GEOMORPHIC AND HYDRAULIC ASSESSMENT OF THE BEAR RIVER IN AND NEAR EVANSTON, WYOMING

By M.E. SMITH *and* M.L. MADERAK

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 93-4032

Prepared in cooperation with the
CITY OF EVANSTON and
UINTA COUNTY

Cheyenne, Wyoming
1993

U.S. DEPARTMENT OF THE INTERIOR

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
cubic foot per second	0.02832	cubic meter per second
foot	0.3048	meter
foot per mile	0.1894	meter per kilometer
inch	2.54	centimeter
inch	25.4	millimeter
mile	1.609	kilometer
square mile	2.590	square kilometer
ton, short	.9072	megagram

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 9/5\ (°C) + 32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Geomorphic and hydraulic characteristics of the Bear River in and near Evanston, Wyoming, were assessed to provide information needed by planners to stabilize the river channel. Present-day channel instability is the result of both human activities and natural processes. The primary factor is channelization of the river in Evanston, where several meander loops were cut off artificially during early development of the city. Other contributing factors include channel-width constrictions, bank stabilization, isolated bend cutoffs upstream from the city, and flooding in 1983 and 1984.

The study reach is 5.6 river miles long. A geomorphic analysis of bankfull-channel pattern, based on four aerial photographs taken during 1946-86, quantified geomorphic properties (sinuosity, bend sinuosity, bend radius of curvature, and bend length) that are characteristic of the study reach. The sinuosity of reach 1 (downstream from Evanston) ranged from 1.31 to 1.52 and that of reach 3 (upstream from Evanston) from 1.17 to 1.26. The sinuosity of reach 2 (the channelized reach in Evanston) was 1.18 in 1986 and remained about the same throughout the period (1946-86). The sinuosity of reach 2 prior to channelization was substantially larger, about 2.3 as determined from maps prepared before 1946. Channel-pattern analyses of time-sequential aerial photographs indicated that few individual bends in reaches 1 and 3 were stable during 1946-86. The median bend sinuosity was between 1.2 and 1.3. Among bends with sinuosities in this range, the interquartile range (central 50 percent) of values of bend radius of curvature was 180 to 320 feet in reach 1, and 250 to 420 feet in reach 3. Regression analysis indicated that bend length was related linearly to bend radius of curvature.

Hydraulic analysis of the present-day channel (surveyed 1981-87) using a one-dimensional water-surface-profile model identified a bankfull discharge for the study reach of 3,600 cubic feet per second. A comparison of bankfull hydraulic properties for reaches 1, 2, and 3 indicated the effects in reach 2 of channelization and channel-width constriction--increased slope, faster velocities, and greater hydraulic radii. The present-day channel slope in reach 2 is 0.00518 foot per foot, whereas a more stable slope would be between 0.00431 foot per foot (present-day slope in reach 1) and 0.00486 foot per foot (present-day slope in reach 3). The present-day median flow velocity in reach 2 is 6.73 feet per second, compared with 5.00 feet per second in reach 1 and 6.14 feet per second in reach 3. The present-day median hydraulic radius in reach 2 is 4.96 feet, compared with 2.23 feet in reach 1 and 2.38 feet in reach 3.

Hydraulic effects of a proposed diversion structure and straw bales used to stabilize the banks were analyzed using the water-surface-profile model. The proposed diversion structure at the site of the former Red Bridge in reach 2 would raise the water surface of the 100-year peak discharge about 2.5 feet. Bales of straw used to stabilize the banks of an eroding bend in reach 3 caused no substantial hydraulic changes in streamflow or cross-section properties.

Sediment-transport data were collected to assist planners in evaluating erosion problems related to channel instability of the study reach. These data, along with inspection of the channel bed in reaches 1 to 3, indicated that the bed is armored and that bed material would not move substantially for

discharges as large as 1,000 cubic feet per second; the magnitude of discharge needed to initiate movement was not identified. Analysis of incipient motion of bed material reinforced the conclusion that the bed is armored. An evaluation of these results and available flow-duration data indicated that proposed gravel mining of the channel would be subject to unpredictable replenishment rates of minable material from upstream.

INTRODUCTION

The Bear River originates in the Uinta Mountains of Utah, flows through parts of Wyoming and Idaho, then returns to Utah, flowing into the Great Salt Lake. During the 1900's, the river channel in and near Evanston, Wyoming, was altered substantially by agricultural, industrial, and commercial development. These alterations include diversions for irrigation, channel realignment through Evanston, channel encroachments and disjointed bank-stabilization measures, and channel constrictions at bridges. By the late 1970's, channel instability and unsightly debris deposits locally had diminished the scenic beauty of the river.

In 1987, the City of Evanston and Uinta County, in cooperation with State and Federal agencies, began a comprehensive development program to restore the scenic beauty of the Bear River in and near Evanston. The program involves an overall management plan for the river—one that will provide recreational activities for residents and visitors, fish and wildlife habitat, and at the same time continue to meet the agricultural and industrial needs of the valley.

Geomorphic and hydraulic information about the Bear River—its channel pattern, streamflow, and cross-section characteristics—is needed for project planning and engineering development. The U.S. Geological Survey (USGS), in cooperation with the City of Evanston and Uinta County, conducted a study of the river in and near Evanston. The study was designed to evaluate present-day geomorphic and hydraulic conditions, to evaluate historical channel changes, and to develop a geomorphic and hydraulic framework for improving channel stability.

The study reach of the Bear River is shown in figure 1. The study reach extends upstream from a point about 1.2 river miles downstream from the former Evanston sewer treatment plant, through Evanston to a point about 1.9 river miles upstream from the city. The total length of the reach, measured from aerial photographs at a scale of 1 inch equals 400 feet, is 5.6 river miles.

Purpose and Scope

The purpose of this report is to provide a geomorphic and hydraulic assessment of the Bear River in and near Evanston. This assessment includes analyses of channel-pattern changes, flow and channel cross-section characteristics, and instream sediment-transport characteristics. The study combines an analysis of maps and aerial photographs, hydraulic analyses of flow using a one-dimensional water-surface-profile model, and flow and sediment-transport data collected during the study. The study identifies channel characteristics that would stabilize the reach and reduce problems related to erosion and sedimentation. The effects of some bed/bank stabilization options on channel roughness also are discussed.

Acknowledgments

Paul Knoph, planner for the City of Evanston, and Dennis Farley, planning director for Uinta County, provided continual logistical support for the project, as well as technical data, personal observations, and staffing.

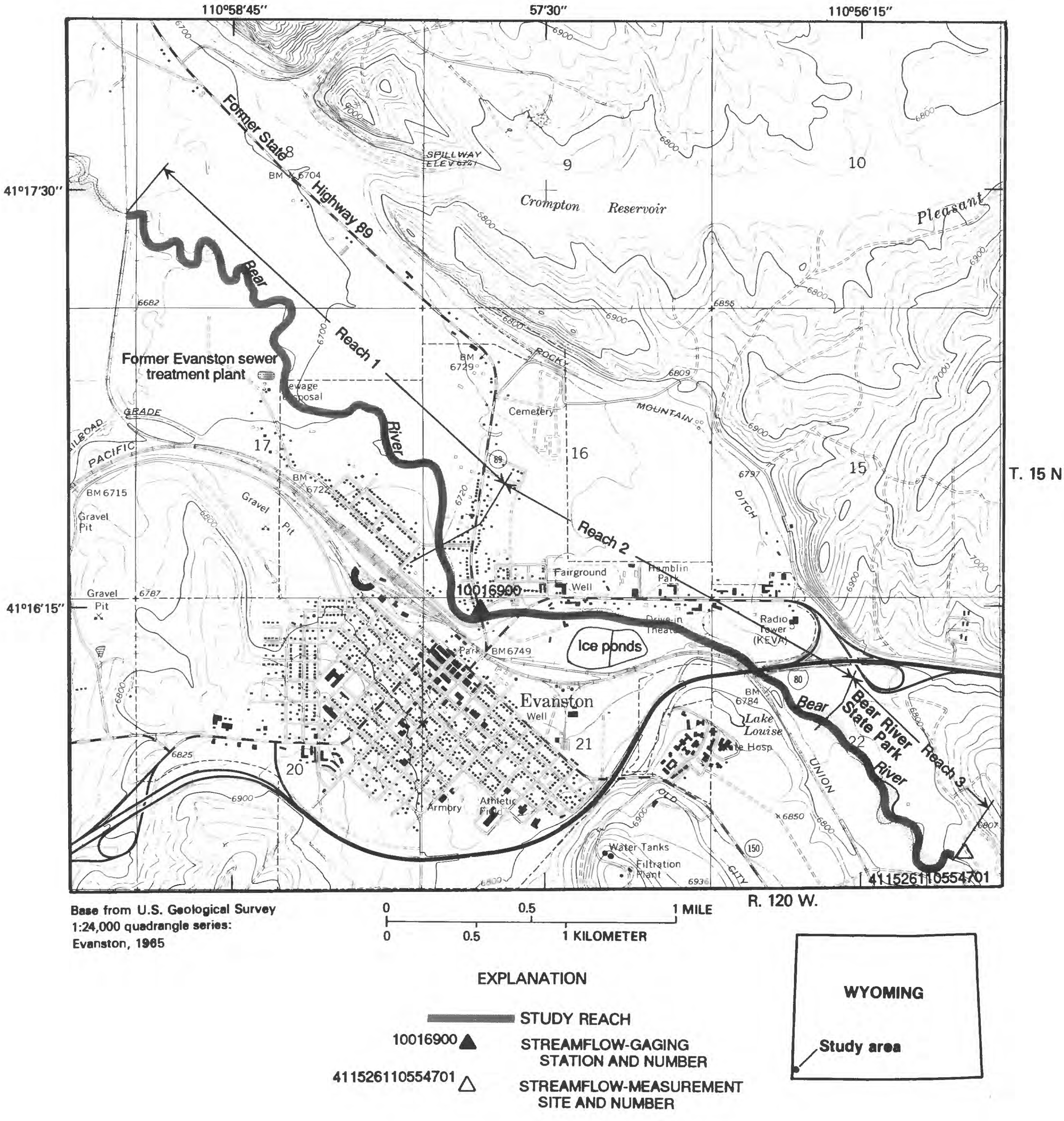

Figure 1.--Location of the study reaches and streamflow-gaging stations and streamflow-measurement sites.

Don Lewis, retired Soil Conservation Service employee, helped with collection of sediment data, and, along with Dennis Farley, prepared a report on riparian vegetation in the study reach. M.E. Cooley, retired USGS employee, provided valuable observations about the surface geology and channel erosion characteristics of the study reach. Stewart Hayduck provided USGS personnel with access to his private bridge crossing, which served as one of the study sampling sites. The Wyoming Water Research Center (University of Wyoming, Laramie) assisted in the installation of an experimental bank-stabilization measure.

APPROACH

To relate channel-pattern characteristics to flow hydraulics, it was necessary to identify a flow that is both morphologically and hydraulically significant for channel development. A channel forms mainly during flood-flows, when a river transports large amounts of sediment. Erosion and deposition occur as the river adjusts its channel to accommodate most of its flows. Although a range of flows probably contributes to channel formation, the formative discharge of a river commonly is defined as the level of flow that just fills the banks of the channel. The flow itself is called the bankfull discharge.

Numerous criteria have been proposed for defining the bankfull channel and corresponding bankfull discharge (Williams, 1978, p. 1,141-1,142). For geomorphic analysis of river channels, the banks of the active floodplain are the most significant indicator of bankfull flow (Wolman and Leopold, 1957, p. 89). In this study, the bankfull discharge was determined through a combined evaluation of aerial photographs and computerized hydraulic data. Once identified, the bankfull channel and bankfull discharge formed the basis for relating the results of the analyses.

Methods of analysis

The study reach was analyzed using three general methods. These methods comprised (1) geomorphic analysis of channel pattern and valley slope, (2) hydraulic analysis of flow and cross-section characteristics, and (3) evaluation of channel roughness coefficients resulting from possible channel renovation and stabilization options. Streamflow data were available from USGS streamflow-gaging station 10019000 (Bear River near Evanston, 1944 and 1946-56), 3 1/2 miles northwest of Evanston, and seasonal station 10016900 (Bear River at Evanston, 1984-1989), at the former State Highway 89 Bridge in Evanston. Onsite data, comprising streamflow measurements, sediment samples, and chemical-water-quality samples, also were collected during water years 1988 and 1989.

Geomorphology

River channels generally have been described as straight, braided, or meandering (Leopold and Wolman, 1957, p. 39-40). A continuum exists in nature between a straight channel pattern and a meandering one, but the term "meandering" is subjective and usually implies a degree of symmetry and regularity of curvature. Some channels may be sinuous, but show an asymmetric, irregular pattern that would not be called "meandering."

Geomorphic analysis of a sinuous channel pattern (plan view) can provide information about channel stability and aid in subsequent analyses of flow hydraulics and cross-section properties. The goals of such an analysis are to identify characteristic channel-pattern properties of a river reach and to define a pattern (or patterns) that tends to be most stable. Geomorphic properties such as sinuosity, bend radius of curvature, bend or meander length, channel width, and meander belt width are related to flow and valley conditions and often are measured to quantify channel pattern.

Sinuosity is important in geomorphic analysis. Schumm and Khan (1972) used flume experiments to show that sinuosity is a function of the slope of the valley. A steep valley slope will cause a channel to be more sinuous, up to some threshold value. The sinuosity of a river channel depends on a number of factors, including the slope of the valley, the flow and sediment load carried by the channel, and the characteristics of the material through which the river flows (Friedkin, 1945, p. 3; Schumm, 1977, p. 111-131). Channel sinuosity (p) is defined as the ratio of channel length (Lc) to valley distance (Lv):

$$p = \frac{Lc}{Lv}. \quad (1)$$

Equivalently, sinuosity also is defined as the ratio of valley slope (Sv) to channel slope (Sc):

$$p = \frac{Sv}{Sc}. \quad (2)$$

Schumm (1977, p. 108) defined channels as stable if they had not undergone substantial, progressive adjustment during a period of 10 years. An analysis of channel-pattern changes might indicate a stable configuration. If maps or aerial photographs of a river are available spanning 40, 50, or even 100 years, the ability to identify a stable channel pattern is greatly improved. Sinuosity is a simple and practical criterion for channel-pattern stability because it links valley conditions (valley slope) with hydraulic conditions (channel slope). For example, Martinson (1984) was able to identify stable reaches of the Powder River in Montana by documenting changes in sinuosity as a function of valley slope.

Once a stable sinuosity is identified, secondary, more site-specific criteria might be appropriate for engineering analyses. For example, bend radius of curvature might be an appropriate criterion for analysis of a river bend during design of a bridge crossing. Because several channel patterns might have the same sinuosity, analysis using secondary criteria can be adapted to individual circumstances.

Analysis of maps or aerial photographs from a single time period also can identify the dominant pattern characteristics of a river reach. Because measured properties tend to follow known distributions (for example, lognormal), central tendencies can be identified using statistics (Brice, 1984, p. 6). Analyses based on maps for more than one time period probably are more reliable for identifying a stable channel pattern, but single time-period analysis can yield a best estimate of stable conditions if adequate time coverage is not available.

Both types of analysis were conducted in this study. A stability analysis of channel-pattern changes was made using aerial photographs from 1946-86. Because the reach is short (relative to the length of reach that might be affected by a given geomorphic stimulus) and the channel is subject to human controls, a statistical analysis of pattern characteristics also was made. While both methods are subjective, they nevertheless can provide quantitative information about geomorphic properties that are related to flow hydraulics in the channel.

Hydraulics of Flow

Hydraulics of flow were analyzed primarily using the Water-Surface Profile (WSPRO) computer model developed by Shearman and others (1986). WSPRO is a one-dimensional water-surface profile computation model developed by the USGS and the Federal Highway Administration (FHWA). It is the result of FHWA's effort to develop a comprehensive model incorporating features available from other models. WSPRO is compatible with conventional step-backwater analyses, has a strong bridge routine, has an algorithm for multiple-opening bridge computations, and can selectively print out summary tables (Shearman and others, 1986, p. 1, 79-80). While the model specifically was developed for analyzing flow hydraulics at bridges and highway encroachments, it also is well-suited for analyzing water-surface profiles in unconstricted channels (Shearman and others, 1986, p. 3).

WSPRO is a fixed-boundary model that uses the standard-step method (Chow, 1959, p. 265-268) for backwater computations in unconstricted valley reaches. The method is based on the open-channel hydraulic principle of conservation of energy, which states that total energy head at an upstream section must equal total energy head at the downstream section plus energy losses. The method assumes gradually varied, steady flow in a modeled reach.

Input for the model includes channel cross-section geometry of the study reach and bed/bank roughness (Manning's *n*) data from onsite evaluations. Once calibrated, the model was used to compute the hydraulics of the present-day channel, including water-surface profiles, flow velocities, and cross-section channel characteristics for a range of flows. Hydraulic properties were analyzed to show how hydraulic conditions change throughout the study reach. The effects of hydraulic structures also were modeled.

Channel Roughness Evaluation

Any form of bed/bank renovation used to improve channel stability will affect the roughness of the channel. Modeling of the many possible scenarios was not feasible because no specific design options have been proposed. Instead, channel stabilization is discussed in terms of changes in channel roughness. Roughness changes would affect the hydraulics of flow, for example, mean velocity, hydraulic radius (in this study, hydraulic radius is used rather than mean depth of flow), and slope.

The evaluation of channel roughness is based on Manning's equation, an empirically derived formula that describes conditions of uniform flow in open channels (Chow, 1959, p. 89-127). The equation has the form

$$V = \left(\frac{1.49}{n}\right) R^{0.67} S^{0.5}, \qquad (3)$$

where V is the mean flow velocity, in feet per second;
n is the roughness coefficient, known as Manning's n;
R is the hydraulic radius, in feet; and
S is the friction slope.

For the purpose of this study, the friction slope is assumed to be equal approximately to the water-surface and channel slopes. Manning's *n* is a measure of flow resistance and depends on such factors as bed/bank material size, channel cross-section geometry, longitudinal channel changes, obstructions to flow, type and density of vegetation, and channel sinuosity.

References pertaining to roughness characteristics for various bed/bank stabilization options, both natural and artificial, are provided in this report, along with tables showing some of these characteristics. The information can be used by planners and engineers to assist in designing stabilization structures for the river.

Limitations of Methods

The methods used in this study are subject to limitations. Geomorphic analyses were developed for, and are best suited to, natural rivers and streams whose channels are free to adjust their shape and alignment in response to changing flow conditions. The Bear River channel in some places has been stabilized or restricted to a certain alignment. Such restrictions disrupt natural development of the channel and need to be recognized during analysis. Channel shape, longitudinal slope, and flood elevations in the reach have been affected by human controls, so the results of this study might not be applicable to reaches upstream or downstream. Geomorphic relations, such as those defined by equations 1 and 2, have been applied in this study with the understanding that the river is not completely free to develop naturally.

The hydraulic analysis is subject to the limitations of the model and the data used for calibration. The step-backwater routine (which includes Manning's equation) used by WSPRO is valid for gradually varied, steady flow conditions. The assumption of a rigid channel boundary means that the effects of erosion and deposition are not considered; changes in channel width, depth, and alignment cannot be computed. Because the Bear River flows through alluvium and actively adjusts its channel, this assumption is a substantial limitation.

The cross-section coverage limits the validity of computer-model results for various flows. Cross-section spacing through the study reach was not detailed enough to predict accurately flow and cross-section properties for low flows. Consequently, the study is limited to computation of high flows ranging from 2,990 (10-year peak discharge) to 4,000 (100-year peak discharge) cubic feet per second.

Compilation of Data

The Bear River is a perennial stream with high flows caused mainly by snowmelt runoff in the spring, and occasionally by rainfall runoff. Average discharge during the 43-year period ending in 1956 (USGS streamflow-gaging station 10019000) was 234 cubic feet per second (Wells, 1958). To establish a framework for the study, a description of hydrologic and streamflow conditions during the study period is needed. This information, along with results of previous studies, is summarized first, followed by a discussion of geomorphic characteristics and hydraulic data compiled for onsite measurements and sampling.

Hydrologic and Streamflow Conditions

Snowpack in the Bear River drainage basin during water years 1988 and 1989 was below normal. In April 1988 snow accumulation was 23 percent below normal in the upper Bear River Basin, with cumulative precipitation for the water year at about 71 percent of normal. In April 1989 snow accumulation was 19 percent below normal, but cumulative precipitation for the water year was normal (U.S. Department of Agriculture, 1988; 1989). Average monthly temperatures from April to September 1988 ranged from 6.4 to 19.6 degrees Celsius, generally above normal for the period. During the same months of 1989, average monthly temperatures ranged from 6.8 to 19.8 degrees Celsius, again above normal for the period. Precipitation, however, generally was below normal from April through September 1988 and 1989. During April to September 1988, cumulative precipitation was 1.38 inches, about 4.27 inches below normal. During the same months of 1989, cumulative precipitation was 4.56 inches, about 1.33 inches below normal (U.S. Department of Commerce, 1988; 1989).

As a result of these hydrologic conditions, streamflow during data-collection periods of water years 1988 and 1989 was relatively low. Continuous stage data for the study reach were provided by seasonal streamflow-gaging station 10016900 (Bear River at Evanston), operated by the USGS since 1984; the contributing drainage area is 433 square miles. Hydrographs of daily mean discharge for April through September 1988 and 1989, are compared in figure 2 with a hydrograph of mean daily discharge for April through September, developed using published data from USGS streamflow-gaging station 10019000 (Bear River near Evanston) for 1944 and 1946-56; the contributing drainage area is 715 square miles. The mean-daily-discharge hydrograph represents the long-term (in this case, 1944 and 1946-56) average discharge for each day of the hydrograph period. These data best reflect hydrograph characteristics of the study reach, although a direct comparison between flows at station 10016900 during the study period and average flows at station 10019000 cannot be made because of the difference in contributing drainage area. Figure 2 shows that the highest daily flows normally were at the end of May and early June (Bear River near Evanston; 1944 and 1946-56). The highest daily flows during the study period (Bear River at Evanston; 1988, 1989) were near the middle of May (although the 1988 hydrograph is otherwise similar in shape to the long-term average), probably reflecting the smaller snowpack, warmer temperature, and consequent early melting of the high-elevation snow.

Floodplain studies were conducted by Forsgren-Perkins Engineering[1] (1983) and by Simons, Li and Associates, Inc. for the Federal Emergency Management Agency (1988). Forsgren-Perkins Engineering used graphic techniques to develop a flow-frequency curve for the Bear River in and near Evanston on the basis of records from streamflow-gaging station 10019000 (Bear River near Evanston); peak-flow data for 1914-56 were used. Simons, Li and Associates, Inc. used log-Pearson Type III analysis and generally confirmed the results of Forsgren-Perkins Engineering. The analysis by Simons, Li and Associates, Inc. identified peak-flow values for recurrence intervals of 10, 50, and 100 years (table 1)--these flows have a 10-, 2-, and 1-percent chance of being equaled or exceeded in any 1 year. The results were used in hydraulic analyses for this study and can be considered valid for the entire study reach.

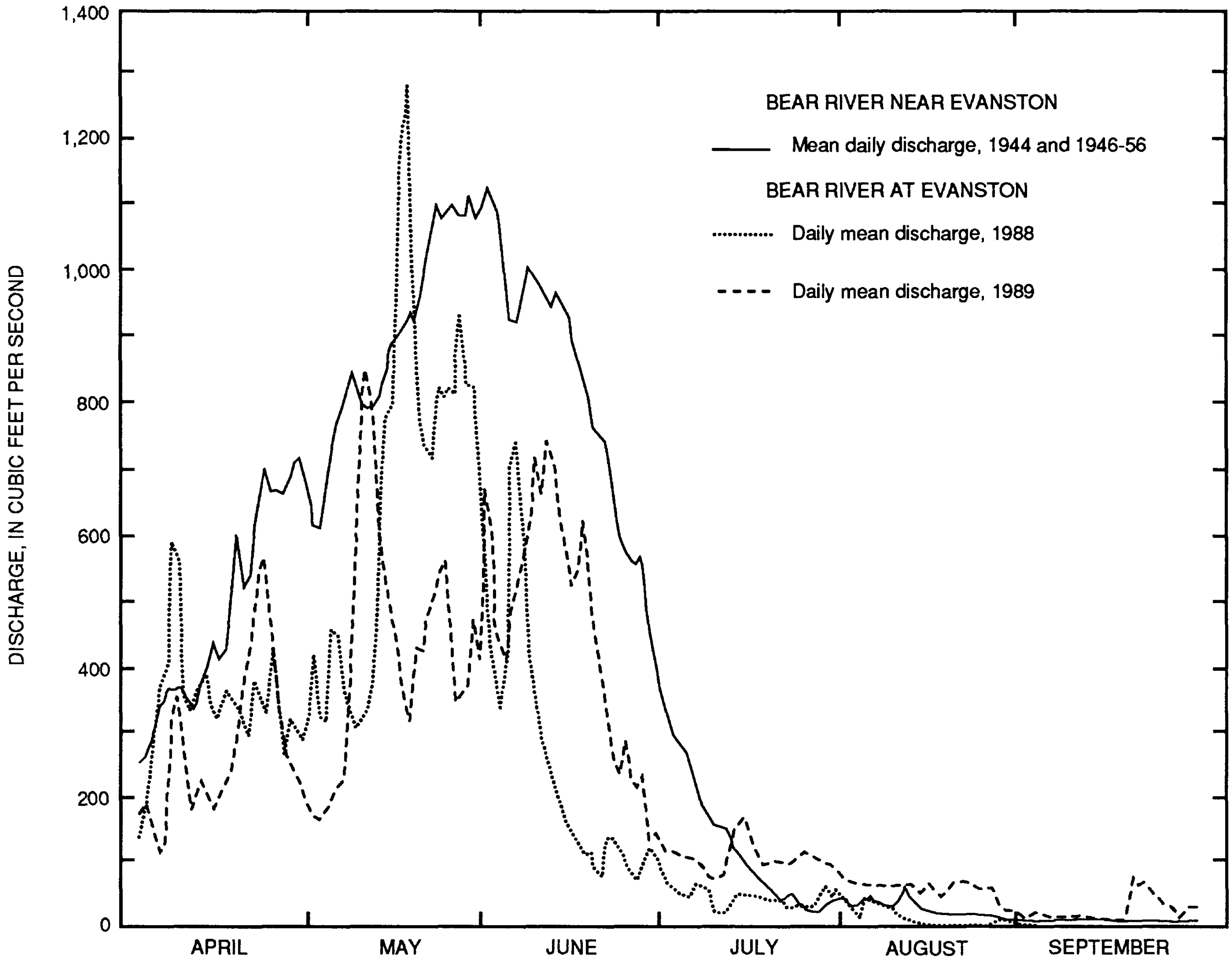

Figure 2.--Relation of streamflow conditions during the study period to long-term average conditions.

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[1]Use of firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Table 1--Recurrence intervals and peak discharges for the Bear River study reach

[Source: Federal Emergency Management Agency (1988)]

Recurrence interval (years)	Peak discharge (cubic feet per second)	Chance of occurrence (percent)
10	2,990	10
50	3,715	2
100	4,000	1

Peak discharge (instantaneous) at streamflow-gaging station 10016900 (Bear River at Evanston) during 1984-89 are listed in table 2. Flooding during the 1984 runoff peaked close to the 50-year peak discharge. Flooding in 1983 (prior to installation of the gage) probably was even more severe, on the basis of accounts from Evanston residents.

Table 2--Peak discharges recorded at streamflow-gaging station 10016900 (Bear River at Evanston), 1984-89

Peak discharge (cubic feet per second)	Date
3,680	May 16, 1984
1,490	May 4, 1985
3,140	June 6, 1986
1,520	May 17, 1987
1,380	May 18, 1988
1,030	May 10, 1989

A flow-duration curve is a frequency distribution of daily mean discharges, plotted using a lognormal scale (Riggs, 1968, p. 14). Such a curve represents the cumulative percentage of time the daily mean discharge of a stream equaled or exceeded a given value during the period of record. To minimize variability caused by abnormally high or low runoff, the discharge data should have a length of record of at least several years (usually 10 years or more). While the flow-duration curve cannot be interpreted as a probability curve, it does describe the distribution of the daily means for the period of record and indicates the distribution of daily means that might be expected over the next several years, assuming that flow conditions remain about the same.

A flow-duration curve developed using values of daily mean discharge from streamflow-gaging station 10019000 (1944 and 1946-56) is shown in figure 3. The highest daily mean discharge in 1988 was 1,280 cubic feet per second on May 18 (fig. 2); the instantaneous peak flow was 1,380 cubic feet per second (table 2). Figure 3 shows that, on average, this daily mean discharge is equaled or exceeded about 4 percent of the time. Likewise, in 1989, the highest daily mean discharge was 854 cubic feet per second on May 10 (fig. 2) and is equaled or exceeded about 9 percent of the time; the instantaneous peak flow was 1,030 cubic feet per second (table 2).

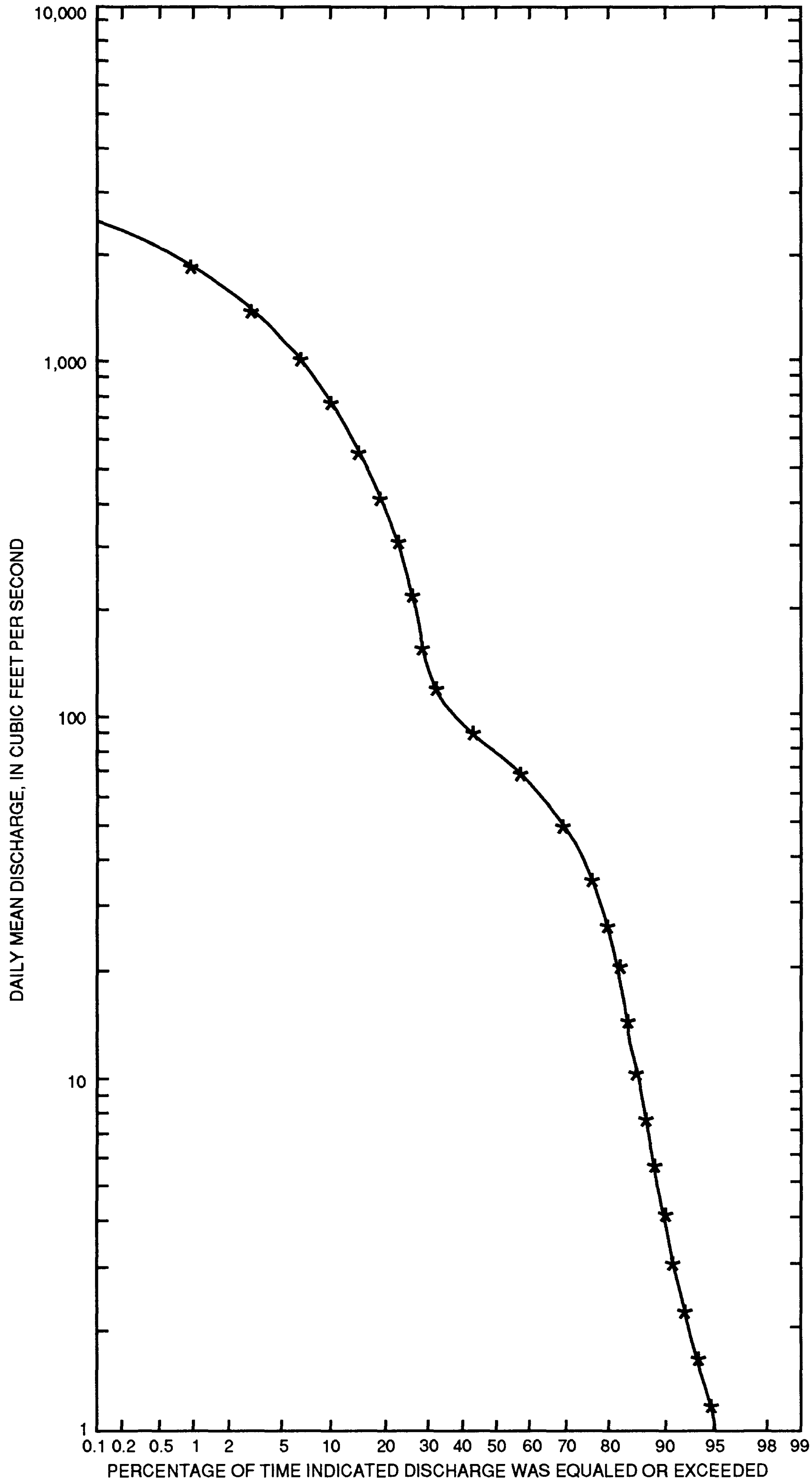

Figure 3.--Flow-duration curve for streamflow-gaging station 10019000 (Bear River near Evanston), 1944 and 1946-56.

While the highest daily mean discharges during the study period reflect small durations (4 to 9 percent of the time), flows were much lower than those during periods of snowmelt runoff in 1983 and 1984. This condition is important in assessing the data collected during the period because flow hydraulics may be different at higher, channel-forming flows. Sediment-transport characteristics, especially, might differ greatly at flows higher than those measured in the course of this study.

Geomorphic Characteristics

Maps and aerial photographs of the study area, made between 1946 and 1986, were compiled for the geomorphic analysis. Photographs made in 1986 (scale 1 inch = 400 feet, Uinta County Planning Department, Evanston) are the most recent and were used as the base map for the study. Photographs made in 1946-47, 1969 (no coverage upstream from Evanston; Horizons Inc., Rapid City, South Dakota), and 1981 (color satellite imagery; Department of Agriculture, APFO, Salt Lake City, Utah) were converted to the base scale of 1 inch = 400 feet for analysis. In addition to the photographs, available data included a USGS topographic map of the area (Evanston, 1965; 1 inch = 2,000 feet), large-scale topographic maps of the river channel in Evanston, and a blueprint drawing of the channel made in the early 1900's.

Channel-pattern changes between 1946 and 1986 were determined by overlaying successive aerial photographs. The study reach was divided, on the basis of channel-pattern characteristics and onsite observations, into three subreaches (figs. 4 to 6):

- Reach 1 (downstream)
- Reach 2 (Evanston)
- Reach 3 (upstream)

Channel-pattern changes reflected by the 1946-47 and 1986 photographs are shown in figures 4 to 6; the aerial photographs used in the figures are from 1986. Some additional growth and cutoffs of bends (not shown) were evident from the 1969 and 1981 photographs, providing good documentation of channel changes through the time period. The orientation of instream bars in reach 2 is shown in the 1946 channel overlay. Bar development in 1986 is evident from the aerial photographs.

Measurements of valley slope were made from USGS 7.5-minute topographic maps (scale, 1 inch = 2,000 feet). Longitudinal distance and altitude changes were measured along the valley centerline. An average valley slope was computed for each subreach.

Geometric measurements of channel-pattern properties were made from each set of aerial photographs and reflect the bankfull channel. Measured properties include reach and bend sinuosity, bend radius of curvature, and bend length. Reach sinuosity was computed according to equation 1 as the length of the bankfull channel centerline divided by the valley distance. Bend sinuosity was computed as the channel length of an individual bend divided by the bend length, where bend length was measured as the linear distance from the midpoint of the upstream crossing to the midpoint of the downstream crossing. Because bend sinuosity does not account for straight reaches and low-frequency directional changes of the channel with respect to the valley, computed reach sinuosity generally is larger than bend sinuosity.

Bend radius of curvature was measured as the radius of a circle fit to the bankfull-channel centerline through the bend (Brice, 1984, p. 4; Richardson and others, 1987, p. IV-15). Individual bends were measured to describe the channel pattern because bends generally were not symmetrical enough to be linked as meanders. A definition sketch of measured properties is shown in figure 7.

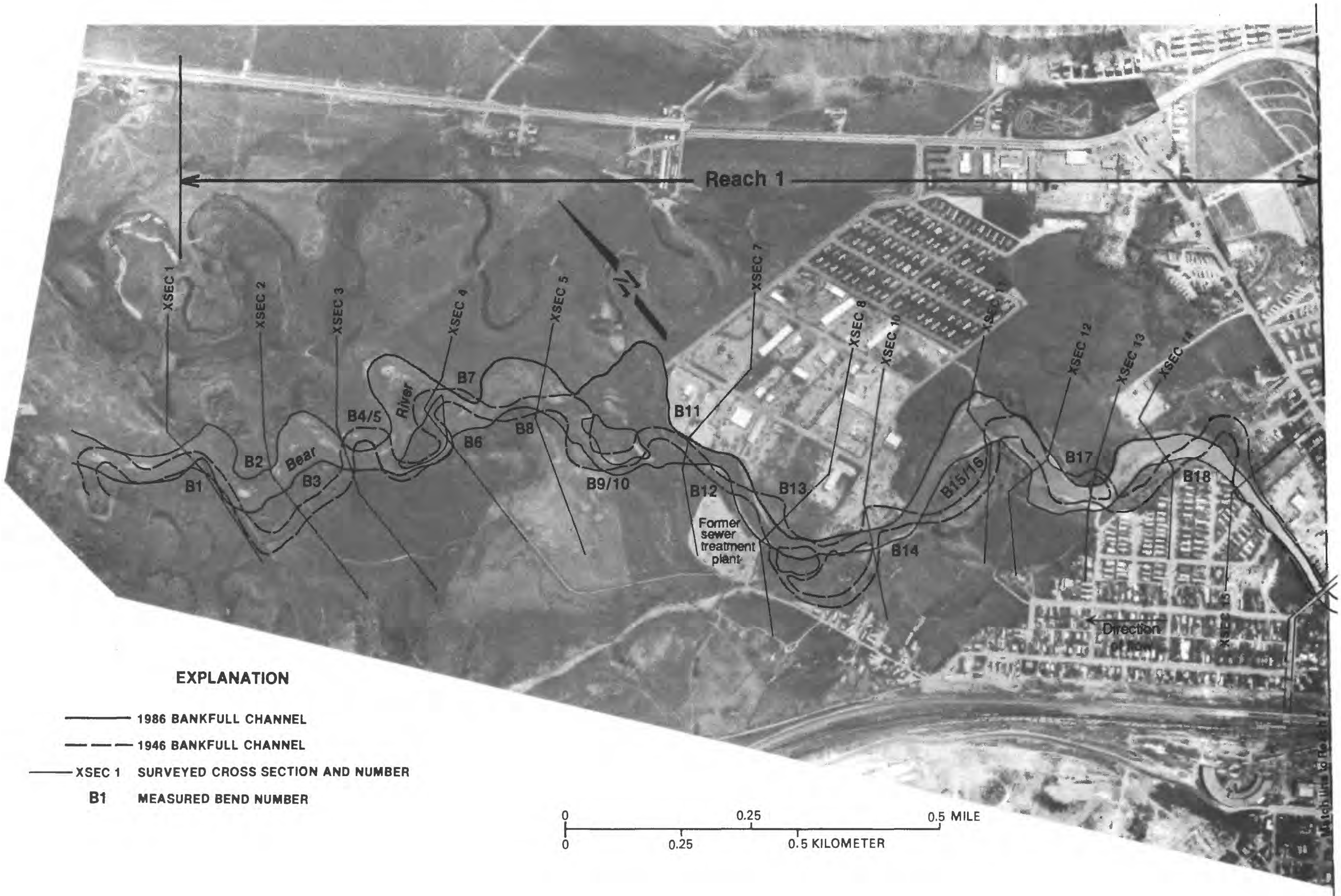

Figure 4.--Aerial photograph showing channel-pattern changes and onsite-measurement locations in study reach 1, Bear River.

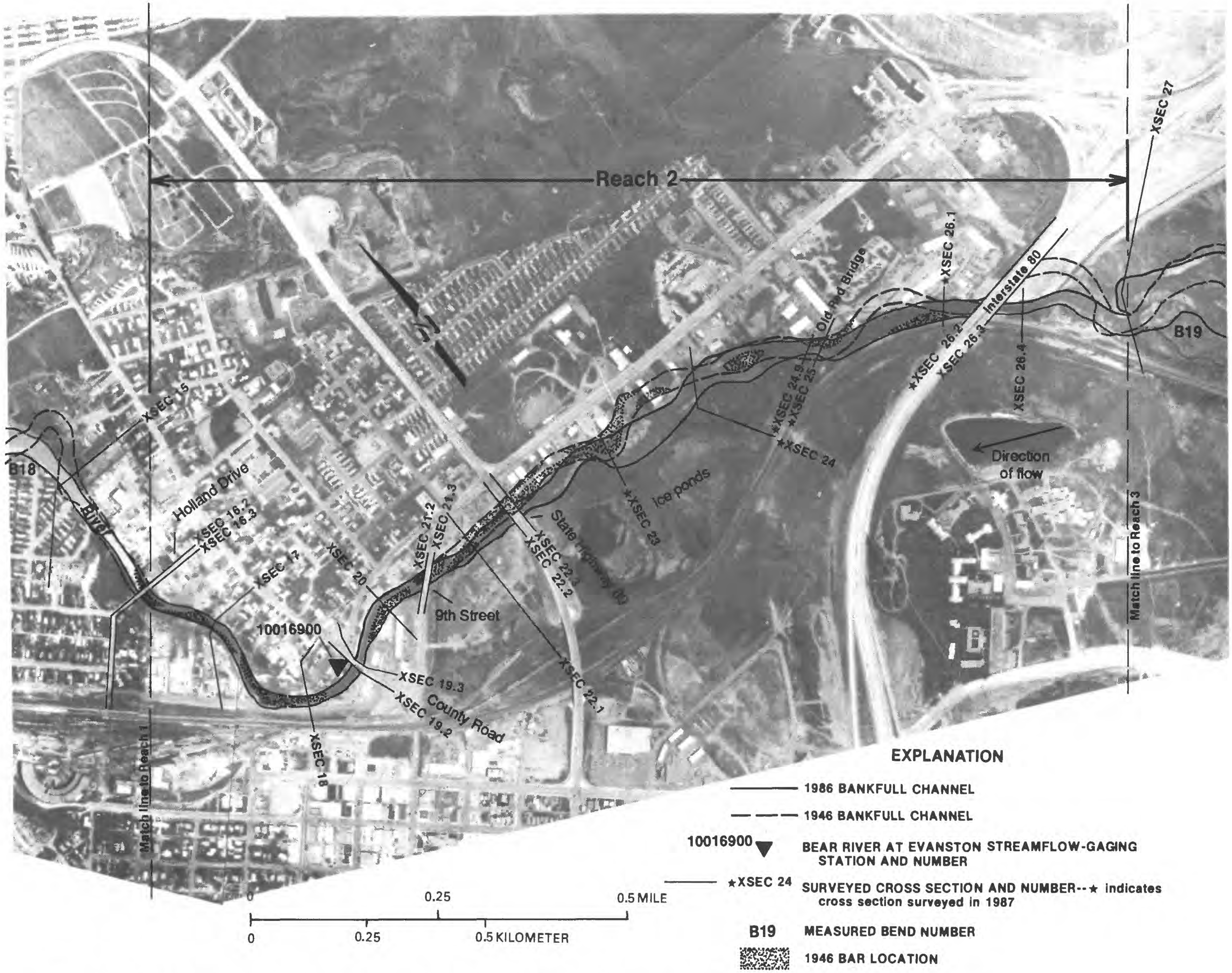

Figure 5.--Aerial photograph showing channel-pattern changes and onsite-measurement locations in study reach 2, Bear River.

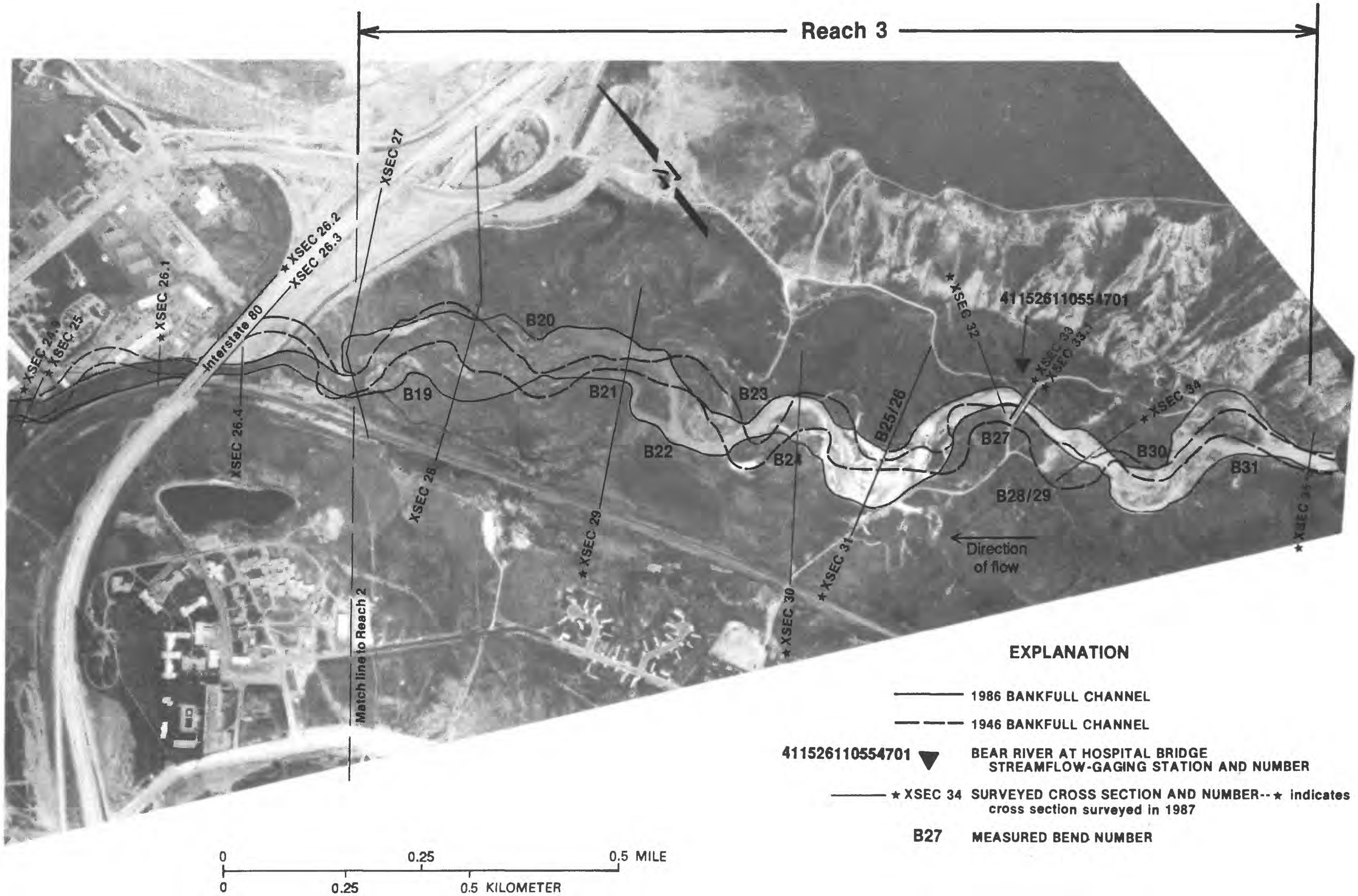

Figure 6.--Aerial photograph showing channel-pattern changes and onsite-measurement locations in study reach 3, Bear River.

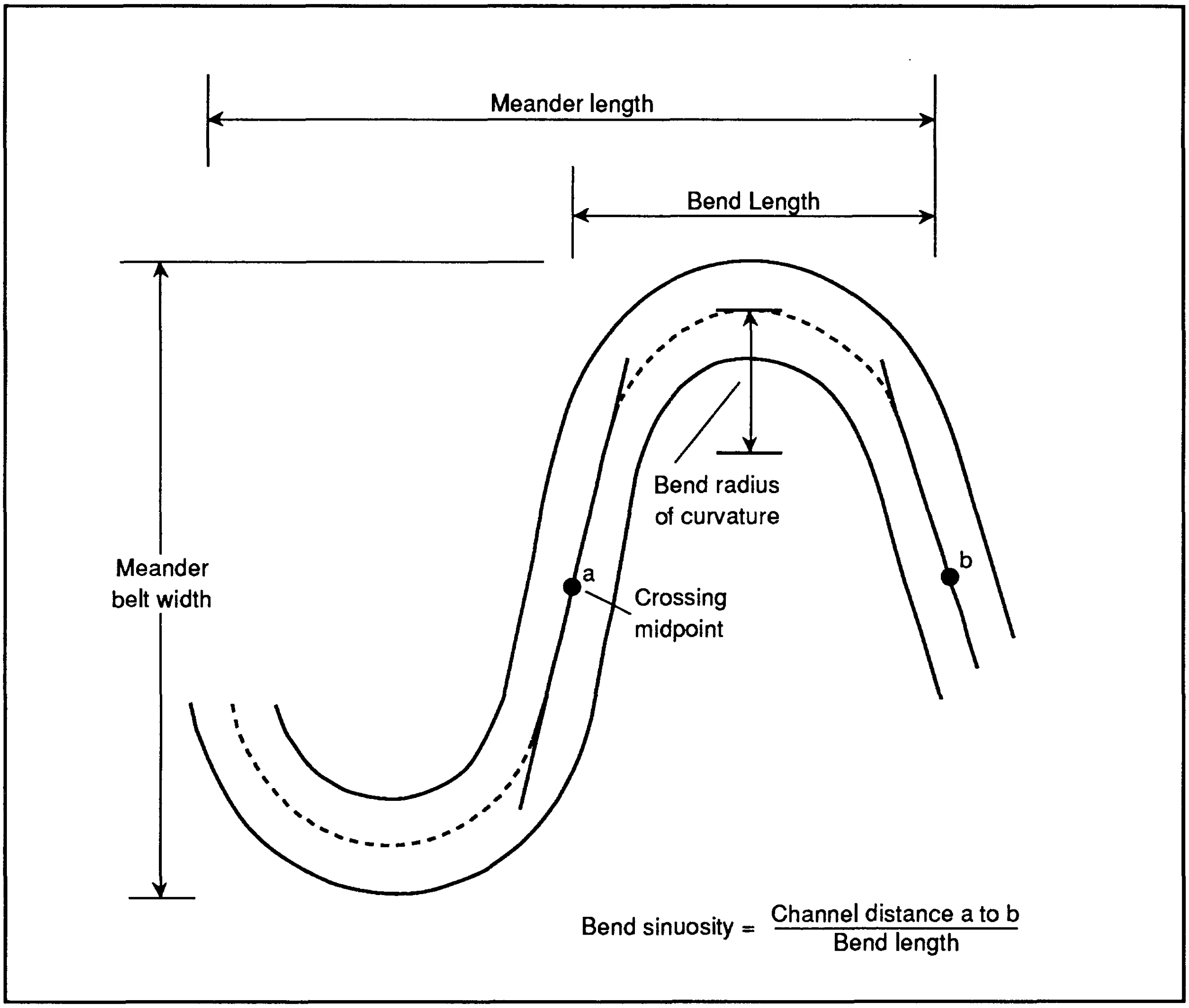

Figure 7.--Definition sketch for bend and meander properties.

A compilation of valley slopes and measured channel-pattern properties is included in table 7 (at the back of this report). Measured bends are identified in figures 4 to 6, according to their 1986 orientation, with a "B" and the bend number. The data reflect channel-pattern evolution between 1946 and 1986.

Onsite Measurements and Sampling

A data-collection program was designed to provide other necessary analytical data for the study. Existing cross-section data (surveyed beginning in 1981) from the floodplain study by the Federal Emergency Management Agency (1988) were used as input for WSPRO modeling. These data were augmented with additional cross-section surveys (1987) in the upstream part of the study reach; some existing cross sections also were resurveyed where substantial channel changes were apparent. Uinta County personnel conducted the 1987 surveys at sites specified by USGS personnel. All sites were tied to USGS bench marks of known altitude.

Cross sections are numbered from 1 to 35 beginning at the downstream end of the study reach. Their locations, spaced on average about 850 feet apart, are shown in figures 4 to 6; cross sections surveyed in 1987 are identified in the figures. All cross-section coordinates are available from USGS, 2617 E. Lincolnway, Suite B, Cheyenne, Wyoming 82001.

Channel roughness coefficients (Manning's *n* values) at each cross section were determined by USGS personnel. Values used for the study by the Federal Emergency Management Agency (1988) were revised where channel conditions had changed. The cross sections were subdivided on the basis of roughness and shape to allow for varying bed and bank conditions across the channel. The WSPRO model permits up to five roughness subdivisions for each cross section.

Three streamflow-measurement and sampling sites were established along the study reach. The downstream site, at a privately owned bridge about 2.6 river miles downstream from cross-section 1, was identified as Bear River above Yellow Creek, near Evanston (site number 411826111002001; site not shown on fig. 1). The second site was at streamflow-gaging station 10016900 (Bear River at Evanston), and the third site was near the upstream end of the study reach and identified as Bear River at Hospital Bridge, near Evanston (site number 411526110554701). The Bear River at Evanston site, shown in figure 5, is defined by surveyed cross-section 19.2; the Bear River at Hospital Bridge site, shown in figure 6, is defined by surveyed cross-section 33. All three sites provided bridge access for measurement of flows too high to wade.

In water year 1988, 10 visits (9 at Bear River above Yellow Creek) were made to each site from April 7 to June 16. In water year 1989, 5 visits were made to each site from April 27 to June 2. Bedload and suspended-sediment samples were collected at each visit except for May 24, 1989, when chemical-water-quality samples were collected at each of the 3 sites. A second set of chemical-water-quality samples (base-flow conditions) was collected on November 21, 1989 (water year 1990), at the Bear River above Yellow Creek and Bear River at Hospital Bridge sites. Flow and sediment data are listed in table 8 (at the back of this report) and also are included in the publications of USGS (Druse and others, 1989; 1990; 1991). Daily discharge data (April to September), based on continuous stage record and measurements by field office personnel for streamflow-gaging station 10016900 (Bear River at Evanston), are presented for each water year in the same publications.

Streamflow data in table 8 include stream width, mean velocity, and instantaneous discharge. Bedload data comprise computed discharge (tons per day) and size-fraction analyses. Suspended-sediment data comprise concentration (milligrams per liter), computed discharge (tons per day), and size-fraction analyses.

Chemical-water-quality data are listed in table 9 (at the back of this report), comprising laboratory analyses for major constituents, nutrients, trace metals, and pesticides. Onsite measurements of specific conductance, pH, and dissolved oxygen also are included. These samples provide baseline chemical-water-quality data for high (631 to 642 cubic feet per second) and low (28 to 34 cubic feet per second) streamflows. Water-quality conditions, such as dissolved oxygen and temperature, will be important for fisheries planning in the study reach. Releases from Sulphur Creek Reservoir might affect low-flow water-quality conditions in the Bear River and impact fish habitat. Levels of pesticides and selected minor constituents might need to be evaluated by city, county, and State planners for future development. Chemical-water-quality data are included for use by planners; the data neither are analyzed nor interpreted in this report.

GEOMORPHIC AND HYDRAULIC ASSESSMENT

The Bear River is an alluvial river that has actively shifted its course across the valley in recent history. This is evidenced by aerial photographs used for the study and by physical features visible during onsite inspections; these features include abandoned channels, meander cutoffs, and vegetational growth patterns. Such activity indicates that, even without human influences, the Bear River is naturally subject to change and likely cannot be described by a single, stable channel configuration. Geomorphic analyses used in this study were designed to identify a range of channel-pattern characteristics that might be easiest for the river to maintain.

Reasons for Channel Instability

The river channel in and near Evanston is unstable as a result of a number of human and natural factors. The most important factor identified during this study that has affected stability in reaches 1 and 2 is channelization of the river through Evanston. City and county officials located a map of the river drawn during the early 1900's.

The map shows the channel following several large meander loops at that time--this historical channel pattern is shown as an overlay to the present-day (1986) channel in figure 8. At some time afterward, the river was straightened and shortened by more than a mile and confined to its present-day configuration.

Channelization of a meandering alluvial river has substantial consequences. A river meanders to adjust its slope toward a state of equilibrium for valley and flow conditions. When the river is straightened and its length shortened, its slope is increased as a consequence. The energy that was dissipated by the meander process is instead directed toward downcutting of the channel bed. The river also tries to redevelop a meander pattern, causing bank erosion that requires continual stabilization and maintenance. The overall effect is to destabilize the river channel.

H.W. Lowham (U.S. Geological Survey, oral commun., 1989) notes that degradation, or streambed erosion, in the upper part of reach 2 has been evident for several years. Degradation has lowered the streambed up to 3 feet in some places and probably is a direct result of channelization. Advance of this process farther upstream into reach 3 is being prevented by bedrock outcrops. This rock (fig. 9) forms the channel bed between the Interstate-80 Bridge and cross-section 27 (fig. 5) and appears to resist erosion by the river. If erosion eventually destroys this control, it might be expected that degradation processes will continue to advance upstream and promote downcutting and channel instability in reach 3 related to downstream channelization.

Islands and channel braiding have developed since 1946 in reach 3, when aerial photographs showed a single-channel pattern. The specific cause of this change is unclear, but might be related to human-induced channel changes during the period or to natural evolution of the channel in response to flooding since 1946. Channel braiding and migration in reach 3 is of concern because design of the Bear River State Park has incorporated the existing configuration of the channel.

Bed/bank erosion of the channel throughout the study reach has led to individual efforts to stabilize channel banks with various forms of riprap. Onsite inspection of the channel by M.E. Cooley (U.S. Geological Survey, oral commun., 1987) determined that much of the channel in reach 2 has been stabilized and that some bends in reaches 1 and 3 also have been protected. These stabilization measures have proved to be inadequate, as evidenced by deposition of dislodged riprap material downstream from the placement sites. Materials used to protect banks include bags of cement, concrete slabs, boulders, and tires [fig. 10 (A)]. Other human influences include channel infilling for property enhancement, dredged cutoffs of meander loops by landowners (upstream from reach 3) for land management and farming, and artificial channel constrictions at bridge crossings.

Where no bank protection is in place, the channel banks are eroding actively. Extensive areas of bank erosion are evident throughout reach 2, where the river is trying to redevelop a more sinuous channel pattern. Because the river has actively shifted its course in the past, some bank erosion might be expected. However, the bank erosion and downcutting evident in reach 2 are related primarily to channelization and will be difficult to control without correcting the steepened channel slope.

Flooding in 1983 and 1984 (the peak discharge in 1984 was 3,680 cubic feet per second at streamflow-gaging station 10016900, Bear River at Evanston) magnified all of these problems. Riprap materials, along with large amounts of sediment and natural debris, were dislodged from the channel in reach 2. Deposition of these materials downstream from Evanston has caused damming, widening, and braiding of the channel [fig. 10 (B)]. In many places in reach 3, the channel is jammed with dead trees and other debris transported by floodwater from upstream and deposited around existing islands. Throughout the study reach, the channel generally is wider than it was prior to flooding and might be expected to be unstable until the river adjusts its alignment and morphology to post-flood conditions.

Geomorphology

Geomorphic characteristics of the bankfull channel were analyzed so that results could be related to more detailed hydraulic analyses. Defined as the streamward limits of the active floodplain, the bankfull channel was distinguished qualitatively on aerial photographs as the lower limit of perennial vegetation (Schumm, 1960,

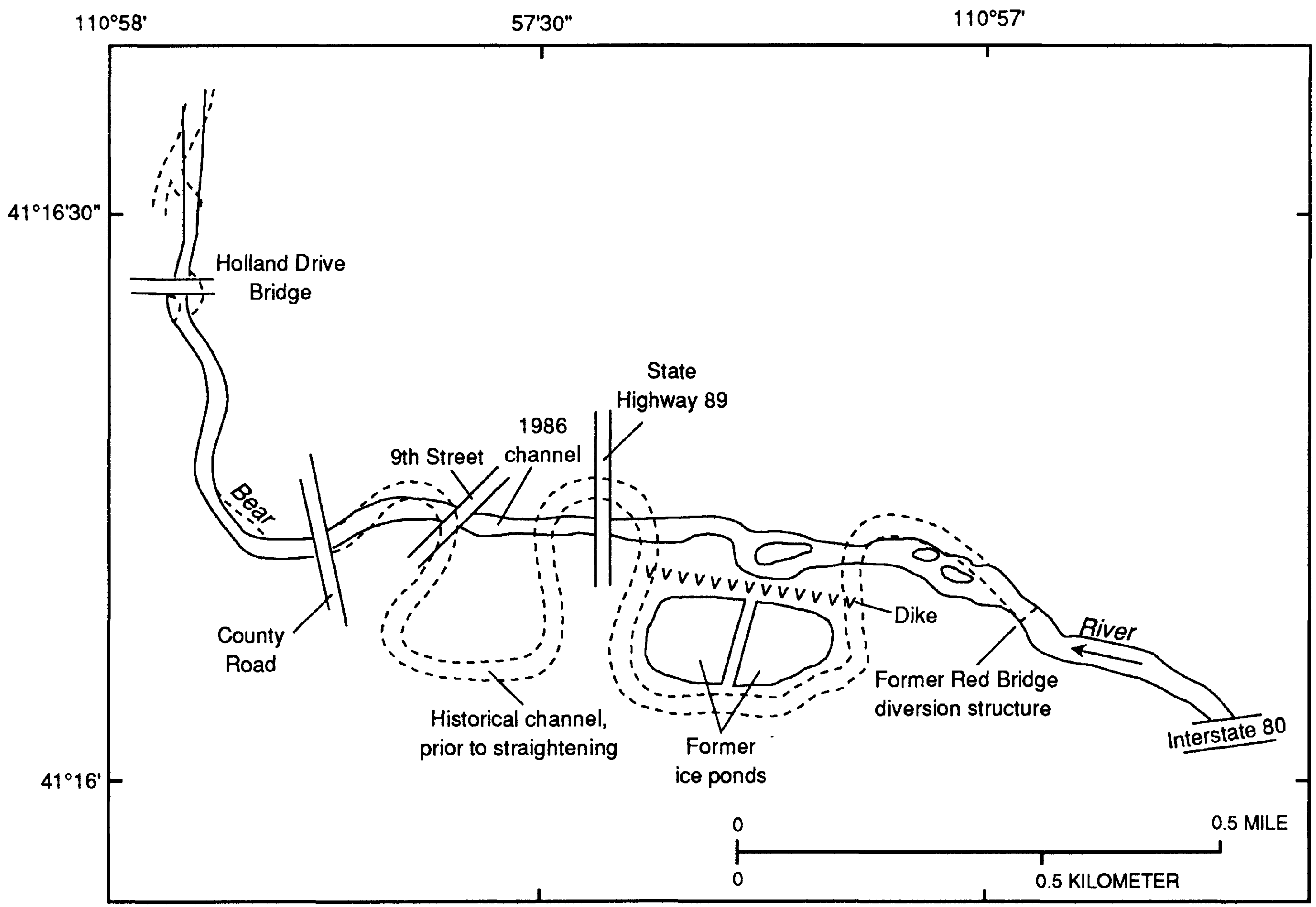

Figure 8.--Sketch showing the present-day (1986) and historical channel patterns of the Bear River in Evanston.

October 1983

September 1990

Figure 9.--Photographs of the Bear River showing the resistant bedrock outcrops controlling the channel immediately upstream from Interstate 80 near Evanston. Both views are upstream.

A
September 1983

B
September 1983

Figure 10.--A, present-day bank erosion and riprap materials used for bank protection; B, deposition of debris and channel braiding downstream from Evanston. Both views are downstream.

p. 17-30). The method is useful to help define the active floodplain (Williams, 1978, p. 1,142), but cannot be regarded as an accurate, quantitative tool. Because onsite measurements to delineate the streamward limits of the active floodplain were not available, existing cross-section data were used to verify (to the extent possible) bankfull channel limits on aerial photographs. The bankfull condition at a cross section can be identified as that level where a further increase in stage will result in a large increase in cross-section width compared with cross-section area (that is, where the flow spreads onto the floodplain). Comparison of bankfull channel widths measured from photographs with bankfull channel widths identified from cross sections showed acceptable agreement.

The bankfull channel and corresponding discharge identified for the study reach probably do not reflect the historical (pre-channelization) condition of the river. Channelization and other artificial channel changes have altered the Bear River in and near Evanston substantially so that conditions in the study reach cannot be considered valid upstream or downstream. The bankfull channel is identified in this study for the purpose of relating geomorphic characteristics to flow hydraulics.

Reach Sinuosity and Valley Slope

The effect of valley alluvium on channel pattern probably is not important for the study reach. Onsite observations by Lewis (1972) and by M.E. Cooley (oral commun., 1987) indicate that valley alluvium is uniform, consisting of sandy to gravelly loams, underlain by sands, gravels, and cobbles. Without substantial lateral changes in alluvial material, and because the discharge through the reach is not affected substantially by flow into or out of the channel, channel-pattern characteristics primarily should be a function of valley slope and human-made factors.

Reach sinuosity is related to valley slope according to equation 1. Variation of reach sinuosity in each of the defined reaches 1 to 3 and the effect of valley slope is discussed in this section. The sinuosity of individual bends is evaluated in the section entitled "Channel-Pattern Geometry."

- Reach sinuosity

The sinuosity of reach 1 in 1946 was about 1.52. A period of shortening and bend cutoffs from 1946-69 reduced the reach sinuosity to 1.31. The channel then lengthened through bend and meander growth from 1969-81, when the reach sinuosity was 1.44.

The present-day (1986) sinuosity of reach 1 is 1.33. The channel shortened during 1981-86, probably the result of flooding in 1983 and 1984. The present-day braided character of reach 1, with its wide, poorly defined channel and numerous bend cutoffs, suggests that the present channel alignment is unstable and will not be maintained for long. The change of reach sinuosity suggests, however, that the river in reach 1 tries to maintain a reach sinuosity greater than 1.31, but less than 1.44 to 1.52.

Reach 2 has been channelized and confined throughout the period 1946-86, so its reach sinuosity, 1.18 in 1986, has remained relatively constant. This is in contrast to the reach sinuosity of the historical channel prior to channelization, which was about 2.3 (the historical map probably delineates the low-flow channel, so the reach sinuosity of the bankfull channel might be slightly less than 2.3).

Because there are no other historical maps of the natural channel in reach 2, it was not possible to trace the evolution of the channel and determine how stable that alignment might have been. It is clear, however, that the present-day (1986) channel alignment is much straighter than what would develop naturally.

Braiding and channel instability in reach 1 is related to the channelization in reach 2. Increased erosion in reach 2, caused by the steepened channel slope and consequent faster flow velocities than in reach 1, results in more sediment and debris being carried into the downstream reach. Material carried into this reach is deposited abruptly as the energy of the river is reduced, and it begins to reestablish its natural channel pattern and flow conditions. Much of the larger debris that at present is damming the downstream channel was deposited during flooding in 1983 and 1984 because of this abrupt change from channelized to natural flow.

The channel in reach 3 shows a different development pattern than that in reach 1. The reach sinuosity in 1946 was 1.26 and by 1981 had shortened to 1.17 (no photographic coverage of reach 3 in 1969). The 1986 photographs showed little change from 1981, with a sinuosity of about 1.18. Much of the shortening during 1946-81 is the result of braiding and permanent island development upstream from the Interstate-80 Bridge.

Development of this braided pattern probably is not related to channelization of reach 2 because of the bedrock outcrops upstream from the Interstate-80 Bridge. The braided channel is upstream from these outcrops, and, according to principles of open-channel hydraulics, should be subject to control by the outcrops and not by conditions (streambed degradation) below it.

- Valley slope

The average valley slope is 0.0059 foot per foot (31 feet per mile) in reach 1, 0.0083 foot per foot (44 feet per mile) in reach 2, and 0.0066 foot per foot (35 feet per mile) in reach 3. Because of the many human-induced changes through the entire study reach, quantification of the relation between sinuosity and valley slope (Schumm and Khan, 1972) was not possible. However, the substantially steeper valley slope in reach 2 may explain the relatively higher (higher than 2.0) reach sinuosity of the historical channel there. According to equation 2, as valley slope increases, sinuosity also would increase to maintain the existing channel slope. In view of this circumstance, present-day channelization of the river through Evanston increases channel instability in reaches 1 and 2.

Channel-Pattern Geometry

On the basis of the bankfull channel-geometry measurements listed in table 7, stable-bend geometry was evaluated in reaches 1 and 3. Reaches 1 and 3 were analyzed together because of the limited size of the data set. The valley slope is similar in each reach so that the effect of equation 2 should be negligible. Reach 2 was not included because of the substantially steeper valley slope and because of channelization and almost complete confinement of the river.

- Reaches 1 and 3

For this study of channel characteristics, the use of sinuosity as a stability criterion seemed most appropriate (Schumm and Khan, 1972; Schumm, 1977; Martinson, 1984). A bend was determined to be stable or unstable according to the change in bend sinuosity from one generation of aerial photographs to the next. This determination was subjective, so an absolute numerical value of bend sinuosity change was not chosen. However, by observing the sequence of change during 1946-86 from the four aerial photographs, it was clear which bends tended to cut off and which tended to remain stable.

Because of human activities along the river, many of the bends through the study reach have been protected artificially. This analysis indicated that, during the timespans represented by the aerial photographs, few of the bends with no known bank stabilization could be considered stable using the bend-sinuosity criterion. Channel migration and pattern changes, the result of the natural behavior of the river and also the degree of artificial control, are so active that individual bends cannot be expected to remain stable for even a few years.

An alternative, statistical approach was pursued, on the basis of the observation of Brice (1984, p. 7-8) that dominant geomorphic properties of channel pattern can be identified from the distribution of data. Data measured from each set of aerial photographs were analyzed separately, again using bend sinuosity as a criterion. All data measured from each photograph (bend sinuosity, bend radius of curvature, and bend length) were ordered according to increasing bend sinuosity. The median (defined as the value for which 50 percent of the data is smaller and 50 percent is larger) bend sinuosity was identified from the ordered distribution. The median is a robust statistical measure of central tendency of a distribution. Bend radii of curvature and bend lengths corresponding to median bend sinuosity then were compiled.

The median bend sinuosity among measured bends in 1946 was 1.25. A similar analysis of the other aerial photographs showed the median in 1969 (reach 1 only; no coverage of reach 3) was 1.30; in 1981, 1.22; and in 1986, 1.25. For practical purposes, this analysis suggests that median bend sinuosity is between about 1.2 and 1.3, and that this range might represent the dominant, or most characteristic, sinuosity of bends in reaches 1 and 3.

A compilation of all bends (1946-86) having bend sinuosities between 1.2 and 1.3 indicates a range of bend radius of curvature from 130 to 520 feet and a range of bend length from 220 to 960 feet. Among these data, it was found that bend length was related linearly to bend radius of curvature, as shown in figure 11. Linear regression defined the relation as

$$Lb = 1.92Rc - 12.7, \qquad (4)$$

where Lb is bend length, in feet, and Rc is bend radius of curvature, in feet. The correlation coefficient (R) of equation 4 is 0.92, and the standard error of the estimate is 83 feet.

Bend radius of curvature often is an important secondary criterion for river engineering projects. It usually is necessary to determine optimum bend radii in a reach by observing bends that tend to be stable through time (Vanoni, 1975, p. 526-527). Because channel pattern in the Bear River study reach generally is unstable, radii of bends with sinuosities between 1.2 and 1.3 were evaluated statistically. In reach 1, the median bend radius of curvature was 230 feet, and the interquartile range (IQR)--the range of the central 50 percent of the data--was 180 to 320 feet. Radii in reach 3 tended to be slightly longer, with a median of 300 feet and an IQR of 250 to 420 feet. A site-specific design for channel alignment or stabilization would maintain a bend sinuosity between 1.2 and 1.3 and also would reflect dominant bend radius of curvature in either reach 1 or 3; again, the range of values identified here allows flexibility for local conditions. A corresponding bend length could be computed using equation 4.

Meander belt width (fig. 7) is variable throughout the study reach. Rather than try to quantify this variable, it seems reasonable that any channel alignment or stabilization effort would consider the local meander belt width upstream and downstream, while maintaining a desirable sinuosity of individual bends. The range of bend radius of curvature and bend length identified previously would allow this flexibility in engineering design. Channel width, like meander belt width, varies greatly, and a characteristic width was not identified from channel-pattern analysis. Given present-day channel widening and instability, projects to improve channel alignment need to be flexible enough to accommodate progressive width adjustments by the river.

- Reach 2

The confined channel in reach 2 was not included in the aforementioned channel-pattern analysis. However, an examination of width changes and bar development during 1946-86 indicates that the river is trying to reestablish a meandering pattern.

The 1946 and 1986 channels are shown in figure 5. Although the general alignment is nearly the same, channel widening and bar growth is evident in 1986 between the former ice ponds and the former diversion structure (Red Bridge). Judging from figure 8, the former ice ponds originally were constructed by cutting off the large, historical meander bend that followed the outer edge of the pond area. The large sand bar developing in the present-day channel at the former ice ponds indicates that the river is trying to rebuild the historical meander loop. Bank stabilization through the reach prevents meander development, but maintenance and repair of stabilization structures always will be required. A dike wall that separates the ponds from the river channel was rebuilt in 1990 as part of this ongoing effort.

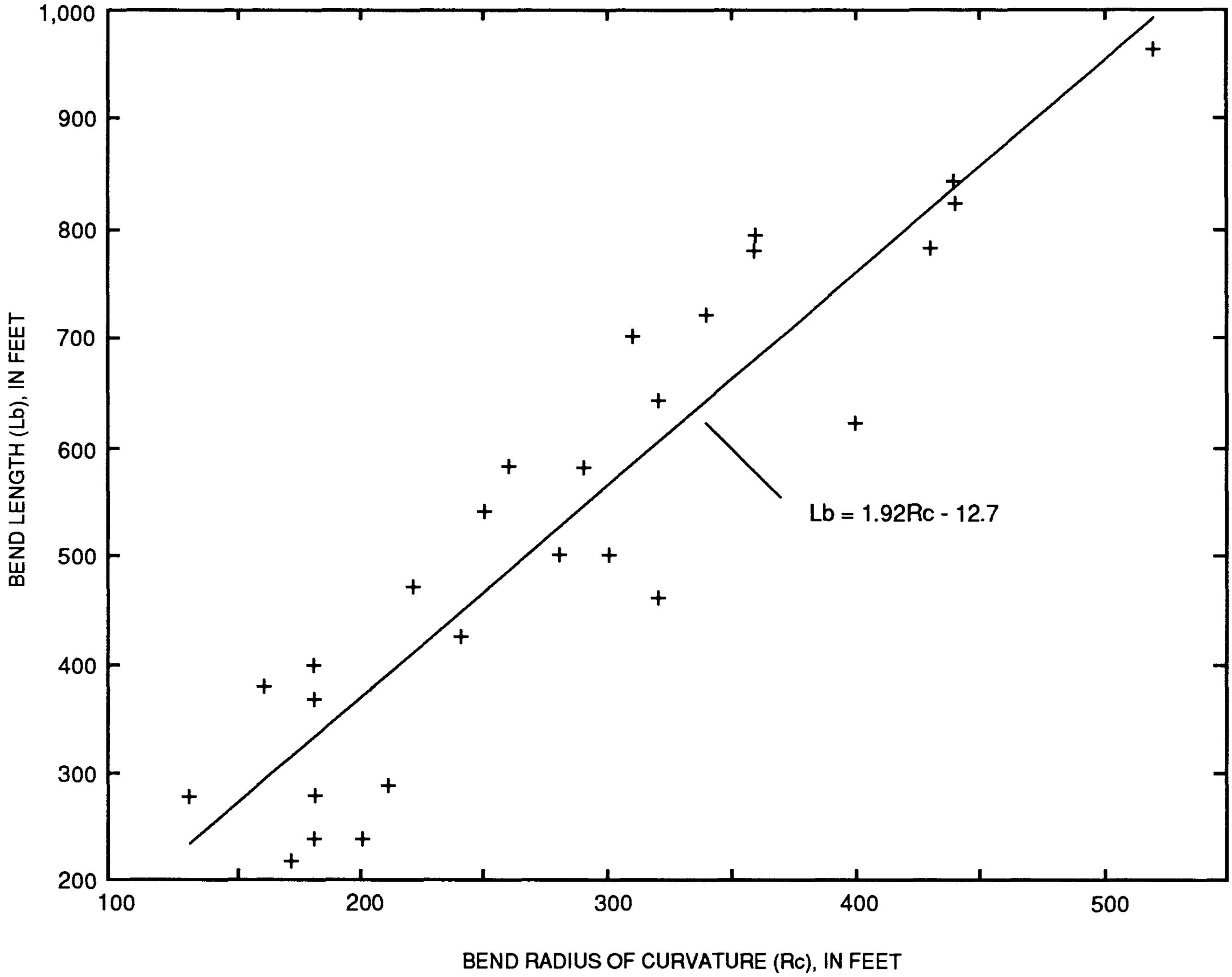

Figure 11.--Relation of bend length to bend radius of curvature.

The process of bank erosion and instream bar development (that is, meander development) during 1946-86 is evident throughout the channelized reach. Along with the streambed degradation discussed earlier, these channel changes emphasize the present-day instability in the reach caused by channelization. Because the goals of city, county, and State planners include river stabilization and beautification, an understanding of the hydraulic effects of channelization will be important to future development projects.

Hydraulics of Flow

Flow and cross-section hydraulic properties were analyzed using the Water-Surface Profile (WSPRO) computer model. The present-day channel was modeled for the 10-year, bankfull, and 100-year peak discharges; smaller discharges were not modeled because of limitations previously noted in the subsection entitled "Approach." As part of the analysis, the hydraulic effects of a proposed diversion structure and an experimental bank-stabilizing measure also were evaluated. Subsequent discussions of the relation between geomorphic properties and flow hydraulics are based on the bankfull channel and bankfull discharge.

The bankfull channel was identified on aerial photographs as part of the geomorphic analysis. The first step in the hydraulic analysis was to quantify the bankfull discharge, so that WSPRO-model results could be related to geomorphic properties of the bankfull channel.

Bankfull-Discharge Determination

Williams (1978, p. 1,142-1,143) discussed methods for identifying bankfull discharge, either for a single cross section or for an entire reach. Throughout the study reach of the Bear River, channel shape and bank height vary considerably. As noted by Williams (1978), these differences substantially influenced the determination of bankfull discharge. Therefore, an average discharge representing the entire reach seemed most appropriate.

Stage-discharge relations at gaged sites, along with cross-section surveys of the channel, often are used for such analyses. The method devised for this study used stage-discharge relations computed at each cross section by the WSPRO model. Once calibrated, the model was used to generate water-surface profiles for various discharges for comparison with bankfull-channel levels in the study reach.

Bankfull-channel elevations were identified from cross sections as part of the geomorphic analysis. These elevations, in profile, were the basis for the comparison. In order to reflect best the natural condition of the channel, only reaches 1 and 3 were considered, because most banks in reach 2 are artificially elevated by bank protection. Certain cross sections in reaches 1 and 3, where banks are artificially elevated or stabilized (for example, at bridges and stabilization structures), also were excluded.

Once the bankfull profile was established, water-surface profiles were generated by successive WSPRO runs for various discharges. The cumulative difference (*dH*) between the bankfull-channel elevation and the computer-generated water-surface elevation at all cross sections was defined as follows:

$$dH = (BCE1 - WSE1) + (BCE2 - WSE2) + \ldots + (BCEn - WSEn) \ , \qquad (5)$$

where $BCEn$ is the bankfull-channel elevation, and $WSEn$ is the water-surface elevation at a given cross section. For a given discharge, dH would be positive if most of the flow is contained in the bankfull channel and negative if most of the flow overtops the banks. A best-fit water-surface profile was determined by minimizing the absolute value of dH.

The analysis produced a good fit of water-surface profile to bankfull channel through the reach. The resulting bankfull discharge was 3,600 cubic feet per second, which is slightly less than the 50-year peak discharge (3,715 cubic feet per second). While many studies of natural rivers and streams suggest that the recurrence interval of bankfull discharge tends to be about 1 to 2 years, Williams (1978, p. 1,152) showed that documented recurrence intervals of bankfull discharge can range as high as the 200-year peak discharge.

Present-Day Hydraulic Properties

While previous studies (Forsgren-Perkins Engineering, 1983; Federal Emergency Management Agency, 1988) primarily were concerned with defining floodplain limits for various discharges, the objective of this study was to determine flow and cross-section properties of the river channel. Present-day hydraulic properties were determined using WSPRO for the 10-year (2,990 cubic feet per second), bankfull (3,600 cubic feet per second), and 100-year (4,000 cubic feet per second) discharges. The 10-year data are included primarily as a summary of lower flow characteristics that might be useful to planners in future engineering projects. This proved to be the lowest level of discharge that could be modeled reliably with the existing cross-section coverage; flows less than 2,990 cubic feet per second become increasingly influenced by local bed/bank configurations and would require more closely spaced cross sections for accurate results. The 100-year data are included: (1) to update 100-year water-surface elevations for recent channel changes and new cross-section surveys made since the study by the Federal Emergency Management Agency (1988); and (2) for use by planners in evaluating the effects of proposed hydraulic structures and stabilization measures.

Data for the 50-year peak discharge (3,715 cubic feet per second) are not included in the report because that discharge is close to the bankfull discharge of 3,600 cubic feet per second. Differences in hydraulic properties between the two discharges are small, and the conceptual significance of the bankfull discharge seemed most important for the purposes of this study.

Calibration of WSPRO for this study was based on the 100-year water-surface profile determined by Simons, Li and Associates, Inc. for the Federal Emergency Management Agency (1988). As noted earlier, cross sections were resurveyed where channel changes were evident and augmented by new sections as indicated in figures 4 to 6. Channel-roughness coefficients also were reevaluated and modified according to onsite inspections of the channel in 1987. The 100-year water-surface profile then was calibrated to the results of Simons, Li and Associates, Inc., considering any channel changes. Flood levels photographed at Holland Drive Bridge (fig. 8) on May 16, 1984 (peak discharge of 3,680 cubic feet per second), as well as high-flow measurements made at streamflow-gaging station 10016900 (Bear River at Evanston), were evaluated as part of the calibration.

Present-day (1986) flow and cross-section characteristics for the 10-year, bankfull, and 100-year peak discharges are compiled in table 10 (at the back of this report). Data consist of reach, cross-section number, location of cross section (channel distance, in feet, starting at 0 for cross-section 1), water-surface elevation, mean bed elevation, thalweg elevation (deepest part of the channel), Froude number, mean flow velocity, conveyance, area, top width, and hydraulic radius. The following equations were used in computations:

$$F = \frac{Q}{\left(A\left(\frac{gA}{\alpha T}\right)^{0.5}\right)}, \tag{6}$$

$$V = \frac{Q}{A}, \tag{7}$$

$$K = \left(\frac{1.49}{n}\right) A \left(R\right)^{0.67}, \text{ and} \tag{8}$$

$$R = \frac{A}{P}, \tag{9}$$

where F is the Froude number;
Q is discharge, in cubic feet per second;
A is cross-section flow area, in square feet;
g is gravitational acceleration, in feet per second squared;
α is the kinematic energy correction factor for nonuniform velocity distribution;
T is cross-section top width, in feet;
V is mean flow velocity, in feet per second;
K is cross-section conveyance, in cubic feet per second;
n is Manning's roughness coefficient, in feet$^{1/6}$;
R is cross-section hydraulic radius, in feet; and
P is cross-section wetted perimeter, in feet.

Hydraulic radius essentially is equal to mean depth (A/T) when the cross-section width-to-depth ratio exceeds 10 (Chow, 1959, p. 27). For smaller width-to-depth ratios, hydraulic radius is smaller than mean depth and more accurately reflects edge effects caused by the narrow channel. Because some cross sections have width-to-depth ratios smaller than 10, hydraulic radius is included in table 10 rather than mean depth.

- Conditions for bankfull flow

A statistical summary of computed flow and cross-section properties for the bankfull flow of 3,600 cubic feet per second are shown in table 3. Computed slopes are presented for the entire study reach and for reaches 1, 2, and 3 individually. A longitudinal profile of the entire study reach, comprising elevation of the water surface, mean channel bed (water surface minus hydraulic radius), and thalweg, is shown in figure 12. Normally, the profile would be expected to gradually flatten from upstream (reach 3) to downstream (reach 1), but the data show that the water-surface and bed slopes are steeper in reach 2 than in either reach 1 or 3. This is the result of channelization in reach 2.

Increased flow velocities accompany the steeper slope in reach 2. The median of the mean flow velocities in reach 2 is 6.73 feet per second, compared with 5.00 feet per second in reach 1 and 6.14 feet per second in reach 3. Because of channel confinement and downcutting, the channel in reach 2 is narrower and deeper than in reaches 1 and 3. The median channel top width in reach 2 is 92 feet, compared with 354 feet in reach 1 and 250 feet in reach 3. The median hydraulic radius in reach 2 is 4.96 feet, considerably greater than the median of 2.23 feet in reach 1 and 2.38 feet in reach 3. These cross-section characteristics, as well as cross-section conveyance, cross-section area, and ratio of top width to hydraulic radius, are summarized in table 3 using the median and the range of values encountered.

Boxplots were constructed to compare the three reaches. A boxplot is a graphical representation of the distribution of a data set, describing the median, IQR, quartile skew, and adjacent values (Chambers and others, 1983; McGill and others, 1978, p. 12-16). The median and IQR were defined previously. The quartile skew reflects the degree of symmetry of the data about the median, as indicated by the lower and upper boundaries of the IQR. Adjacent values lie in an extended range defined by the lower boundary of the IQR minus 1.5 times the IQR and the upper boundary of the IQR plus 1.5 times the IQR.

The boxplot comparison of reaches 1, 2, and 3 is shown in figure 13 for mean velocity, hydraulic radius, and channel width. The effects of channelization and channel-width constriction in reach 2--increased flow velocities and a narrower, deeper channel than in reaches 1 or 3--are evident.

Some other observations can be made about the WSPRO data (table 10). Flow at cross-sections 13, 15, 25, and 27 is close to critical or supercritical (Froude number close to or greater than 1). Cross-section 25 is the site of the former Red Bridge diversion structure (fig. 8), and cross-section 27 marks the upstream limit of the rock outcrop separating reaches 2 and 3. Flows at and near critical often produce instability of the channel bed and banks, so any channel renovation or stabilization in the vicinity of these cross sections might need to include measures to reduce velocities.

The bed profiles in figure 12 show scour caused by channel constrictions at three bridge crossings. These sites are Holland Drive Bridge (cross-sections 16.2 and 16.3), Interstate-80 Bridge (cross-sections 26.2 and 26.3), and Hospital Bridge (cross-sections 33 and 33.1). The most substantial change in bed elevation occurs at the Interstate-80 Bridge where the thalweg elevation decreases by 3 feet over a distance of 535 feet (from cross-section 26.1 to 26.4). This change also might reflect the effect of degradation related to channelization downstream from the bedrock outcrop.

- Proposed diversion structure

Construction of a diversion structure in reach 2 is planned to divert water into the former ice ponds (fig. 8) to create additional fish habitat. The planned structure is a submerged dam that would raise the level of the channel bed about 2 feet. Several locations have been proposed, the most likely one is the site of the former Red Bridge. Channel cross-section 25 also is at this site.

Table 3--Summary of present-day flow and cross-section properties for bankfull discharge (3,600 cubic feet per second)

Reach (figs. 4-6)	Slope (foot per foot)			Mean velocity (feet per second)		Conveyance[1] (cubic feet per second)		Area[1] (square feet)		Top width[1] (feet)		Hydraulic radius (feet)		Top width/ hydraulic radius	
	Water surface	Mean bed	Thalweg	Median	Range	Median	Range	Median	Range	Median	Range	Median	Range	Median	Range
1 to 3	0.00496	0.00492	0.00497	6.15	2.35-10.6	57,100	31,200-97,900	585	340-1,530	167	63-1,410	3.91	1.08-7.68	38.5	8.6-1,300
1	.00428	.00431	.00433	5.00	2.35- 7.10	57,100	39,000-75,900	720	507-1,530	354	119-1,410	2.23	1.08-4.82	173	24.7-1,300
2	.00526	.00518	.00525	6.73	4.40-10.6	57,700	34,200-97,900	536	340- 818	92	63- 349	4.96	2.07-7.68	20.6	8.6- 168
3	.00499	.00486	.00464	6.14	3.35- 9.00	55,800	31,200-86,500	585	400-1,080	250	71- 463	2.38	1.61-5.50	108	13.1- 287

[1]Values in this table are taken from table 10 (at the back of this report) and rounded to three significant figures.

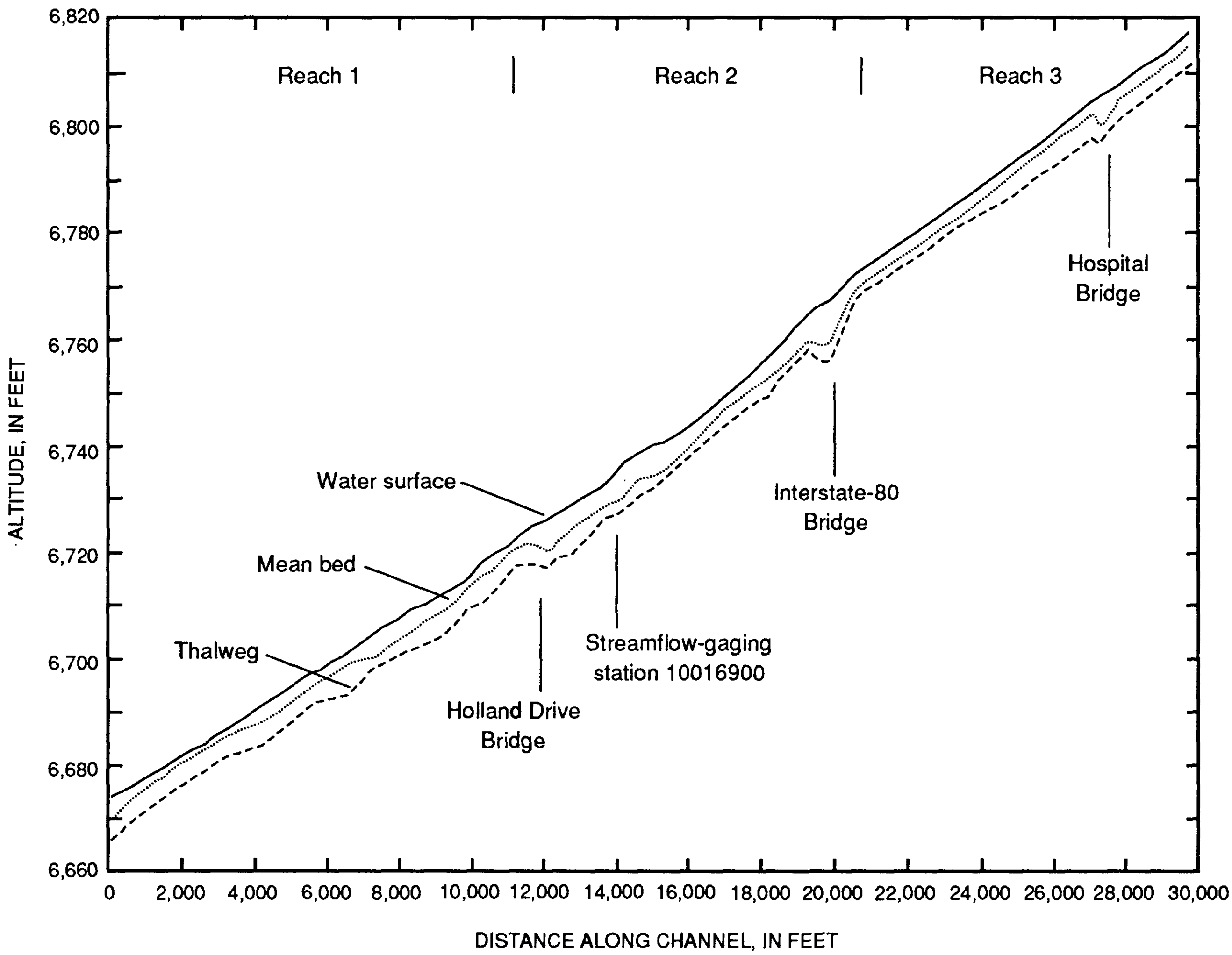

Figure 12.--Present-day bed and bankfull water-surface profiles through the study reach.

Project planners are interested in the hydraulic effects of the proposed structure, particularly the resulting increase in stage for the 100-year peak discharge. As part of the river parkway, a foot bridge is planned at the site of the former Red Bridge; its design will reflect the level of the 100-year peak discharge with the diversion structure in place. Using structural design plans provided by the U.S. Department of Agriculture Soil Conservation Service, the hydraulic effects of the structure, assuming its location immediately downstream from cross-section 25, were evaluated. Calculations indicated that flow over the structure itself would be critical (Froude number equal to 1) even at the 100-year peak discharge (4,000 cubic feet per second). Computed flow and cross-section properties immediately upstream from the structure (cross-section 25) are listed in table 4, along with properties computed for the existing channel.

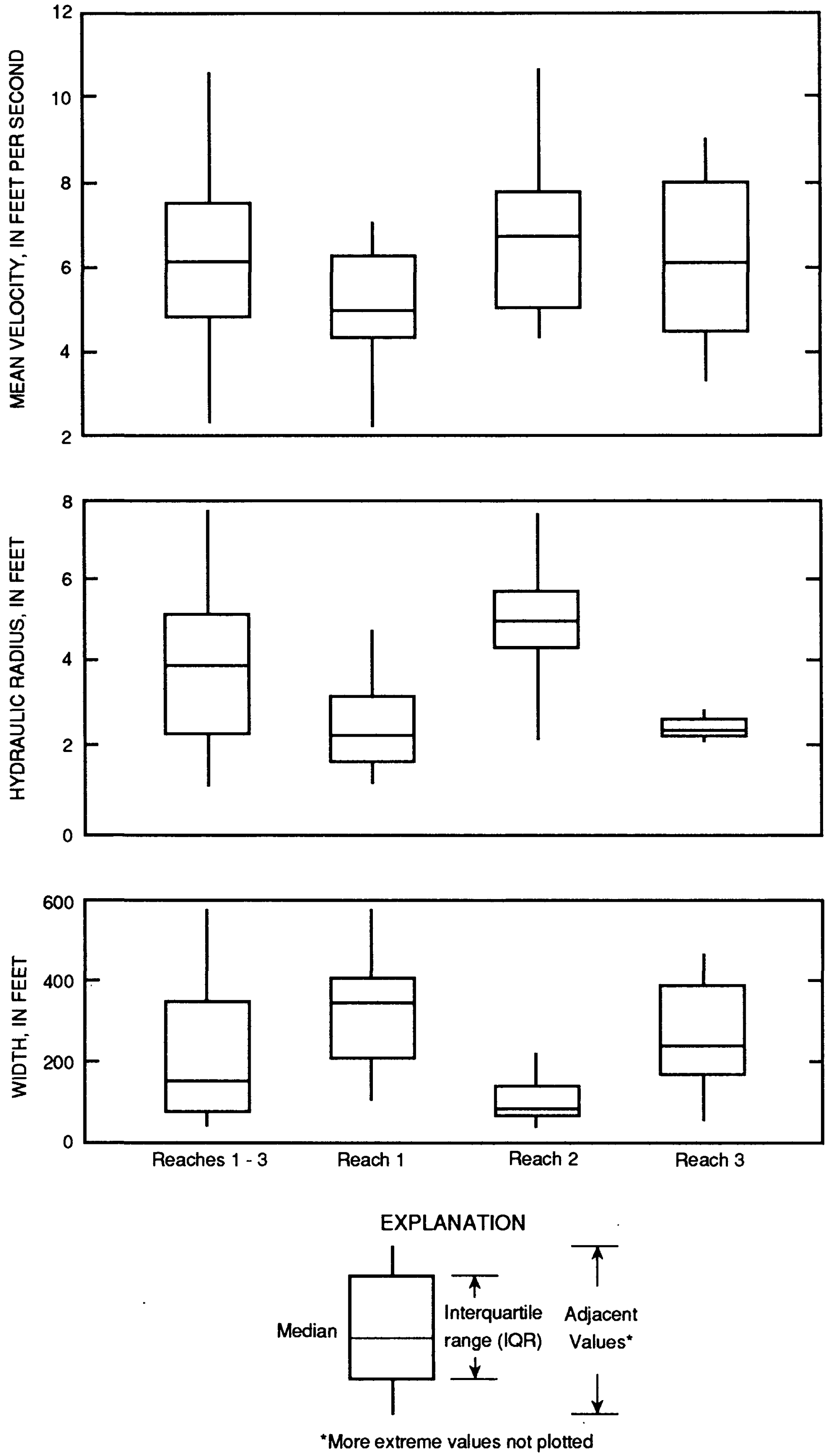

Figure 13.--Boxplots showing a comparison of bankfull hydraulic properties for reaches 1, 2, and 3 of the present-day channel.

Table 4--Flow and cross-section properties at cross-section 25, with and without the proposed diversion structure for the 100-year peak discharge (4,000 cubic feet per second)

Elevation of water surface (feet above sea level)	Froude number	Mean velocity (feet per second)	Conveyance[1] (cubic feet per second)	Area (square feet)	Top width (feet)	Hydraulic radius (feet)
			With diversion structure			
6,760.45	0.50	6.90	78,400	580	94	5.97
			Without diversion structure			
6,757.92	.96	11.1	37,500	361	83	4.15

[1]Values in this table are taken from table 10 (at the back of this report) and rounded to three significant figures.

An increase in stage of about 2.5 feet immediately upstream from the structure could be expected as a result of its placement; this value does not include any safety factor or freeboard. Flow conditions of the existing channel without the structure are close to critical (Froude number of 0.96), indicating that the increase in bed elevation and some constriction of channel width at each end of the structure are translated almost completely into an increase in static head at the upstream approach to the structure. WSPRO analysis showed no hydraulic effects from the structure (assuming proper energy dissipation at the toe of the structure) at adjacent cross sections either upstream or downstream.

- Bank-stabilization measure

In an experiment conducted by Uinta County and the University of Wyoming Water Research Center, bales of straw were used to stabilize the eroding concave bank of bend number 25/26 in reach 3 (fig. 6); such low-cost materials have been used successfully for erosion control in some cases. Placement of the bales in the fall of 1988 resulted in a change in cross-section area (cross-section 31) of only 1 square foot. Comparison of WSPRO data (100-year peak discharge) for the natural and modified channels showed an increase in water-surface elevation at cross-section 31 of only 0.1 foot as a result of placement of the bales.

Onsite inspection in the summer of 1990 revealed that the entire bank-stabilizing measure had washed out during high flows that overtopped the banks at the site. The bales of straw apparently failed after water flowed in behind the bales and forced them away from the bank. The bales used for construction were old and dry and were not anchored in place, but were packed into the banks and braced with riprap. Saturation of the loosely compacted straw, the water pressure behind the bales, and the shear stress exerted by the streamflow were sufficient to dislodge the material. Current (1991) plans are to replace the bales with a tree revetment designed by the Wyoming Game and Fish Department.

Relation of Geomorphic Properties to Flow Hydraulics

Channel pattern was analyzed with respect to bankfull conditions, so that geomorphic properties compiled for the 1986 channel are compatible with flow and cross-section properties computed for the bankfull discharge (3,600 cubic feet per second) using WSPRO. However, specific correlation of bend geometry with flow hydraulics was not possible. Cross sections generally were not located in bends, and of those that were, only three cross sections were situated in bends whose bend sinuosities lie within the range of 1.2 to 1.3. Further, the fact that WSPRO is a one-dimensional, fixed-boundary model limits its use in computing two-dimensional flow and cross-section effects related to channel curvature.

The bedrock outcrops above the Interstate-80 Bridge were identified as a hydraulic control, from onsite inspections and geomorphic analysis. This controlling effect, both in preventing degradation processes from moving farther upstream and in defining the lower limit of channel braiding in reach 3, is supported by WSPRO analysis. Even at the 100-year peak discharge, the Froude number in cross-section 27 is close to 1 (0.96), indicating that flow is close to critical. Hydraulically, this result confirms that channel conditions upstream and downstream of these outcrops are effectively independent of each other.

WSPRO could not be used to model the historical channel in reach 2 because no cross-section data were available. The historical map shows the greater channel length prior to channelization, but gives only an indication of main-channel width through Evanston. WSPRO modeling would require simply too much conjecture to expect realistic results. However, an evaluation of present-day channel slope is useful.

An increase in channel slope in reach 2 as a result of channelization is predicted qualitatively by equation 2. The historical sinuosity of 2.3 in reach 2 is almost twice the present-day (1986) sinuosity of 1.18, indicating that channel slope was increased dramatically. Channel-bed erosion in reach 2 can be expected to continue until equilibrium conditions are reestablished.

A comparison of present-day channel slopes (table 3) in reaches 1 to 3 quantifies the progress of this adjustment. The present-day slope (mean bed elevation) in reach 2 is 0.00518 foot per foot, significantly steeper than that in reach 1 (0.00431 foot per foot) or in reach 3 (0.00486 foot per foot). Given present-day conditions, the most stable slope in reach 2 would be between 0.00431 and 0.00486 foot per foot; an average value would be about 0.00458 foot per foot. Because the historical channel was closer to an equilibrium state, the historical slope in reach 2 probably was different than that suggested by this analysis. However, it is clear that the present-day slope needs to be reduced to reestablish more natural hydraulic conditions and to stabilize the channel.

If the slope in reach 2 was reduced, changes in the river system could be expected. These changes would occur mainly in reach 2 and downstream into reach 1; upstream effects probably would be limited because of the controlling bedrock outcrop. A qualitative relation for channel response to changing conditions (Lane, 1955a) states

$$QS \sim Q_s d_{50}, \quad (10)$$

where Q is water discharge, S is channel slope, Q_s is sediment discharge, and d_{50} is the median particle size of the bed material. If the channel slope is reduced and water discharge and bed-material composition remain constant, then sediment discharge will decrease. A smaller channel slope would result in less erosion and smaller sediment discharges in reach 2. In turn, less sediment would be carried into reach 1, where reduced sediment loads could be expected to decrease channel width-to-depth ratios, decrease meander wavelength, and increase bend (or meander) sinuosity (Schumm, 1977, p. 135).

Relation of Sediment-Transport Data to Flow Hydraulics

Bed- and suspended-sediment-transport data (table 8) were collected at the three measurement sites for instantaneous water discharges ranging from 124 to 984 cubic feet per second. Bedload material generally was sand-sized, with d_{50} for all samples in the range of medium to coarse sand (0.250 to 1.00 millimeter). Some gravel-sized material (2 to 64 millimeters), up to very coarse gravel, was collected with a few of the samples. Suspended-sediment loads were analyzed for concentration, but particle-size analysis was limited by a lack of sand-sized or larger material (greater than 0.062 millimeter in diameter) carried in suspension.

Bedload- and suspended-sediment discharge are plotted as functions of water discharge in figure 14. Sediment-transport curves for each of these relations were developed using regression analysis and are compiled in table 5. These relations, shown separately in figure 14 and grouped in figure 15, can be considered valid for streamflows ranging from about 100 to 1,000 cubic feet per second.

Considering all three measurement sites, bedload discharge averaged about 5 percent of suspended-sediment discharge through the study reach. A statistical analysis (Kleinbaum and others, 1988, p. 271-279) of the bedload-discharge data (fig. 14) at the three sites showed that differences in the transport curves are significant statistically and probably reflect physical differences in bedload-transport characteristics at each of the sites. The slope of the bedload-transport curve at Bear River above Yellow Creek is steeper than those of the other sites and might reflect the effects of channel constriction and scour caused by the bridge at that site; the other sites are less subject to bridge scour over the range of sampled flows. However, considerable scatter among the data (fig. 14) limits quantitative interpretation of observed differences.

A similar statistical analysis of the suspended-sediment-discharge data (fig. 14) showed that transport rates of suspended sediment (over the range of sampled flows) at the three measurement sites are essentially the same. These rates, therefore, can be considered representative of the entire study reach.

Mean velocities for sampled flows at the Bear River above Yellow Creek site ranged from about 0.71 foot per second at a discharge of 124 cubic feet per second to 3.26 feet per second at a discharge of 984 cubic feet per second. Mean velocities over the same range of flows at the Bear River at Evanston site ranged from 1.61 to 4.47 feet per second, and at the Bear River at Hospital Bridge site from 1.00 to 3.97 feet per second. The faster velocities related to channelization in the reach 2 site are apparent from these data, just as they were from the WSPRO data. However, faster velocities at the Bear River at Evanston site apparently do not result in larger sediment discharges, suggesting that sediment transport in the reach may be limited by supply.

No in-place bed-material samples were collected during the study. However, onsite inspections of the channel during low flows indicate that the bed material consists of large amounts of coarse material ranging in size from coarse gravel up to cobbles (16 to 256 millimeters). In many areas, especially reach 3, the bed appears to be armored with small to large cobbles. This would preclude substantial transport of bed material except at high flows (certainly higher than those sampled during this study). Because the bed generally is composed of these coarser materials and because bedload samples consisted mainly of sand particles in motion over the range of sampled flows, the sediment-transport curves in figure 15 (and the equations in table 5) cannot be extended to predict sediment-transport characteristics for flows higher than 1,000 cubic feet per second. In other words, sediment-transport relations derived from these data cannot be considered valid for the 10- to 100-year peak discharges modeled using WSPRO.

Instream Gravel Mining

The results of sediment-transport analysis can be applied to proposed instream gravel mining in the study reach. Ideally, the river channel would provide a source of minable material that would be replenished continually by sediment transported from upstream. A pit from which gravel is removed would be expected to refill naturally with more minable material. Channel conditions of the Bear River indicate that such an operation probably would not be economical.

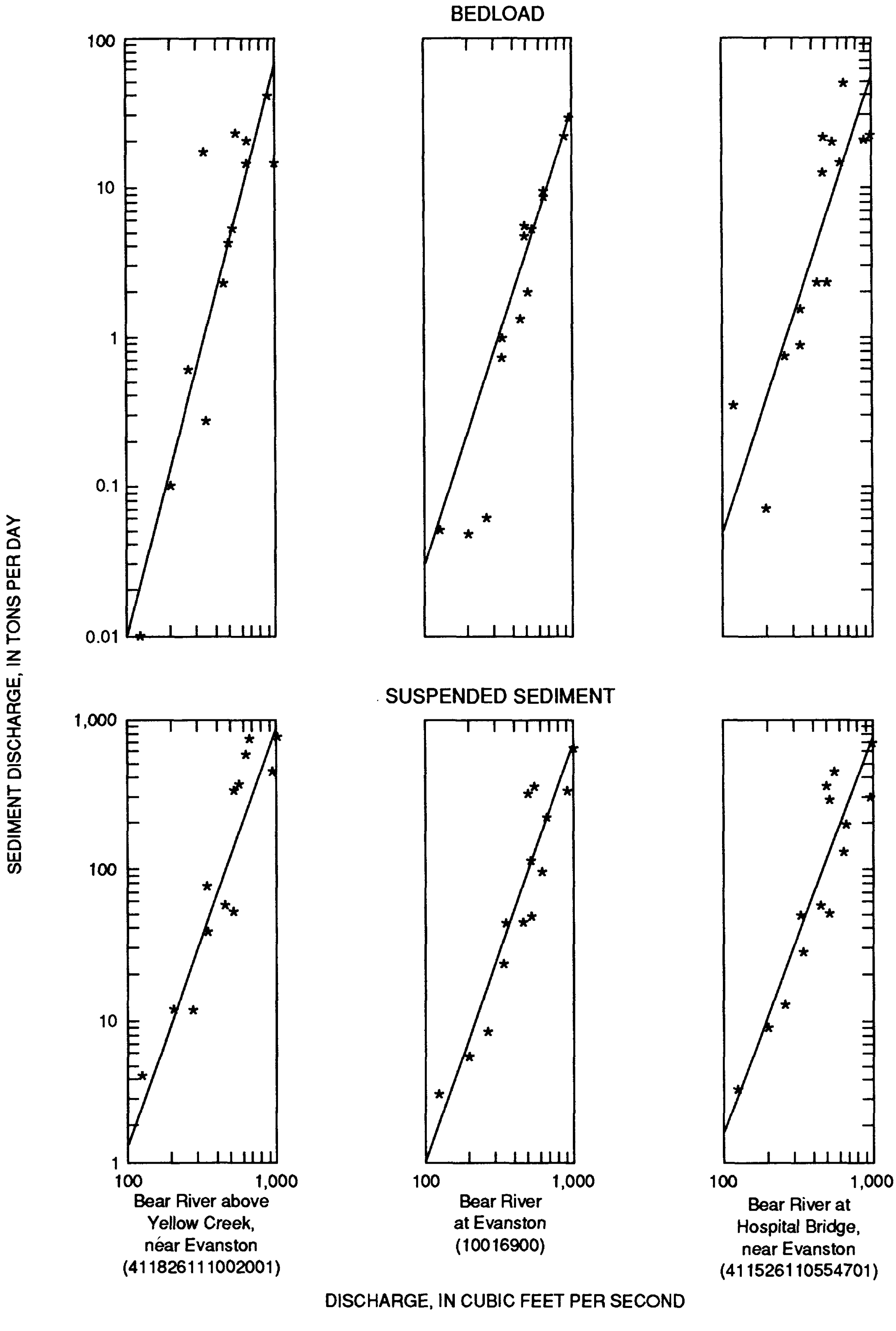

Figure 14.--Bedload- and suspended-sediment-discharge data for the three measurement sites.

Table 5--Summary of sediment-transport relations for measured bedload and suspended-sediment discharges at each measurement site

[Q_b, bedload discharge, in tons per day; Q, water discharge, in cubic feet per second; Q_s, suspended-sediment discharge, in tons per day]

Measurement site	Regression equation	Correlation coefficient (R)	Average standard error of estimate (percent)	Equation number
Bear River above Yellow Creek, near Evanston	$Q_b = (2.57 \times 10^{-10})Q^{3.81}$	0.93	74	11
	$Q_s = (3.31 \times 10^{-6})Q^{2.83}$	.90	144	12
Bear River at Evanston	$Q_b = (3.73 \times 10^{-8})Q^{2.96}$	.93	70	13
	$Q_s = (3.45 \times 10^{-6})Q^{2.75}$	.97	42	14
Bear River at Hospital Bridge, near Evanston	$Q_b = (4.45 \times 10^{-8})Q^{3.03}$	.92	73	15
	$Q_s = (8.42 \times 10^{-6})Q^{2.64}$	.87	116	16

The bed appears to be armored with cobbles that can be expected to move only at flows much larger than those sampled during the study. This observation is reinforced by an analysis of incipient motion of bed sediments using Shield's equation (Vanoni, 1975, p. 96) and an equation for bed shear stress of the form

$$\tau = \gamma R S, \tag{17}$$

where τ is the average shear stress on the bed, γ is the specific weight of water, R is the hydraulic radius, and S is the channel slope.

Assuming a mean bed slope in reach 1 of 0.00431 foot per foot, in reach 2 of 0.00518 foot per foot, and in reach 3 of 0.00486 foot per foot, a relation between hydraulic radius and particle size was developed for each reach to determine the size of material that might be expected to move for the largest sampled discharge (984 cubic feet per second). Because the cross-section width-to-depth ratio at each of the three measurement sites was larger than 10, mean depth (A/T) was used to approximate hydraulic radius (Chow, 1959, p. 27). Mean depth was computed from the data in table 8.

For a discharge of 984 cubic feet per second, mean depth at the three measurement sites was between 3.1 and 3.9 feet. The analysis of incipient motion showed that, for these mean depths, the expected median particle size (d_{50}) of sediments in motion would be 41 millimeters at the Bear River above Yellow Creek site, 58 millimeters at the Bear River at Evanston site, and 51 millimeters at the Bear River at Hospital Bridge site. These sizes correspond to very coarse gravel.

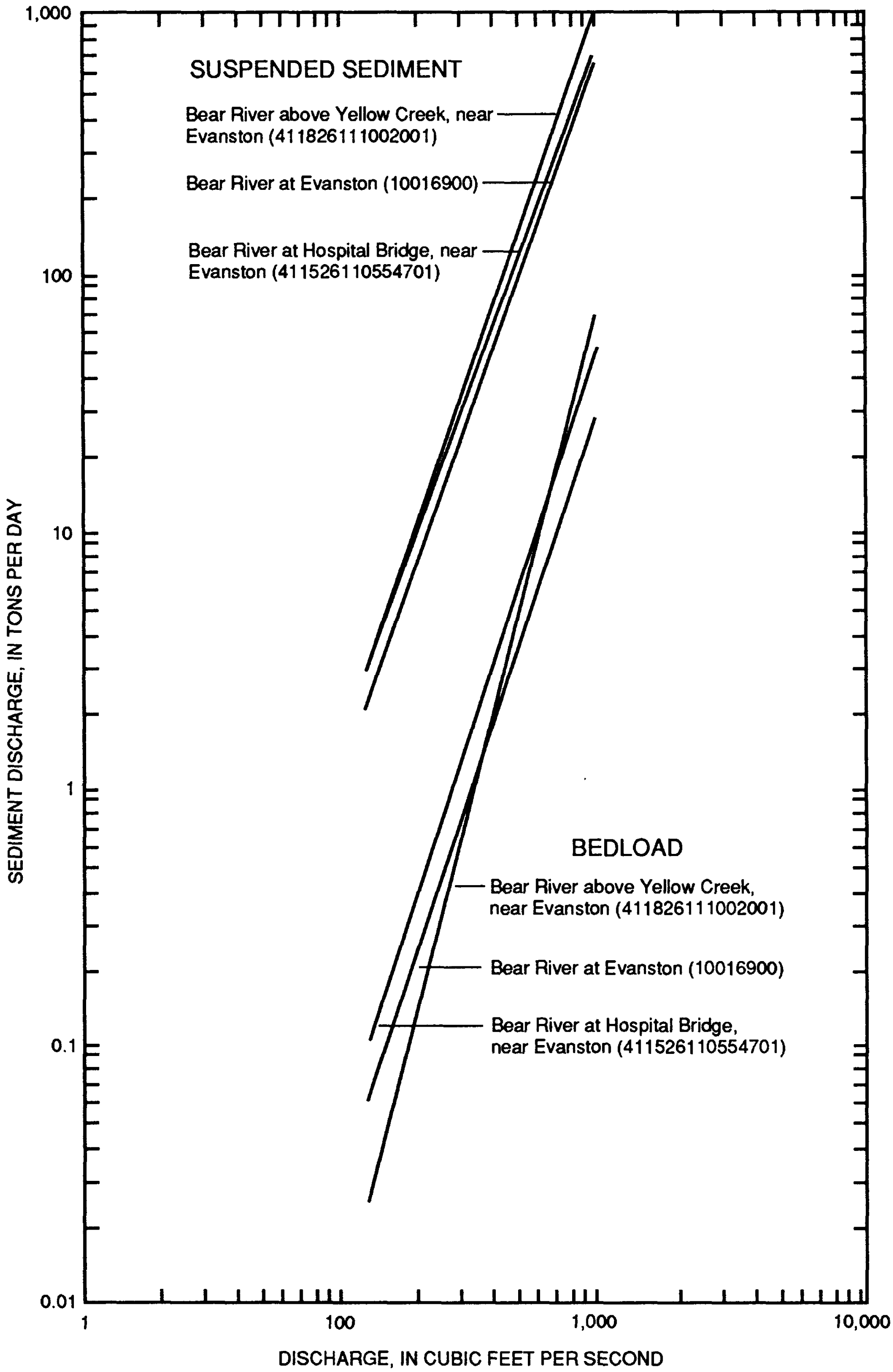

Figure 15.--Sediment-transport curves for bedload discharge and suspended-sediment discharge for the three measurement sites.

Actual samples, however, consisted of mostly medium to coarse sands. This is a further indication that the bed is armored with large material that does not go into motion as bedload except at high streamflows. If this is the case, the mine pit would tend to become filled with fine materials (sand), and could not be expected to replenish itself on a regular basis with minable material from upstream. Similar conclusions regarding instream mining of gravel in an armored channel were reported in a study of the Wind River near Riverton, Wyoming (W.W. Emmett, U.S. Geological Survey, written commun., 1991).

What streamflow magnitude would be required on an annual basis for effective resupply of the proposed mine is not clear. The highest sampled discharge was 984 cubic feet per second. The corresponding daily mean discharge, 971 cubic feet per second, can be expected to occur about 7 percent of the time (based on fig. 3). Because the threshold for motion of the larger particles armoring the bed was not identified, an expected duration for such a discharge cannot be computed.

Bank Erosion and Channel Migration

Entrainment processes are related to the shear stress exerted by the flow on the banks, physical properties of the bank material, and the bank configuration. Lane (1955b) showed that the maximum shear stress on the banks of a wide channel (width-to-depth ratio greater than 4) was about 0.75 times the shear stress on the bed:

$$\tau_b = 0.75\gamma RS, \tag{18}$$

where τ_b is the maximum shear stress on the bank. If the shear stress exerted on the banks overcomes the tractive strength of the material (which is a function of the internal angle of repose and the slope angle formed by the bank), then the banks will erode.

The banks throughout the study reach generally are composed of noncohesive sands, gravels, and cobbles overlain by sandy and gravelly loams (Lewis, 1972). Such materials are subject to erosion by entrainment once the tractive strength of the material is overcome. While values of bank shear stress could be computed from the data in this report, tractive strength properties of the alluvium were not measured. Erosion-control efforts at specific sites in the study reach might require this type of analysis.

Even without site-specific analyses, it is apparent that most of the channel in the study reach is eroding actively. Onsite observations made by M.E. Cooley (oral commun., 1987) indicate that channel banks, where not artificially stabilized, are being eroded. This also is supported by geomorphic analysis, which showed continual channel-pattern changes from one set of aerial photographs to the next. In view of these conditions, channel-stabilization measures will be most effective if they incorporate geomorphic and hydraulic characteristics that have been identified in this study.

Effects of Channel Renovation on Channel Roughness

Although a comprehensive plan for channel renovation has not (1991) been completed, some options can be discussed with respect to changes in channel roughness associated with them. Manning's n values for the existing Bear River channel were determined from onsite inspections (1987) and reflect high-flow roughness characteristics of the existing channel. Values of Manning's n for the main (bankfull) channel generally ranged from 0.035 to 0.040. These values reflect the existing bed-material size and shape (smooth or angular), cross-section irregularities, and any obstructions or vegetation that affect the flow.

Determination of n values involves selection of a base value for a channel reach, given the material forming the bed and assuming a straight, uniform, smooth channel. The base value is then modified to reflect various additional factors that affect channel roughness (Chow, 1959, p. 101-127). A general equation for evaluating the channel roughness for a given depth of flow is

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)\, m, \tag{19}$$

where n_0 is the base value of n for the channel;
n_1 is the added value reflecting cross-section irregularities;
n_2 is the added value reflecting variations in channel shape and size;
n_3 is the added value reflecting the effect of obstructions;
n_4 is the added value reflecting type and density of vegetation; and
m is the multiplicative factor reflecting the degree of meandering of the channel.

Further information about the selection of Manning's n for a variety of channel conditions can be found in reports by Barnes (1967), Benson and Dalrymple (1967, p. 20-24), and Arcement and Schneider (1989).

Jarrett (1985, p. 14-20) studied roughness coefficients in Colorado streams with relatively steep slopes (greater than 0.002 foot per foot). Jarrett presented tables for selection of roughness values that reflect these conditions. The study reach of the Bear River, with mean bed slopes ranging from 0.00431 to 0.00518 foot per foot, fits the criteria defined in Jarrett's study, and the following discussion of channel-roughness changes is based on his results.

Base n values (n_0) for bed/bank materials comprising the present-day channel, or that might be used for channel renovation, are listed in table 6. Ranges of adjustment values (n_1, n_3, and n_4) that quantify the roughness effects of various channel renovation and stabilization options are listed as additive, incremental roughness. The effect of sinuosity is included as the multiplicative adjustment factor m.

The range of values of n_0 for gravels and cobbles is 0.028 to 0.050, which reflects base roughness conditions that could exist in the present-day channel. Riprap materials used to line the bed and banks could range in size from gravel up to small boulders and, depending on gradation and shape, could have base roughness values between 0.028 and 0.070. Riprap design and sizing are beyond the scope of this report, but the effects on roughness of using various materials are listed in table 6. Substantial channel alterations caused by dredging, excavation, or concrete lining would require further analysis of base roughness (Jarrett, 1985, p. 37-38).

The historical reach sinuosity in reach 2 was greater than 1.50, suggesting that meandering probably increased the total channel roughness in the reach by a factor of about 1.3 times what it is today. Restoration of the historical meander pattern as a corrective (slope reduction) measure is not feasible for a number of reasons. Industrial and commercial development is established firmly along the present-day river banks. Much of the land is privately owned. In addition, restoration of the former ice ponds is an integral part of the river-parkway development and requires maintenance of the present-day channel alignment.

Alternative measures that would reduce channel slope in the reach include grade-control and stabilization structures. These structures are designed to control bed elevation and to prevent streambed degradation. Structures that have been developed for this purpose include channel stabilizers and drop structures (Petersen, 1986, p. 207-214). The proposed diversion structure that would divert water into the former ice ponds also could be designed to serve as a grade-control structure.

Table 6--Base values and adjustment factors of Manning's *n* for various bed/bank stabilization options (based on Jarrett, 1985)

[>, greater than]

Description	*n* value
Main channel composition (n_o):	
Gravel (2 to 64 millimeters)	0.028-0.035
Cobble (64 to 256 millimeters)	.030- .050
Boulder (>256 millimeters)	.040- .070
Adjustment factor related to bed/bank irregularities (n_1):	
Tree revetments	0.001-0.005
Bales of straw	.001- .005
Rock riprap and revetment	.001- .005
Adjustment factor related to obstructions (n_3):	
Rock and boulder deflectors, instream boulders; structure occupies	
less than 5 percent of cross-section area	0.000-0.004
5 to 15 percent of cross-section area	.005- .015
15 to 50 percent of cross-section area	.020- .030
more than 50 percent of cross-section area	.040- .060
Adjustment factor related to vegetation (n_4):	
Bushes and willows (small)	0.002-0.010
Bushes and willows (medium)	.010- .025
Bushes and willows (large)	.025- .050
Adjustment factor related to channel sinuosity (m):	
Sinuosity 1.0-1.2	1.00
Sinuosity 1.2-1.5	1.15
Sinuosity >1.5	1.30

In a channel reach, a lower slope would tend to decrease turbulence and flow resistance, thereby reducing the base *n* value of the channel (Jarrett, 1985, p. 14). However, grade-control and stabilization structures create flow conditions (rapidly varied flow) for which Manning's equation is not valid and so cannot be evaluated for changes in cross-section roughness. Because the slope in reach 2 needs to be reduced as part of the stabilization program, these options might need to be evaluated using more appropriate analyses. On the other hand, strategic placement of large boulders might be used to control slope and could be evaluated using table 6 as roughness changes related to obstructions to flow (n_3).

Throughout the study reach, erosion control and bank stabilization are important concerns. Ideally, grade-control and stabilization structures and bank-stabilizing materials would enhance the natural beauty of the river or would have minimal visual impact. Some desirable options for increasing roughness and reducing erosion include tree revetments, bales of straw, rock deflectors, rock riprap or revetment, and vegetation.

Bank stabilization would increase channel roughness by the additive factor for bed/bank irregularities (n_1) or for channel obstructions (n_3). Tree revetments have been used successfully by the Wyoming Game and Fish Department to stabilize banks and to reduce erosion (Binns, 1986, p. 26-28). The use of tree revetments is more aesthetically pleasing than artificial materials and tends to improve fish habitat. Bales of straw are inconspicuous and, properly placed, they would serve to reduce erosion of concave banks in bends. Because of the failure of the experimental straw-bale installation, an anchoring system might need to be considered. Rock deflectors, essentially jetties or spur dikes constructed of rocks or boulders, can be placed alternatively along opposite banks of the channel to reduce flow velocities, dissipate energy, and inhibit erosion (Binns, 1986, p. 18-25). Lining an unstable bank with rock riprap or revetment can be effective as bank stabilization and is relatively inexpensive. Any such measure that uses rocks or boulders along the banks or in the channel bed would tend to improve fish habitat. The additive roughness effect of each of these measures is shown in table 6. Structures that obstruct flow in the channel (deflectors, instream boulders) could have a substantial effect on roughness, depending on the resulting change in channel cross-section area.

Vegetation is a natural method of bank protection that improves fish habitat, reduces transport of suspended sediment, and is visually attractive (Richardson and others, 1987, p. V-35, V-36; Binns, 1986, p. 14-17). D. Farley (Uinta County) and D.J. Lewis (retired from U.S. Soil Conservation Service, written commun., 1989) studied the effects of natural vegetation on streambank stability in the study reach. They concluded that shrubby plants such as willow, serviceberry, buffalo berry, and currant could be used to protect banks in the study reach. Thick cover of these shrubs along the river banks appeared to inhibit erosion because of the deep, matted root system developed by the shrubs. Bank and floodplain growth of these shrubs would tend to increase channel roughness during high flows and so decrease erosion. Such vegetation might create an additive roughness adjustment (n_4) of 0.002 to 0.050, depending on size, density, and location (table 6).

Once options are chosen for stabilization of a specific reach of channel, the hydraulic effects of these options need to be considered. Increasing channel roughness will decrease flow velocities and help to decrease erosion, but also might increase the hydraulic radius (depth of flow) and decrease channel capacity. While hydraulic changes might occur slowly in response to increased roughness, the decrease in channel capacity quickly will cause a reduction in bankfull discharge. Specific hydraulic analyses, such as those conducted for the proposed diversion structure and straw-bale installation, can identify changes in flow velocity and hydraulic radius that might result from placement of stabilization structures.

CONCLUSIONS

Channel instability of the Bear River in and near Evanston is the result of a number of factors, both human-made and natural. The primary factor is channelization in reach 2, causing increased channel slope, faster velocities, and erosion. Other contributing factors include channel-width constrictions, bank stabilization, human-made bend cutoffs upstream from the city, and flooding in 1983 and 1984.

A geomorphic analysis of bankfull channel-pattern changes during 1946-86 identified reach and bend sinuosities, bend radii of curvature, and bend lengths that are characteristic of the study reach and would be most stable. The sinuosity of reach 1 (downstream from Evanston) ranged from 1.31 to 1.52, suggesting that an optimum value might be close to 1.40. The sinuosity of reach 2 (the channelized reach in Evanston) was 1.18 in 1986 and remained about the same throughout the period (1946-86). The sinuosity of reach 2 prior to channelization was substantially larger, about 2.3, as determined from maps constructed before 1946. The sinuosity of reach 3 was 1.26 in 1946, and, because of braiding, decreased to 1.17 by 1981. An optimum sinuosity for this reach was not apparent from the analysis.

The relative stability of individual bends was evaluated on the basis of channel-pattern changes between the dates of successive aerial photographs and on the basis of the statistical distribution of properties measured from each photograph. Using bend sinuosity as a criterion for analysis, it was determined that bends rarely remained stable; substantial channel changes were evident for the time between the dates of each aerial photograph. The statistical analysis, also based on bend sinuosity, was independent of channel changes through time. Analysis of each of the four photographs showed that the median bend sinuosity in reaches 1 and 3 was between 1.2 and 1.3. Among bends with sinuosities in this range, the interquartile range of bend radius of curvature was 180 to 320 feet in reach 1 and 250 to 420 feet in reach 3. Regression analysis indicated that bend length was related linearly to bend radius of curvature. Use of these results for channel alignment and stabilization would allow flexibility to adapt to local channel-pattern conditions, while at the same time satisfying the condition for sinuosity.

Hydraulic data were compiled for the 10-year, bankfull, and 100-year peak discharges, but this analysis was conducted primarily using the bankfull discharge of 3,600 cubic feet per second. The effects of channelization and channel-width constriction in reach 2 were apparent in the form of increased slope, faster velocities, and greater hydraulic radii. The present-day channel slope in reach 2 is 0.00518 foot per foot, whereas a more stable slope would be between 0.00431 foot per foot (present-day slope in reach 1) and 0.00486 foot per foot (present-day slope in reach 3). Such a change in slope, however, can be expected to initiate other hydraulic changes in reaches 1 and 2.

Sediment-transport relations were developed for the three measurement sites in the study reach. These relations are valid for discharges ranging from 100 to 1,000 cubic feet per second. Because no data were collected for high discharges and because of the apparent armored condition of the channel, these relations probably are not valid for flows modeled using WSPRO. The analysis of sediment-transport data also indicates that instream gravel mining would be affected by channel-bed armoring, because the mined site probably would not be replenished regularly with minable material transported from upstream.

Channel stabilization is one of the primary goals of city, county, and State planners. The effects of channelization in reach 2 will need to be addressed, probably through a combination of channel-slope reduction and bed/bank stabilization measures. A flexible program of stabilization and erosion control will be needed so that channel changes (both geomorphic and hydraulic) can be managed effectively. Some stabilization options that might provide this flexibility, along with related channel-roughness changes, are discussed in this report. Changes in hydraulic properties (particularly depth of flow and channel capacity) related to these options will need to be considered.

Once specific design options are developed, further hydraulic modeling, perhaps with a river-sedimentation-and-erosion model, might be useful. Such modeling would help to predict hydraulic and sediment-transport changes that might result from each design option, which in turn would help to identify the best option for stabilizing the river channel. Once any design is implemented, ongoing measurements of streamflow and sediment transport can determine the relative success or failure of the project and indicate modifications that might be needed in the future.

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PAGE 45 FOLLOWS

SUPPLEMENTAL DATA

Table 7--Measured geomorphic properties of the study reach

[--, no data; C/O, cutoff of a bend during time period; **, bend has cut off and is now part of an adjacent bend; *, bend with known bank stabilization, 1987; B, channel braiding, no measurement of bend geometry]

Reach (figs. 4-6)	Valley slope (foot per foot)	Bend number	1946	1969	1981	1986
			Sinuosity			
1	0.0059		1.52	1.31	1.44	1.33
2	.0083		--	--	--	1.1
3	.0066		--	1.26	1.17	1.18
			Bend sinuosity			
1	0.0059	1	1.25	1.29	1.22	1.50
		2	1.43 C/O	1.32	1.41	1.48
		3	1.25	1.09	1.47	1.31
		4	1.61 C/O	1.11	1.67	1.35
		5	2.10 C/O	**	**	**
		6	1.52 C/O	1.45	1.81	B
		7	1.04	1.19	1.19	B
		8	1.25	1.38 C/O	1.29	B
		9	1.59 C/O	1.41	1.21	B
		10	1.35 C/O	1.43 C/O	1.20	B
		11	1.02	1.31 C/O	1.14	B
		12 *	1.09	1.15 C/O	1.18	1.15
		13 *	1.25	1.30	1.32	1.38
		14	1.25 C/O	**	**	**
		15 *	1.13	1.39	1.40 C/O	1.25
		16	1.56 C/O	**	**	**
		17 *	1.25	1.28	1.29	1.33
		18 *	1.43 C/O	1.29	1.22	1.19
3	.0066	19	1.22	--	B	B
		20	1.20	--	B	B
		21	1.07	--	B	B
		22	1.09	--	B	B
		23	1.48	-- C/O	1.17	1.08
		24	1.49	-- C/O	1.15 C/O	1.16
		25	1.15	--	1.29	1.25
		26	1.25	-- C/O	**	**
		27 *	1.45	--	1.22	1.16
		28 *	1.19	-- C/O	**	**
		29 *	1.25	-- C/O	**	**
		30 *	1.19	-- C/O	1.18	1.30
		31 *	1.14	-- C/O	1.28	1.25
			Bend radius of curvature, in feet			
1	0.0059	1	180	130	180	200
		2	180 C/O	130	210	220
		3	200	180	140	280
		4	140 C/O	210	250	180
		5	200 C/O	**	**	**
		6	120 C/O	150	130	B
		7	280	150	140	B
		8	160	150 C/O	240	B
		9	220 C/O	130	210	B
		10	120 C/O	170 C/O	320	B
		11	700	200 C/O	420	B
		12 *	350	120 C/O	260	240
		13 *	250	440	460	540

Table 7--Measured geomorphic properties of the study reach--Continued

Reach (figs. 4-6)	Valley slope (foot per foot)	Bend number	1946	1969	1981	1986
			Bend radius of curvature, in feet--Continued			
1	0.0059	14	180 C/O	**	**	**
		15 *	520	310	250 C/O	340
		16	140 C/O	**	**	**
		17 *	520	290	310	290
		18 *	120 C/O	360	360	500
3	.0066	19	440	--	B	B
		20	300	--	B	B
		23	140	-- C/O	360	350
		24	200	-- C/O	270 C/O	340
		25	180	--	260	320
		26	180	-- C/O	**	**
		27 *	170	--	430	310
		28 *	260	-- C/O	**	**
		29 *	170	-- C/O	**	**
		30 *	200	-- C/O	300	280
		31 *	280	-- C/O	220	400
			Bend length, in feet			
1	0.0059	1	400	280	370	300
		2	420 C/O	375	460	440
		3	240	375	340	400
		4	280 C/O	420	510	520
		5	380 C/O	**	**	**
		6	280 C/O	390	360	B
		7	480	370	440	B
		8	380	320 C/O	425	B
		9	440 C/O	330	290	B
		10	240 C/O	460 C/O	460	B
		11	440	440 C/O	440	B
		12 *	320	260 C/O	340	340
		13 *	540	820	840	780
		14	280 C/O	**	**	**
		15 *	800	750	750 C/O	720
		16	320 C/O	**	**	**
		17 *	960	580	700	600
		18 *	280 C/O	790	780	920
3	.0066	19	840	--	B	B
		20	500	--	B	B
		21	420	--	B	B
		22	760	--	B	B
		23	320	-- C/O	640	600
		24	420	-- C/O	480 C/O	560
		25	260	--	580	640
		26	240	-- C/O	**	**
		27 *	500	--	780	720
		28 *	440	-- C/O	**	**
		29 *	220	-- C/O	**	**
		30 *	400	-- C/O	700	500
		31 *	480	-- C/O	470	620

Table 8--Flow and sediment-transport characteristics measured during onsite sampling

[ft, feet; ft/s, feet per second; ft^3/s, cubic feet per second; °C, degrees Celsius; tons/d, tons per day; %, percent; mm, millimeters; mg/L, milligrams per liter; --, no data]

Date	Time	Stream width (ft)	Stream velocity, mean (ft/s)	Discharge, instantaneous (ft^3/s)	Temperature, water (°C)	Sediment discharge, bedload (tons/d)	Sediment, bedload, sieve diameter, % finer than 0.062 mm	Sediment, bedload, sieve diameter, % finer than 0.125 mm	Sediment, bedload, sieve diameter, % finer than 0.250 mm
411826111002001 - Bear River above Yellow Creek, near Evanston, Wyo. (latitude 41°18'26", longitude 111°00'20")									
April 1988									
28	1415	84	1.44	336	--	17	0.2	0.3	2
May									
05	1410	95	2.00	509	--	5.3	.1	.4	.8
12	1315	97	2.06	545	--	23	1	2	4
19	1330	96	3.26	984	--	14	.4	.6	2
26	1330	100	3.11	904	--	40	.4	.7	2
June									
02	1130	32	1.88	443	--	2.3	--	.1	.4
07	1355	90	2.38	626	--	14	.2	.4	1
09	1020	30	1.48	340	--	.28	--	--	--
16	1135	18	.71	124	--	.01	--	--	--
April 1989									
27	1400	30	1.24	265	7.0	.60	--	--	0
May									
04	1410	30	1.02	199	12.5	.10	--	0	.1
23	1405	75	2.48	653	13.0	20	.2	.5	2
June									
02	1325	77	2.04	495	13.0	4.3	.2	.4	.8

Table 8--Flow and sediment-transport characteristics measured during onsite sampling--Continued

Date	Sediment, bedload, sieve diameter, % finer than 0.500 mm	Sediment, bedload, sieve diameter, % finer than 1.00 mm	Sediment, bedload, sieve diameter, % finer than 2.00 mm	Sediment, bedload, sieve diameter, % finer than 4.00 mm	Sediment, bedload, sieve diameter, % finer than 8.00 mm	Sediment, bedload, sieve diameter, % finer than 16.0 mm	Sediment, bedload, sieve diameter, % finer than 32.0 mm	Sediment, bedload, sieve diameter, % finer than 64.0 mm
411826111002001 - Bear River above Yellow Creek, near Evanston, Wyo. (latitude 41°18'26", longitude 111°00'20")--Continued								
April 1988					--			
28	36	98	100	--	--	--	--	--
May								
05	36	98	100	--	--	--	--	--
12	47	94	98	100	--	--	--	--
19	40	65	68	68	68	72	100	--
26	52	94	99	100	--	--	--	--
June								
02	64	97	100	--	--	--	--	--
07	72	99	100	--	--	--	--	--
09	52	98	100	--	--	--	--	--
16	42	75	100	--	--	--	--	--
April 1989								
27	45	96	100	--	--	--	--	--
May								
04	51	96	99	100	--	--	--	--
23	61	81	82	82	82	82	82	100
June								
02	71	99	100	--	--	--	--	--

Table 8--Flow and sediment-transport characteristics measured during onsite sampling--Continued

Date	Sediment, suspended (mg/L)	Sediment, discharge, suspended (tons/d)	Sediment, suspended, sieve diameter, % finer than 0.062 mm	Sediment, suspended, fall diameter, % finer than 0.062 mm	Sediment, suspended, fall diameter, % finer than 0.125 mm	Sediment, suspended, fall diameter, % finer than 0.250 mm	Sediment, suspended, fall diameter, % finer than 0.500 mm	Sediment, suspended, fall diameter, % finer than 1.00 mm
411826111002001 - Bear River above Yellow Creek, near Evanston, Wyo. (latitude 41°18'26", longitude 111°00'20")--Continued								
April 1988								
28	39	35	80	--	--	--	--	--
May								
05	235	323	23	--	--	--	--	--
12	241	355	74	--	--	--	--	--
19	299	794	--	57	66	81	99	100
26	176	430	43	--	--	--	--	--
June								
02	44	53	59	--	--	--	--	--
07	329	556	10	--	--	--	--	--
09	78	72	--	--	--	--	--	--
16	12	4.0	--	--	--	--	--	--
April 1989								
27	15	11	--	--	--	--	--	--
May								
04	21	11	--	--	--	--	--	--
23	410	723	13	--	--	--	--	--
June								
02	36	48	--	--	--	--	--	--

Table 8--Flow and sediment-transport characteristics measured during onsite sampling--Continued

Date	Time	Stream width (ft)	Stream Velocity, mean (ft/s)	Discharge instantaneous (ft^3/s)	Temperature, water (°C)	Sediment discharge, bedload (tons/d)	Sediment, bedload, sieve diameter, % finer than 0.062 mm	Sediment, bedload, sieve diameter, % finer than 0.125 mm
10016900 - Bear River at Evanston, Wyo.								
April 1988								
07	1410	60	3.45	483	--	4.7	0.7	1
28	1115	65	2.87	336	--	.71	.3	.3
May								
05	1100	67	3.44	509	--	2.0	.4	.8
12	1040	67	3.49	545	--	5.3	1	2
19	1035	69	4.47	984	--	29	.2	.4
26	1045	65	4.28	904	--	22	.4	.8
June								
02	1005	65	3.31	443	--	1.3	.4	.8
07	1050	65	3.56	626	--	8.3	.6	.9
09	1000	40	2.68	340	--	.97	.1	.5
16	1000	30	1.61	124	--	.05	--	--
April 1989								
27	1120	62	2.41	265	4.0	.60	--	--
May								
04	1115	59	2.05	199	8.5	.47	--	--
23	1105	66	3.80	653	10.5	9.0	.6	1
June								
02	1055	65	3.34	495	10.0	5.5	.4	.7

Table 8--Flow and sediment-transport characteristics measured during onsite sampling--Continued

Date	Sediment, bedload, sieve diameter, % finer than 0.250 mm	Sediment, bedload, sieve diameter, % finer than 0.500 mm	Sediment, bedload, sieve diameter, % finer than 1.00 mm	Sediment, bedload, sieve diameter, % finer than 2.00 mm	Sediment, bedload, sieve diameter, % finer than 4.00 mm	Sediment, bedload, sieve diameter, % finer than 8.00 mm	Sediment, suspended (mg/L)	Sediment, discharge, suspended (tons/d)
10016900 - Bear River at Evanston, Wyo.--Continued								
April 1988								
07	2	52	96	99	100	--	240	313
28	.8	58	97	99	100	--	44	40
May								
05	1	61	96	99	100	--	80	110
12	3	60	94	98	99	100	234	344
19	1	45	95	99	100	--	234	622
26	2	52	97	99	100	--	133	325
June								
02	2	59	97	100	--	--	34	41
07	2	61	98	100	--	--	54	91
09	.9	55	97	99	100	--	24	22
16	--	53	89	100	--	--	9	3.0
April 1989								
27	0	57	98	100	--	--	11	7.9
May								
04	0	39	95	99	100	--	10	5.4
23	2	60	97	99	100	--	125	220
June								
02	1	48	95	100	--	--	34	45

Table 8--Flow and sediment-transport characteristics measured during onsite sampling--Continued

Date	Sediment, suspended, sieve diameter, % finer than 0.062 mm	Sediment, suspended, fall diameter, % finer than 0.004 mm	Sediment, suspended, fall diameter, % finer than 0.008 mm	Sediment, suspended, fall diameter, % finer than 0.016 mm	Sediment, suspended, fall diameter, % finer than 0.062 mm	Sediment, suspended, fall diameter, % finer than 0.125 mm	Sediment, suspended, fall diameter, % finer than 0.250 mm	Sediment, suspended, fall diameter, % finer than 0.500 mm
10016900 - Bear River at Evanston, Wyo.--Continued								
April 1988								
07	--	55	64	72	85	91	97	100
28	--	--	--	--	--	--	--	--
May								
05	76	--	--	--	--	--	--	--
12	80	--	--	--	--	--	--	--
19	--	--	--	--	71	78	90	100
26	55	--	--	--	--	--	--	--
June								
02	70	--	--	--	--	--	--	--
07	51	--	--	--	--	--	--	--
09	--	--	--	--	--	--	--	--
16	--	--	--	--	--	--	--	--
April 1989								
27	--	--	--	--	--	--	--	--
May								
04	--	--	--	--	--	--	--	--
23	67	--	--	--	--	--	--	--
June								
02	--	--	--	--	--	--	--	--

Table 8--Flow and sediment-transport characteristics measured during onsite sampling--Continued

Date	Time	Stream width (ft)	Stream velocity, mean (ft/s)	Discharge, instantaneous (ft^3/s)	Temperature, water (°C)	Sediment discharge, bedload (tons/d)	Sediment, bedload, sieve diameter, % finer than 0.062 mm	Sediment, bedload, sieve diameter, % finer than 0.125 mm
411526110554701 - Bear River at Hospital Bridge, near Evanston, Wyo. (latitude 41°15'26", longitude 110°55'47")								
April 1988								
07	1045	42	2.65	483	--	12	1	2
28	0820	62	1.98	336	--	1.5	.3	.6
May								
05	0820	63	2.57	509	--	12	4	.6
12	0815	62	2.66	545	--	20	1	2
19	0815	64	3.97	984	--	22	.4	.7
26	0820	60	3.80	904	--	20	.6	1
June								
02	0755	60	2.45	443	--	2.2	.2	.3
07	0820	55	2.90	626	--	14	.7	1
09	0815	42	1.94	340	--	.83	.2	.7
16	0805	30	1.00	124	--	.35	1	2
April 1989								
27	0900	60	1.26	265	2.0	.71	2	3
May								
04	0815	58	1.07	199	7.0	.07	--	0
23	0810	64	2.68	653	9.0	48	.4	.8
June								
02	0830	63	2.15	495	9.0	21	.4	.7

Table 8--Flow and sediment-transport characteristics measured during onsite sampling--Continued

Date	Sediment, bedload, sieve diameter, % finer than 0.250 mm	Sediment, bedload, sieve diameter, % finer than 0.500 mm	Sediment, bedload, sieve diameter, % finer than 1.00 mm	Sediment, bedload, sieve diameter, % finer than 2.00 mm	Sediment, bedload, sieve diameter, % finer than 4.00 mm	Sediment, bedload, sieve diameter, % finer than 8.00 mm	Sediment, suspended (mg/L)	Sediment, discharge, suspended (tons/d)
411526110554701 - Bear River at Hospital Bridge, near Evanston, Wyo. (latitude 41°15'26", longitude 110°55'47")--Continued								
April 1988								
07	3	47	98	100	--	--	276	360
28	.8	49	98	100	--	--	50	45
May								
05	2	53	98	100	--	--	193	265
12	4	61	97	99	100	--	286	421
19	1	40	94	98	99	100	260	691
26	2	49	95	100	--	--	122	298
June								
02	1	51	98	100	--	--	44	53
07	2	62	98	100	--	--	71	120
09	1	59	98	100	--	--	28	26
16	4	86	99	100	--	--	10	3.3
April 1989								
27	5	75	95	99	100	--	17	12
May								
04	.1	70	89	97	100	--	15	8.1
23	2	32	97	100	--	--	105	185
June								
02	1	45	98	100	--	--	37	49

Table 8--Flow and sediment-transport characteristics measured during onsite sampling--Continued

Date	Sediment, suspended, sieve diameter, % finer than 0.062 mm	Sediment, suspended, fall diameter, % finer than 0.004 mm	Sediment, suspended, fall diameter, % finer than 0.008 mm	Sediment, suspended, fall diameter, % finer than 0.016 mm	Sediment, suspended, fall diameter, % finer than 0.062 mm	Sediment, suspended, fall diameter, % finer than 0.125 mm	Sediment, suspended, fall diameter, % finer than 0.250 mm	Sediment, suspended, fall diameter, % finer than 0.500 mm
411526110554701 - Bear River at Hospital Bridge, near Evanston, Wyo. (latitude 41°15'26", longitude 110°55'47")--Continued								
April 1988								
07	--	51	60	68	83	90	97	100
28	61	--	--	--	--	--	--	--
May								
05	67	--	--	--	--	--	--	--
12	68	--	--	--	--	--	--	--
19	68	--	--	--	--	--	--	--
26	52	--	--	--	--	--	--	--
June								
02	65	--	--	--	--	--	--	--
07	54	--	--	--	--	--	--	--
09	--	--	--	--	--	--	--	--
16	--	--	--	--	--	--	--	--
April 1989								
27	--	--	--	--	--	--	--	--
May								
04	--	--	--	--	--	--	--	--
23	63	--	--	--	--	--	--	--
June								
02	--	--	--	--	--	--	--	--

Table 9--Physical properties, major ions, nutrients, trace elements, and pesticides in water samples from the Bear River

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mm of Hg, millimeters of mecury; mg/L, milligrams per liter; tons/acre-ft, tons per acre foot; tons/d, tons per day; µg/L, micrograms per liter; <, less than; --, no data]

Date	Time	Discharge, instantaneous (ft^3/s)	Specific conductance (µS/cm)	pH	Temperature, water (°C)	Barometric pressure (mm of Hg)	Oxygen, dissolved (mg/L)	Oxygen, dissolved (percent saturation)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
411826111002001 - Bear River above Yellow Creek, near Evanston, Wyo. (latitude 41°18'26", longitude 111°00'20")												
05-24-89	1700	631	150	8.3	12.5	590	8.5	103	76	21	5.6	2.5
11-21-89	1400	28	350	8.5	4.0	597	11.1	108	190	48	16	8.0
10016900 - Bear River at Evanston, Wyo.												
05-24-89	1400	642	160	7.5	11.0	590	9.0	106	75	21	5.5	2.3
11-21-89	1130	37	355	8.4	.5	594	11.4	102	180	48	15	6.9
411526110554701 - Bear River at Hospital Bridge, near Evanston, Wyo. (latitude 41°15'26", longitude 110°55'47")												
05-24-89	1100	642	160	7.5	10.0	590	9.2	106	74	21	5.3	2.3
11-21-89	0830	34	300	8.4	.5	594	10.8	96	170	46	14	6.0

Table 9--Physical properties, major ions, nutrients, trace elements, and pesticides in water samples from the Bear River--Continued

Date	Time	Sodium adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Solids, dissolved (tons/acre-ft)	Solids, dissolved (tons/d)	Nitrogen, $NO_2 + NO_3$, total (mg/L as N)
411826111002001 - Bear River above Yellow Creek, near Evanston, Wyo. (latitude 41°18'26", longitude 111°00'20")												
05-24-89	1700	0.1	0.70	72	6.0	2.5	0.10	4.6	86	0.12	147	<0.100
11-21-89	1400	.3	1.3	160	16	6.5	.20	6.6	199	.27	15.0	<.100
10016900 - Bear River at Evanston, Wyo.												
05-24-89	1400	0.1	0.60	70	6.0	2.3	0.10	4.6	85	0.11	147	<0.100
11-21-89	1130	.2	<.90	170	16	6.0	.10	6.6	--	--	--	<.100
411526110554701 - Bear River at Hospital Bridge, near Evanston, Wyo. (latitude 41°15'26", longitude 110°55'47")												
05-24-89	1100	0.1	0.60	70	6.0	2.1	0.70	4.7	85	0.12	147	<0.100
11-21-89	0830	.2	1.2	150	15	3.8	.10	6.6	183	.25	16.8	<.100

Date	Time	Nitrogen, $NO_2 + NO_3$, dissolved (mg/L as N)	Nitrogen, ammonia, total (mg/L as N)	Nitrogen, organic, total (mg/L as N)	Nitrogen, ammonia + organic, total (mg/L as N)	Phosphorus, total (mg/L as P)	Arsenic, dissolved, (µg/L as As)	Barium, dissolved (µg/L as Ba)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Copper, dissolved (µg/L as Cu)
411826111002001 - Bear River above Yellow Creek, near Evanston, Wyo. (latitude 41°18'26", longitude 111°00'20")											
05-24-89	1700	<0.100	0.020	0.48	0.50	<0.010	<1	86	<1.0	<1	2
11-21-89	1400	<.100	.010	.19	.20	<.010	<1	190	<1.0	2	<1
10016900 - Bear River at Evanston, Wyo.											
05-24-89	1400	<0.100	0.020	0.68	0.70	<0.010	<1	84	<1.0	1	1
11-21-89	1130	<.100	.020	.28	<.30	<.010	<1	190	<1.0	40	1
411526110554701 - Bear River at Hospital Bridge, near Evanston, Wyo. (latitude 41°15'26", longitude 110°55'47")											
05-24-89	1100	<0.100	0.030	0.17	0.20	<0.010	<1	78	<1.0	<1	3
11-21-89	0830	<.100	.020	--	<.20	<.010	<1	180	<1.0	2	1

Table 9--Physical properties, major ions, nutrients, trace elements, and pesticides in water samples from the Bear River--Continued

Date	Time	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Selenium, dissolved (µg/L as Se)	Silver, dissolved (µg/L as Ag)	Zinc, dissolved (µg/L as Zn)	Dicamba, total (µg/L)	Picloram, total (µg/L)	2,4-D, total (µg/L)	2,4-DP, total (µg/L)
411826111002001 - Bear River above Yellow Creek, near Evanston, Wyo. (latitude 41°18'26", longitude 111°00'20")											
05-24-89	1700	60	<1	11	<1	<1.0	7	<0.01	<0.01	<0.01	<0.01
11-21-89	1400	29	<1	24	<1	<1.0	<3	<.01	<.01	<.01	<.01
10016900 - Bear River at Evanston, Wyo.											
05-24-89	1400	62	<1	10	<1	1.0	8	<0.01	<0.01	<0.01	<0.01
11-21-89	1130	26	<1	15	<1	<1.0	6	--	--	--	---
411526110554701 - Bear River at Hospital Bridge, near Evanston, Wyo. (latitude 41°15'26", longitude 110°55'47")											
05-24-89	1100	62	1	13	<1	<1.0	14	<0.01	<0.01	<0.01	<0.01
11-21-89	0830	28	<1	12	<1	<1.0	5	<.01	<.01	<.01	<.01

Date	Time	2,4,5-T, total (µg/L)	Silvex, total (µg/L)	DEF, total (µg/L)	Diazinon, total (µg/L)	Disyston, total (µg/L)	Ethion, total (µg/L)	Malathion, total (µg/L)	Methyl parathion, total (µg/L)	Methyl trithion, total (µg/L)	Parathion, total (µg/L)	Phorate, total (µg/L)	Total trithion (µg/L)
411826111002001 - Bear River above Yellow Creek, near Evanston, Wyo. (latitude 41°18'26", longitude 111°00'20")													
05-24-89	1700	<0.01	<0.01	--	<0.01	--	<0.01	<0.01	<0.01	<0.01	<0.01	--	<0.01
11-21-89	1400	<.01	<.01	<0.01	<.01	<0.01	<.01	<.01	<.01	<.01	<.01	<0.01	<.01
10016900 - Bear River at Evanston, Wyo.													
05-24-89	1400	<0.01	<0.01	--	<0.01	--	<0.01	<0.01	<0.01	<0.01	<0.01	--	<0.01
11-21-89	1130	--	--	--	--	--	--	--	--	--	--	--	--
411526110554701 - Bear River at Hospital Bridge, near Evanston, Wyo. (latitude 41°15'26", longitude 110°55'47")													
05-24-89	1100	<0.01	<0.01	--	<0.01	--	<0.01	<0.01	<0.01	<0.01	<0.01	--	<0.01
11-21-89	0830	<.01	<.01	<0.01	<.01	<0.01	<.01	<.01	<.01	<.01	<.01	<0.01	<.01

Table 10--Streamflow and cross-section hydraulic properties of the present-day channel of the Bear River

[ft, feet; ft/s, feet per second; ft^3/s, cubic feet per second; ft^2, square feet]

Reach	Cross-section number	Channel distance (ft)	Altitude (feet above sea level) Water surface	Mean bed	Thalweg	Froude number	Mean velocity (ft/s)	Conveyance (ft^3/s)	Area (ft^2)	Top width (ft)	Hydraulic radius (ft)
					Discharge of 3,600 ft^3/s						
1	XSEC1	0	6,674.30	6,669.48	6,665.60	0.50	6.17	64,738	583	119	4.82
(fig. 4)	XSEC2	810	6,676.73	6,674.89	6,670.60	.67	4.05	69,725	889	480	1.84
	XSEC3	1,765	6,680.85	6,679.42	6,675.30	.71	4.34	50,620	830	577	1.43
	XSEC4	3,140	6,686.13	6,685.05	6,681.20	.46	2.35	75,900	1,533	1,413	1.08
	XSEC5	4,270	6,691.31	6,688.60	6,683.90	.78	6.92	43,809	520	189	2.71
	XSEC7	5,600	6,697.26	6,695.03	6,691.60	.53	4.17	65,815	864	386	2.23
	XSEC8	6,580	6,701.04	6,699.13	6,693.20	.74	4.66	52,792	772	403	1.91
	XSEC10	7,365	6,705.18	6,700.73	6,698.80	.55	6.52	57,091	552	122	4.45
	XSEC11	8,560	6,709.91	6,706.72	6,702.20	.48	4.83	61,465	746	230	3.19
	XSEC12	9,350	6,712.55	6,709.35	6,705.60	.50	5.00	62,874	720	223	3.20
	XSEC13	9,770	6,714.63	6,713.01	6,709.30	.93	6.14	38,964	586	359	1.62
	XSEC14	10,400	6,718.60	6,716.17	6,711.10	.79	6.26	47,487	575	235	2.43
	XSEC15	11,175	6,722.25	6,720.83	6,717.40	1.27	7.10	46,354	507	354	1.42
2	XSEC16.2	12,010	6,725.92	6,720.26	6,717.00	.56	7.32	60,281	492	83	5.66
(fig. 5)	XSEC16.3	12,185	6,726.58	6,721.41	6,718.80	.64	7.91	52,066	455	86	5.17
	XSEC17	12,680	6,728.58	6,724.24	6,719.70	.48	4.80	68,910	750	167	4.34
	XSEC18	13,650	6,733.14	6,728.86	6,726.70	.82	9.68	36,474	372	85	4.28
	XSEC19.2	14,070	6,736.31	6,730.24	6,727.80	.56	8.35	53,509	431	63	6.07
	XSEC19.3	14,115	6,736.56	6,730.44	6,727.90	.55	8.16	55,279	441	64	6.13
	XSEC20	14,580	6,738.86	6,734.16	6,730.80	.55	6.96	54,005	517	104	4.70
	XSEC21.2	14,955	6,740.30	6,734.74	6,732.40	.33	4.40	97,948	818	145	5.56
	XSEC21.3	15,020	6,740.39	6,734.86	6,732.50	.33	4.43	97,034	813	145	5.53
	XSEC22.1	15,344	6,741.02	6,736.07	6,734.70	.59	7.58	52,082	475	93	4.95
	XSEC22.2	15,675	6,742.64	6,738.10	6,736.50	.43	5.18	72,367	695	151	4.54
	XSEC22.3	15,760	6,742.89	6,738.21	6,736.60	.40	4.96	77,194	726	153	4.68
	XSEC23	16,610	6,746.91	6,744.74	6,742.20	.68	5.66	39,871	636	291	2.17
	XSEC24	17,415	6,752.04	6,749.97	6,746.70	.73	4.96	50,883	726	349	2.07
	XSEC24.9	18,260	6,757.29	6,753.33	6,750.20	.77	8.82	38,641	408	100	3.96
	XSEC25	18,330	6,757.67	6,753.76	6,751.90	.94	10.59	34,192	340	83	3.91
	XSEC26.1	19,260	6,765.23	6,760.26	6,758.50	.61	7.71	55,916	467	92	4.97
	XSEC26.2	19,500	6,766.18	6,759.42	6,756.70	.43	6.50	80,368	554	76	6.76
	XSEC26.3	19,615	6,766.51	6,759.83	6,756.70	.40	5.73	91,206	628	90	6.68
	XSEC26.4	19,795	6,766.72	6,759.04	6,755.50	.40	6.34	93,856	568	66	7.68
3	XSEC27	20,620	6,772.53	6,770.19	6,768.30	1.00	8.65	31,209	416	177	2.34
(fig. 6)	XSEC28	21,970	6,778.91	6,776.48	6,774.70	.42	3.35	86,534	1,075	440	2.43
	XSEC29	23,280	6,785.40	6,782.72	6,781.20	.83	7.52	40,765	479	176	2.68
	XSEC30	24,955	6,793.90	6,791.84	6,787.70	.68	4.16	61,753	866	418	2.06
	XSEC31	25,810	6,798.26	6,796.65	6,792.30	.69	4.79	46,760	751	463	1.61
	XSEC32	27,070	6,805.10	6,802.79	6,798.30	.74	6.14	59,529	586	250	2.31
	XSEC33	27,255	6,805.50	6,800.09	6,797.60	.69	9.00	54,007	400	71	5.41
	XSEC33.1	27,290	6,805.75	6,800.25	6,797.60	.65	8.61	57,519	418	72	5.50
	XSEC34	27,810	6,808.25	6,805.68	6,801.90	.46	3.78	76,433	952	369	2.57
	XSEC35	29,830	6,818.10	6,815.78	6,812.50	.80	6.15	52,580	585	250	2.32

Table 10--Streamflow and cross-section hydraulic properties of the present-day channel of the Bear River--Continued

Reach	Cross-section number	Channel distance (ft)	Altitude (feet above sea level) Water surface	Mean bed	Thalweg	Froude number	Mean velocity (ft/s)	Conveyance (ft^3/s)	Area (ft^2)	Top width (ft)	Hydraulic radius (ft)
				Discharge of 4,000 ft^3/s							
1	XSEC1	0	6,674.90	6,669.61	6,665.60	0.47	6.10	77,796	656	122	5.29
(fig. 4)	XSEC2	810	6,677.11	6,675.12	6,670.60	.58	3.70	86,191	1,080	540	1.99
	XSEC3	1,765	6,681.00	6,679.52	6,675.30	.71	4.37	56,921	916	616	1.48
	XSEC4	3,140	6,686.24	6,685.08	6,681.20	.45	2.38	86,308	1,683	1,447	1.16
	XSEC5	4,270	6,691.46	6,688.69	6,683.90	.81	7.29	47,112	549	195	2.77
	XSEC7	5,600	6,697.48	6,695.05	6,691.60	.51	4.21	75,072	949	388	2.43
	XSEC8	6,580	6,701.21	6,699.19	6,693.20	.74	4.76	57,777	841	414	2.02
	XSEC10	7,365	6,705.35	6,700.77	6,698.80	.58	6.98	60,406	573	123	4.58
	XSEC11	8,560	6,710.21	6,706.77	6,702.20	.47	4.90	70,942	816	233	3.44
	XSEC12	9,350	6,712.77	6,709.53	6,709.53	.52	5.20	69,225	769	235	3.24
	XSEC13	9,770	6,714.82	6,713.09	6,709.30	.90	6.11	44,698	655	375	1.73
	XSEC14	10,400	6,718.77	6,716.37	6,711.10	.84	6.49	51,659	616	255	2.40
	XSEC15	11,175	6,722.48	6,720.88	6,717.40	1.23	6.78	51,496	590	367	1.60
2	XSEC16.2	12,010	6,726.15	6,720.34	6,717.00	.59	7.83	63,830	511	84	5.81
(fig. 5)	XSEC16.3	12,185	6,726.83	6,721.53	6,718.80	.67	8.39	55,849	477	87	5.30
	XSEC17	12,680	6,728.98	6,724.28	6,719.70	.47	4.90	77,773	817	167	4.70
	XSEC18	13,650	6,733.35	6,728.97	6,726.70	.85	10.26	39,056	390	86	4.38
	XSEC19.2	14,070	6,736.74	6,730.37	6,727.80	.57	8.71	58,653	459	64	6.38
	XSEC19.3	14,115	6,736.99	6,730.57	6,727.90	.56	8.53	60,496	469	64	6.42
	XSEC20	14,580	6,739.32	6,734.31	6,730.80	.54	7.07	62,245	566	106	5.01
	XSEC21.2	14,955	6,740.71	6,734.82	6,732.40	.33	4.56	109,325	878	147	5.89
	XSEC21.3	15,020	6,740.80	6,734.94	6,732.50	.33	4.58	108,337	873	147	5.86
	XSEC22.1	15,344	6,741.39	6,736.20	6,734.70	.60	7.86	58,174	509	95	5.19
	XSEC22.2	15,675	6,743.03	6,738.19	6,736.50	.42	5.30	81,890	755	154	4.84
	XSEC22.3	15,760	6,743.25	6,738.30	6,736.60	.40	5.12	86,328	782	156	4.95
	XSEC23	16,610	6,747.11	6,744.75	6,742.20	.66	5.77	45,950	693	292	2.36
	XSEC24	17,415	6,752.17	6,750.01	6,746.70	.74	5.16	54,959	775	357	2.16
	XSEC24.9	18,260	6,757.56	6,753.37	6,750.20	.78	9.17	42,832	436	101	4.19
	XSEC25	18,330	6,757.92	6,753.77	6,751.90	.96	11.08	37,504	361	83	4.15
	XSEC26.1	19,260	6,765.64	6,760.42	6,758.50	.61	7.91	62,976	506	94	5.22
	XSEC26.2	19,500	6,766.58	6,759.62	6,756.70	.44	6.84	87,186	585	77	6.96
	XSEC26.3	19,615	6,766.94	6,759.99	6,756.70	.41	6.00	99,697	667	92	6.95
	XSEC26.4	19,795	6,767.15	6,759.31	6,755.50	.42	6.71	100,674	596	68	7.84
3	XSEC27	20,620	6,772.77	6,770.21	6,768.30	.96	8.71	36,599	459	178	2.56
(fig. 6)	XSEC28	21,970	6,779.17	6,776.52	6,774.70	.40	3.35	100,923	1,194	446	2.65
	XSEC29	23,280	6,785.57	6,782.76	6,781.20	.85	7.86	44,682	509	177	2.81
	XSEC30	24,955	6,794.10	6,791.87	6,787.70	.66	4.21	69,530	949	425	2.23
	XSEC31	25,810	6,798.38	6,797.04	6,792.30	.79	4.89	52,105	818	607	1.34
	XSEC32	27,070	6,805.31	6,803.17	6,798.30	.80	6.20	65,253	645	298	2.14
	XSEC33	27,255	6,805.69	6,800.17	6,797.60	.73	9.66	56,658	414	72	5.52
	XSEC33.1	27,290	6,806.01	6,800.35	6,797.60	.68	9.17	61,175	436	73	5.66
	XSEC34	27,810	6,808.67	6,805.71	6,801.90	.40	3.62	95,541	1,105	372	2.96
	XSEC35	29,830	6,818.27	6,815.80	6,812.50	.80	6.38	57,404	627	251	2.47

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