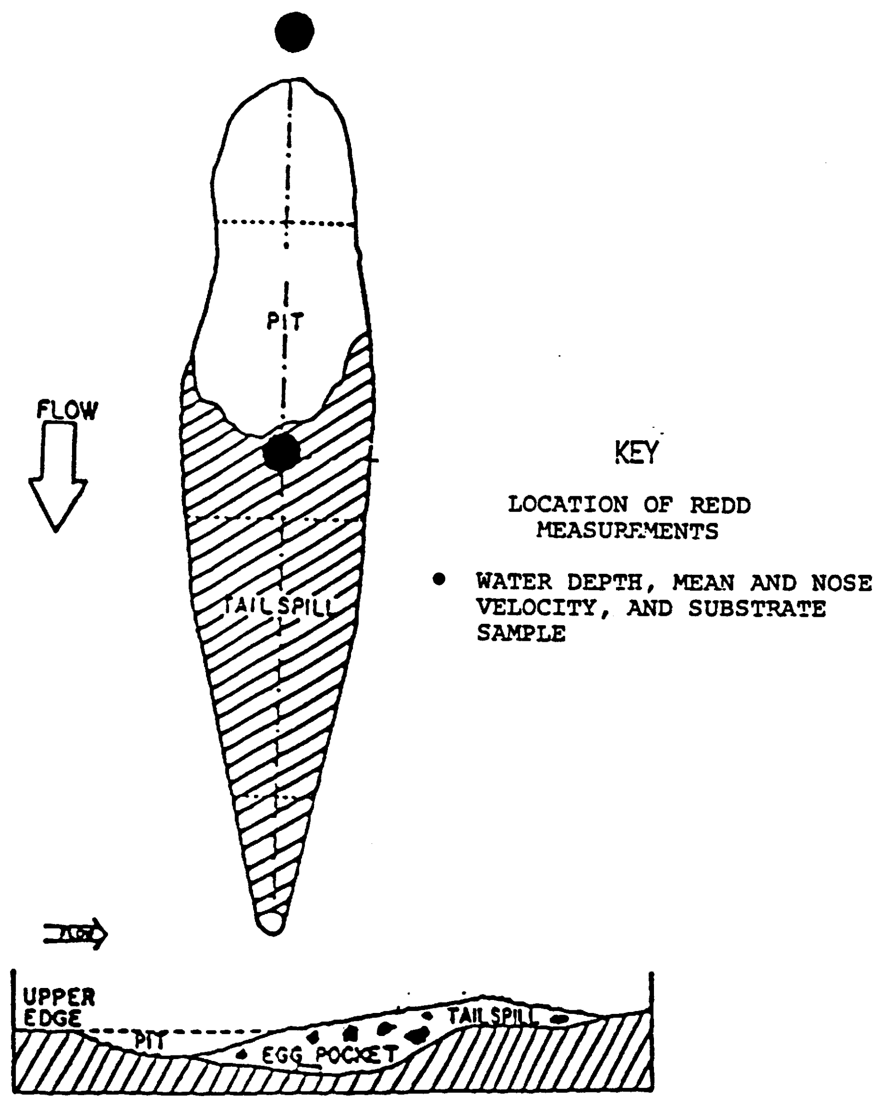
## Tributary Study

The WGFD has concern about the amount of sediment entering the Bighorn River and has identified two tributaries (Red Canyon and Buffalo creeks) that may contribute large quantities into the mainstem. To quantify the amount of sediment entering the Bighorn River, a study site near the mouth of each tributary was established. At each site a multiple-stage suspended sediment sampler and crest gage were installed. All key elevations of the suspended sediment sampler were surveyed to develop stage - sediment discharge relations. Along a transect near the confluence of the Bighorn River, streamflow was measured and suspended sediment samples were also collected and analyzed. Methods for collection and analysis of these samples were presented in the section entitled **Sediment Transport**.

## Redd Analysis

The WGFD has identified several areas of the river that have previously exhibited brown trout and rainbow trout spawning. During the fall of 1993, spring of 1994 and fall of 1994, I observed those areas as well as other sections of the river to locate trout redds. Identification of redds were based upon clearly defined areas that had a definite pit and tailspill and the presence of spawning fish.

McNeil core samples were used to determine the bed material composition of redds. Samples were taken from the upstream portion of the tailspill to represent materials mobilized by spawning trout (Grost *et al.* 1991; Reiser and Wesche 1977; Wenzel 1993) and at the head of the pit at each redd to represent unaltered conditions (Figure 4). Comparison of the samples provided insight regarding the amount of fine sediment moved during spawning activities. In addition to the amount of fines moved during spawning, fredle indices were calculated using the following equation (Chapman 1988):




LONGITUDINAL SECTION OF TROUT REDD
(MODIFIED FROM HOBBS 1937 AND WENZEL 1993)

Figure 4. Location of redd measurements.

| | | |
|---|---|---|
| $f_i$ | = | $d_g$ / $S_o$ |
| $d_g$ | = | geometric mean diameter, $(d_{16}d_{84})^{0.5}$; |
| $d_{16}$,$d_{84}$ | = | the substrate diameters at the 16% and 84% of cumulative sample weight. |
| $S_o$ | = | a sorting coefficient, $(d_{75}/d_{25})^{0.5}$; |
| $d_{75}$,$d_{25}$ | = | the substrate diameters at the 75% and 25% of cumulative sample weight. |

Additional McNeil core samples were taken at randomly selected locations within the most heavily utilized spawning channels. Random locations were selected using a grid system and a random numbers table. If the selected sampling location was too deep (> 2 ft.) or fell on a redd it was rejected. This allowed for a comparison between used and unused gravels. Analysis of McNeil core samples will be presented in the section entitled **Lab Analysis**.

Water depth, mean velocity, and nose velocity (0.2 ft. from the river bottom) were measured at each substrate sampling location (front of pit and tailspill). Data from the front of the pit was used to develop reach specific spawning suitability curves (Raleigh *et al.* 1984a) for habitat availability analysis. The Non-Parametric Tolerance Interval method (Bovee 1986) was used to develop curves. Percentiles of the data were calculated. A suitability index of 0 was assigned to the data minimum and maximum; 0.1 was assigned to the range of data that encompasses the 5th and 95th percentiles; 0.2 to the 10th and 90th percentiles; 0.5 to the 12.5th and 87.5th percentiles; and a 1.0

(optimum suitability) to the 25th and 75th percentiles (Bovee 1986). These data were also used to compliment similar information collected for rainbow trout on the North Platte River, Wyoming (Wenzel 1993).

## Spawning Flows

The Physical Habitat Simulation Model (PHABSIM) developed by the U.S. Fish and Wildlife Service (Bovee and Milhous 1978) was applied at the primary study sites to describe available spawning habitat and develop discharge - habitat relationships for the Bighorn River. From the transect data at the three primary study sites, weighted useable spawning area ($ft^2$. per 1000 ft. of channel) curves were developed using the HABTAE portion of PHABSIM. Substrate sizes were classified according to Instream Flow Incremental Methodology (IFIM) procedures (Table 2).

Table 2. Substrate categories and approximate particle size ranges (mm) within each category from Bovee (1986).

| Substrate Type | Class | Particle Size Range |
|---|---|---|
| Plant detritus | 1 | |
| Attached algae | 2 | |
| Clay | 3 | .00024 - .004 |
| Silt | 4 | .004 - .062 |
| Sand | 5 | .062 - 2.0 |
| Fine/medium gravel | 6 | 2 - 16 |
| Coarse gravel | 7 | 16 - 64 |
| Small cobbles | 8 | 64 - 128 |
| Large cobbles | 9 | 128 - 256 |

## Lab Analysis

All sediment samples were analyzed at the Watershed Laboratory in the College of Agriculture, University of Wyoming. Bedload, freeze cores and bed material (McNeil) core samples were oven dried, dry sieved, and weighed. All samples were sieved (mesh sizes; 75, 50, 25, 12.5, 6.3, 3.35, 2, 1, 0.5, 0.212, and 0 mm) and weighed to determine the particle size composition of each sample.

## Statistical Analysis

All statistical analyses were conducted using *STATISTIX 4.0* (Analytical Software 1992). A Kruskal-Wallis non-parametric one-way analysis of variance (ANOVA) was used to determine differences in particle size distributions ($d_{50}$, fredle index, and percent fines < 2.0 mm) among the primary study sites. The test was also used to determine differences in water depth, water velocity, and nose velocity among sampling locations. The Wilcoxon Signed Rank Test was used to determine if differences occurred between pits and tailspills at different spawning sites. The Mann Whitney U statistic was used to determine if differences occurred between random locations, pits, and tailspills.

The two-sample t-test was used to determine if differences in pre- and post-flushing flow pool elevations were significant. The test was also used to determine if differences in post and summer pool elevations were significant. The Wilcoxon Signed Rank Test was used to determine if differences in pre and post channel elevations were significant.

# CHAPTER IV

# RESULTS

## Surface Hydrology

The streamflow regime of the Bighorn River near Thermopolis has been altered by the construction of Boysen Reservoir. Historic flood peaks have decreased 66%, while baseflow conditions were enhanced 109% (Figure 5). Based upon USGS records, the average annual flow at the pre-Boysen gage (#06259500) near Thermopolis was 1,810 cfs. The average annual flow at the post-Boysen gage (#06259000), just downstream from Boysen Reservoir was 1,433 cfs. A significant portion of the decrease in total annual flow is due to the location of pre- and post-Boysen Dam USGS gaging stations, period of record and development of irrigated agriculture upstream of Boysen Reservoir (Scott Boelman, BOR, personal communication).

Flow duration curves for the Bighorn River are shown in Figure 6. Average annual flow prior to Boysen Reservoir was equalled or exceeded 23% of the time compared to 35% of the time after Boysen Reservoir construction. The 2-year, mean daily peak flow prior to Boysen Dam was 9,326 cfs and the 7-day, 5-year return period low flow was 325 cfs. Since completion of Boysen Dam the 2-year, mean daily peak flow has been reduced 76% to 2,279 cfs and the 7-day, 5-year return period low flow has increased 48% to 482 cfs (Figures 7 and 8).

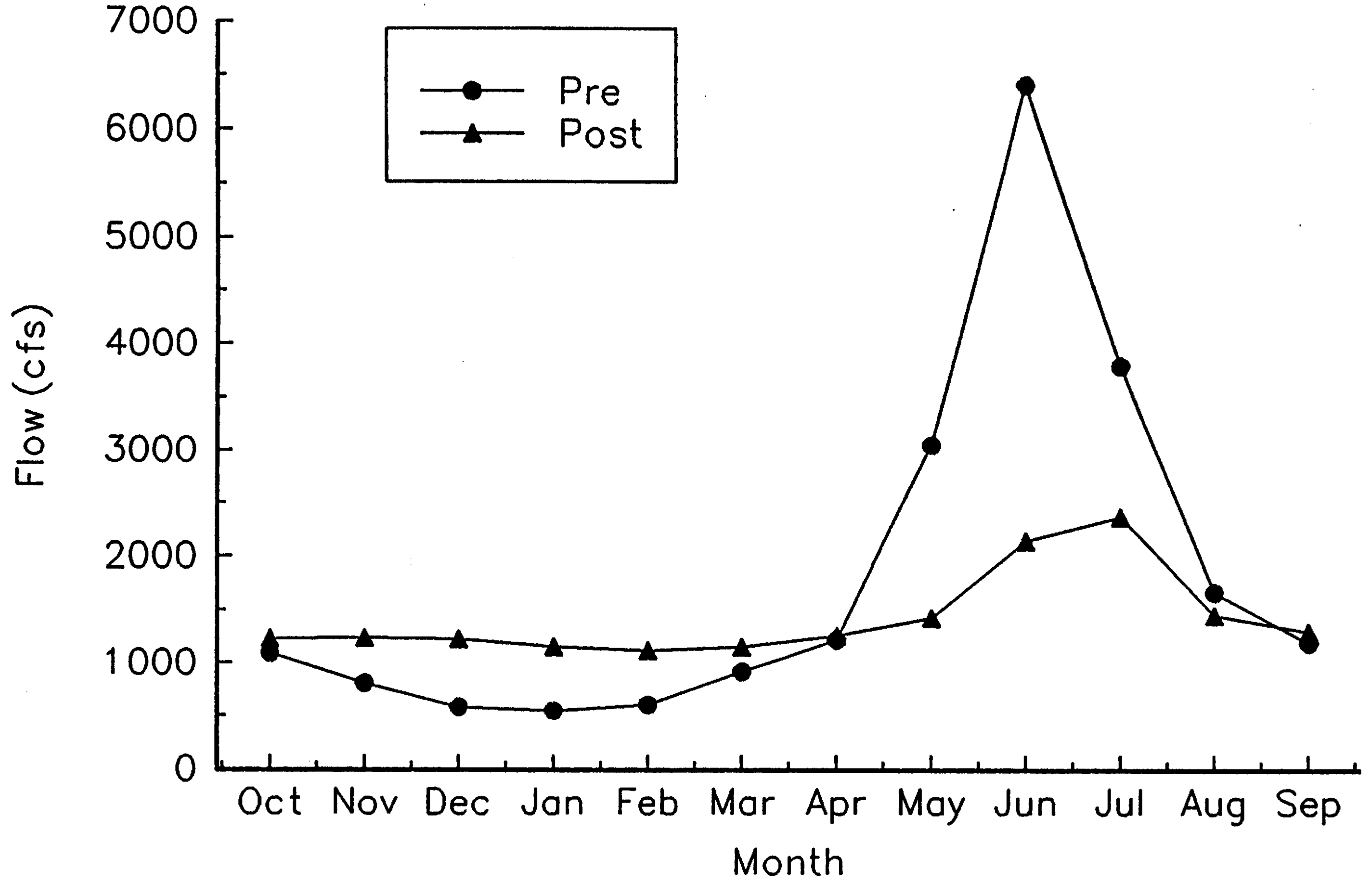



Figure 5. Mean monthly hydrographs for pre (water years 1912-1952, USGS #06259500) and post (water years 1953-1993, USGS #0625900) Boysen Dam, Bighorn River, Wyoming.

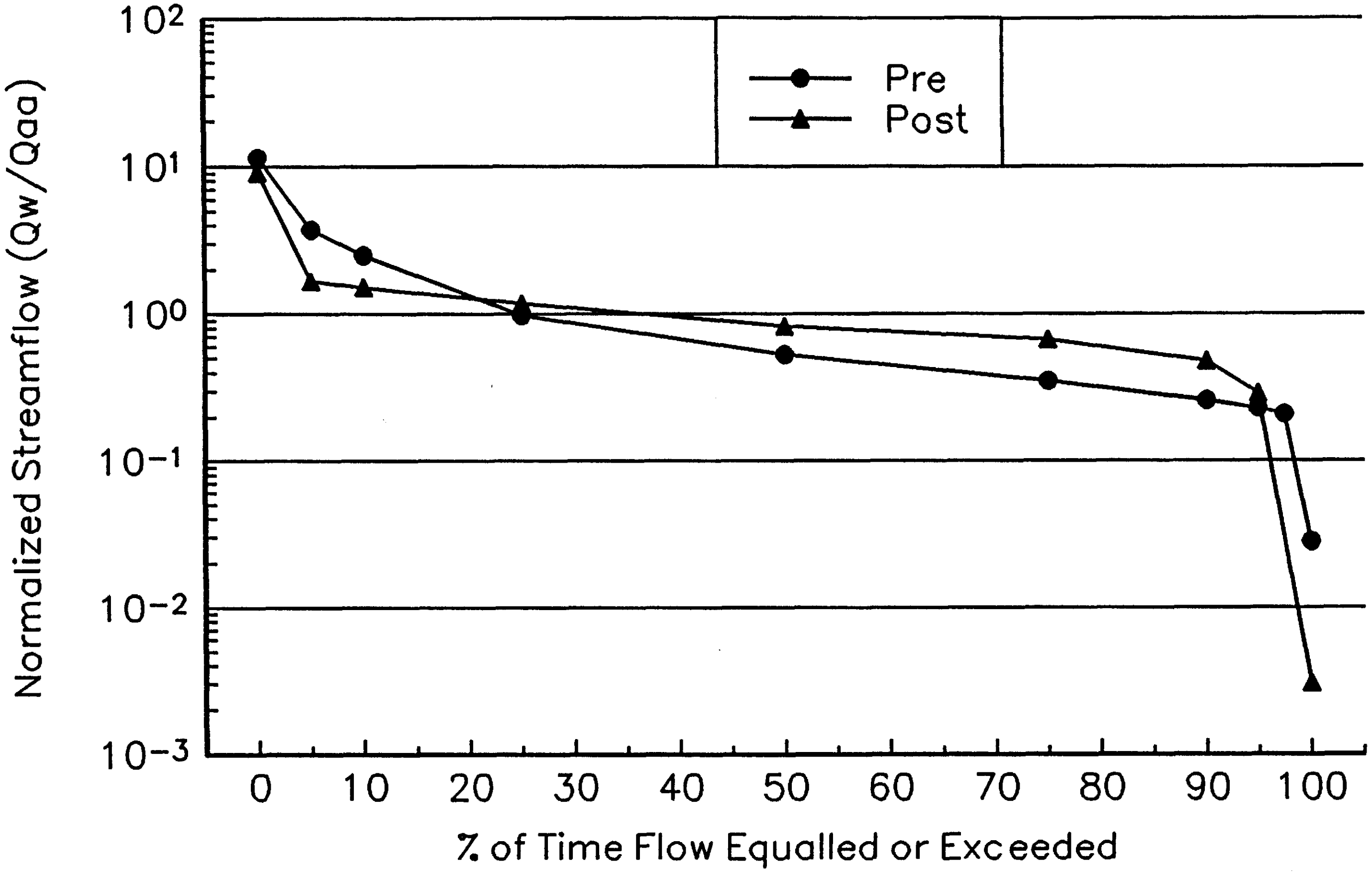



Figure 6. Normalized ($Q_w/Q_{aa}$) flow duration curves using mean daily data for pre and post Boysen Dam, Bighorn River, Wyoming.

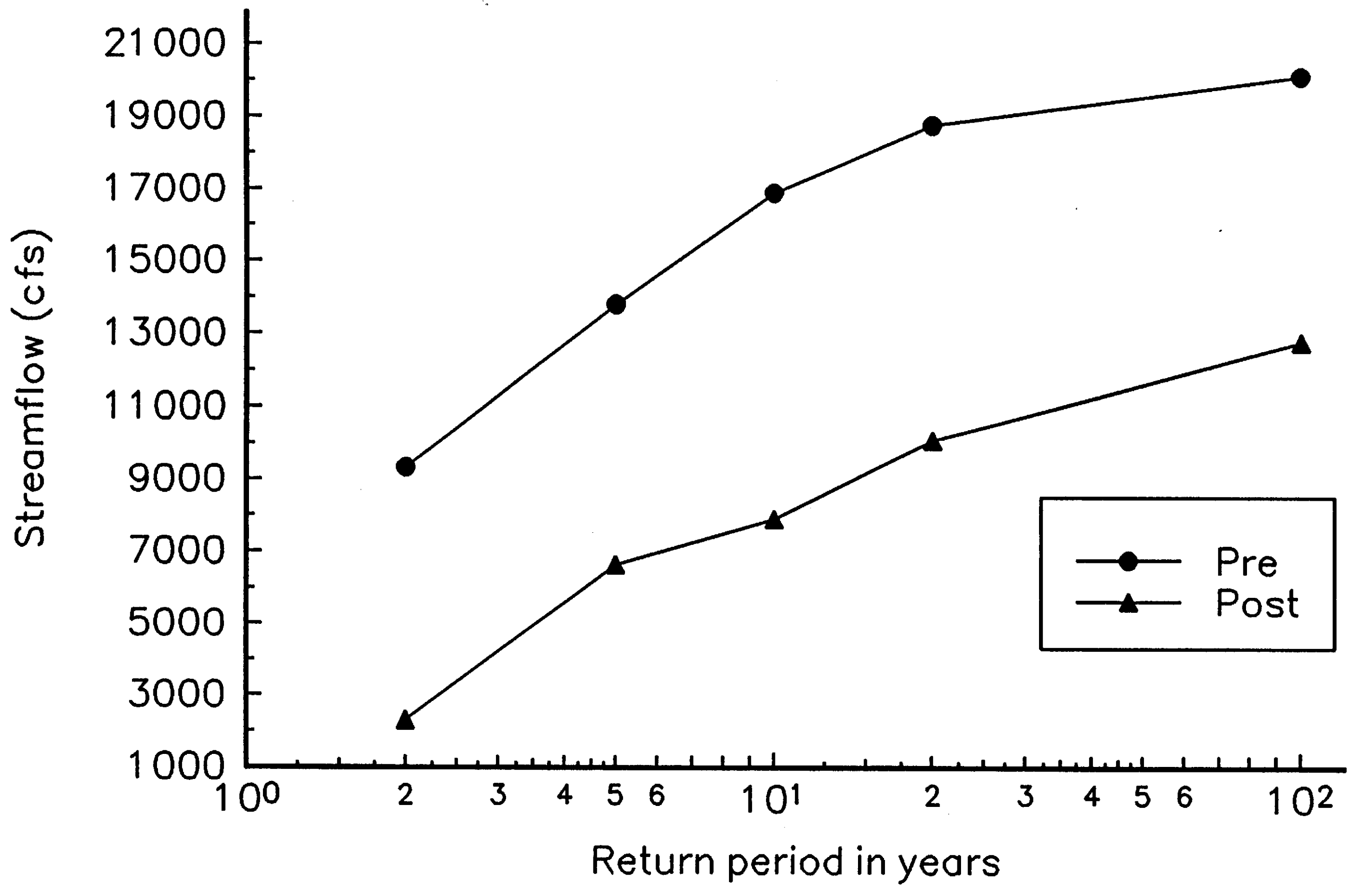



Figure 7. Mean daily peak flow frequency analysis for pre-Boysen and post-Boysen dam construction on the Bighorn River, Wyoming.

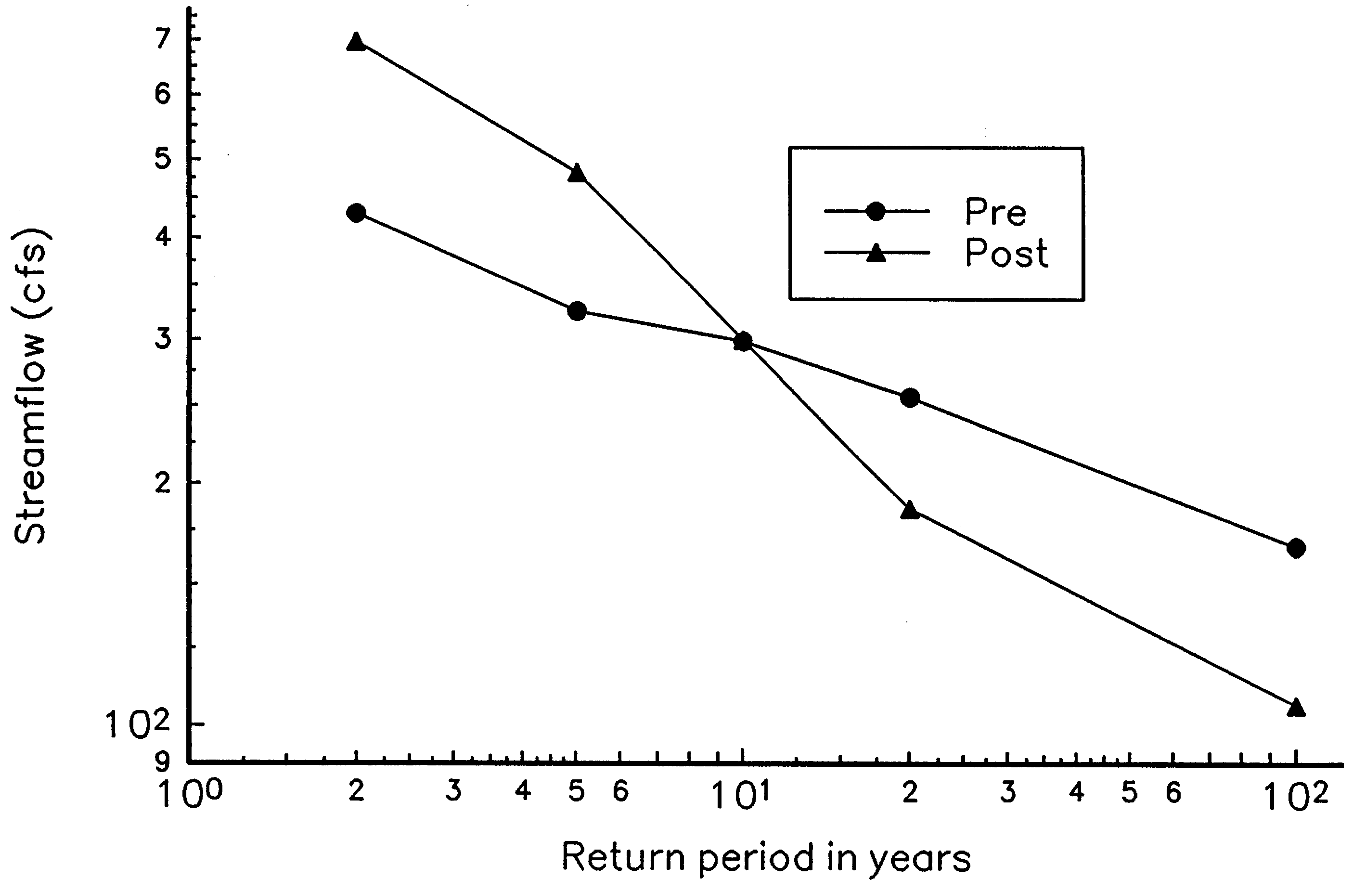



Figure 8. Seven day low flow frequency analysis for pre-Boysen and post-Boysen dam construction on the Bighorn River, Wyoming.

A test flow release peaking at 6,737 cfs was implemented and evaluated in March 1994. The total water volume required for the release was 20,600 acre feet (Figure 9). A peak of 6,737 cfs prior to Boysen dam was equalled or exceeded about 5% of the time compared to 2% of the time after Boysen Reservoir construction.

## Sediment Transport

### Suspended Sediment

Seasonal (April 1 - November 4, 1994) suspended sediment transport characteristics varied throughout the study reach (Figure 10 and Appendix A.). Suspended sediment concentrations decreased between Wedding of the Waters and the City site, while concentrations increased between the City and Mills sites. Average suspended sediment concentrations over the season ranged from 212 mg/l at Wedding of the Waters to 78 mg/l at the City site (Figure 10). Analysis of seasonal suspended sediment transport characteristics suggests that 430 tons of suspended sediment per day was deposited between the Wedding of the Waters and the City sites.

Significant differences were found among the suspended sediment concentrations at the four study sites during the March 1994 test release. The peak suspended sediment concentration at Wedding of the Waters was nearly 3.5 times greater than the peak concentration at the Red Bluffs site (Table 3). Suspended sediment concentrations at 3 sites, excluding Wedding of the Waters, peaked as the flow increased from 3,000 to 4,600 cfs (Table 3). At the Wedding of the Waters, suspended sediment concentrations peaked as the flow increased from 4,600 to 6,737 cfs (Figures 11, 12, 13 and 14).

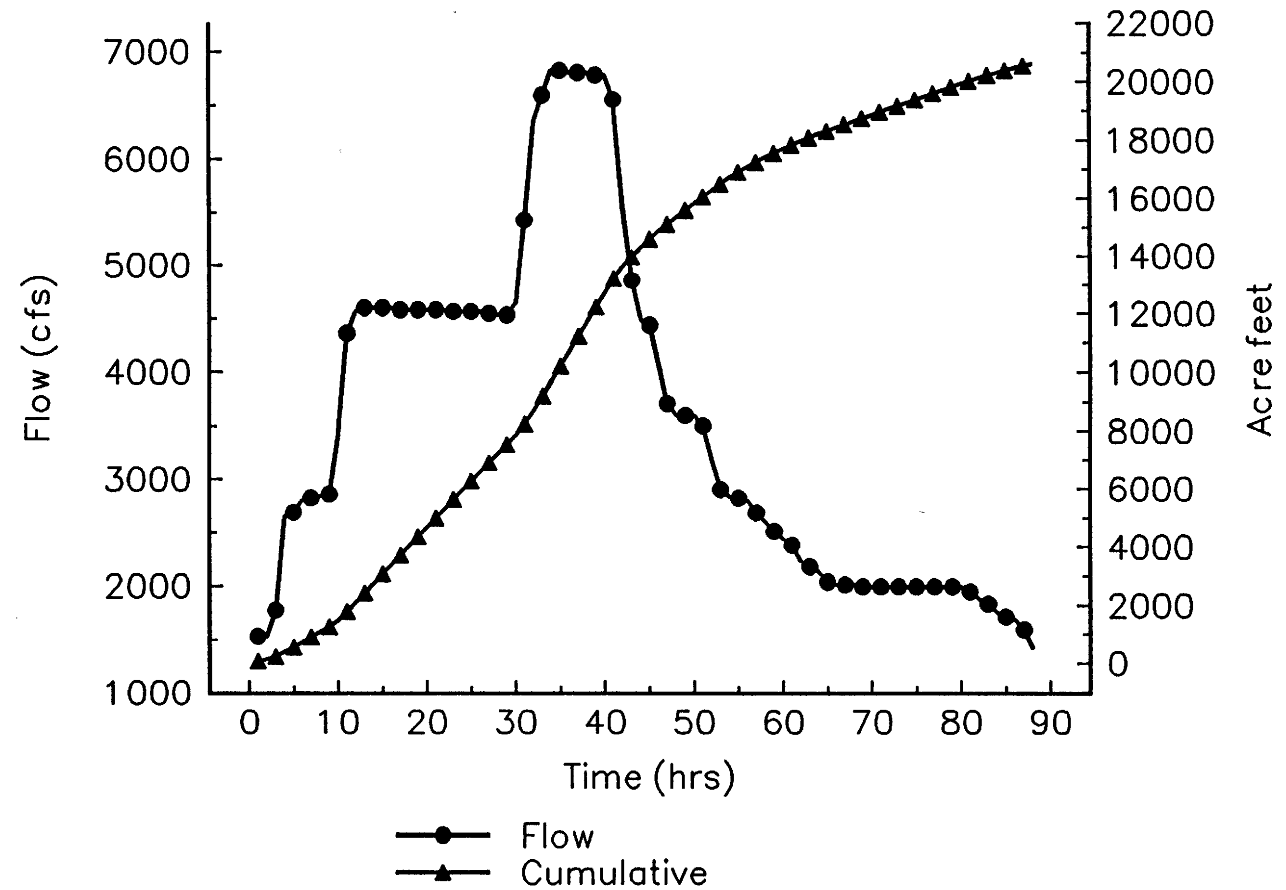



Figure 9. Hourly hydrograph and cumulative flow plot (AF) for March 1994 flushing flow release, Bighorn River, Wyoming.

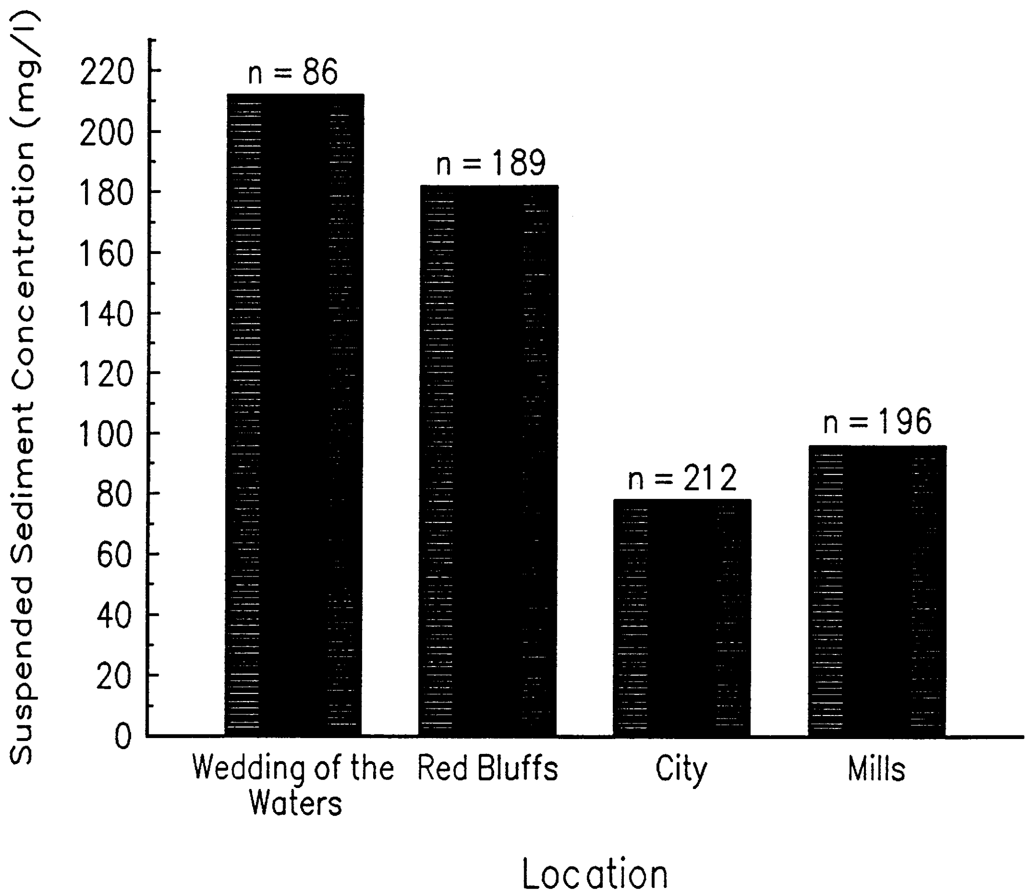



Figure 10. Average suspended sediment concentrations (mg/l) for the four study sites on the Bighorn River, Wyoming.

Table 3. Peak suspended sediment concentrations (mg/l) at two flows during test release (March 1994) at the four study sites, Bighorn River, Wyoming.

| Site | 4,600 cfs | 6,737 cfs |
|---|---|---|
| Wedding of the Waters | 1,129 | 1,469 |
| Red Bluffs | 433 | 183 |
| City | 141 | 115 |
| Mills | 464 | 276 |

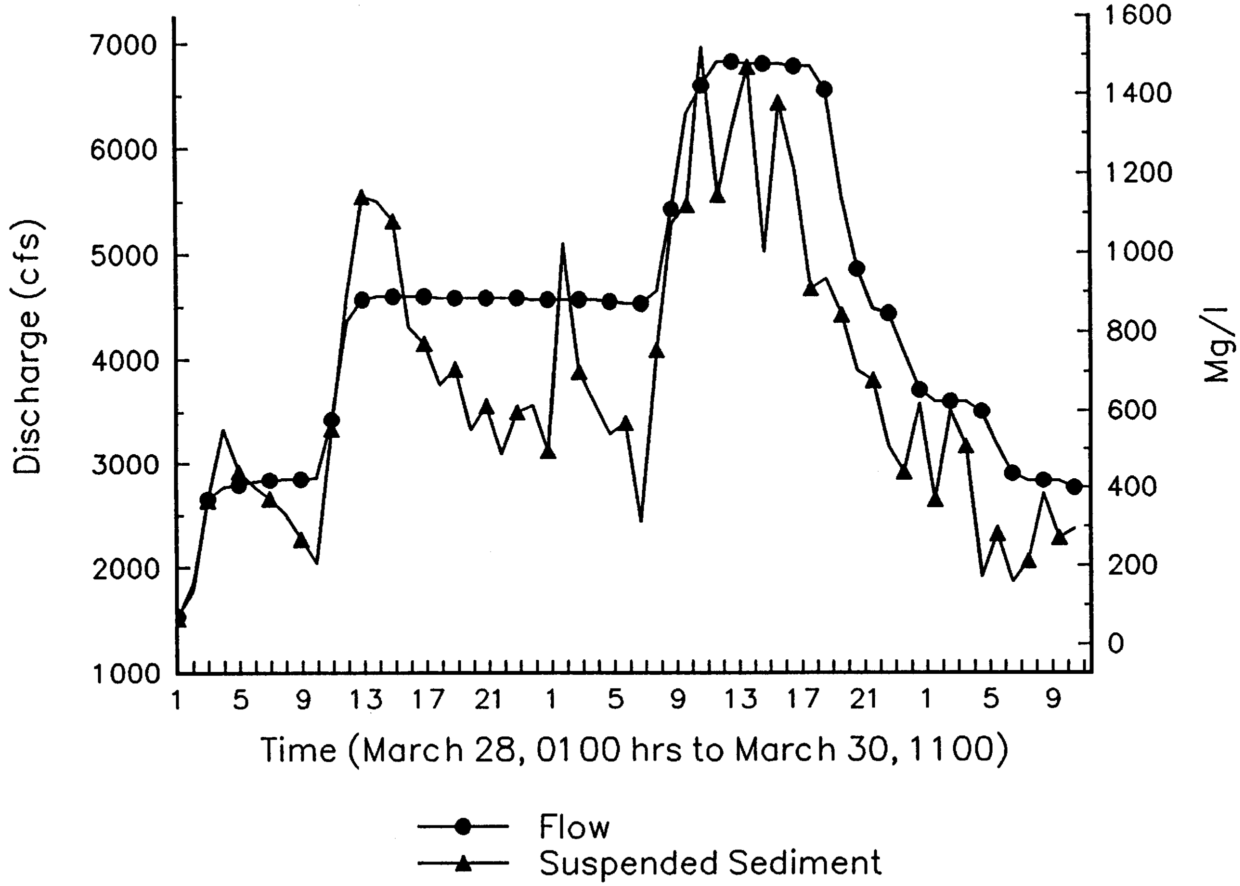



Figure 11. Mean hourly hydrograph and suspended sediment concentrations (mg/l) for Wedding of the Waters, Bighorn River, Wyoming, March 28 - 30, 1994.

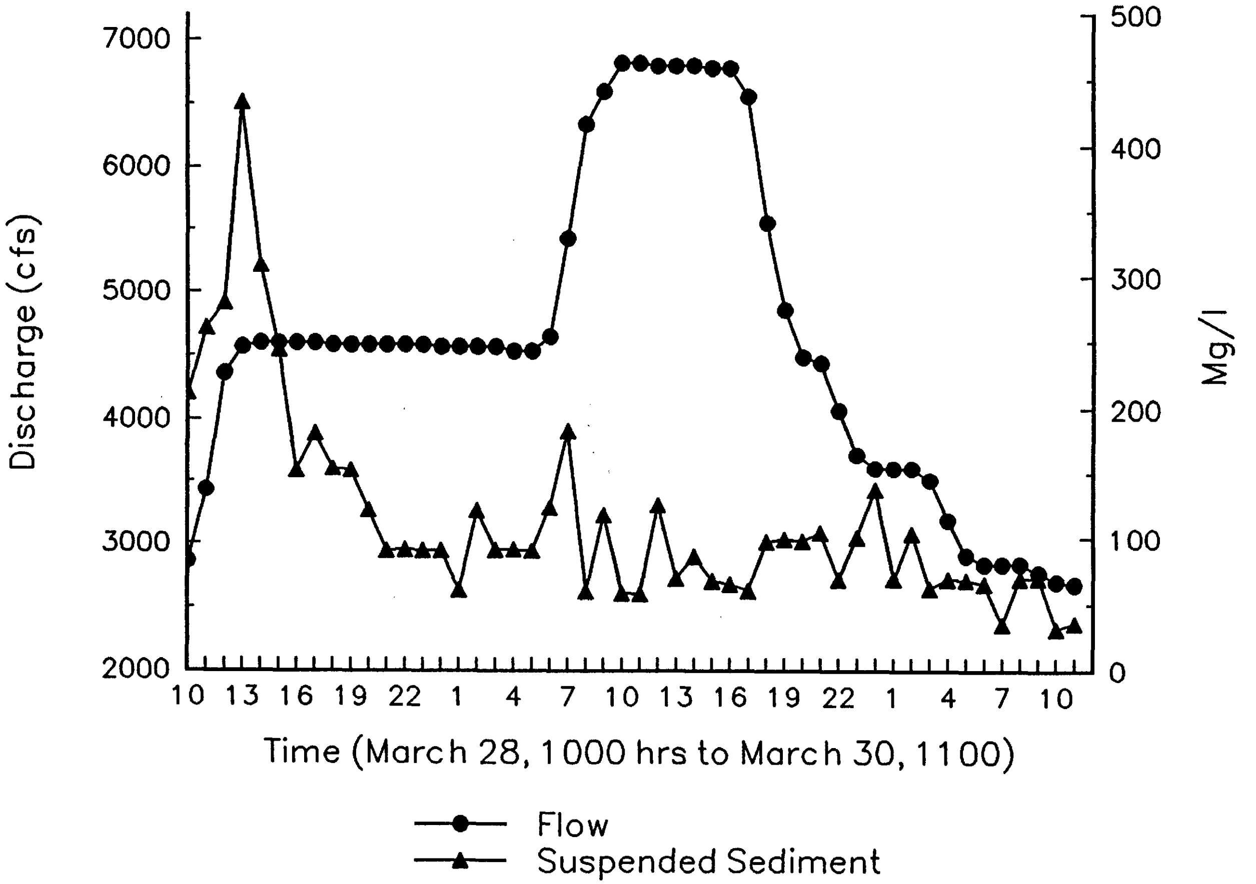



Figure 12. Mean hourly hydrograph and suspended sediment concentrations (mg/l) for the Red Bluffs Main Channel, Bighorn River, Wyoming, March 28 - 30, 1994.

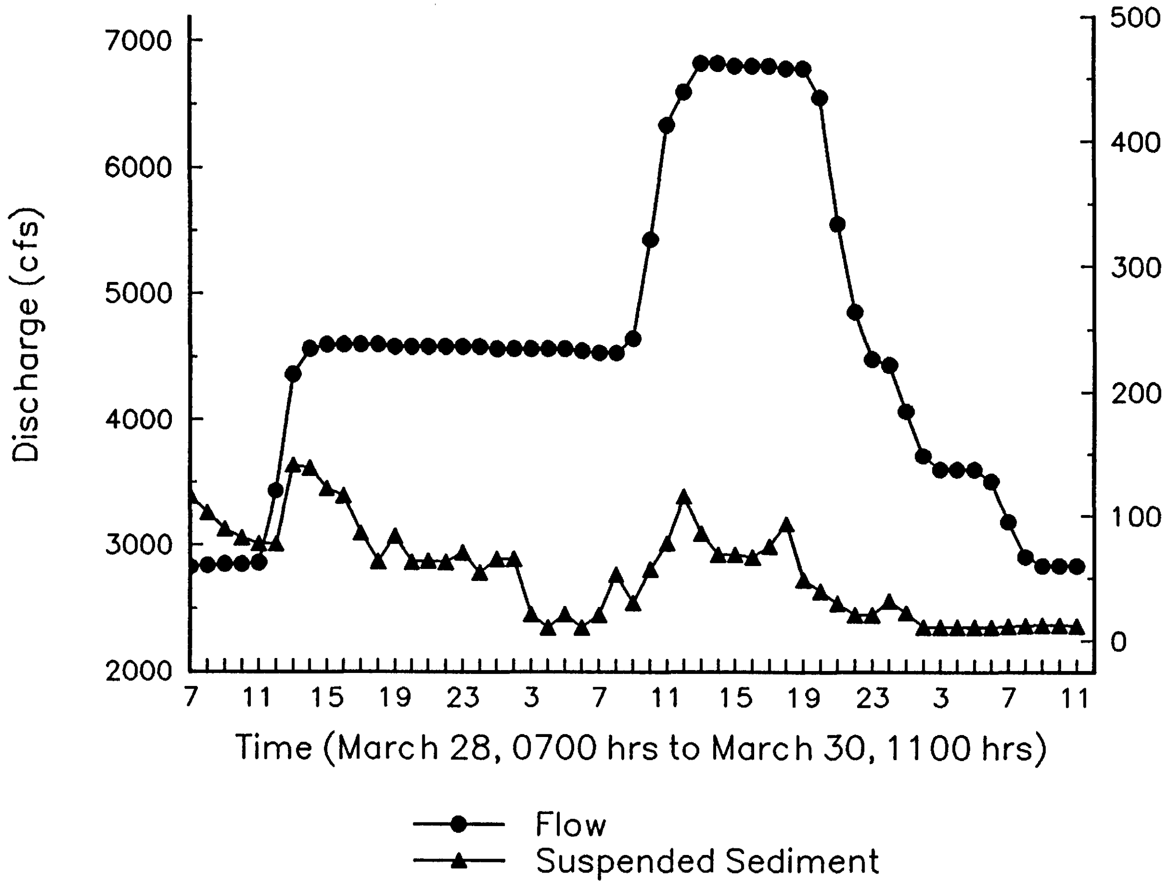



Figure 13. Mean hourly hydrograph and suspended sediment concentrations (mg/l) for the City Main Channel, Bighorn River, Wyoming, March 28 - 30, 1994.

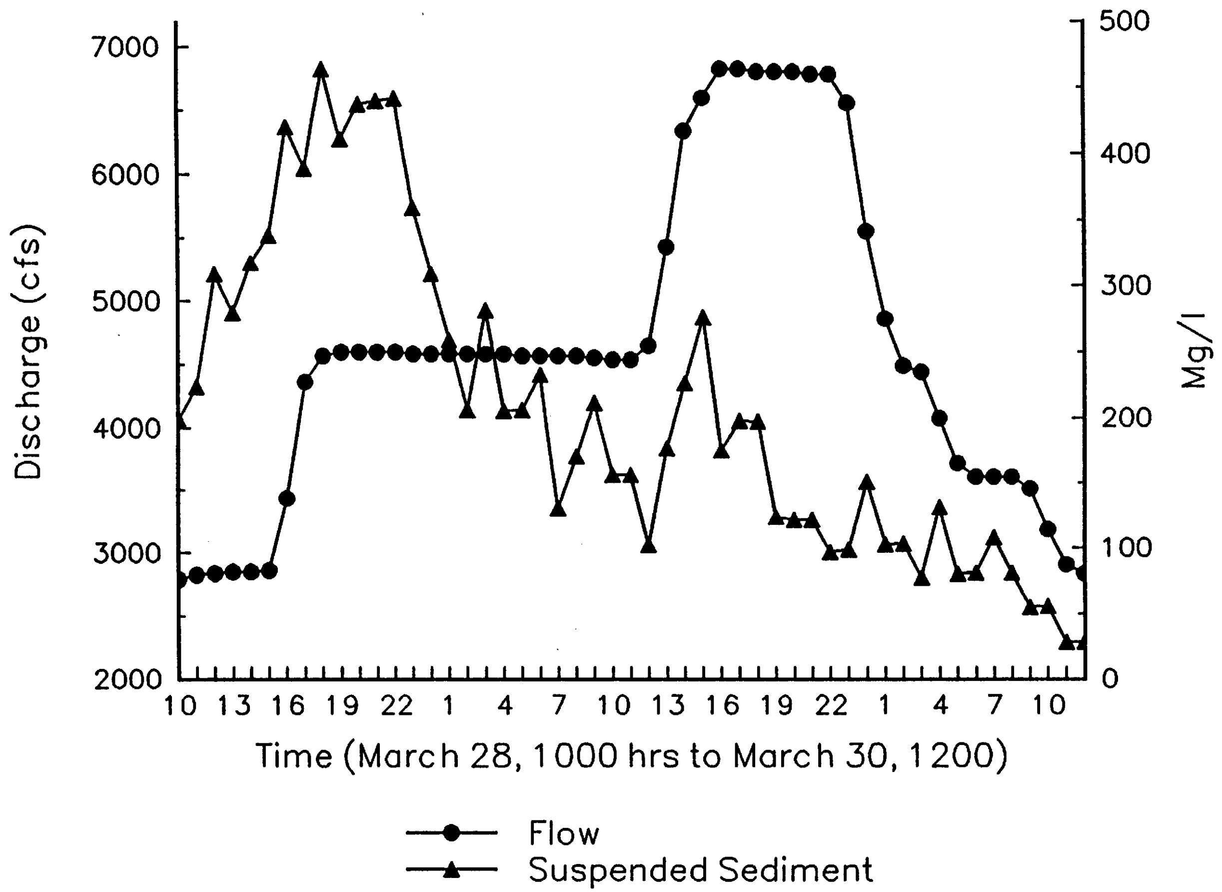



Figure 14. Mean hourly hydrograph and suspended sediment concentrations (mg/l) for the Mills Main Channel, Bighorn River, Wyoming, March 28 - 30, 1994.

Suspended sediment accounted for over 97% of the total load transported in the City secondary channel during the test release (Figure 15). Suspended sediment concentrations measured by the EWI method in the City secondary channel followed the same pattern as observed in the main channel. However, concentrations were slightly greater in the secondary channel. Different methods of sampling suspended sediment in the main channel and secondary channel could have accounted for this difference. As the flow increased from 250 to 1,800 cfs (3,000 to 4,600 cfs in the main channel) the suspended sediment concentrations peaked at 252 mg/l (Figure 16).

Analysis of the suspended sediment data suggests that about 17,400 tons of suspended sediment deposited between Wedding of the Waters and Red Bluffs during the test release. During the test release (1000 hrs on March 28 to 0800 hrs on March 30) 20,272 tons of suspended sediment was transported past the Wedding of the Waters site, 2,913 tons past the Red Bluffs site, 1,440 tons past the City site, 1,312 tons past the City secondary channel site, and 4,825 tons past the Mills site (Figures 17a, b). As the flow increased from 4,600 cfs to 6,737 cfs, the cumulative suspended sediment transported at the Wedding of the Waters, Red Bluffs, City, and Mills sites increased by approximately 162, 61, 64, and 93%, respectively.

## Bedload

Analysis suggests that bedload transport is a small portion (< 3%) of the total load. As shown on Figure 18, bedload transport rates ranged from 0.19 tons/day at base flow to 24.76 tons/day at peak flow in the City secondary channel. Bedload discharge

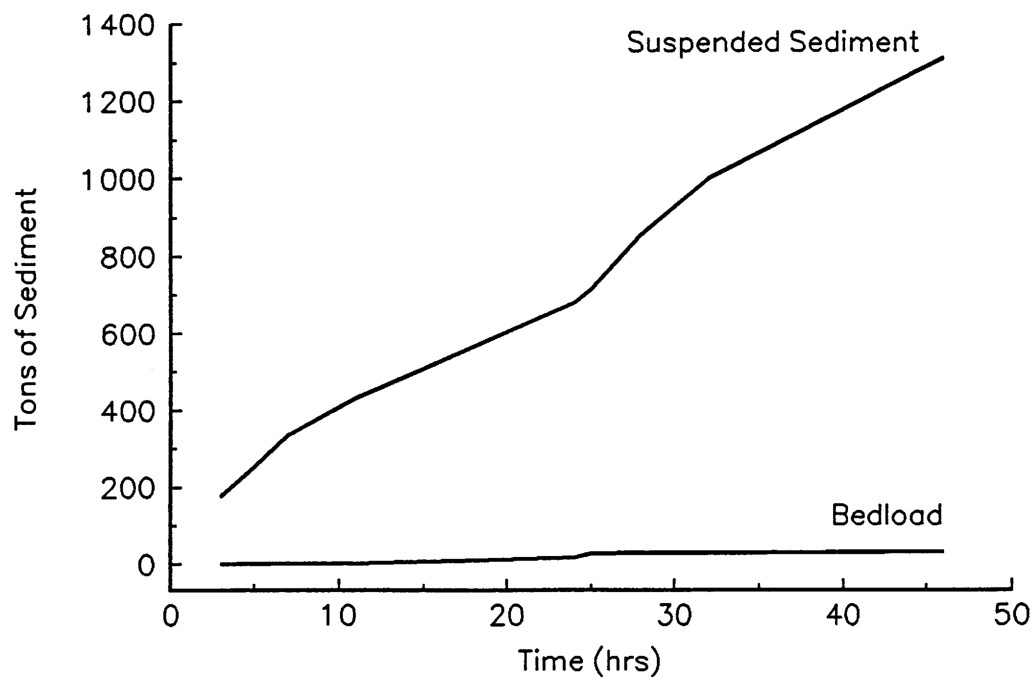



Figure 15. Sediment mass curves for bedload and suspended sediment transport for the City secondary channel during March, 1994 test flow release on the Bighorn River, Wyoming.

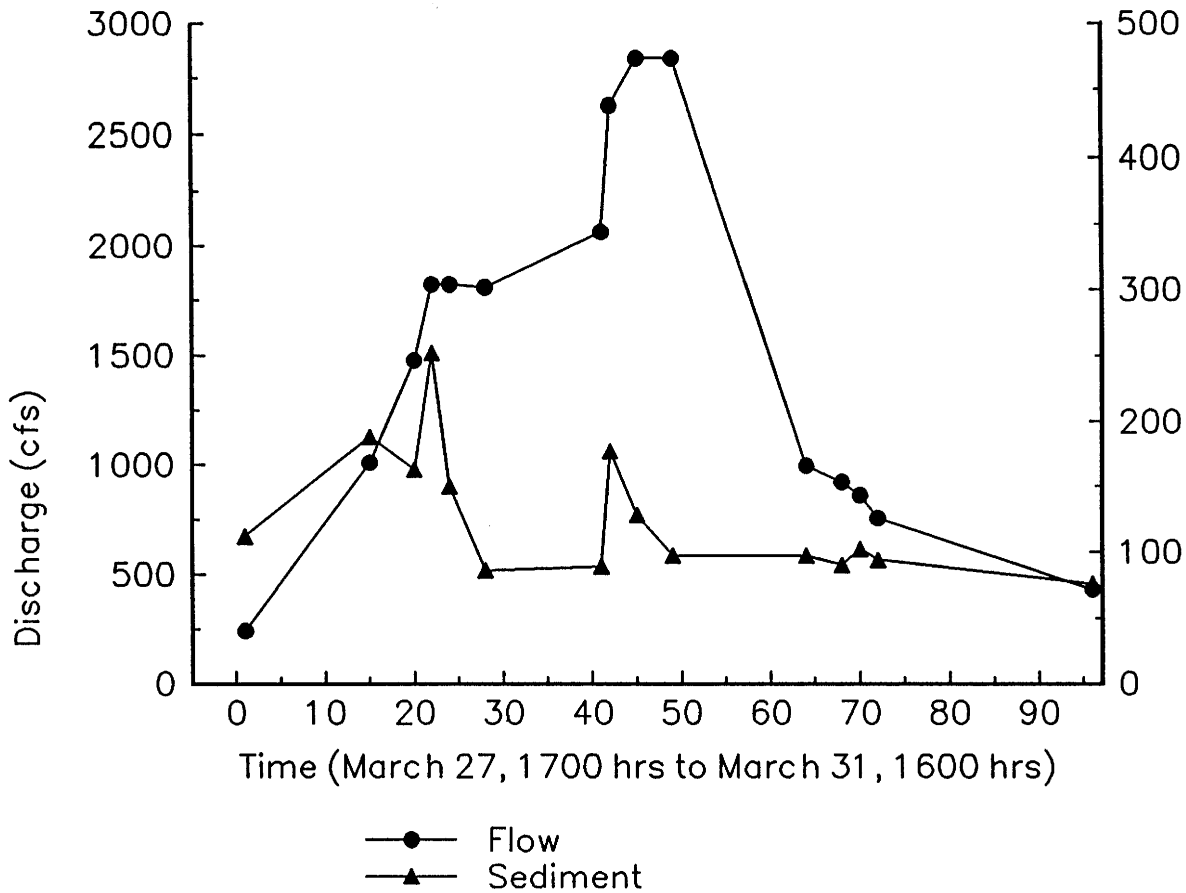
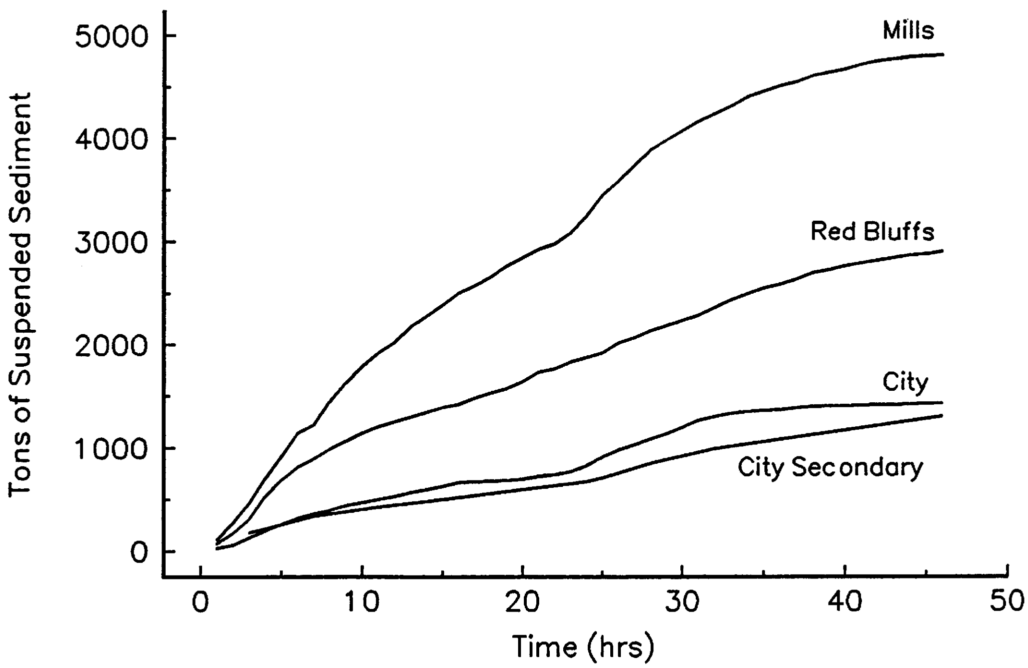



Figure 16. Hydrograph and suspended sediment concentrations (mg/l) for the City Secondary Channel, Bighorn River, Wyoming, March 27 - 31, 1994 (n = 15).

A.


B.




Figures 17a. and 17b. Sediment mass curves for the four study sites during March 1994 test flow release on the Bighorn River, Wyoming.

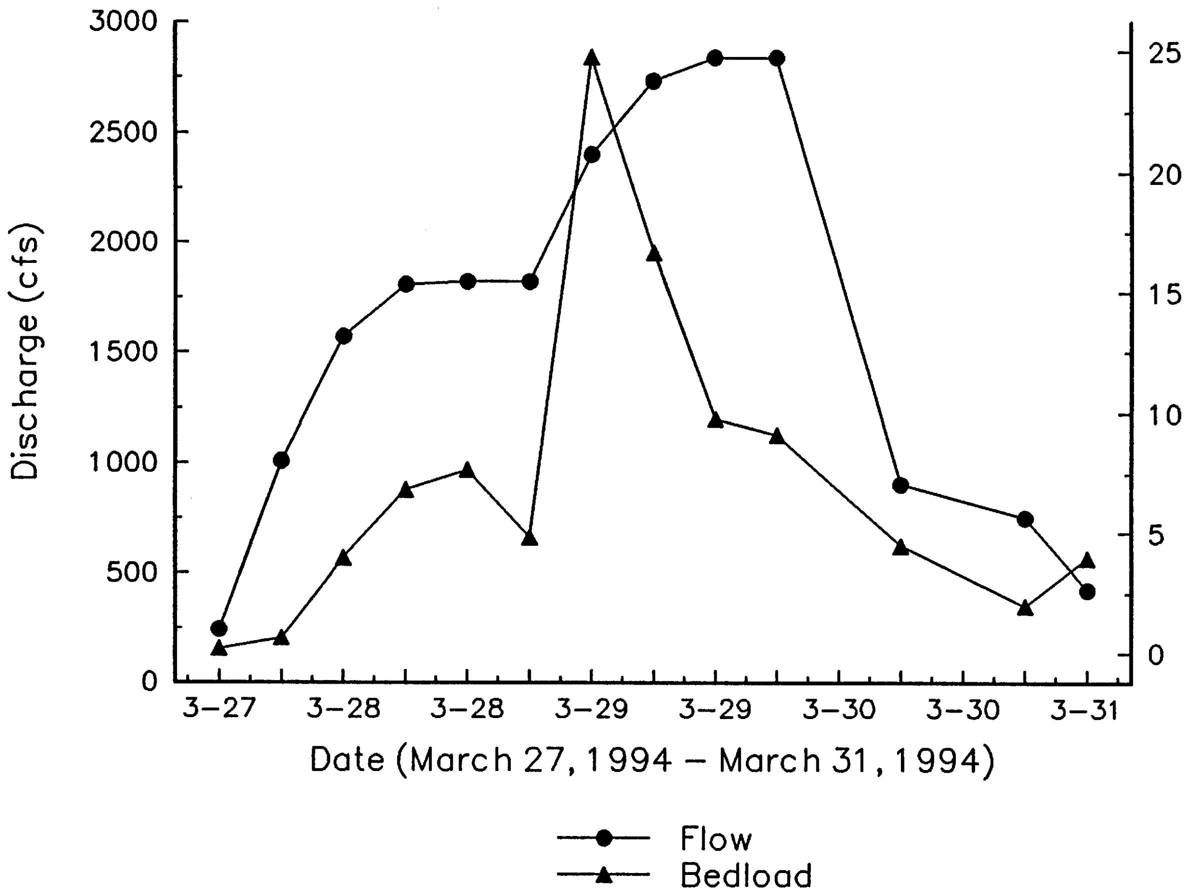



Figure 18. Hydrograph and bedload transport (tons/day) for the City Secondary Channel of the Bighorn River, Wyoming, March 27 - 31, 1994 (n = 13).

(tons/day) followed the pattern of the hydrograph and suspended sediment plot at the City secondary channel. However, peak bedload discharge occurred as the flow increased from 1,800 to 2,840 cfs (4,600 to 6,737 cfs in the main channel, Figure 18). The largest particle size collected in the bedload was 13.0 mm in diameter. Approximately 50% of the bedload was comprised of particles 2.0 mm or less (Figure 19). The $d_{50}$ peaked at 3.3 mm as the flow increased from 3,000 to 4,600 cfs (Figure 19).

## Bed Material Dynamics

### Substrate Samples

A significant difference was found between the pre- and post-release McNeil core data at the Mills site (Table 4). The $d_{50}$ increased from 18.2 to 27.0 mm, while the percent fines < 2.0 mm decreased from 22.4% (pre-release) to 18.8% (post-release). These findings suggest that substrate quality has been enhanced. The particle size distribution plots (Figure 20) suggest little change in the quality of the substrate at the Red Bluffs and City sites. No significant differences at the Red Bluffs and City sites occurred as a result of the test release (Table 4).

Comparison of the particle size distribution plots (Figure 20) suggests that the substrate is heterogenous between sites. The $d_{50}$ ranged from 8.2 mm at the City site to 27.0 mm at the Mills site, $f_i$'s ranged from 1.59 at the City site to 2.94 at the Mills site, while percent fines < 2.0 mm ranged from 18.5% at the Red Bluffs site to 27.4% at the City site (Table 4).

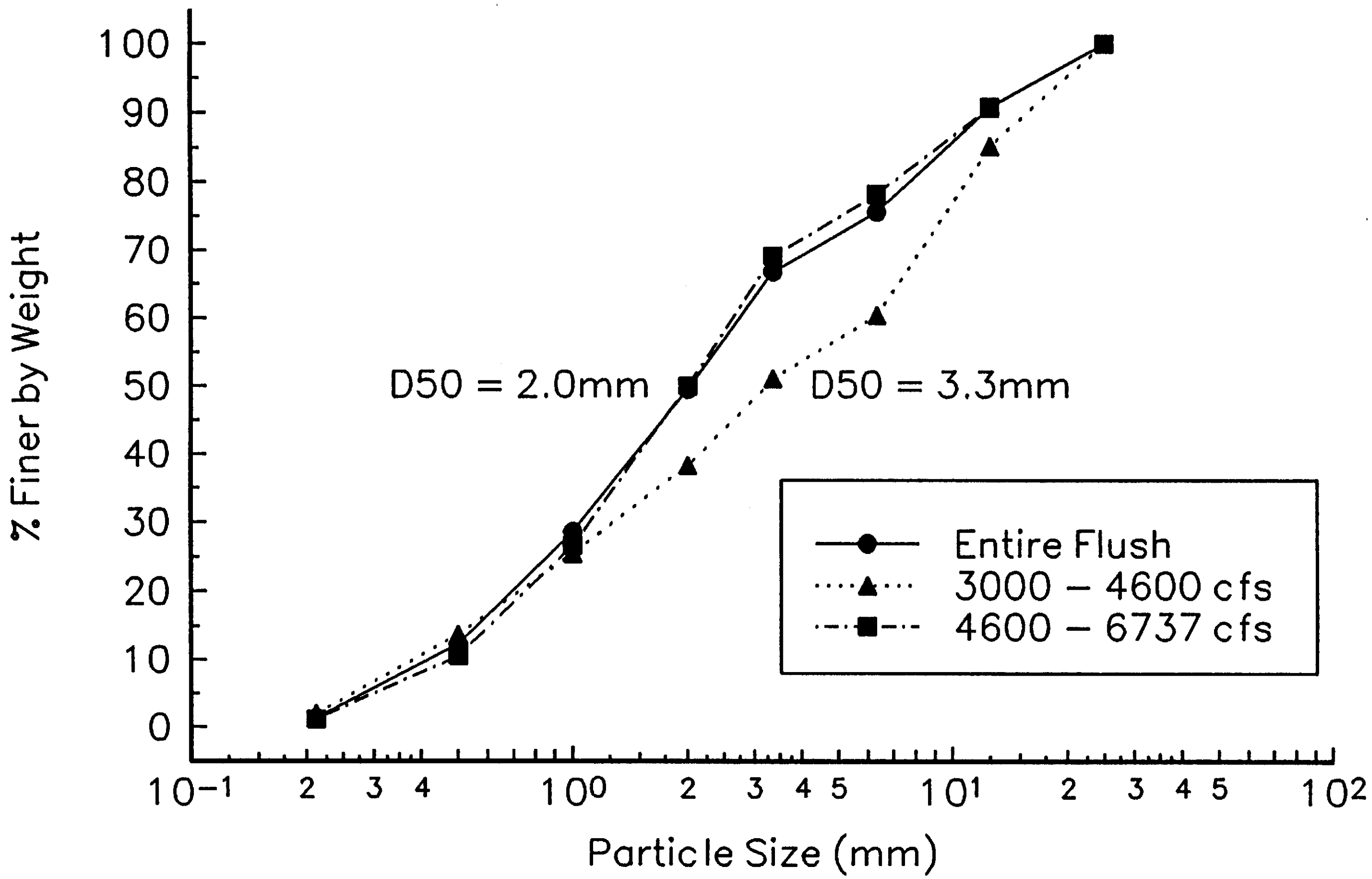
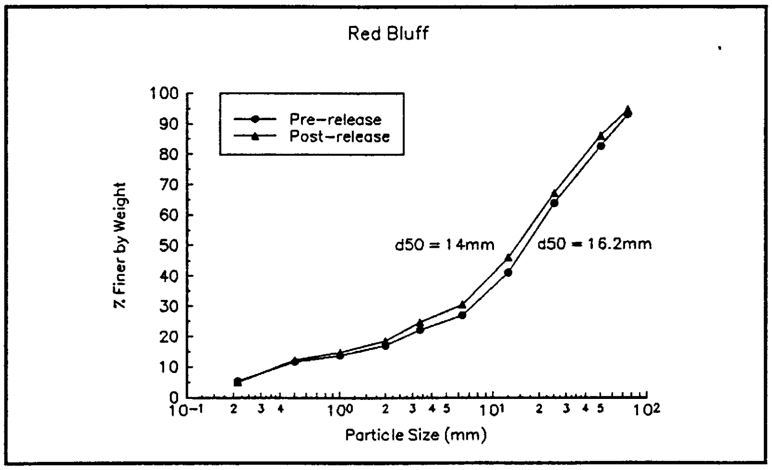


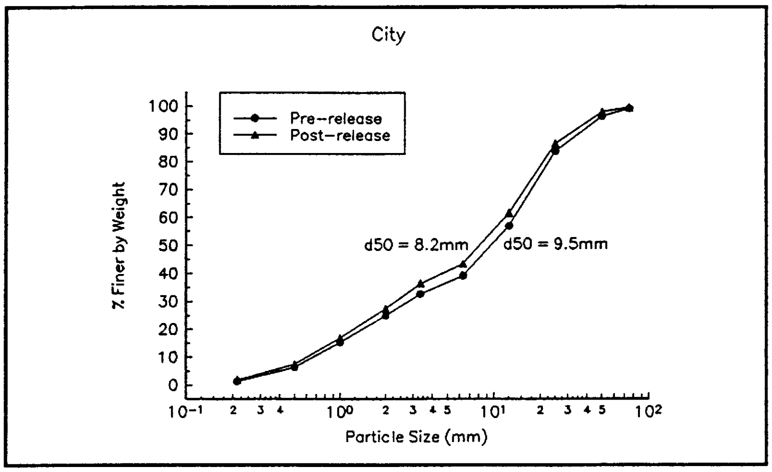

Figure 19. Particle size distributions for bedload samples collected at the City Secondary Channel during March 1994 test release, Bighorn River, Wyoming.

Table 4. Results of McNeil core samples collected pre (n = 20) and post (n = 20) March 1994 test release on the Bighorn River, Wyoming.

| Location | $d_{50}$ | Fredle Index | % fines < 2.0mm |
|---|---|---|---|
| Red Bluffs | | | |
| Pre Release | 16.2 | 3.51 | 17.0 |
| Post Release | 14.0 | 2.53 | 18.5 |
| P - value | (0.417) | (0.735) | (0.776) |
| | | | |
| City | | | |
| Pre Release | 9.5 | 1.71 | 24.9 |
| Post Release | 8.2 | 1.59 | 27.4 |
| P - value | (0.156) | (0.117) | (0.164) |
| | | | |
| Mills | | | |
| Pre Release | 18.2 | 1.73 | 22.4 |
| Post Release | 27.0 | 2.94* | 18.8* |
| P - value | (0.081) | (0.006) | (0.010) |

* = Statistically significant at $\alpha = .05$



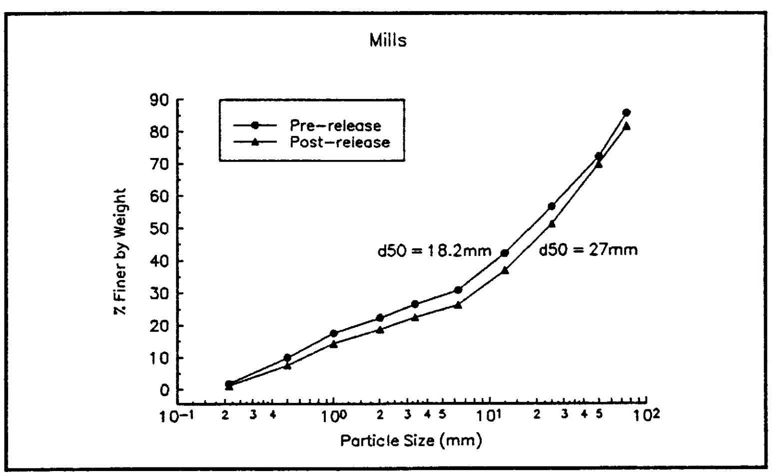




Figure 20. Particle size distributions for pre and post-release McNeil core samples collected at the Red Bluff, City, and Mills sites, Bighorn River, Wyoming.

Analysis of the freeze core data supports the McNeil core findings, indicating a significant difference between pre- and post-release values at the Mills site (Table 5). However, results from the freeze core data may provide better insight to the effect of the test release in comparison to the McNeil data, as they provide an undisturbed stratigraphic record and an assessment of changes in substrate composition with depth. The particle size distribution plots (Figure 21) suggest that the substrate quality of the Mills site has been enhanced. The $d_{50}$ increased from 15.5 to 24.0, while the percent fines < 2.0 mm decreased from 21.3% (pre-release) to 11.0% (post-release). The freeze core particle size distribution plots (Figure 21) suggest little change in the quality of the substrate at the Red Bluffs and City sites. No significant differences between pre- and post-release freeze core data at the Red Bluffs and City sites were observed (Table 5).

Analysis of the freeze core data suggests substrate heterogeneity among sites. The $d_{50}$ ranged from 11.5 mm at the City site to 24.0 mm at the Mills site, $f_i$'s ranged from 2.26 at the City site to 9.25 at the Red Bluffs site, while percent fines < 2.0 mm ranged from 11.0% at the Mills site to 19.8% at the City site (Table 5).

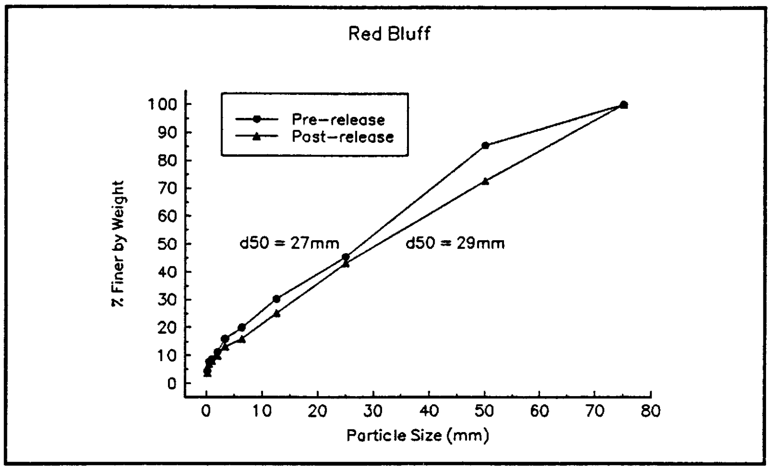
## Cross-section Channel Profiles

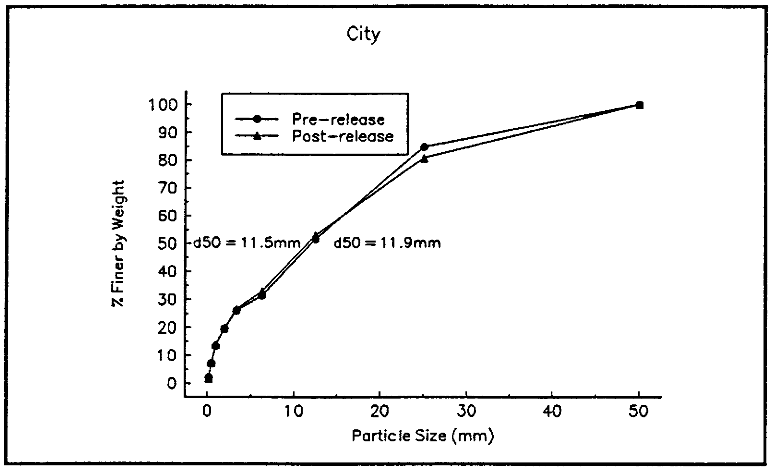
A significant difference was found between the pre- and post-bed elevations at the Red Bluffs and City main channel sites (Table 6). However, pre- and post-release bed surveys show only minor changes in depth in the main channel (less than 0.42 in.) (Figures 22 and 23).

Table 5. Results of freeze core samples collected pre (n = 10) and post (n = 10) March 1994 test release on the Bighorn River, Wyoming.

| Location | $d_{50}$ | Fredle Index | % fines < 2.0mm |
|---|---|---|---|
| Red Bluffs | | | |
| Pre Release | 27.0 | 6.14 | 11.2 |
| Post Release | 29.0 | 9.25 | 10.0 |
| | (0.970) | (0.571) | (0.734) |
| City | | | |
| Pre Release | 11.9 | 2.37 | 19.6 |
| Post Release | 11.5 | 2.26 | 19.8 |
| | (0.701) | (0.701) | (0.791) |
| Mills | | | |
| Pre Release | 15.5 | 1.98 | 21.3 |
| Post Release | 24.0* | 7.57* | 11.0* |
| P - value | (0.034) | (0.002) | (0.002) |

* Statistically significant at $\alpha = .05$



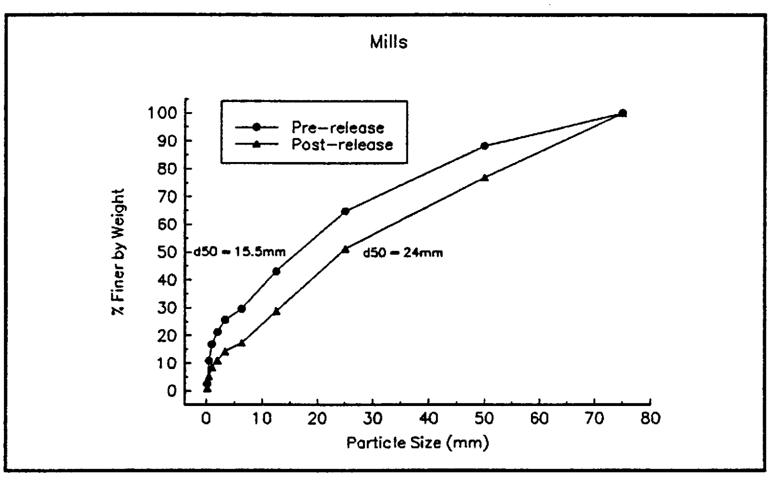
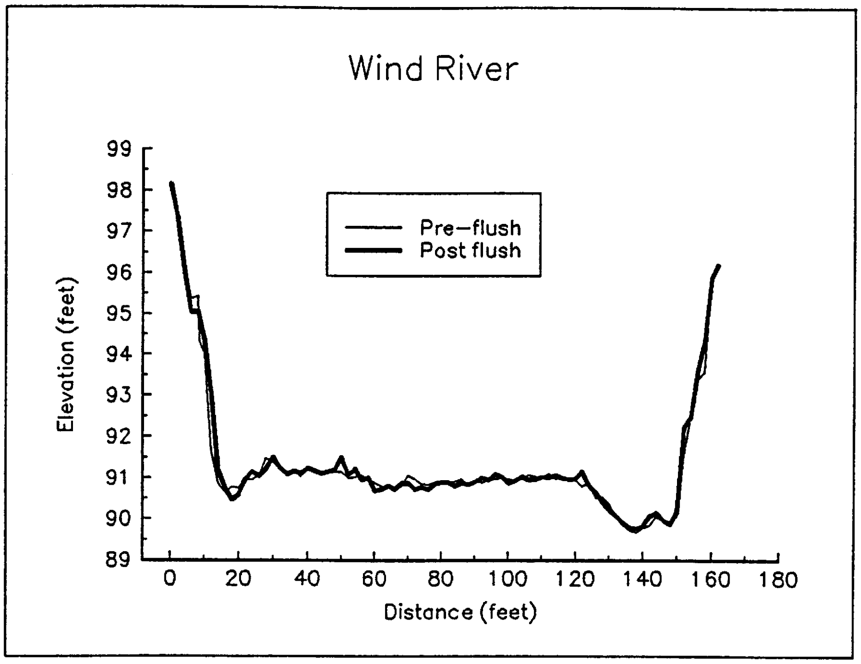




Figure 21. Particle size distributions for pre and post-release freeze core samples collected at the Red Bluff, City, and Mills sites, Bighorn River, Wyoming.

Table 6. Mean change in bed elevation (ft.) for all transects on the Wind/Bighorn River, Wyoming, as a result of March 1994 test release.

| Transect location | Mean bed elevation change (ft.) | P |
|---|---|---|
| Wind River | -0.035 | 0.532 |
| Red Bluffs Main Channel | 0.035 | 0.028 |
| Red Bluffs Secondary Upper | -0.040 | 0.028 |
| Red Bluffs Secondary Middle | -0.004 | 0.629 |
| Red Bluffs Secondary Lower | -0.105 | 0.057 |
| City Main Channel | -0.093 | <0.001 |
| City Secondary Upper | -0.053 | 0.002 |
| City Secondary Middle | -0.041 | <0.001 |
| City Secondary Lower | 0.018 | 0.777 |
| Mills Main Channel | 0.001 | 0.056 |
| Mills Secondary Upper | 0.015 | 0.509 |
| Mills Secondary Middle | -0.036 | 0.018 |
| Mills Secondary Lower | -0.008 | 0.022 |



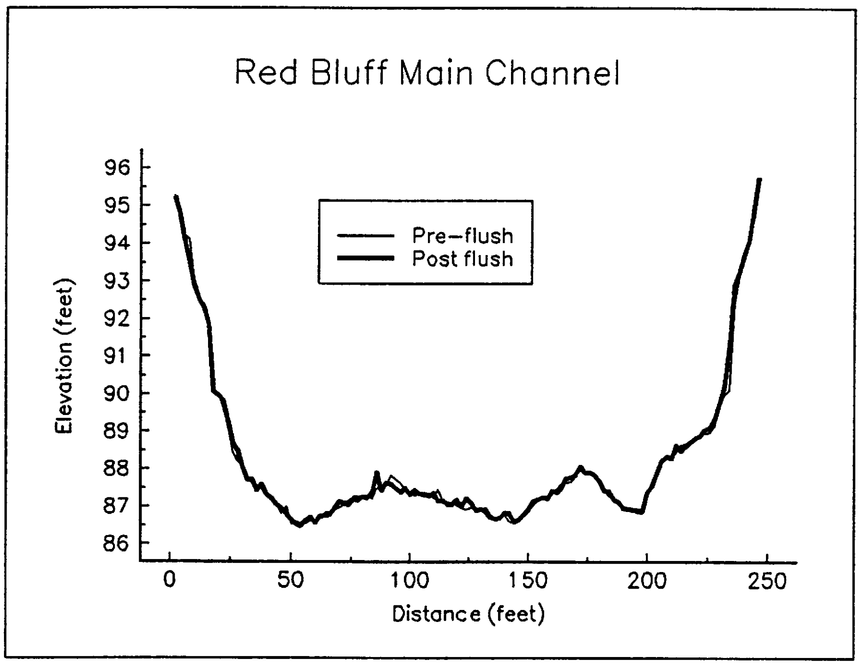




Figure 22. Pre and post-test release (March 1994) channel profiles of the Wind River and Red Bluff main channel, Bighorn River, Wyoming.

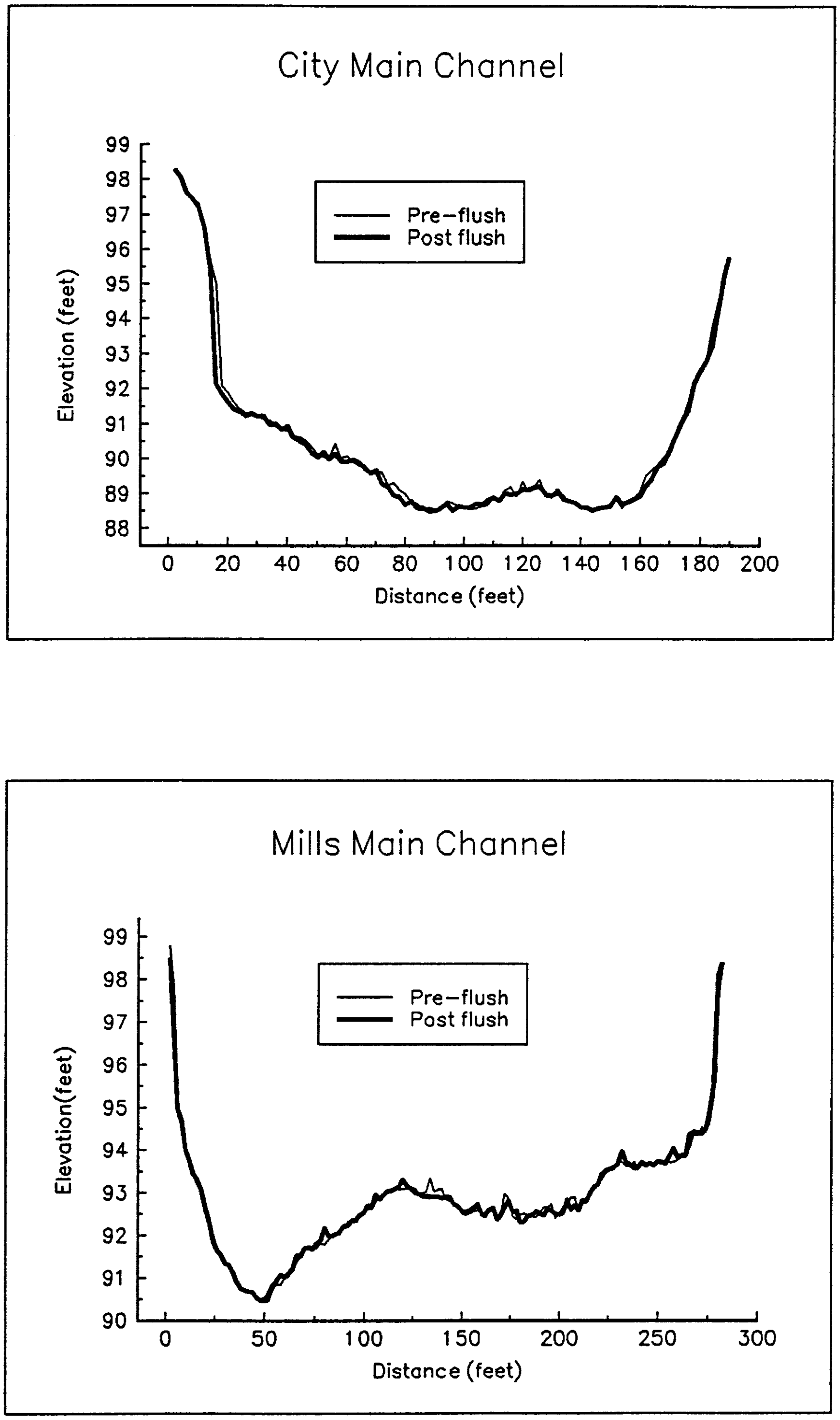


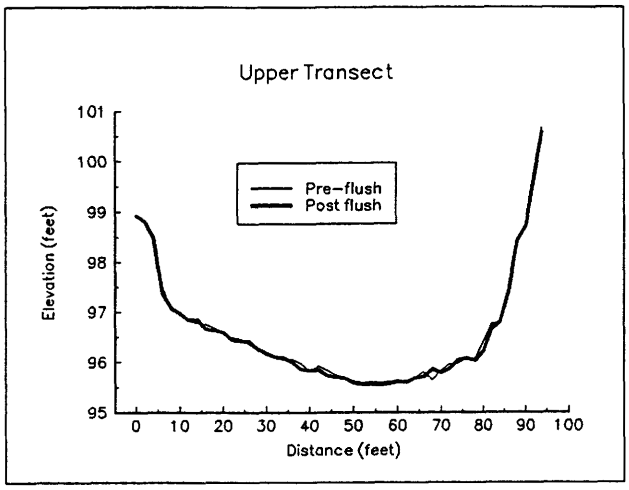

Figure 23. Pre and post-test release (March 1994) channel profiles of the City and Mills main channel, Bighorn River, Wyoming.

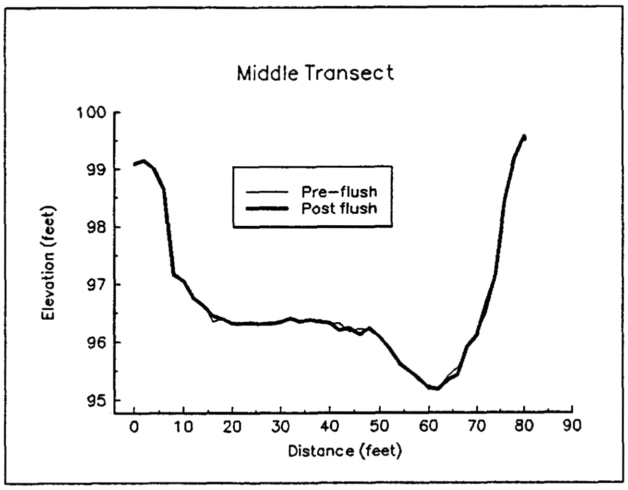
The overall trend, in the secondary channels, was toward degradation with 7 out of the 9 transects showing a mean decrease in bed elevation (Table 6). The lower transect at the Red Bluffs secondary channel displayed some bank erosion (Figure 24). The upper transect at the City secondary channel displayed signs of scour in the thalweg portion of flow (Figure 25) . The upper transect at the Mills secondary channel aggraded on the left side of the channel and degraded on the right side of the channel (Figure 26). A significant difference was seen between the pre- and post-bed elevations at 5 of the 9 secondary channel transects (Table 6).

## Pool Analysis

The survey data indicate approximately one-third of the pool aggraded, one-third displayed no change, and one-third scoured as a result of the test release (Table 7). A significant increase (1.1 ft.) in channel elevation during the test release occurred at the pool. The majority of the scouring occurred near the main channel (Figure 27). Deposition occurred along the right (facing downstream) side of the pool (Figure 27).

Pre- and post-summer (seasonal change) bed elevations were not significantly different (Table 7, Figure 28). Survey data indicated that 31% of the pool aggraded, 53% of the pool displayed no change, and 16% scoured over the summer (April - November). Areas of no change and deposition were uniform throughout the pool. Mean daily discharge during the period was about 1,000 cfs, while peak discharge was about 1,500 cfs.



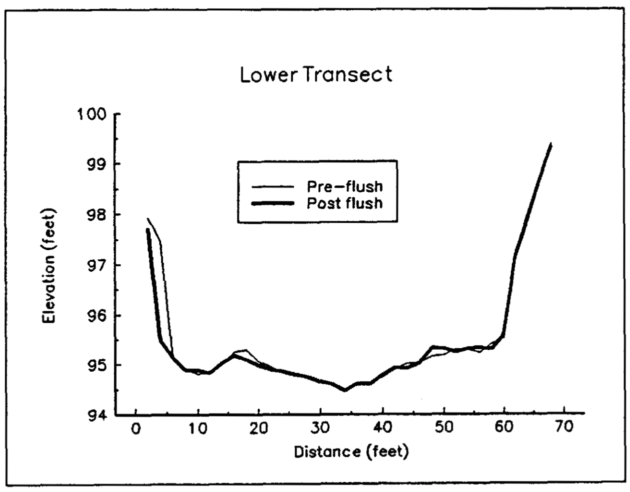




Figure 24. Pre and post-test release (March 1994) channel profiles of the Red Bluffs secondary channel, Bighorn River, Wyoming.

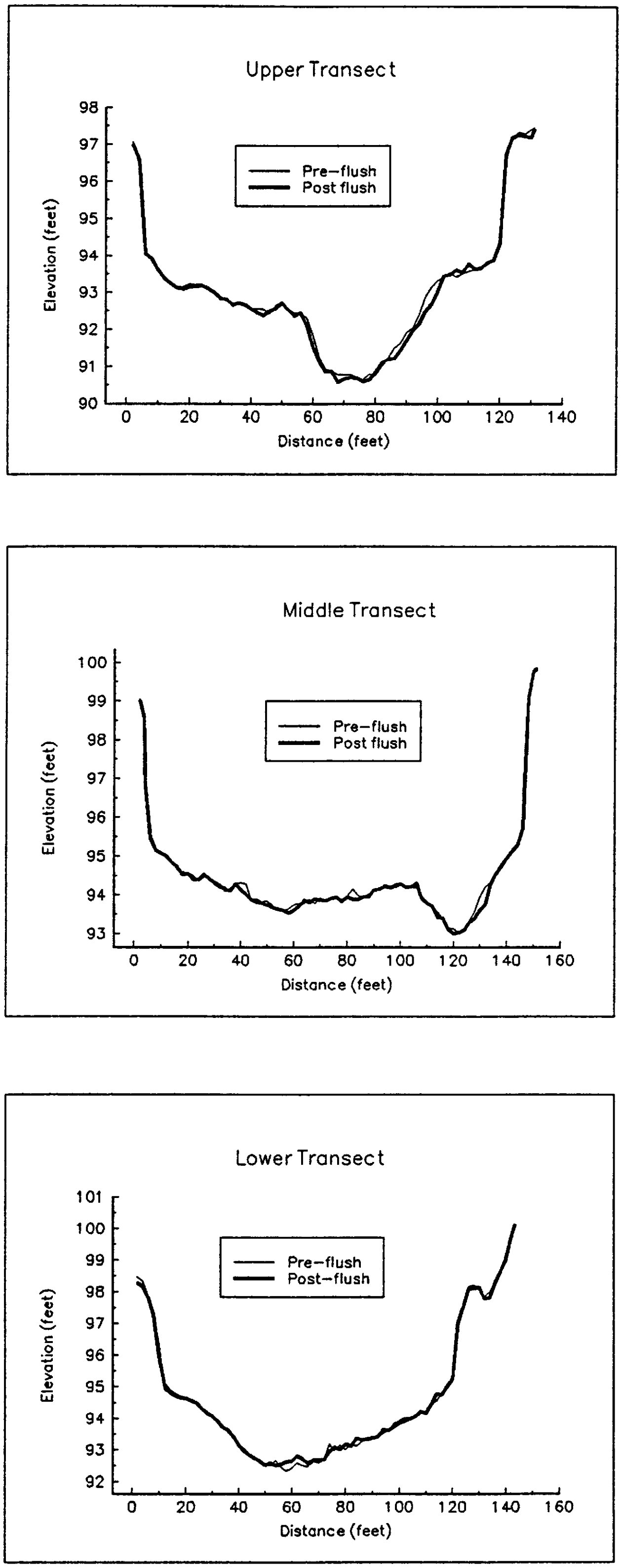



Figure 25. Pre and post-test release (March 1994) channel profiles of the City secondary channel, Bighorn River, Wyoming.

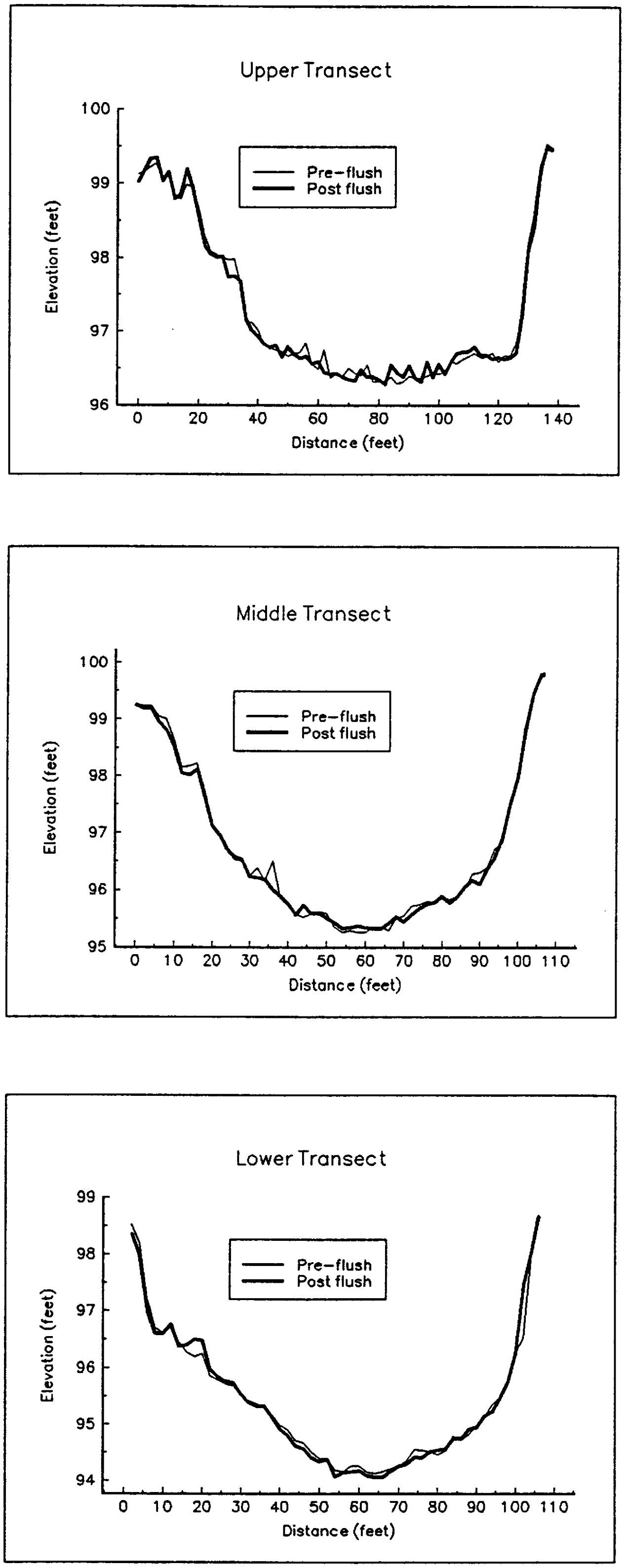



Figure 26. Pre and post-test release (March 1994) channel profiles of the Mills secondary channel, Bighorn River, Wyoming.

Table 7. Bed elevation changes in large pool, below confluence of Buffalo Creek, Bighorn River, Wyoming (% = percent of total surface area).

| Depth of change (ft.) | Pre- and post-test release (%) | Seasonal change (%) |
|---|---|---|
| -2.00 ± 0.25 | 0.10 | 0.00 |
| -1.50 ± 0.25 | 1.50 | 0.00 |
| -1.00 ± 0.25 | 10.40 | 1.28 |
| -0.50 ± 0.25 | 21.80 | 14.30 |
| 0.00 ± 0.25 | 23.60 | 52.90 |
| 0.50 ± 0.25 | 21.50 | 21.50 |
| 1.00 ± 0.25 | 8.00 | 6.40 |
| 1.50 ± 0.25 | 0.50 | 2.90 |
| 2.00 ± 0.25 | 0.00 | 0.20 |
| 2.50 ± 0.25 | 0.00 | 0.00 |

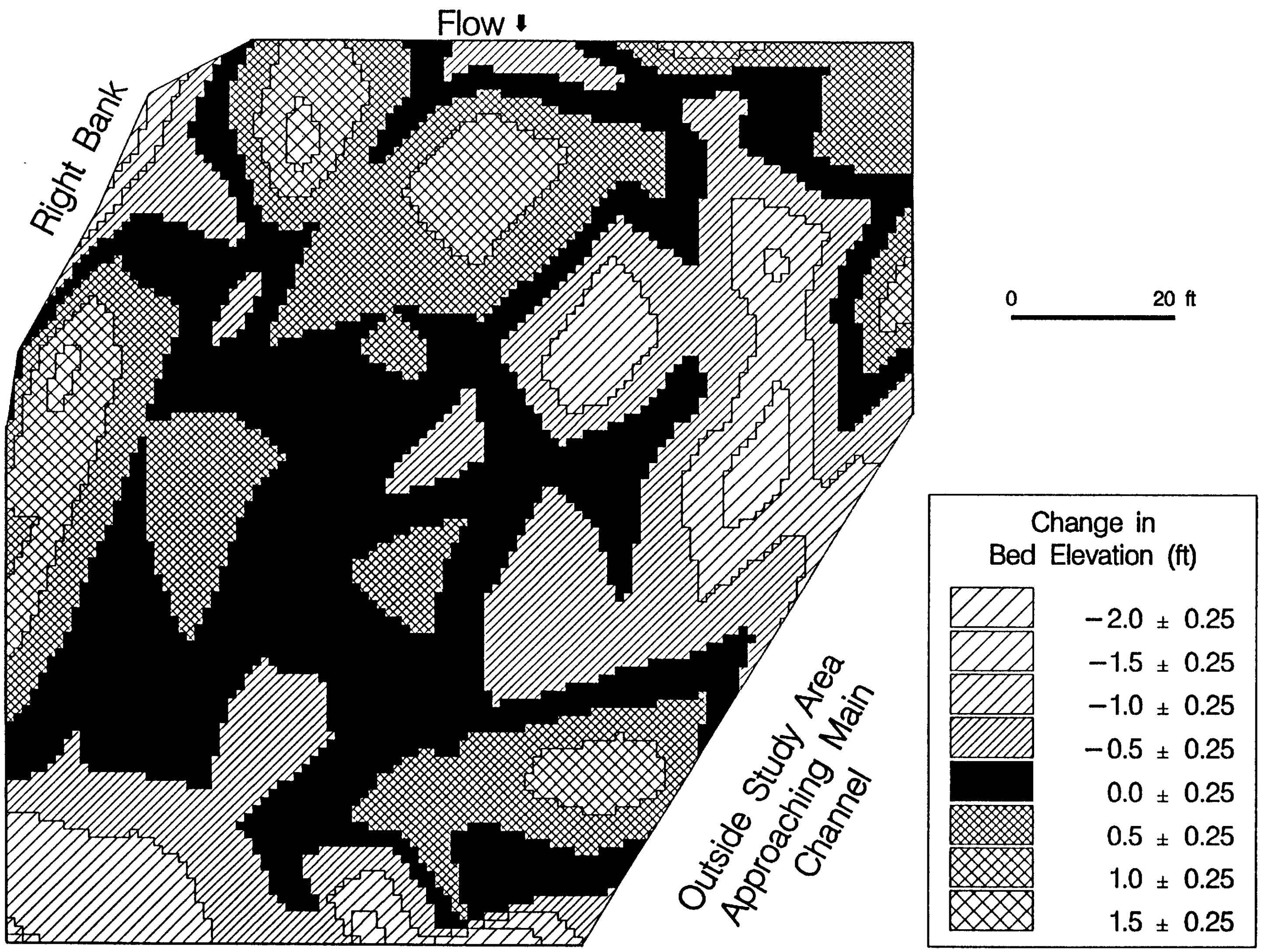



Figure 27. Bed elevation changes in large pool, below confluence of Buffalo Creek, as a result of the March 1994 test release, Bighorn River, Wyoming.

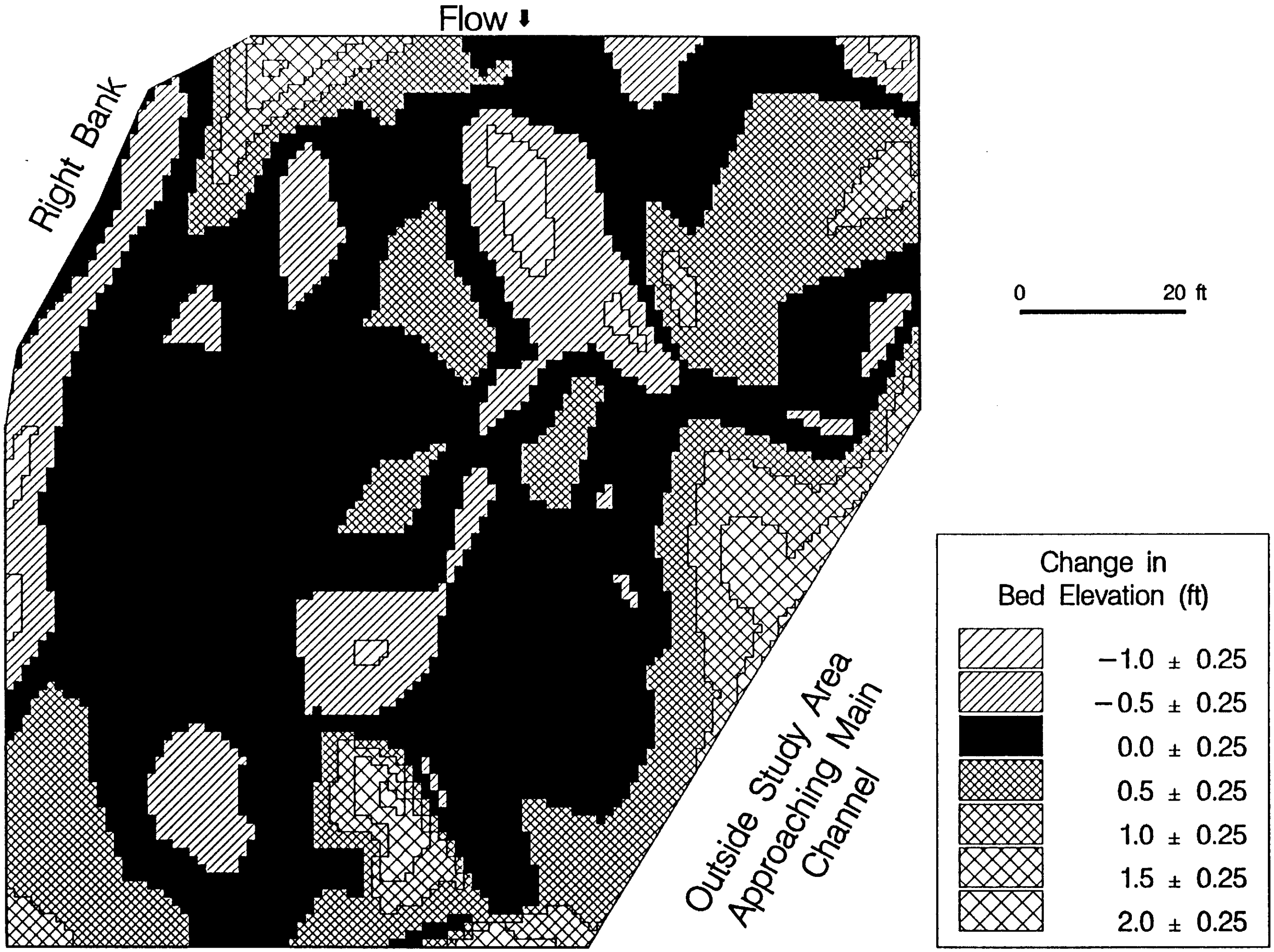



Figure 28. Seasonal bed elevation changes in large pool, below confluence of Buffalo Creek, Bighorn River, Wyoming.

## Tributary Study

There were no flows in Red Canyon Creek during summer/fall 1994, while only one flow event (5 August 1994) occurred in Buffalo Creek. The estimated peak flow in Buffalo Creek was 24 cfs. On the descending limb of the hydrograph the measured flow was 1.8 cfs. The average suspended sediment concentration at the measured flow was 37,400 mg/l. Unfortunately, the multiple-stage suspended sediment sampler did not sample the peak flow. Taking a conservative approach based upon the measured suspended sediment concentration measured in the field and assuming the peak to have lasted 4 hours, the minimum amount of sediment entering the Bighorn River was calculated. This analysis suggests that 400 tons of suspended sediment entered the Bighorn River as a result of this flow event in Buffalo Creek. However, suspended sediment concentrations at the City and Mills sites, Bighorn River, did not differ on the descending limb of the hydrograph as a result of the flow event in Buffalo Creek. Suspended sediment concentrations at the Red Bluffs site were only 2.0 mg/l higher.

## Redd Analysis

Sixty-seven brown trout redds were located in 1993/1994 and 9 rainbow trout redds were located in 1994 (Table 8). Average length of brown trout and rainbow trout in the Bighorn River, 1994 were 17.4 in. and 18.0 in., respectively. All redds were located in braided sections or secondary channels, indicating that these locations provide spawning habitat. In 1994, 5 brown trout redds were located 0.5-mi. upstream of the City

Table 8. Number and location of rainbow trout and brown trout redds sampled during fall, 1993 and 1994, Bighorn River, Wyoming, (RB = Red Bluffs, LI = Lunch Island).

| | Location of Redd | | | |
|---|---|---|---|---|
| Species | RB | LI | City | Big Bend |
| Rainbow trout | 9 | - | - | - |
| Brown trout (1993) | 1 | 12 | 17 | - |
| Brown trout (1994) | - | 14 | 18 | 5 |

study site (termed Big Bend site). Substrate samples were not collected on redds located at the Big Bend site and 7 of the redds located at Lunch Island because water depths exceeded the height of the sampler.

Rainbow trout selected shallower, faster water with larger substrate than brown trout (Table 9). The particle size distribution plots (Figure 29) suggest that the substrate is larger at the rainbow trout spawning location than at the brown trout locations. The $d_{50}$ varied from 20.3 mm at the Red Bluffs site and 17.0 mm at Lunch Island to 9.7 mm at the City site (Table 10). The $d_{50}$, $f_i$, and percent fines < 2.0 mm were significantly different between rainbow trout and brown trout spawning areas, therefore they were treated separately (Tables 10, 11 and 12). However, particle size distributions were not significantly different between brown redds sampled in 1993 and 1994.

Mean spawning depth for rainbow trout was 1.09 ft., while mean spawning depth for brown trout ranged from 1.60 ft. at the City site to 2.06 ft. at the Big Bend site. Mean water velocity for rainbow trout were 2.58 ft./s, while mean water velocity for brown trout ranged from 1.63 ft./s at the Big Bend site to 2.21 ft./s at the City site.

Differences in depth, mean, and nose velocities between the rainbow trout spawning area and the three brown trout spawning areas were significant, therefore each site was treated separately. Depths for both species of fish were significantly different at all sites (Table 9).

Rainbow trout and brown trout appear to move fines from bed material during redd construction (Table 12), with about 30% and 42% of the fines lost during the construction, respectively. The loss of fines result in larger $d_{50}$'s and higher $f_i$ values

Table 9. Depth, mean, and nose velocity data for brown trout and rainbow trout redds comparing rainbow trout, brown trout at Lunch Island, City, and Big Bend sites, Bighorn River, Wyoming, RT = rainbow trout, BT = brown trout, LI = Lunch Island, BB = Big Bend.

| Parameter | Comparison | Data means | P |
|---|---|---|---|
| Depth (ft.) | RT/BT-LI | 1.09/1.81 | <0.001 |
| | RT/BT-City | 1.09/1.60 | <0.001 |
| | RT/BT-BB | 1.09/2.06 | 0.003 |
| | BT-LI/BT-City | 1.81/1.60 | 0.026 |
| | BT-LI/BT-BB | 1.81/2.06 | 0.033 |
| | BT-City/BT-BB | 1.60/2.06 | 0.008 |
| Mean Velocity (ft./s) | RT/BT-LI | 2.58/2.05 | 0.100 |
| | RT/BT-City | 2.58/2.21 | 0.211 |
| | RT/BT-BB | 2.58/1.63 | 0.082 |
| | BT-LI/BT-City | 2.05/2.21 | 0.144 |
| | BT-LI/BT-BB | 2.05/1.63 | 0.047 |
| | BT-City/BT-BB | 2.21/1.63 | 0.024 |
| Nose Velocity (ft./s) | RT/BT-LI | 1.52/0.80 | 0.004 |
| | RT/BT-City | 1.52/1.02 | 0.054 |
| | RT/BT-BB | 1.52/0.65 | 0.019 |
| | BT-LI/BT-City | 0.80/1.02 | 0.020 |
| | BT-LI/BT-BB | 0.80/0.65 | 0.419 |
| | BT-City/BT-BB | 1.02/0.65 | 0.032 |

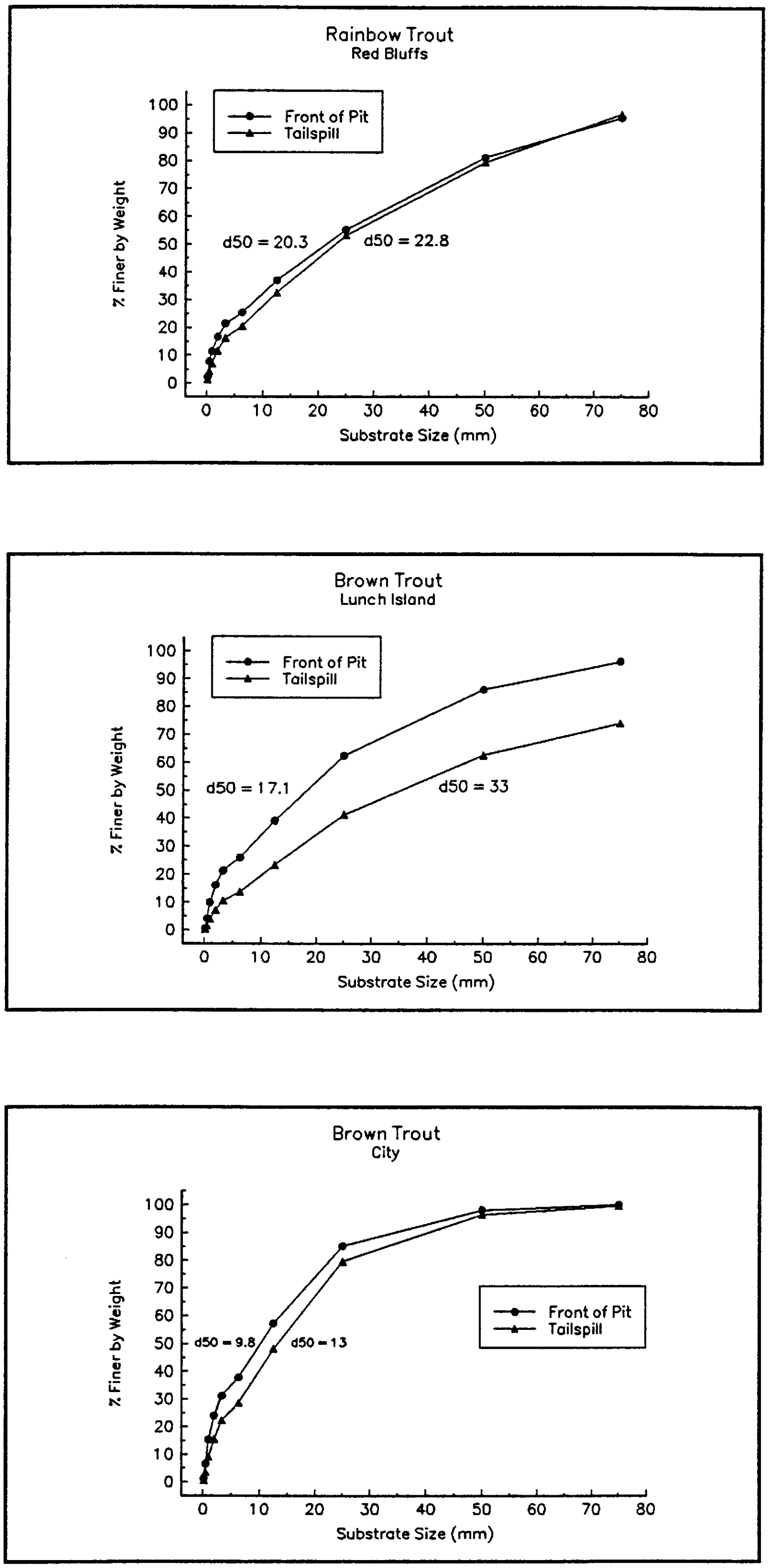



Figure 29. Particle size distributions for rainbow and brown trout redds at the Red Bluffs, Lunch Island, and City sites, Bighorn River, Wyoming.

Table 10. McNeil core sample results comparing median particle size ($d_{50}$) at different locations in brown trout and rainbow trout redds, Bighorn River, Wyoming, LI = Lunch Island.

| Species | Comparison | $d_{50}$ (mm) | P |
|---|---|---|---|
| Rainbow Trout | Random/Pit | 21.5/20.3 | 0.981 |
| | Random/Tailspill | 21.5/22.8 | 0.572 |
| | Pit/Tailspill | 20.3/22.8 | 0.407 |
| Brown Trout - LI | Random/Pit | 16.8/17.0 | 0.730 |
| | Random/Tailspill | 16.8/33.5 | 0.005 |
| | Pit/Tailspill | 17.0/33.5 | 0.024 |
| Brown Trout - City | Random/Pit | 9.0/9.7 | 0.803 |
| | Random/Tailspill | 9.0/13.0 | <0.001 |
| | Pit/Tailspill | 9.7/13.0 | <0.001 |

Table 11. McNeil core sample results comparing fredle index ($f_i$) at different locations in brown trout and rainbow trout redds, Bighorn River, Wyoming, LI = Lunch Island.

| Species | Comparison | $f_i$ | P |
|---|---|---|---|
| Rainbow Trout | Random/Pit | 4.3/3.8 | 0.795 |
| | Random/Tailspill | 4.3/5.7 | 0.556 |
| | Pit/Tailspill | 3.8/5.7 | 0.155 |
| Brown Trout - LI | Random/Pit | 3.4/3.9 | 0.293 |
| | Random/Tailspill | 3.4/10.6 | <0.001 |
| | Pit/Tailspill | 3.9/10.6 | <0.001 |
| Brown Trout - City | Random/Pit | 1.5/1.8 | 0.467 |
| | Random/Tailspill | 1.5/3.4 | <0.001 |
| | Pit/Tailspill | 1.8/3.4 | <0.001 |

Table 12. McNeil core sample results comparing percent fines < 2.0 mm at different locations in brown torut and rainbow trout redds, Bighorn River, Wyoming, LI = Lunch Island.

| Species | Comparison | % < 2.0 mm | P |
|---|---|---|---|
| Rainbow Trout | Random/Pit | 14.9/16.5 | 0.621 |
| | Random/Tailspill | 14.9/11.6 | 0.556 |
| | Pit/Tailspill | 16.5/11.6 | 0.124 |
| Brown Trout - LI | Random/Pit | 17.6/16.2 | 0.185 |
| | Random/Tailspill | 17.6/7.2 | <0.001 |
| | Pit/Tailspill | 16.2/7.2 | 0.003 |
| Brown Trout - City | Random/Pit | 26.2/24.0 | 0.854 |
| | Random/Tailspill | 26.2/15.5 | <0.001 |
| | Pit/Tailspill | 24.0/15.5 | <0.001 |

(Table 12). The $f_i$ values in brown trout redds more than doubled as a result of redd construction, while $f_i$ values increased by 31% in rainbow trout redds. Lunch Island had the greatest $f_i$ values, while the City site had the lowest. The Redd Bluffs site was intermediate (Table 12). Statistical analyses using the Wilcoxon test support these observations, indicating that the distributions of $d_{50}$, $f_i$, and percent fines < 2.0 mm within brown trout redds and at the head of the pits were significantly different (Table 12). Differences in particle size distributions at random locations and at the head of the pit were not significant. (Table 12).

Brown trout and rainbow trout spawning suitability curves were developed for substrate, depth, nose, and mean velocity (Figures 30 and 31). Optimal (suitability = 1.0) substrate, depth, nose, and mean velocities are shown in Table 13. Spawning depth suitability curves developed for brown trout and rainbow trout in the Bighorn River are similar to published habitat suitability curves (Wenzel 1993; Raleigh *et al.* 1984a and b; Smith 1974). Optimal mean velocities over rainbow trout redds are similar to curves developed in the North Platte River (Wenzel 1993) and other published habitat suitability curves (Raleigh *et al.* 1984a; Smith 1973). Optimal mean velocities over brown trout redds in the Bighorn River were similar to those over rainbow trout redds. However, brown trout curves indicate a narrower range. Greater mean velocities over brown trout redds were observed in the Bighorn River compared to other studies (Raleigh *et al.* 1984b; Shirvell and Dungey 1983; Witzel and MacCrimmon 1983; Smith 1973). Greater velocities observed in the Bighorn River may be a result of larger spawning fish; larger fish can tolerate higher velocities. Rainbow trout spawning suitability curves generated

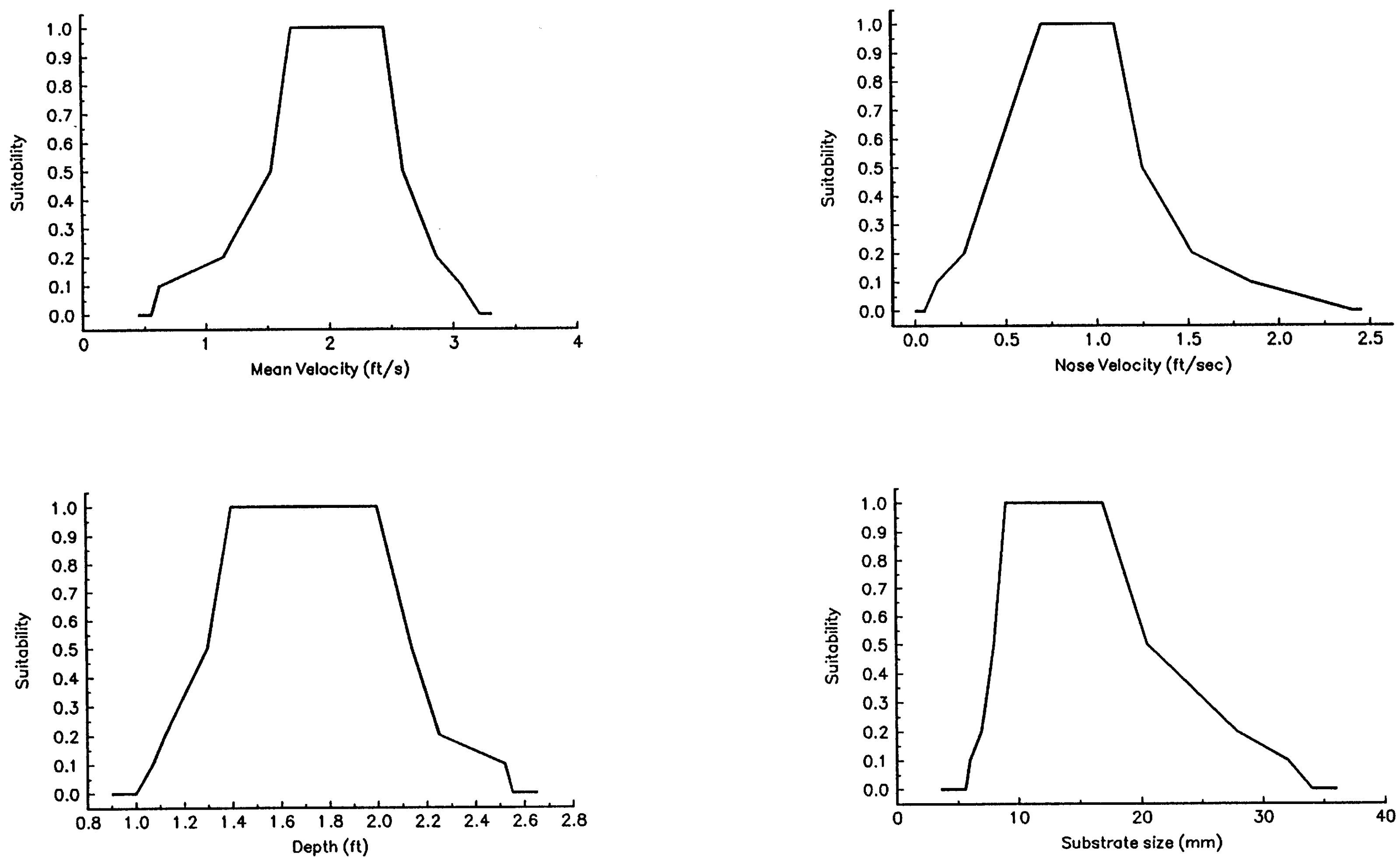



Figure 30. Suitability curves for brown trout spawning mean velocity, nose velocity, substrate, and depth utilization, 1993-1994, Bighorn River, Wyoming.

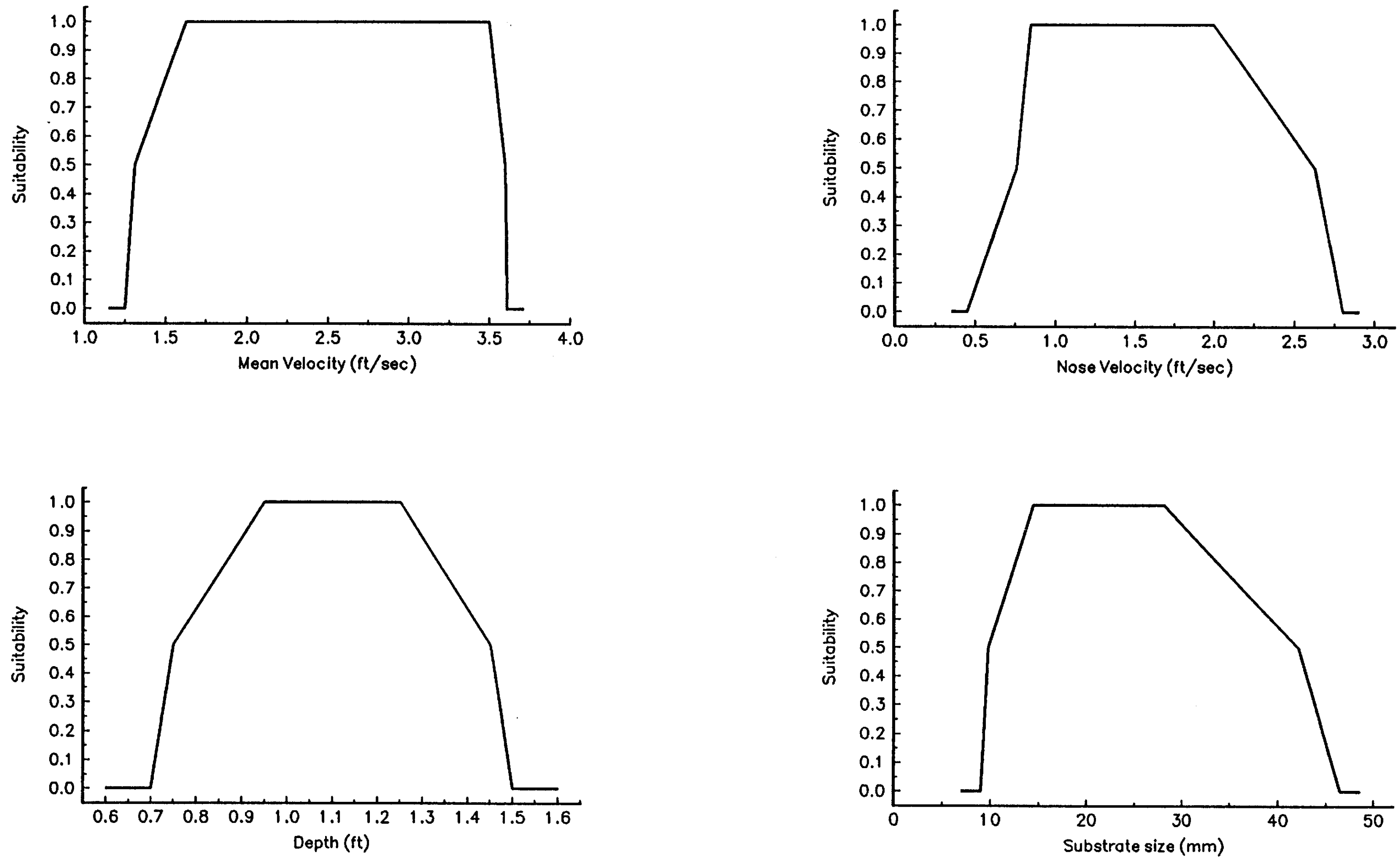



Figure 31. Suitability curves for rainbow trout spawning mean velocity, nose velocity, substrate ($d_{50}$), and depth utilization, 1994, Bighorn River, Wyoming.

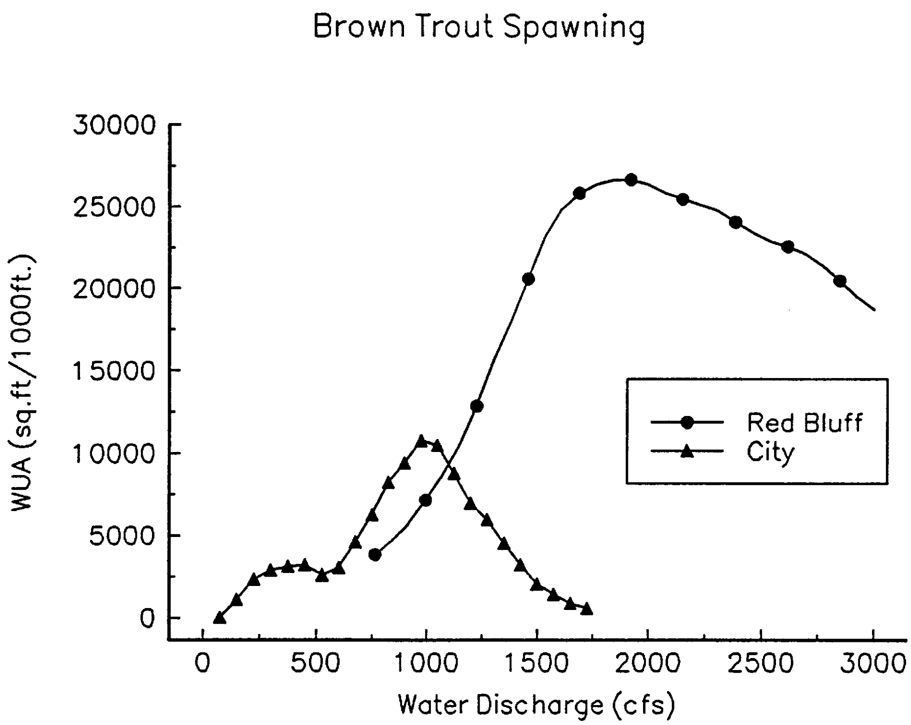
Table 13. Optimal ranges for substrate, water depth, nose and mean velocities for brown trout and rainbow trout, Bighorn River, Wyoming.

| | Substrate ($d_{50}$ mm) | Water depth (ft.) | Nose Velocity (ft./s) | Mean Velocity (ft./s) |
|---|---|---|---|---|
| Brown Trout | 9.0 - 16.9 | 1.4 - 2.0 | 0.7 - 1.1 | 1.7 - 2.45 |
| Rainbow Trout | 14.6 - 28.2 | 0.95 - 1.25 | 0.85 - 2.0 | 1.63 - 3.5 |

for the Bighorn River indicate a narrow range of optimal substrate (14.6 - 28.2 mm). Existing curves (Raleigh *et al.* 1984a) indicate substrate sizes ranging from 0.03 to 102 mm are optimal. Curves developed for the North Platte River indicate that substrate sizes greater than 64 mm are less than optimal (Wenzel 1993). The difference between North Platte and Bighorn river substrate sizes could be due to the substrate sampling location. The tailspills of redds were sampled in the North Platte River, whereas the head of pits were sampled in the Bighorn river. Head of pits were sampled to represent unaltered conditions. Spawning substrate suitability curves generated for brown trout in the Bighorn River indicate a smaller optimal substrate than for rainbow trout. My curves also indicate a narrower range (9 - 16.9 mm) than existing curves (Raleigh *et al.* 1984b) where optimal substrate sizes range from 6 to 76 mm.

## Spawning Flows

Weighted Usable Area (WUA) curves (Figure 32) suggest that brown trout had the most available habitat for spawning at 26,637 $ft^2$/1,000ft. of stream. The Red Bluffs site had the most available habitat for brown trout spawning, while the City site had the most available habitat for rainbow trout spawning at 13,203 $ft^2$/1,000ft. of stream. Optimal discharges for brown trout spawning at the Red Bluffs and City sites occur at 1,844 cfs and 975 cfs, respectively. Optimal discharges for rainbow trout spawning occur at the Red Bluffs and City sites occur at 1,689 cfs and 675 cfs, respectively.



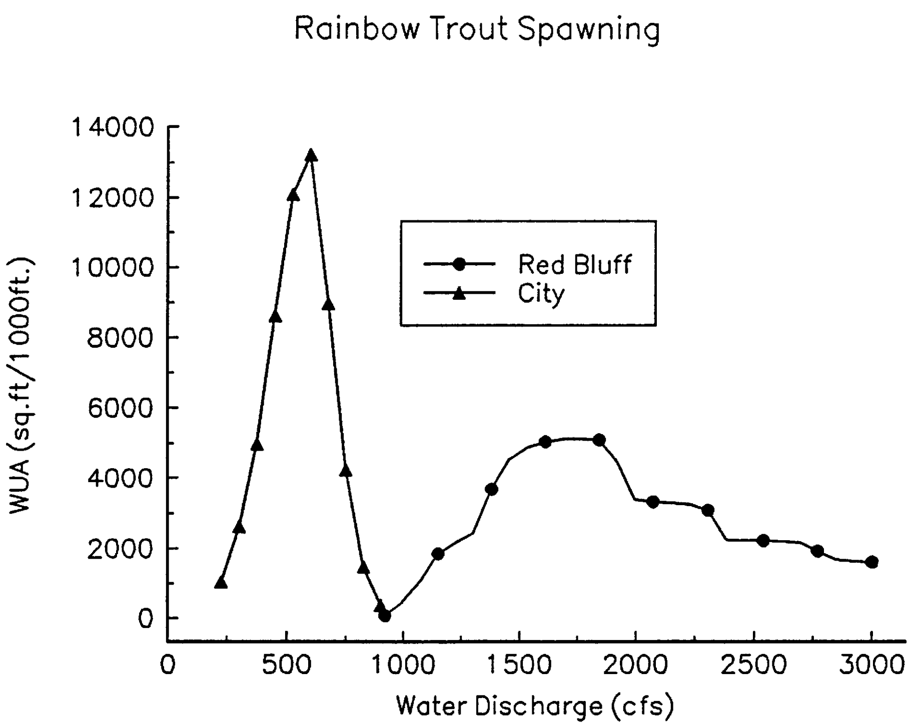




Figure 32. Weighted useable area curves for brown trout and rainbow trout spawning at the three study sites on the Bighorn River, Wyoming.

# CHAPTER V

# DISCUSSION

The goal of this study was to assess the need for flushing flows to enhance the natural recruitment of rainbow trout and brown trout in the Bighorn River. I have assessed the effects of a March 1994 flushing flow on substrate and spawning habitat in the Bighorn River. Data from this test release provided insight regarding the magnitude, duration, and timing of flushing flow regimes to scour pools, clean spawning gravel, maintain secondary channels, and remove fine sediment from the reach of the Bighorn River managed as a "blue ribbon" trout fishery.

## Spawning Habitat

All known brown trout and rainbow trout spawning occurs within the 2.5-mi. reach of the Bighorn River immediately downstream from the Red Bluffs site. Comparison of the substrate quality between the Bighorn, North Platte (Leonard 1995), and the Henry's Fork (Wesche 1994) rivers suggests the substrate in the Bighorn River is in better condition than these other large regulated rivers, but still may be considered detrimental to the natural recruitment of salmonids. Sand and fines comprise 22% of the streambed of the Bighorn River, compared to 28% of the North Platte River and 24% of the Henry's Fork. The fredle index ($f_i$), a measure of gravel quality that incorporates elements of gravel permeability and pore size, was used by Chapman (1988) [data from of Tappel and Bjornn (1983), Koski (1966), Cooper (1965), and Lotspeich and Everest (1981)] to evaluate survival to emergence of salmonid fry. At $f_i$ values of 5.0-7.0, survival of chinook salmon, coho salmon and steelhead exceeded 90%. The $f_i$ (2.35) of samples collected outside of trout redds in the Bighorn River was greater than in the North Platte (1.18) and Henry's Fork (2.06), but substantially less than what Chapman (1988) identified as optimum for survival. Although the Bighorn River was highest of the three rivers, fine sediment levels may still be considered high and natural recruitment of salmonids may be limited by substrate features.

Spawning trout can significantly reduce the amount of fines during redd construction (Grost *et al.* 1991; Foerster 1968; and Hobbs 1937). Such "cleaning" was also observed in the Bighorn River. Emergence of salmonid embryos is likely to be reduced in spawning gravel containing more than 20% fines of < 2.0 mm (Hausle and Coble 1976). Fines in spawning gravels from the Bighorn River, immediately after redd construction, ranged from 7.2 to 15.5%. The $f_i$ for brown trout tailspills in the Bighorn River ranged from 3.4 at the City site to 10.6 at Lunch Island. The $f_i$ for rainbow trout tailspills averaged 5.7, considerably higher than rainbow trout tailspills in the North Platte River ($f_i = 3.42$). These values would suggest that fines may not inhibit emergence in the Bighorn River. However, spring runoff from highly erosive tributary streams supplies additional sediment to the Bighorn River at the time of rainbow trout incubation, thereby potentially reducing emergence of fry. Lisle and Eads (1991) suggested that a better measure of fry survival would include assessment of changes in redd material resulting from sediment transport during the period between redd construction and emergence of fry. To better monitor changes in substrate composition of redds, substrate core samples should be taken immediately after redd construction and just prior to emergence of fry.

There may not be an optimum discharge during brown trout spawning to maximize spawning habitat at all spawning locations in the Bighorn River. During brown trout spawning (November), discharge from Boysen Reservoir averages 1,200 cfs, but habitat simulations suggest optimal flow conditions for brown trout spawning occur at about 1,800 cfs at the Red Bluffs site. However, field examination of brown trout redds located only at the City and Lunch Island sites, suggests that 975 cfs (Figure 32) may be optimal for brown trout spawning in these two critical locations. Discharges of 1,800 cfs would probably concentrate spawning success at one currently unused location (Red Bluffs), to the detriment of known downstream spawning sites.

During rainbow trout spawning (April - May), discharge averages 1,300 cfs, but habitat simulations suggest that 675 cfs would provide optimal flow conditions for rainbow trout at the City secondary channel. However, field observation of rainbow trout redds suggests that about 1,700 cfs (Figure 32) would provide better spawning habitat at the Red Bluffs site, the location of all observed rainbow trout spawning activity. Analyses of substrate data indicates that the Red Bluffs site is more suitable for spawning compared to the City site. Additionally, discharges of 675 cfs during rainbow trout spawning may conflict with the management of the Bighorn River/Boysen Reservoir, as April-May discharges increase (Figure 5) to meet downstream irrigation needs.

The highest proportions of gravels were found at the Red Bluffs, Lunch Island, and City study sites. These sites support the greatest potential for spawning habitat maintenance and enhancement by flushing flows. In addition, based on WGFD analyses of flow data and fish population estimates, high magnitude short duration flow events may enhance age-0 salmonid recruitment in the Bighorn River (Michael Welker, WGFD, personal communication). The WGFD fish population estimates for 1994 show an increase in age-0 brown trout and rainbow trout, which may be related to the March 1994 test release (Michael Welker, WGFD, personal communication). Therefore, removal of fines with a flushing flow may enhance natural recruitment of trout in the Bighorn River.

## Sediment Dynamics

### Suspended Sediment

Seasonal (April 1 - November 4, 1994) suspended sediment concentrations were higher at the Wedding of the Waters site than downstream sites. As a result, a large amount of sediment deposition is likely occurring between the Wedding of the Waters and the City site. This can be explained by changes in channel morphology and hydraulic geometry. Near the Wedding of the Waters, the channel slope decreases (Figure 2) and the channel widens, resulting in decreased water velocities. As velocities decrease, stream power is reduced and less energy is available to transport sediment.

Buffalo Creek appears to be a source of fine sediment. During an August 1994 flow event in Buffalo Creek, suspended sediment concentrations approached 37,500 mg/l.

Using a mass balance approach, an increase of about 50 mg/l should have been observed at the Red Bluffs site if all the Buffalo Creek sediment stayed in suspension once it reached the Bighorn River. However, concentrations at the Red Bluffs site were only 2.0 mg/l higher than average seasonal concentrations. Fines appear to be settling out in the large pool between Buffalo Creek and the Red Bluffs site.

Data obtained during the test flushing flow suggest that the magnitude of a flushing flow for the Bighorn River should be in the range of 5,000 cfs. Suspended sediment concentrations within the brown trout and rainbow trout spawning areas are maximized as the flow approaches 5,000 cfs.

## Bedload

Movement of bed material is important to flushing flow success (Beschta and Jackson 1979). If gravels remain stationary, fines which settle onto the channel bottom can intrude into the substrate (Beschta and Jackson 1979). Peak bedload movement on the Bighorn River occurred as the flow approached 6,700 cfs. However, the median particle size in bedload samples was maximized as the flow reached 5,000 cfs. This suggests that 5,000 cfs was sufficient to mobilize larger bed material particles enabling fines to be released. Gravels suitable for brown trout and rainbow trout spawning were not transported from spawning areas. This is desirable in such a regulated environment because movement of these gravels downstream would likely result in a loss of already limited spawning habitat for rainbow trout and brown trout.

## Streambed

The effect of the March 1994 test release on the substrate at the Red Bluffs and City sites was less pronounced than at the Mills site. Deposition occurred in the section of river that provides important spawning habitat (Figures 11, 12, 13, 14 and 15) as the flow increased from 5,000 cfs to 6,700 cfs. This flow increase caused pronounced increases in suspended sediment concentrations at the Wedding of the Waters, with minimal increases observed downstream. The test flushing flow successfully enhanced the substrate at the Mills site, thereby extending the potential salmonid spawning habitat in the reach.

The effects of the test release downstream of Kirby Creek were not addressed since the focus of the WGFD and BOR was to maintain or enhance the existing blue ribbon trout fishery. Further investigations to evaluate effects on other fish species such as smallmouth bass, channel catfish (*Ictalurus punctatus*) and sauger may be warranted.

## Flushing Flows

Tailwater fisheries are some of the most productive trout waters in the West. In general, reservoir releases are characterized by cool, clear, highly oxygenated water that have created several blue ribbon fisheries in Wyoming. However, clear water discharge can erode the stream channel and accelerate channel degradation (Leopold *et al.* 1964). Since downcutting is probable, secondary channels are likely to be dewatered over time. The loss of secondary channels can result in a loss of habitat for age-0 trout and for spawning (Harris 1991; Lanning 1992; Mullner 1992). Wenzel (1993) reported that the number of islands and braided sections and length of secondary channels in the North Platte River have decreased since reservoir construction, and likely resulted in less habitat for age-0 and spawning trout. A similar trend may be occurring in the Bighorn River. However, bed elevation changes (Table 6) associated with the March 1994 test release indicate that secondary channels may be maintained through flushing flows. This is an important aspect of flushing flows requiring additional study to determine the fate of secondary channels in the Bighorn River over time.

Flow regulation in streams can also result in long-term sediment deposition (Reiser *et al.* 1989). In general, upstream reservoirs tend to lessen the natural peak flow of the stream, thereby reducing its ability to transport sediment. The overall effect can be the accumulation of sediment in the mainstem (Reiser *et al.* 1989). Surficial flushing of fines may occur, but as bedload transport is diminished and bed mobilization occurs less frequently, fine sediments in the intergravel environment increase. If sufficiently high flows are not released to mobilize bed material, fines can accumulate and impact aquatic ecosystems.

One approach to determine the magnitude of suitable flushing flows is to determine bankfull discharge. Bankfull discharges can be an effective means of removing fine sediment from gravels (Reiser *et al.* 1985; Wesche *et al.* 1985; Reiser *et al.* 1989). Generally, bankfull discharge is characterized as the channel-forming flow. It is anticipated that such flows maintain the integrity of channels by continuing sediment transport processes and by preventing vegetation encroachment into the channels (Wesche 1977). Leonard (1995) evaluated a flushing flow on the North Platte River downstream from Gray Reef Dam, Wyoming, and determined that an effective flushing flow should be about 4,000 cfs. A flow of 4,000 cfs has a recurrence interval of about 4 years (post reservoir construction) on the North Platte River and is approaching bankfull (Wenzel 1993).

Data from the 1994 flushing flow in the Bighorn River suggest that the magnitude of a flushing flow should be 5,000 cfs, which is approaching bankfull in secondary channels. Prior to Boysen Dam, a peak flow of 5,000 cfs was equalled or exceeded about 8% of the time and had a recurrence interval of about 1.2 years. Since Boysen Reservoir construction, a peak of this magnitude is equalled or exceeded about 2% of the time and has a recurrence interval of about 3.5 years. A flow of this magnitude would likely decrease the amount of deposition between Wedding of the Waters and Red Bluffs, while maximizing suspended sediment transport at the Red Bluffs, City and Mills sites.

Once fines are suspended it is important to determine the duration of the flushing flow. The duration of a flushing flow is based upon the water travel time and the distance downstream fines are to be transported. Reiser *et al.* (1985) reported that a reasonable estimate of duration would be about 1.5 times the water travel. Time of travel from Wedding of the Waters to the Mills site is approximately 6 hours. Taking this approach, a peak of about 5,000 cfs should be maintained for at least 9 hours to transport fines past the Mills site. However, additional study is needed to assure this duration will not lead to a reduction in habitat quality below Mills for non-salmonid fishes.

To maximize the effectiveness of the flushing flow, I recommend the release be made in mid to late March prior to rainbow trout spawning. Water temperature at this time would still be low, resulting in denser water with greater transport ability. A flushing flow prior to rainbow trout spawning could also mitigate the effects of sediment input from spring runoff. If low water availability or icing conditions do not permit a flushing flow prior to rainbow trout spawning, I recommend waiting until the following year.

## Comparison to Large Tailwaters in Wyoming

In Wyoming, some of the most productive tailwaters are the Bighorn River downstream from Boysen Reservoir, North Platte River downstream from Gray Reef Reservoir, Shoshone River downstream from Buffalo Bill Reservoir, Green River downstream from Fontenelle Reservoir, and the Snake River downstream from Jackson Lake. Based on the Bighorn River and North Platte River flushing flow studies, insight can be provided regarding flushing flows needed to maintain or enhance trout habitat in these tailwaters. Several Wyoming studies (Wenzel 1993; Leonard 1995 and this thesis) indicate that the magnitude of a flushing flow should have a recurrence interval of 3.5 - 4 years (post-reservoir construction) to be effective. Flushing flows should be of a magnitude approaching bankfull conditions to transport peak bedload and suspended sediment. Regardless of the similarity of the rivers, flushing flows should only occur if there is a specific need and they should be tailored to the specific stream and drainage basin.

Flushing flow needs in the Shoshone River are probably similar to the Bighorn River because these two rivers have quite similar hydrologic and morphological characteristics. The WGFD would like to focus more upon natural reproduction in these two rivers and emphasize wild trout management. Secondary channels in both stream systems provide spawning habitat for salmonids (Steve Yekel, WGFD, personal communication). However, gravel recruitment is limited in both streams, therefore maintaining or enhancing spawning habitat in secondary channels is critical.

Flushing flows in the Green River downstream from Fontenelle Reservoir may be similar to the North Platte River based on channel morphology and hydraulic characteristics. The altered streamflow and sediment regime is believed to have contributed to the decline in the trout populations in both rivers. Lack of spawning gravel recruitment and a reduction in peak flows appear to have limited spawning habitat in both rivers (Wenzel 1993; Mark Fowden, WGFD, personal communication). In addition, channel degradation below the dams has resulted in morphologic changes. Several secondary channels have been cutoff and dewatered, resulting in a loss of habitat for age-0 and spawning fish (Harris 1991; Lanning 1992; Mullner 1992).

Flushing flows to maintain or enhance spawning habitat in the Snake River downstream from Jackson Lake Dam may not be necessary. Turbidity during cutthroat trout spawning, substrate types in the Snake River, and levee development along the river may defeat the purpose of such a flow release. Additionally, all known spawning occurs in the tributaries, which apparently provide the only source of natural recruitment to the mainstem (John Kiefling, WGFD, personal communication).

Another direct effect of reservoir construction on downstream river systems can be a change in riparian habitat. The riparian mosaic along the Bighorn River has been altered since the construction of Boysen Reservoir (Akashi 1988). Col. D.B. Sacket in 1877 wrote, "All along the Bighorn River . . . large cottonwood timber grows" (Dorn 1986). Comparing pre- and post-Boysen Dam aerial photographs, Akashi (1988) showed a decrease in woodland areas and how some woodlands, shrublands and meadows are in different locations than they were 50+ years ago. These changes have been caused by several factors; less frequent prairie fires, agricultural clearing and flood control. An important factor causing rapid change along the Bighorn River is flood control (Knight 1994; Akashi 1988). Reproduction of many native woodland species, such as cottonwood, require frequent over-bank flooding with deposition of sands/silts for seedling establishment. A general decline in woodland areas will likely continue as long as the Bighorn River remains regulated (Akashi 1988).

## Management Recommendations

(1) A flushing flow of 5,000 cfs for at least 9 hours is recommended for the Bighorn River below Boysen Dam (Figure 33). Such a flow will remove fine sediments from spawning gravels and is expected to improve survival to emergence of brown trout and rainbow trout. To maximize effectiveness of the flushing flow, I recommend a mid to late March release prior to rainbow trout spawning.

(2) Future flushing flows should be evaluated using similar methods as used in this study. In addition:

(A) Several transects should be established between Wedding of the Waters and Red Bluffs to measure the observed reductions in suspended sediment concentrations and potential associated aggradation.

(B) Bedload transport should be monitored along one of these newly established transects to ensure that spawning gravels are not flushed out of the Wind River canyon during future flushing flows.

(C) Monitoring and measuring the changes in redd material resulting from sediment transport in the period between redd construction and emergence of fry to better quantify sedimentary conditions of spawning habitat.

(3) Monitoring of Red Canyon and Buffalo Creeks should continue to develop stage - sediment discharge relations in order to quantify the amount of sediment input to the Bighorn River.

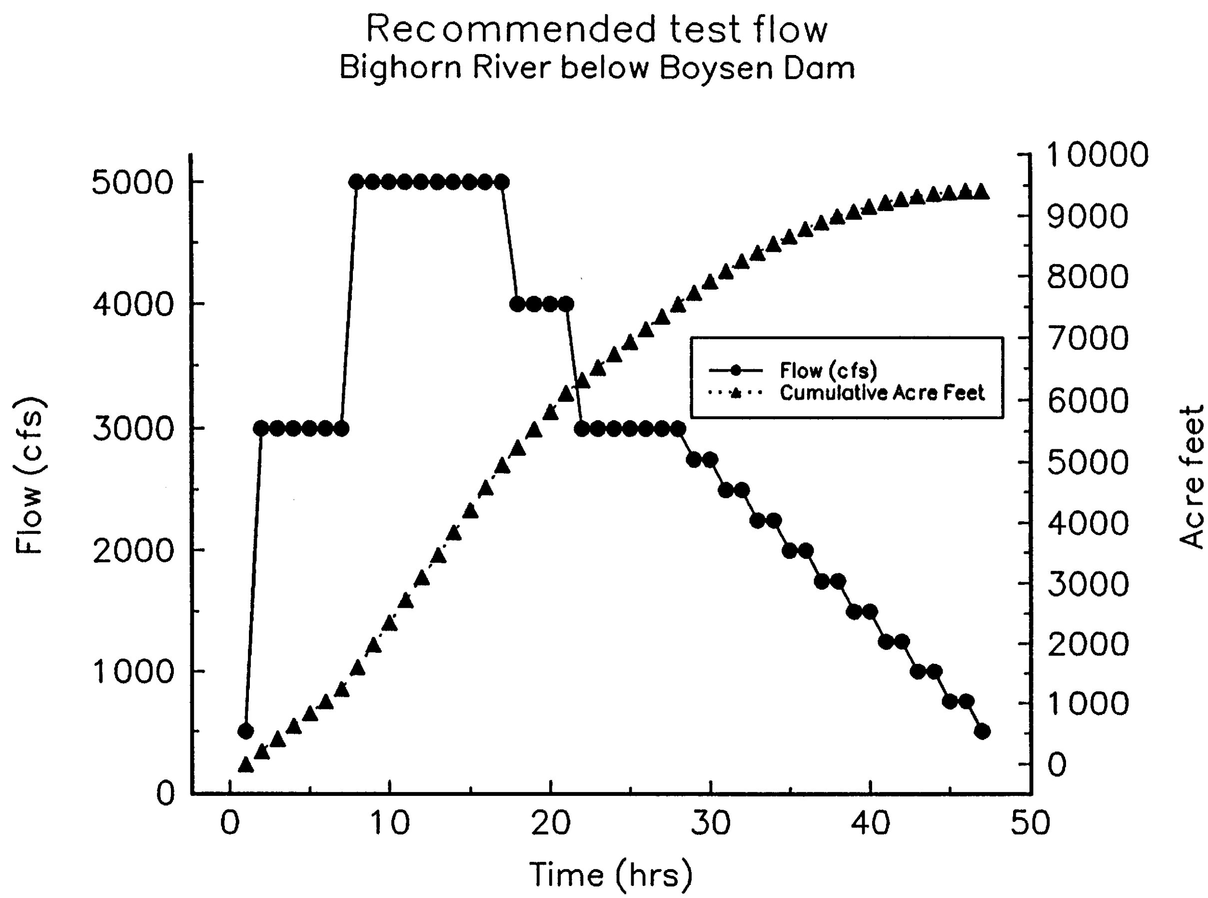



Figure 33. Proposed hourly hydrograph with cumulative acre feet data for the Bighorn River below Boysen Dam.

(4) A flow of about 1,700 cfs is recommended during rainbow trout spawning (April 1 - May 15) to optimize habitat quality for spawning. A flow of 975 cfs is recommended during brown trout spawning (October 15 - December 15) to optimize available spawning habitat.

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Appendix A. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994.

Appendix A. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994. (N/S = no sample taken).

| Date | Wedding of the Waters | Red Bluffs | City | Mills |
|---|---|---|---|---|
| 4-1 | 442 | 55 | 100 | 210 |
| 4-2 | 301 | 53 | 121 | 354 |
| 4-3 | 281 | 109 | 103 | 146 |
| 4-4 | 268 | 39 | 72 | 127 |
| 4-5 | 242 | 41 | 97 | 142 |
| 4-6 | 217 | 54 | 106 | 144 |
| 4-7 | 177 | 41 | 37 | 134 |
| 4-8 | 233 | 53 | 51 | 288 |
| 4-9 | 22 | 40 | 45 | 244 |
| 4-10 | 231 | 40 | 40 | 199 |
| 4-11 | 152 | 53 | 91 | 178 |
| 4-12 | 236 | 80 | 58 | 182 |
| 4-13 | 263 | 40 | 148 | 215 |
| 4-14 | 288 | 39 | 122 | 193 |
| 4-15 | 233 | 118 | 106 | 208 |
| 4-16 | 204 | 52 | 49 | 105 |
| 4-17 | 181 | 78 | 47 | 212 |
| 4-18 | 145 | 80 | 86 | 243 |
| 4-19 | 201 | 119 | 69 | 267 |
| 4-20 | N/S | 80 | 64 | 248 |
| 4-21 | 140 | 40 | 67 | 312 |
| 4-22 | 58 | 40 | 88 | 173 |
| 4-23 | N/S | 41 | 25 | 140 |

Appendix A, continued. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994, (N/S = no sample taken).

| Date | Wedding of the Waters | Red Bluffs | City | Mills |
|---|---|---|---|---|
| 4-24 | N/S | 76 | 36 | 172 |
| 4-25 | N/S | 75 | 58 | 95 |
| 4-26 | N/S | 77 | 83 | 61 |
| 4-27 | N/S | 76 | 92 | 132 |
| 4-28 | N/S | 114 | 50 | 96 |
| 4-29 | N/S | 37 | 116 | 94 |
| 4-30 | N/S | 39 | 82 | 69 |
| 5-1 | N/S | 78 | 94 | 69 |
| 5-2 | N/S | 78 | 139 | 99 |
| 5-3 | N/S | 50 | 150 | 101 |
| 5-4 | N/S | 77 | 185 | 102 |
| 5-5 | N/S | 76 | 117 | 237 |
| 5-6 | N/S | 76 | 115 | 133 |
| 5-7 | N/S | 76 | 115 | 135 |
| 5-8 | N/S | 76 | 9 | 130 |
| 5-9 | N/S | 77 | N/S | 209 |
| 5-10 | N/S | 76 | N/S | 135 |
| 5-11 | N/S | 82 | N/S | 101 |
| 5-12 | N/S | 157 | 15 | 103 |
| 5-13 | N/S | 114 | 29 | 133 |
| 5-14 | N/S | 75 | 29 | 133 |
| 5-15 | N/S | 74 | 14 | 140 |
| 5-16 | N/S | 114 | 15 | 69 |
| 5-17 | N/S | 112 | 42 | 132 |

Appendix A, continued. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994, (N/S = no sample taken).

| Date | Wedding of the Waters | Red Bluffs | City | Mills |
|---|---|---|---|---|
| 5-18 | N/S | 76 | 51 | 100 |
| 5-19 | N/S | 109 | 58 | 68 |
| 5-20 | N/S | 152 | 43 | 67 |
| 5-21 | N/S | 108 | 59 | 33 |
| 5-22 | N/S | 112 | 87 | 34 |
| 5-23 | N/S | 95 | 44 | 33 |
| 5-24 | N/S | 110 | 58 | 102 |
| 5-25 | N/S | 148 | 58 | 101 |
| 5-26 | N/S | 112 | 59 | 101 |
| 5-27 | N/S | 111 | 73 | 68 |
| 5-28 | N/S | 391 | 58 | 363 |
| 5-29 | N/S | 144 | 43 | 202 |
| 5-30 | N/S | 220 | 57 | 99 |
| 5-31 | N/S | 219 | 57 | 99 |
| 6-1 | 94 | 147 | 57 | 101 |
| 6-2 | 148 | 153 | 107 | 98 |
| 6-3 | 174 | 224 | 119 | 97 |
| 6-4 | 150 | 374 | 102 | 65 |
| 6-5 | 197 | 335 | 89 | 65 |
| 6-6 | 245 | 367 | 103 | 135 |
| 6-7 | 193 | 440 | 87 | 159 |
| 6-8 | 205 | 429 | 72 | 62 |
| 6-9 | 280 | 479 | 116 | 132 |
| 6-10 | 287 | 473 | 73 | 99 |

Appendix A, continued. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994, (N/S = no sample taken).

| Date | Wedding of the Waters | Red Bluffs | City | Mills |
|---|---|---|---|---|
| 6-11 | 254 | 553 | 75 | 67 |
| 6-12 | 245 | 542 | 72 | 64 |
| 6-13 | 285 | 613 | 87 | 69 |
| 6-14 | 287 | 289 | 71 | 95 |
| 6-15 | 306 | 287 | 56 | 193 |
| 6-16 | 335 | 318 | 84 | 128 |
| 6-17 | 266 | 326 | 87 | 98 |
| 6-18 | 335 | 430 | 88 | 99 |
| 6-19 | 306 | 609 | 71 | 97 |
| 6-20 | 337 | 474 | 75 | 100 |
| 6-21 | 184 | 550 | 73 | 66 |
| 6-22 | N/S | 149 | 194 | 92 |
| 6-23 | 269 | 186 | 233 | 168 |
| 6-24 | 531 | 260 | 301 | 197 |
| 6-25 | 501 | 450 | 253 | 130 |
| 6-26 | 326 | 594 | 218 | 133 |
| 6-27 | 268 | 413 | 191 | 129 |
| 6-28 | 259 | 433 | 249 | 99 |
| 6-29 | 322 | 454 | 216 | 100 |
| 6-30 | 210 | 552 | 191 | 132 |
| 7-1 | 236 | 494 | 177 | 101 |
| 7-2 | 179 | 591 | 159 | 132 |
| 7-3 | 174 | 510 | 200 | 161 |
| 7-4 | 150 | 719 | 319 | 98 |

Appendix A, continued. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994, (N/S = no sample taken).

| Date | Wedding of the Waters | Red Bluffs | City | Mills |
|---|---|---|---|---|
| 7-5 | 227 | 734 | 330 | 130 |
| 7-6 | 253 | 848 | 351 | 122 |
| 7-7 | 169 | 1077 | 344 | 188 |
| 7-8 | 258 | 829 | 289 | 128 |
| 7-9 | 138 | 662 | 280 | 224 |
| 7-10 | 168 | 729 | 276 | 264 |
| 7-11 | 223 | 725 | 307 | 97 |
| 7-12 | 138 | 402 | 265 | 130 |
| 7-13 | 135 | 490 | 345 | 127 |
| 7-14 | 32 | 37 | 121 | 33 |
| 7-15 | N/S | 35 | 71 | 32 |
| 7-16 | N/S | 35 | 87 | 32 |
| 7-17 | N/S | 36 | 116 | 32 |
| 7-18 | N/S | 36 | 144 | 33 |
| 7-19 | N/S | 72 | 57 | 31 |
| 7-20 | N/S | 70 | 71 | 64 |
| 7-21 | N/S | 71 | 72 | 32 |
| 7-22 | N/S | 70 | 73 | 32 |
| 7-23 | N/S | 107 | 141 | 32 |
| 7-24 | N/S | 106 | 99 | 32 |
| 7-25 | N/S | 36 | 99 | 32 |
| 7-26 | N/S | 35 | 85 | 32 |
| 7-27 | N/S | 36 | 72 | 33 |
| 7-28 | N/S | 36 | 114 | 33 |

Appendix A, continued. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994, (N/S = no sample taken).

| Date | Wedding of the Waters | Red Bluffs | City | Mills |
|---|---|---|---|---|
| 7-29 | N/S | 35 | 57 | 32 |
| 7-30 | N/S | 35 | 141 | 32 |
| 7-31 | N/S | 36 | 55 | 32 |
| 8-1 | N/S | 37 | 69 | 32 |
| 8-2 | N/S | 35 | 83 | 32 |
| 8-3 | N/S | 38 | 29 | 32 |
| 8-4 | N/S | 35 | 43 | 32 |
| 8-5 | N/S | 75 | 118 | 95 |
| 8-6 | N/S | 37 | 102 | 66 |
| 8-7 | N/S | 35 | 71 | 64 |
| 8-8 | N/S | 34 | 96 | 63 |
| 8-9 | N/S | 35 | 58 | 33 |
| 8-10 | N/S | 35 | 72 | 32 |
| 8-11 | N/S | 35 | 43 | 64 |
| 8-12 | N/S | 34 | 42 | 32 |
| 8-13 | N/S | 36 | 28 | 31 |
| 8-14 | N/S | 42 | 28 | 95 |
| 8-15 | N/S | 47 | 42 | 63 |
| 8-16 | N/S | 51 | 28 | 63 |
| 8-17 | N/S | 64 | 28 | 95 |
| 8-18 | N/S | N/S | 55 | 63 |
| 8-19 | N/S | N/S | 28 | 125 |
| 8-20 | N/S | N/S | 41 | 125 |
| 8-21 | N/S | N/S | 68 | 95 |

Appendix A, continued. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994, (N/S = no sample taken).

| Date | Wedding of the Waters | Red Bluffs | City | Mills |
|---|---|---|---|---|
| 8-22 | N/S | N/S | 41 | 97 |
| 8-23 | N/S | N/S | 41 | 62 |
| 8-24 | N/S | 44 | 48 | 67 |
| 8-25 | N/S | 47 | 71 | 32 |
| 8-26 | N/S | 51 | 57 | 32 |
| 8-27 | N/S | 91 | 70 | 31 |
| 8-28 | N/S | 174 | 57 | 33 |
| 8-29 | N/S | 68 | 42 | 65 |
| 8-30 | N/S | 119 | 28 | 32 |
| 8-31 | N/S | 60 | 42 | 32 |
| 9-1 | N/S | 142 | 14 | 64 |
| 9-2 | N/S | 128 | 28 | 63 |
| 9-3 | N/S | 128 | 14 | 64 |
| 9-4 | N/S | 153 | 14 | 64 |
| 9-5 | N/S | 97 | 28 | 63 |
| 9-6 | N/S | 157 | 14 | 96 |
| 9-7 | N/S | 69 | 14 | 64 |
| 9-8 | N/S | 82 | 14 | 95 |
| 9-9 | N/S | 73 | 28 | 32 |
| 9-10 | N/S | 67 | 14 | 65 |
| 9-11 | N/S | 91 | 14 | 64 |
| 9-12 | N/S | 75 | 14 | 65 |
| 9-13 | N/S | 65 | 14 | 64 |
| 9-14 | N/S | 82 | 28 | 95 |

Appendix A, continued. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994, (N/S = no sample taken).

| Date | Wedding of the Waters | Red Bluffs | City | Mills |
|---|---|---|---|---|
| 9-15 | N/S | 81 | 14 | 32 |
| 9-16 | N/S | 58 | 14 | 34 |
| 9-17 | N/S | 55 | 14 | 32 |
| 9-18 | N/S | 55 | 14 | 32 |
| 9-19 | N/S | 57 | 14 | 32 |
| 9-20 | N/S | 61 | 14 | 33 |
| 9-21 | N/S | 78 | 13 | 32 |
| 9-22 | N/S | 69 | 14 | 32 |
| 9-23 | N/S | 65 | 14 | 32 |
| 9-24 | N/S | 71 | 14 | 32 |
| 9-25 | N/S | 75 | 14 | 65 |
| 9-26 | N/S | 76 | 14 | 32 |
| 9-27 | N/S | 72 | 14 | 32 |
| 9-28 | N/S | 77 | 14 | 32 |
| 9-29 | N/S | 86 | 14 | 33 |
| 9-30 | N/S | 113 | 14 | 34 |
| 10-1 | N/S | 99 | 14 | 32 |
| 10-2 | N/S | 121 | 14 | 66 |
| 10-3 | N/S | 989 | 14 | 63 |
| 10-4 | N/S | 369 | 14 | 65 |
| 10-5 | N/S | 230 | 28 | 66 |
| 10-6 | N/S | 359 | 14 | 33 |
| 10-7 | N/S | 270 | 14 | 33 |
| 10-8 | N/S | 249 | 31 | 32 |

Appendix A, continued. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994, (N/S = no sample taken).

| Date | Wedding of the Waters | Red Bluffs | City | Mills |
|---|---|---|---|---|
| 10-9 | N/S | 210 | 14 | 31 |
| 10-10 | N/S | 111 | N/S | 31 |
| 10-11 | N/S | 104 | N/S | 63 |
| 10-12 | N/S | 184 | N/S | 64 |
| 10-13 | N/S | N/S | 87 | 75 |
| 10-14 | 264 | N/S | 44 | N/S |
| 10-15 | 225 | N/S | 29 | N/S |
| 10-16 | 228 | N/S | 29 | N/S |
| 10-17 | 219 | N/S | 29 | N/S |
| 10-18 | 234 | N/S | 42 | N/S |
| 10-19 | 200 | N/S | 42 | N/S |
| 10-20 | 215 | N/S | 28 | N/S |
| 10-21 | 161 | N/S | 14 | N/S |
| 10-22 | 226 | N/S | 14 | N/S |
| 10-23 | 233 | N/S | 14 | N/S |
| 10-24 | 95 | N/S | 28 | N/S |
| 10-25 | 71 | N/S | 28 | N/S |
| 10-26 | 140 | N/S | 28 | N/S |
| 10-27 | 97 | N/S | 28 | N/S |
| 10-28 | 38 | N/S | 57 | N/S |
| 10-29 | 163 | N/S | 56 | N/S |
| 10-30 | 114 | N/S | 42 | N/S |
| 10-31 | 167 | N/S | 57 | N/S |
| 11-1 | 236 | N/S | 56 | N/S |

Appendix A, continued. Suspended sediment samples (mg/l) from automatic samplers, Bighorn River, Wyoming, 1994, (N/S = no sample taken).

| Date | Wedding of the Waters | Red Bluffs | City | Mills |
|---|---|---|---|---|
| 11-2 | 62 | N/S | 57 | N/S |
| 11-3 | 31 | N/S | 43 | N/S |
| 11-4 | 61 | N/S | 42 | N/S |