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Natural history of the South Fork Snake River eastern Idaho emphasizing geomorphology hydrology and vegetation

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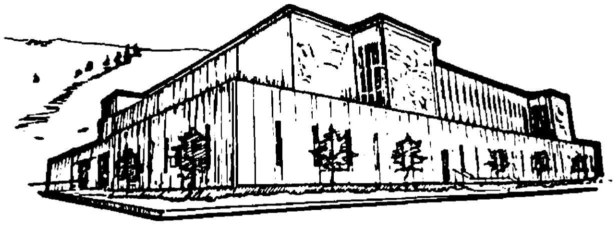
MICHAEL MERIGLIANO



A NATURAL HISTORY OF THE SOUTH FORK SNAKE RIVER, EASTERN IDAHO, EMPHASIZING GEOMORPHOLOGY, HYDROLOGY, AND VEGETATION

by

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ABSTRACT

The geomorphology, hydrology, and vegetation of the upper Snake River, which is also known as the South Fork Snake River, was studied to assess the effects of the Palisades dam and other land uses on the river environment. These assessments were made using a variety of data sources including hydrologic data collected by the U.S. Geological Survey, aerial photography, plant collections, repeat photography of landscape scenes, channel material borings, plan and profile maps, and early explorer journals. Much of the data spans about 80 years.

The South Fork Snake River is a proglacial, cobble-bedded stream that is braided over much if its length. Streamflow is dominated by snowmelt. Ninety two percent of the drainage basin is forested. Steppe, pasture, and cropland occupies most of the remaining area.

The most important affects on the river results from Palisades reservoir management, which began in 1956. These affects are elimination of peak flows greater than the natural 3-year event and sediment trapping by the reservoir. Channel response to these affects are local channel degradation and widening in the first 0.5 river miles (RM) downstream from the dam. No changes in width or channel roughness were detected at a gaging stations 1.6 (RM) and 42 (RM) downstream from the dam. Reaches from 15 RM to 42 RM downstream from the dam had a 4% increase in width. For these same reaches, total sinuosity, which includes active anabranches, was 1.98 in 1941 and 2.02 in 1987. Lateral channel migration since dam closure is less than during periods with high floods. The at-a-station hydraulic geometry for five Snake River gaging stations, including one above the reservoir, was examined. Large shifts in the constants occurred at one station after passing a large flood. Shifts were statistically significant yet very slight at the stations with records spanning the pre- and post-dam periods.

The most obvious vegetation change is an increase in mature cottonwood (*Populus angustifolia*) forest. This increase is due to a combination of natural flood history and human-induced flood control. Other important vegetation changes are an invasion of exotic grasses and forbs, and an increase in the native reed canary grass (*Phalaris arundinacea*) on young channel deposits.

Methodology and interpretation for hydraulic geometry are also explored.

PREFACE

Some years ago, while working as a forester, I was asked to find out "what's going on" with the cottonwood forest on the South Fork of the Snake River. This open–ended question has guided me from the beginning. Even the study's beginning is hard to define, because my familiarity with the area began long before a study name, number, and materials were connected with my thoughts a few years after the original question. This vagueness has advantages, for there are fewer limits on scope and experience. Furthermore, this study complements a more specific study dealing with the South Fork cottonwood forest.

Of course, any investigation must have bounds, and as the title suggests, this one focuses on the physical make–up of the river, it's associated vegetation, and the surrounding landscape. Also, interactions between these on various time and spatial scales are considered. My approach is largely exploratory and there is no overall hypothesis, but several hypotheses are tested in the usual, deductive manner. This approach is apt to yield spurious results, so to counteract this as much as possible, the various hypotheses or ideas are again tested against each other, when possible, in a network of more inductive inference.

Doing a broad natural history when the original question deals with cottonwoods is a matter of control over processes through time. Obviously, the cottonwood forest has a strong connection to the river, but is river the same through time? Also, the river and its vegetation are not in isolation; factors such dams, animals, and land use also can have effects. This study attempts to sort out these various factors, especially in respect to the more specific study on the cottonwood forest. As the latter study progressed, many questions from interested parties emerged, and these were an incentive for the present study. Occasional references to "future work" in the text relate to the cottonwood forest study, which progressed concurently with the present one.

Many people helped with this study, from giving ideas, encouragement, criticism, and providing and lending insight about historical data, to helping with logistics and fieldwork. First and foremost is Karen Aslett, ecologist with the Bureau of Land Management, who has thought long and hard about the South Fork cottonwoods. She put many of these thoughts into action, including much early field work, passing the main cottonwood study through many bureaucratic hoops, and piloting jet boats amongst rocks, trees, and my incessant arm–waving. Marv Hoyt, Trout Unlimited and Mark Elsbree, The Nature Conservancy, were also instrumental in getting the parent study funded. Many thanks also to Dr. Paul Hansen, ecologist for the Montana Riparian– Wetland Research Program and my main advisor, who helped me see things as others have, as well as sharpening my own vision for new

things. One cannot ask more from a mentor, but I have received much more. I am most grateful to my other graduate committe menmbers: Donald Potts and Robert Pfister, School of Forestry, and David Patterson, Mathematics.

Much appreciated ideas and criticism were provided by several land managers, hydrologists, botanists, and wildlife biologists, including Pat Koelsch, Dan Kotansky Karl Gebhardt, Bob Moseley, Don Watson, Bob Jones, Doug Henderson, Signe Blair, Cindy Lunte, Brian Richter, Mary Maj, Mike Whitfield, Ann Harvey, Vicki Saab, and Nancy Shaw. I am indebted to the US Geological Survey, who's early workers collected much of the data used here. Also, Sandy Holmes, Lois Douglas, — and especially — Deana Green, miraculously found the gaging station notes that were misplaced many years ago. Joe McGregor, USGS Photo Librarian, hunted down several historic photos, while Jake Jacobsen of the Idaho Falls Field Office helped with the many nuances of discharge measurement at the various gaging stations. Mike Beus, "flow man" at the Bureau of Reclamation Minidoka Project Office, cheerfully supplied various data specific to Palisades Reservoir, while Ken Rice allowed access to files at the Palisades Dam. Doug Kimmel, Skip Staffel, and Duane Olsen provided field notes, maps, and insight about the cadastral survey. Alan Skaar, equipment operator, and others at the Progressive Irrigation Company, helped clear up my confusion about the maintenance history near the Heise gage. Max Mehan and Jason Lonski worked hard on producing usable prints from my crummy negatives, and I am amazed at their skill; George Eastman would be proud. While on vacation, John Young helped me find the long-lost Dry Canyon gage site in head-high brush and thistles after a heavy down pour.

This study was possible due to generous funding provided for the main cottonwood forest study by the Bureau of Land Management, The Idaho Nature Conservancy, Upper Snake River Chapter of Trout Unlimited, and The University of Montana School of Forestry.

Finally, many thanks and love to my very best friend and wife, Linda. From the start, she knew this would mean many sacrifices, including fewer turns together in the mountain snows. If only I knew! (Just kidding).

CONTENTS

CONTENTS

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CONTENTS
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TABLE LIST

FIGURE LIST

FIGURE LIST
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CHAPTER 1

INTRODUCTION

STUDY GOALS AND OBJECTIVES

Although they cover a very small area on the landscape, rivers and their immediate environments are very important human, wildlife, and plant habitat. This general statement is well understood, but our understanding of the relationships between them is not.

Rivers naturally change over time in response to changes in climate, seasonal precipitation, and runoff characteristics of the drainage basin. At a given time, rivers change along their progression from headwaters to the sea. These dynamics are further complicated upon water development such as dams and diversions.

Dams and their impoundments can affect the river environment below them as well as above. The upstream effects on natural resources such as fish and wildlife habitat are obvious and well-known, and these effects are usually accounted for in the more recent mitigation plans. In contrast to the upstream effects, the downstream effects are more insidious and unpredictable, and although different, are also important for long-term maintenance of river-dependent resources. River management is centuries old, but only over the last few decades have we paid close attention to the effects this management can have on downstream environments. With the construction of larger, multi-purpose dams during the last fifty years, the effects are potentially even greater and more complicated.

Other activities can also affect the river environment. Some obvious activities are land clearing for agriculture, road building, residential development, and levee construction. More subtle ones include livestock grazing, introduced plant and animal species, and fire suppression.

The following study is part of a larger study. The larger study mainly deals with the effects of the Palisades dam and reservoir on the cottonwood ecosystem along the Snake River below the dam, but also investigates the more subtle effects. Whenever one looks at changes in river environment due to damming, an important question is "What was this environment like before dam construction, and what activities that occurred before and after dam construction may have affected the river environment?". This question, along with what effects are due to river damming, form the basis for the present study. Physical and biological aspects are examined, with a strong reliance on historical data. Specifically, the main attributes I examined are drainage basin attributes that could affect the river, temporal changes in the river's form and process, and changes in streamside and riparian vegetation.

The goal for the present study was to better understand how this cottonwood ecosystem functioned under natural conditions. This understanding will serve as a foundation for future investigations in this ecosystem, which in turn will aid in management of this ecosystem and those similar.

The study objectives are:

1. Describe the drainage basin features and their bearing on the river and its flood plain.

2. Describe and compare any changes in river form and process over time, and interpret these changes.

3. Describe and compare any changes over time in river-associated vegetation , and interpret these changes.

Although not a main objective, the use and statistical aspects of hydraulic geometry are discussed, using data from this study and the work of others.

STUDY AREA LOCATION

The river valley from below Palisades dam near Irwin, Idaho downstream to near Heise, Idaho forms the primary study area (figure 1). River miles total about 38. This area coincides with that of the larger study mentioned earlier. It was selected because:

1. Much of the ownership is public, and maintenance or enhancement of wildlife and fisheries habitat is a management priority here.

2. It is below the Palisades dam and affected by regulated flows and sediment retention due to the reservoir.

3. There are no large changes in river flow characteristics such as diversions, levees, and large tributaries that would confound the relationship between riparian zone dynamics and dam releases.

In context to the present study, I have expanded the study area to include those aspects of the drainage basin that have a bearing on the primary study area. In short, the expanded study area encompasses the basin above the dam and a short distance downstream below the confluence with the Henrys Fork (figure 2).

Clarification of river names is necessary. The Snake River above the Henrys Fork (or North Fork of the Snake River) was called the South Fork of Snake River by many, including the U.S. Geological Survey until 1910. Many still informally refer to the Idaho portion as the South Fork, and I use the informal "South Fork" because it conveniently separates the primary study area from the Wyoming portions or the entire Snake River in general. An exception to this usage occurs during reference to gage stations, where I use standard published names.

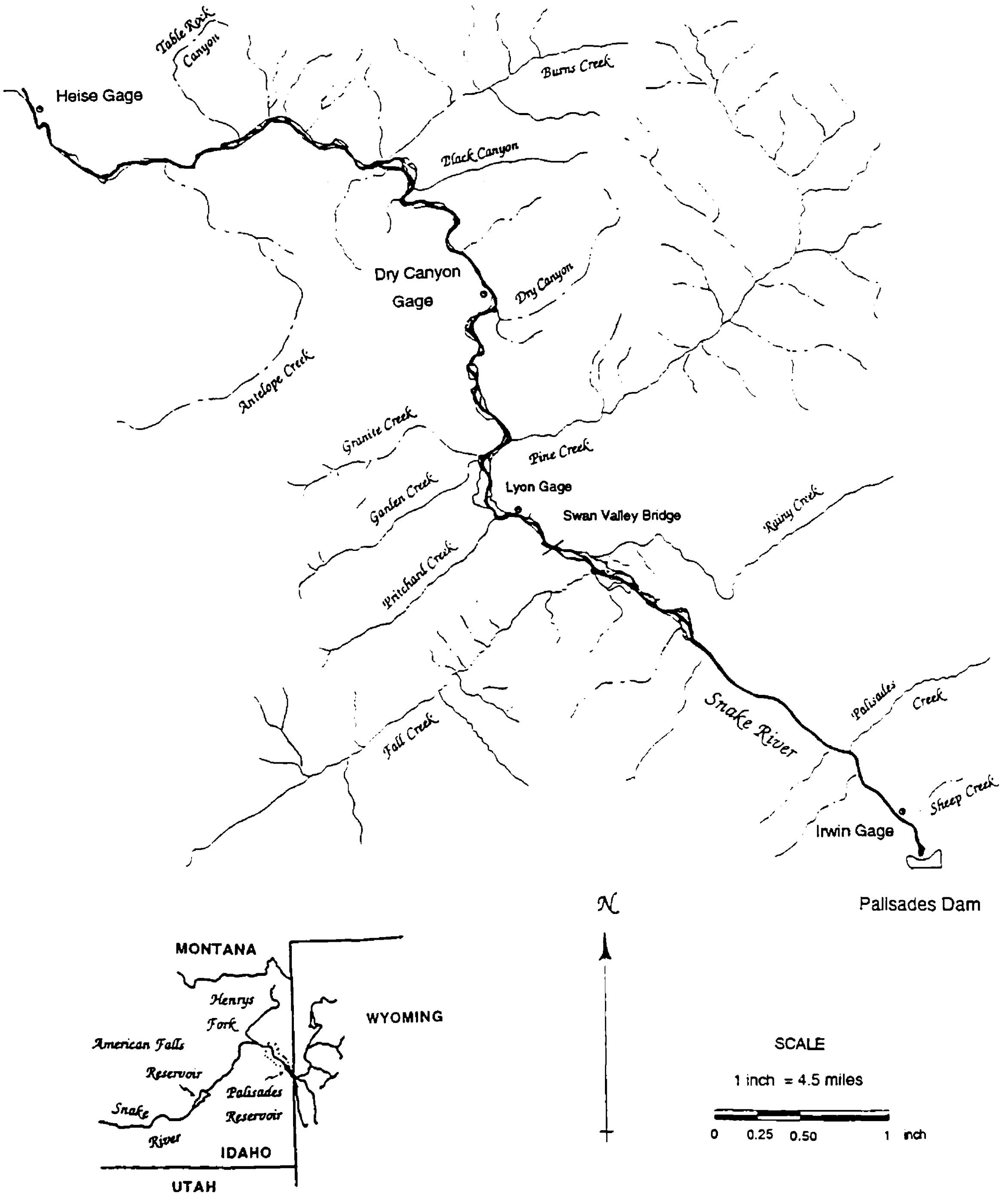


Figure 1. Map of primary study area.

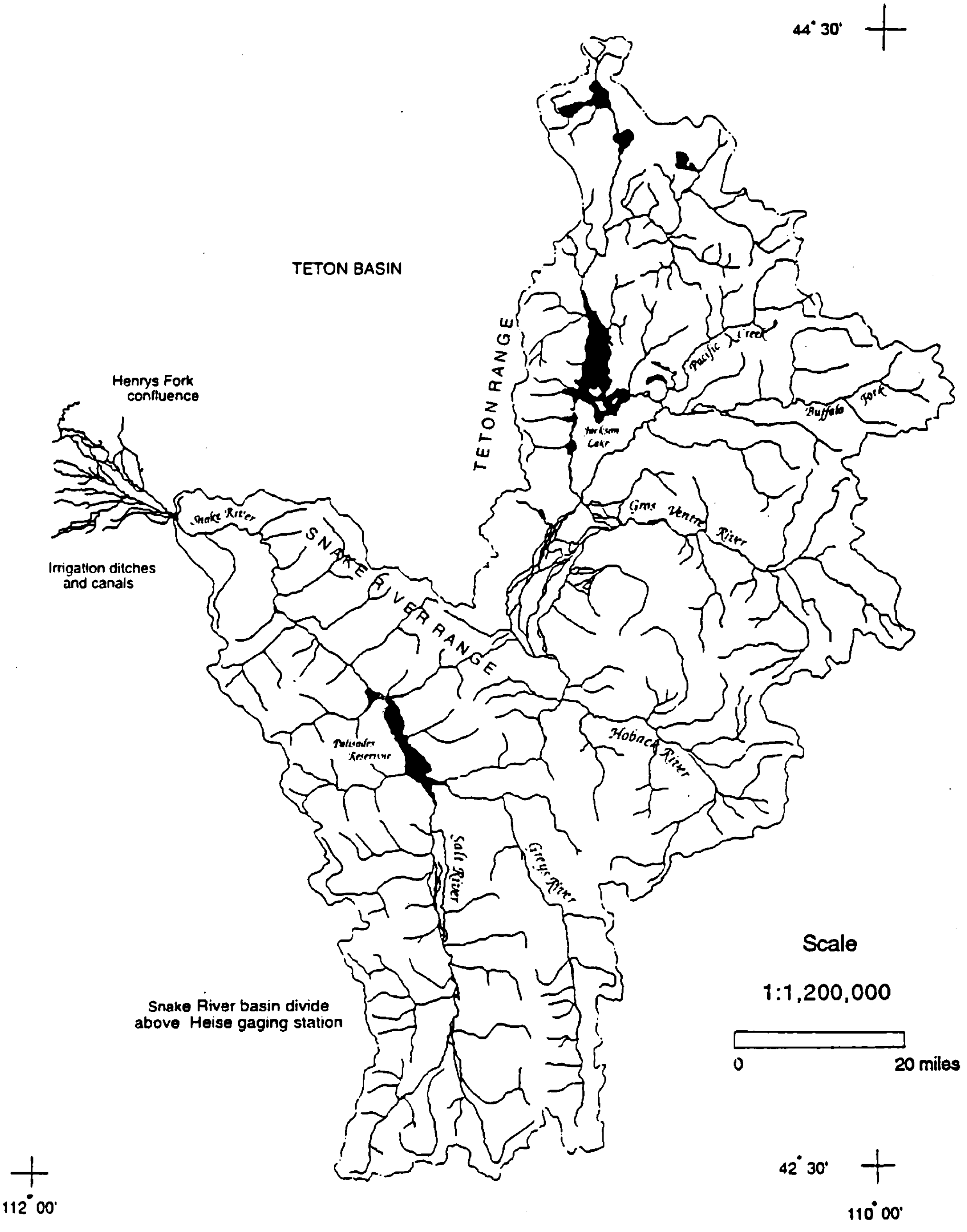


Figure 2. Map of expanded study area.

TEXT ORGANIZATION

The three main study aspects are related but separated for ease of discussion. The drainage basin is discussed first in chapter 2, followed by analysis of the river's form and process through time in chapter 3. These two aspects are mostly physical in nature, and there is a shift to the biological aspect in chapter 4, where the discussion focuses primarily on vegetation. Finally, the main points of chapters 2, 3, and 4 are brought together in chapter 5 for a conclusion.

There is a hierarchy in the level of detail as the discussion progresses. Each chapter starts with a brief overview, using simple terminology and focusing mainly on the line of inquiry and basic concepts. There are no citations in the overviews, although some statements may require them. The ideas in the overview are repeated in detail later and are supported by pertinent literature there. Methods, results, and discussion for each main aspect are included in the respective chapter. Each chapter closes with a simple summary of the findings. Sometimes, a figure is separated from a reference because the figure illustrates more than one concept which are widely separated in the text. Page numbers for figures follow references that are many pages away from the figure.

As usual, information and data important for a complete interpretation but not central to the main discussion are included in appendices.

CHAPTER 2

DRAINAGE BASIN CHARACTERISTICS AND HISTORY

OVERVIEW

This section deals with the runoff characteristics of the watershed through time and important landforms associated with the river. River form and process are related to the climate, geology, and vegetation of the watershed. This relationship is used in two ways: recent climate and watershed characteristics are related to the present river channel and flood plain, while older landforms such as terraces are use to interpret past climate and watershed characteristics. In turn, these older landforms have some effect on the river today. As well, land use can modify the above relationships.

The following discussion aims to sort out the above relationships and set the stage for the following chapters. Because this chapter is mainly a compilation of existing information, there is no methods section. Methods associated with the small amount of analysis performed is presented along with the discussion. My own experience in the area over the last 12 years is incorporated into the discussion where there is no documented information.

GENERAL DRAINAGE BASIN DESCRIPTION

The Snake River above Heise, Idaho drains approximately 5,752 square miles (USGS 1954). About 92 percent of this area is mountainous and forested, and runoff characteristics are dominated by snowmelt. Much of the area was glaciated during the Pleistocene epoch, and although the basin consists of many rock types of various ages, the lasting effects of the glaciers has the most important effect on river morphology today. The Snake River is proglacial, braided in most reaches, graded (Mackin 1948) in its recent pre-dam condition, and bed-load dominated (Schuum 1981). The bed is mostly cobbles and gravel, and overbank-deposits are mostly sand. Most of the larger tributaries appear similar to the Snake River in sediment regime and temporal flow pattern.

GEOLOGY AND PHYSIOGRAPHY

Bed rock stratigraphy and general structure - The dominant, exposed bedrock types are marine sediments, sandstone, volcanics, conglomerate, and plutonic - metamorphic complexes (figure 3). There are several large fault zones which influence the topography to a large extent by creating structural basins and areas of weakness that may locally affect ungraded stream courses. The following discussion is summarized spatially in figure 3.

The drainage basin's entire stratigraphic sequence includes every geologic time-period except the Silurian (Love and Reed 1971; Jobin and Schroeder 1964; Pampeyan et al. 1967; Staatz and Albee 1966). Events most important to shaping the landscape as seen today began during the upper Cretaceous, when mountain building began. Erosion of a large uplift northwest of the present basin created deep deposits of quartzite conglomerate that still exists in the upper-reaches of the Snake River (Blackwelder 1915a; Love and Reed 1971). This deposit is called the Harebell Formation. Since the Pleistocene, the Harebell and a closely related deposit, the Pinyon conglomerate, are probably the most influential deposits affecting the Snake River's sediment regime besides the Quaternary alluvial fills themselves. After this first known large uplift, other mountains were lifted primarily through normal faults or enormous thrust faults. Mountain building essentially ended during the early Cenozoic era (Eocene epoch) with uplift of the Teton range, which is a double fault-block range of Precambrian basement rocks (Love and Reed 1971).

During the Teton uplift volcanic activity renewed, resulting in extensive rhyolite and basalt flows as well as welded tuff deposits —Love and Reed (1971) point out that volcanism and uplift are probably directly related. Most of the lava and tuff associated with the Teton uplift are located in the northern, upper portions of the drainage basin. These volcanics date from the Tertiary, with peak activity during the Miocene epoch (Love and Reed 1971). The Yellowstone caldera and other vents were also important sources of volcanic material in the headwaters region as well as in the primary study area (figure 1).

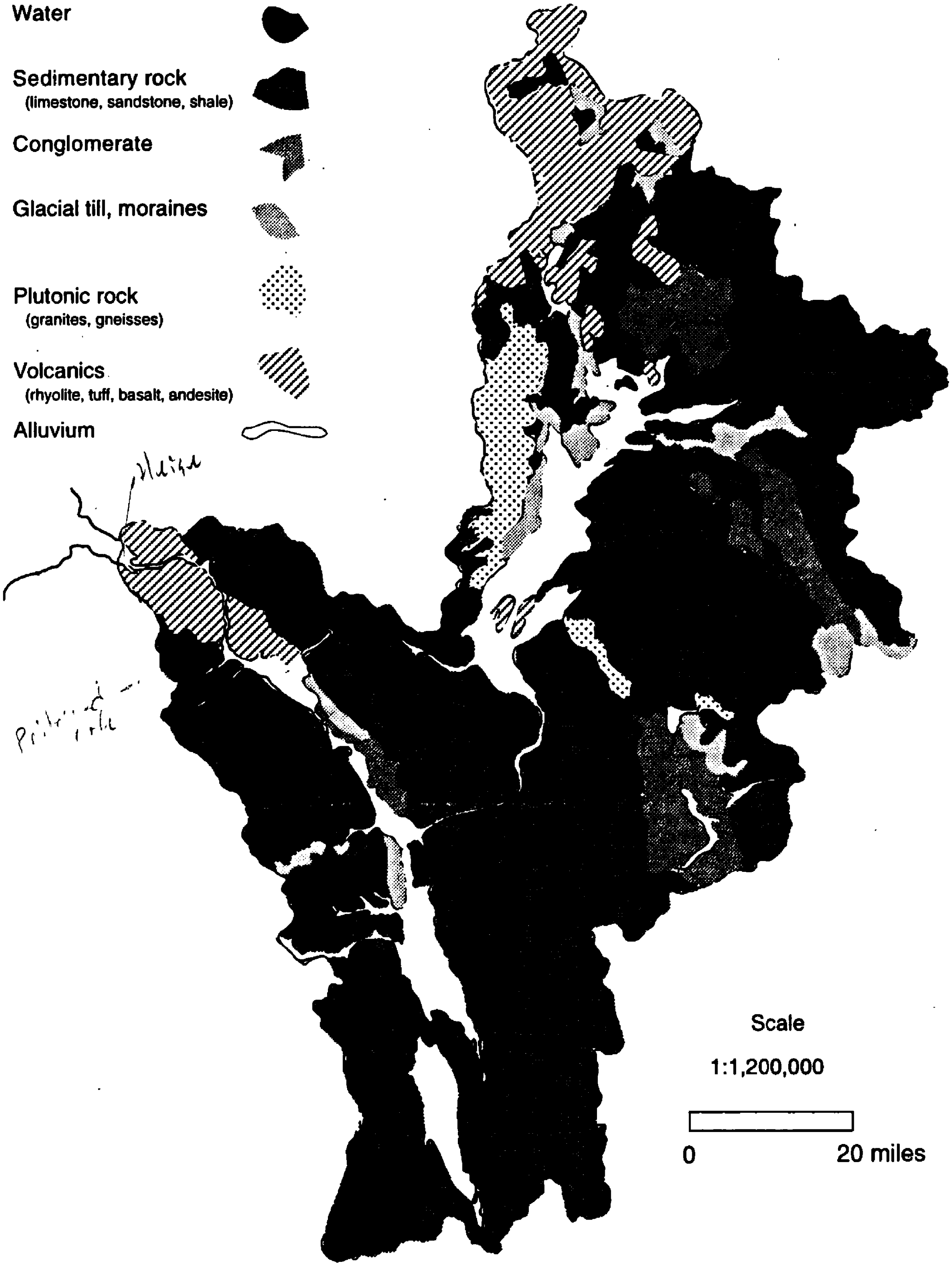


Figure 3. Geologic map of the drainage basin. (Adapted from Love et al. 1955; and Bond, et al. 1978.)

Volcanism outside the Teton and Yellowstone area also occurred, and due to the location and timing, affect the South Fork reaches more directly than the headwater vents. Sources for volcanic material in the primary study area were within the study area itself, down-valley in the Snake River Plain, or in the Yellowstone region (Armstrong et al. 1975, Roberts 1981). The temporal, spatial, and compositional patterns are complex, but in general, the older material is rhyolitic and at a greater depth than the younger material, which is basaltic and caps the older volcanics as well as sedimentary rock (Staatz and Albee 1966; Roberts 1981; Armstrong et al. 1975). The more recent basalt flows in the primary study area can be thought of as an extension of the Snake River Plain. In general, basalt flows become younger in the up -valley direction (Roberts 1981), with the youngest aged rock being about 800,000 years old and in the Swan Valley area (Armstrong et al. 1975).

Two fault pairs are especially important to the present Snake River: the Teton - Hoback faults, and the Grand Valley - Snake River faults. All are normal faults , and their resulting graben-basins have filled with Tertiary and younger deposits (Love and de la Montagne 1956; Jobin and Schroeder 1964; Staatz and Albee 1966). These deposits are primarily volcanic and alluvial. In fact, the Jackson Hole Basin contains the thickest and most complete non-marine Tertiary record in the United States (Love and Reed 1971). The two graben-basins are known as the Jackson Hole Basin and the Grand Valley (figure 2). The Snake River's general course coincides with the alignment of these basins or the associated faults.

Cenozoic geology - Events during the late Cenozoic era have the most direct impact on the way the Snake River in the primary study area looks today. These events can be summarized chronologically as: several volcanic events interspersed with graben subsidence and deposition of course conglomerates during the Tertiary period, alluvial fill deposits during Pleistocene glaciation, loess deposits on the volcanic benches and alluvial terraces during the late Pleistocene epoch, and local graben subsidence in the lower Swan Valley area during the Holocene (Recent) epoch.

In the primary study area, the ancestral Snake River of the Tertiary period probably had a roughly similar course as today. The most compelling evidence for this similarity is the consistent graben basin alignment since last major faulting during the Cretaceous (Staatz and Albee 1966; Love and de la Montagne 1956; Roberts 1981). Other evidence is the juxtaposition of Cenozoic volcanics and Tertiary sedimentary rock; valleys in this sedimentary rock are filled with various volcanic deposits. Judging by the size and orientation of these valleys, they were probably tributaries to the ancestral Snake River. For example, near Dry Canyon, basalt flows extend from the Canyon rim to the river bed. Downstream near Heise, dissected Tertiary rhyolite next to the river is capped with younger basalt. Although many of the contacts between rock units are obscured by colluvium and there are several unconformities, the Tertiary Snake River may have been at a similar or lower elevation than the modern River.

There has been some tectonic movement of the basin floor. Roberts (1981) estimated that the valley floor in the Swan Valley area has tilted about 5° per million years and movement may still be occurring. Local subsidence along the Grand Valley fault near Rainy Creek occurred during the Holocene (Roberts 1981).

A major feature of the primary study area is the canyon cut by the Snake River between Garden Creek and Heise (figures 1 and 3). Basalt from a vent complex in the northwest end of Conant Valley created a large bench. Most of this volcanic activity occurred during the Pliocene and consists of basalt flows as well as pyroclastics (Roberts 1981). The volcanic deposits blocked the rivers's flow causing a lake or marsh to form upstream; lacustrine deposits and pillow basalts from subsequent lava flows are evidence of this event (Roberts 1981). The lake, herein called Lake Conant, probably drained gradually as the canyon was cut. The duration of the lake is not known, but the few exposures of lacustrine deposits are thin enough to suggest its life was not long in a geologic sense. Roberts (1981) usually found pillow basalts at about 5502 feet above sea level. Based on this evidence and assuming a similar river grade, the lake extended from Conant Valley up to about the confluence of Indian Creek of the Snake River Range. The final series of events are related to mountain glaciation during the late Pleistocene and early Holocene. As described by Blackwelder (1915b), three major glaciations affected the drainage basin in general. These are known as the Buffalo (200,000 years ago), the Bull Lake (35,000 to 80,000 years ago), the Pinedale (9,000 to 12,000 years ago). Recent studies recognize at least one more major glaciation which are named pre-Bull Lake (Moss 1949; Williams 1961; Richmond 1962; Walker 1964). More recent minor glaciations occurred; one is named the Temple Lake (< 4,000 years ago) and an unnamed, more recent advance (Moss 1949).

The pre-Bull Lake and Buffalo glaciers may have reached the South Fork's valley, but direct evidence is scarce at best. The more recent glaciers probably did not reach the South Fork's valley. Even so, the glaciers still had an effect on the South Fork valley due to the sediments associated with glacial erosion. Melt-water streams transported these sediments below the glaciers and much of the resulting alluvial fills, or valley trains, are still present. Because each successive glaciation was less intense than the former (Blackwelder 1915b), older valley trains were not completely removed or covered by creation of the newer valley trains. Thus, a complex of valley trains, or alluvial fills representing the various glaciations still exist; portions of this complex extend down to the Bonneville flood deposits at the Portneuf River confluence, near American Falls reservoir (Scott 1982).

Although the valley train complex is a relatively small landscape feature, a discussion is instructive because by examining the valley trains' morphology and history, past climate and river regime can be inferred. The primary diagnostic features of the valley trains are terraces, as well as the slope, sediment type and size, and spatial relationships of the terraces themselves.

Terraces are formed as the river cuts down through former flood plains. Walker (1964) describes the alluvial terraces in the drainage basin from their glacial-moraine origins in Jackson Hole down valley to Swan Valley. Walker found 6 terraces in the Swan and Grand Valleys and referred to them by their approximate elevations above the river at the Idaho–Wyoming border. The heights in feet are 450, 220, 190, 80, 30, and 10. These terraces largely disappear below Swan Valley. In addition, I have noticed one more terrace, and it is about 1 foot above the present flood plain and of non-glacial origin.

Walker (1964) considered the highest terrace as pre–Bull Lake age; only isolated remnants of this terrace exist today in Grand Valley and upper Swan Valley. The 220– and 190–foot terraces are considered as Bull Lake age, with the 220–foot terrace having more remnants. All three high terraces have considerable loess caps on them.

The 80– and 30–foot terraces are probably of Pinedale age. The 30–foot terrace is about 9,000 years old, based on fossil radiocarbon dates (Love and de la Montagne 1956) from the moraine at the terrace's head. Walker (1964) considered the 80–foot terrace to be from the Pinedale as well, based on the small amount of loess on its surface and fresh appearance similar to the 30–foot terrace. Walker (1964) felt the 80–foot terrace is about 12,000 years old. The absolute age difference is uncertain, but the differing origin which implies an age difference is still clearly visible in the field.

Walker could not directly relate the 10–foot terrace to a glacial moraine, but based on the terrace's youthful appearance, correlated it with the Temple Lake glaciation recognized by Moss (1949) in the nearby Wind River Range. The 10–foot terrace may be a cut terrace within the youngest Pinedale–aged terrace (30–foot), but it is likely that the increased alluviation that occurred during the Temple Lake glaciation occurred in the Snake River basin too. However, terraces in separate basins do not connect, and without this direct connection, correlation is less certain.

The 1–foot terrace is common but not continuous in reaches below the dam— especially below Swan Valley. It occurs sporadically in Swan Valley and it may be present in the reservoir-flooded reaches which were similar before dam closure. This lowest terrace is not correlated with any glaciation; based on botanical evidence it is at least 150 years old. Although I am more certain of its continuity within the study area, I have seen surfaces in the Jackson Hole area that may correspond to the 1–foot terrace in the study area. A schematic cross section of the glacial terraces is shown in figure 4.

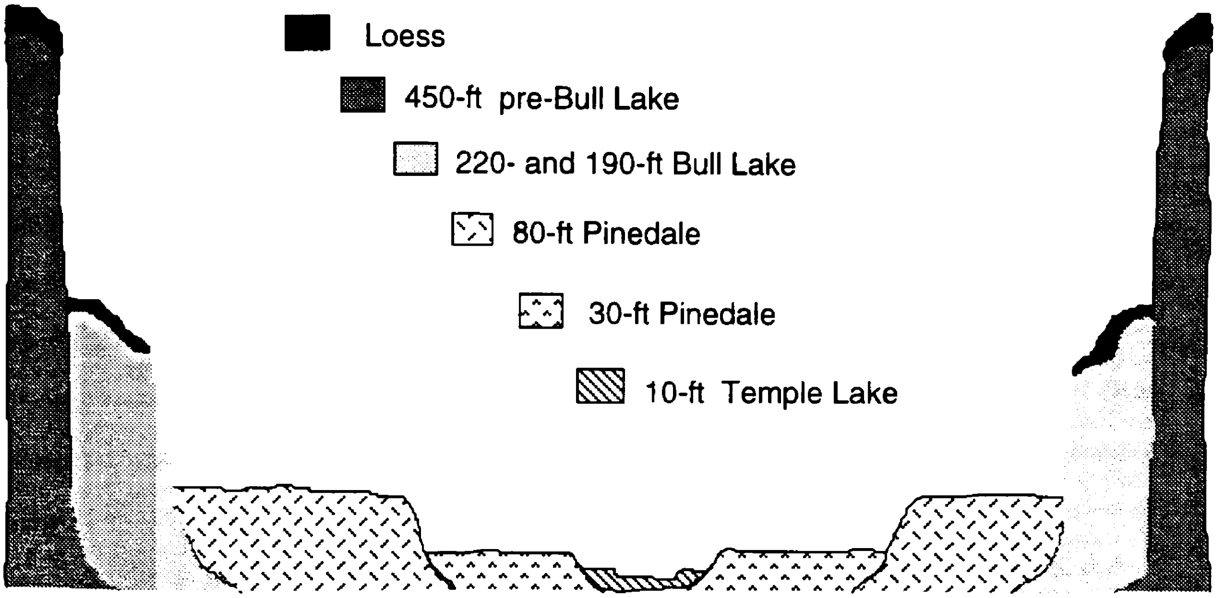


Figure 4. Schematic cross-section of glacial-origin alluvial fills.

Note: The highest terraces are drawn as if paired, but they may not be.

A flood plain's longitudinal slope, or profile, parallels the slope of the river that formed it, thus the profile of the terrace tread represents the profile of the river before the terrace was cut. Sediment quantity and size determine river slope under graded conditions (Mackin 1948). The relative position of deposits and terrace scarps of differing ages reflect relative changes in deposition and erosion (Thornbury 1954).

Walker (1964) suggested that the 450–foot terrace may have been graded to the top of the volcanic bench near Conant Valley, based on the height of the bench and some gravel between the upper-most basalt flow and lowest loess deposit. The presence of granite and quartzite in this gravel suggest an upstream source rather than colluvial deposits from adjacent hill slopes. Walker (1964) also felt that the gradient was less steep than at present. If the river was so graded, the canyon probably did not form until rapid downcutting during the late-Pleistocene. Also, Lake Conant would have filled rapidly with the valley train sediments. This relatively late erosion cycle agrees in time with erosion of the Grand Canyon of the Yellowstone River in Yellowstone National Park, which is also in Cenozoic volcanics (Holmes 1881). Alternatively, there may have been a pre-existing canyon filled to the brim with sediments. This being the case, one would expect the higher terrace remnants below the canyon mouth where the river is not laterally restricted. Perhaps these remnants exist but their existence is not clearly documented and thick loess deposits obscure the true nature of the higher bench-like features. Terraces exist here (Scott 1982) but they appear too young to correlate with the 450–foot terrace. Much less is known or can be interpreted from the 220– and 190–foot terraces, except they obviously represent downcutting. With no traces to an origin and establishment of separate deposition age, these terraces may in fact be a set of cut terraces in one valley train of uniform age.

<u>Terrace genesis and paleoclimate</u> – Due to their extensive continuity, more recent age, and relation to present-day lakes, the 80–, 30–, and 10–foot terraces allow more insight into past climate and prediction of river morphology change. These terraces represent a history that includes periods of net deposition, equilibrium between sediment deposition and erosion, and net erosion.

The sediment size distributions of the these terraces look the same, and are dominated by medium to large cobbles. Walker (1964) plotted the measured terrace and river profiles, and the longitudinal slopes of these terraces are also generally similar to each other. The present river profile deviates from the terrace profiles in some reaches. The largest differences are for the 80– and 30– foot terraces, just below their source moraines, where the terraces have steeper profiles than the present river. This type of deviation is not unusual, and the ancestral river may have been steeper due to rapid downstream fining of sediments below the moraine or, all other factors being equal, higher discharges in the ancestral river (Leopold et al 1964). The rapid convergence of terrace and river profiles suggest domination of the former. The 10–foot terrace more closely parallels the river and although Walker traced it to near the oldest Pinedale moraine, he found no source moraine for this terrace. The three higher terrace profiles are much smoother than the modern river profile in the canyon below the Hoback River (figure 2) because the present river slope has several bed rock knickpoints while the older rivers probably had more consistent alluvial beds.

The 1–foot terrace differs from the older terraces in one main respect: the upper zone of channel deposits is largely made up of sand. The lower stratum consists pebbles and cobbles typical of the more recent channel deposits. At first I assumed that the sand was overbank deposits, but botanical evidence suggests otherwise. Using work of Sigafoos (1964) and Everitt (1968) as a guide, I have excavated cottonwood trees on young (5 to 100 years old) alluvium in the study area, and the root collar gives a close approximation of the demarcation between channel deposits and overbank deposits. Based on the root collar position of older cottonwoods (150 to 200 years old) in the sand, I estimate about half of the height is from channel deposits. The top of these channel deposits (or root collar position) is about a foot above the more recent alluvium. This 1–foot estimate is based on extensive field visits and takes into account local scour and fill of recent alluvium relative to the terrace. One cannot attribute the 1–foot terrace to sediment retention in the Palisades Reservoir, because the terrace separates alluvium that is clearly older than the Palisades Dam, and as discussed in chapter 3, there has been minimal to non-existent channel degradation (downcutting) since Palisades Dam closure.

Based on Walker's (1964) work, most of the existing terraces are inset fills. The 190–foot terrace may be an exception, as discussed earlier. The implication of these inset fills is that much of the alluvium present today owes itself to past glaciations, and there has been an overall decrease in valley floor elevation during the Quaternary. The fact that at least some of these terraces are fills indicates net deposition, but because successively younger valley trains are within previously eroded valley trains (inset), more sediment has been removed from the basin than added, and any net deposition was temporary.

Terrace topography gives an indication of the balance of erosion and deposition over time. Because a terrace is an abandoned flood plain, the cross-valley width of an uneroded terrace tread is related to lateral channel migration. While the river is graded (Mackin 1948), the flood plain is essentially level in the cross-valley direction, and upon downcutting, the resulting terrace tread heights are equal; terraces with equal tread heights on opposite valley sides are called paired terraces (Thornbury 1954).

The Pinedale-aged and younger terraces were formed below medium to large piedmont lakes — the natural Jackson Lake being the largest and on the main trunk stream (figure 2). Whether or not the river was ever graded below these lakes which retain sediment is especially interesting, because it helps predict river response to present day reservoirs. Walker (1964) did not consider whether glacial terraces were paired. I looked at the Pinedale-aged terraces and in general they appear paired over much of their length. However, there are extra terraces within the first mile or so below the source moraines, and they're across-valley heights appear uneven. The unevenness may be due to the rapid slope adjustment due to the initially over-steepened moraine front. Love and de la Montagne (1956) also found some additional low terraces well below the source moraines; these may represent a minor downcutting cycle. The treads of the paired terraces are wide relative to the modern river and its flood plain, implying considerable channel migration during graded conditions. The valley graben has tilted along the Teton and Hoback faults since the terraces were cut (Love and de la Montagne 1956). This tilting complicates the relation somewhat, but the paired terrace relation is still reasonably clear when viewed as a whole.

The periods of net deposition are related to increased erosion rates in the drainage basin during glaciation. The downcutting during periods of net erosion is most likely due to climate change, which causes the subtle balance between sediment load and water discharge to shift. One may attribute a downcutting episode to meltwater alone and this is probably true during initial waning of the glaciers, but paired terraces would not exist if downcutting was continuous. Also, the wide terrace treads probably cannot be attributed to a very wide ancestral river bed (as shown by a Grand Teton Park interpretive sign), because tread width fluctuates considerably down valley, while river width would only increase gradually over the same down valley distance (Leopold and

Maddock 1953). Moreover, the terrace margin sinuosity is incongruous with any imaginable sinuosity of such a wide river.

The effect of climate change on river regime varies regionally, depending largely on the initial sediment yield of the drainage basin (Leopold et al. 1964). Langbein and Schumm (1958) estimated that maximum sediment yield occurs in areas receiving about 10 inches of annual precipitation. Whether the channel degrades or aggrades depends on initial precipitation, whether precipitation decreases or increases, and perhaps more importantly, changes in the seasonal precipitation pattern (Leopold 1951a). Although still not completely understood, river channels tend to degrade during periods of aridity and aggrade during more humid periods— at least for areas that were initially arid. Although counterintuitive, this relationship is due to changes in vegetation cover and frequency of high rainfall events (Thornthwaite et al. 1942; Leopold 1951a). Field evidence supporting this comes mainly from arid and semi-arid areas where channel changes are dramatic and climate changes have been assessed with dendrochronology, fossil flora and fauna in alluvial fills, settlement patterns of aboriginal man, and recent historic data on climate and land use (Bryan 1925; Bryan 1941; Antevs 1952; Leopold and Miller 1954; Leopold et al. 1964; Hereford 1991). If there is one unifying concept from the above studies, it is that degradation occurs when the runoff response of the drainage basin becomes more intense or"flashy". For the Snake River basin during the Quaternary, deposition was probably higher during the more humid glacial periods, and downcutting probably occurred during the Altithermal periods, when the climate was drier and warmer. In between these climatic extremes, the river was apparently graded as evidenced by the paired terraces.

Three other explanations for terrace formation are downcutting during fault movement, regional uplift, and isostatic rebound once the glaciers melted. Fault movement is an unlikely cause, because the valley grabens have been dropping since the Cretaceous (Love and Reed 1971; Roberts 1981), which would encourage filling. Indeed, the graben basins have filled considerably and it is mainly during the late Quaternary that there has been evidence of net erosion. Also, terraces cross many fault lines, and it is unlikely that every bed would tilt in a direction favorable to downcutting. Blackwelder (1915b) submits much evidence for rejuvenation due to a change in base level from regional uplift, but he relies mainly on landforms from the Buffalo glaciation and even older strath terraces. Isostatic rebound may be related to the very old terraces, because evidence of Buffalo glacial ice suggest that the ice flow was about 2000 feet thick (Love and Reed 1971). Subsequent glaciations were much less intense, as evidenced by their present trim lines and moraines; therefore isostatic rebound is a less plausible cause of downcutting.

The genesis of the 1–foot terrace has implications for recent sediment regime, but I cannot determine its true origin and development with available field evidence. However, its age suggests that it was cut during the initial arroyo-cutting episode in the southwestern United States (Bryan 1925; Bryan 1941; Hereford 1991). Leopold and Miller (1954) noted a Recent fill terrace in the plains rivers of eastern Wyoming, which they called the Lightning formation. Their photograph of the Lightning terrace shows old cottonwood trees on it. Although the alluvial fills corresponding to the 1–foot and Lightning terraces may be of differing origins, perhaps similar climatic shifts are responsible for the terraces cut into them.

PRIMARY RIVER REACHES AND THEIR IMPORTANT CHARACTERISTICS

To better understand the dynamic processes of a section or reach of river, a reach should be considered in context to adjacent reaches. Considering gross characteristics such as confinement and channel pattern, the Snake River from Jackson Lake to the Henrys Fork confluence can be divided into 6 primary reaches. In downstream order, the first reach is in Jackson Hole, followed by a mountain canyon reach. The third is in Grand Valley and upper Swan Valley, the fourth is in the subsided part of Swan Valley, the fifth is in the volcanic canyon, and finally, the sixth is on an alluvial fan below the canyon.

Within Jackson Hole, the river has a braided channel with a broad flood plain bounded by terraces. The larger tributaries add significant amounts of water and sediment relative to the main stem. There are many sub-reaches as partly defined by Mills (1991), but due to its remoteness to the primary study area, a single-reach grouping suffices for this discussion.

In the canyon reach, the channel is largely confined by terraces and colluvial slopes. The single, sinuous channel crosses several bedrock knick points, with cobble-bed areas in between the knick points. The Hoback River is the one large tributary joining this reach.

Below the mountain canyon, the river enters the third reach in Grand and upper-Swan Valleys. Before the dam, there was little difference between these two valleys, but Palisades Reservoir largely covers the Grand Valley at full pool. The pre-dam river was largely confined by terraces in both Grand and upper Swan Valleys, with only a few sub-reaches having a relatively wide flood plain. Today, the above-dam valley features show little change since dam closure except for a veneer of clay-sized particles on most of the valley floor and some local mass wasting on steep valley slopes. A delta common to most reservoir inlets is not obvious where the Snake River and other tributaries enter. Undoubtedly, sediment with higher settling velocities than clay is accumulating, but it is probably spread out due to a non-constant pool elevation from year-to-year. This variance allows the river to move previously-deposited sediments downstream during subsequently lower pool elevations. The change in river form and process below the dam is discussed in chapter 3.

In the downstream part of Swan Valley, the channel is braided and is not bounded by glacial terraces, showing much more recent channel migration compared to the second and third reaches. The graben below this part of Swan Valley has subsided after the terraces were deposited (Roberts 1981), so the more recent sediments cover the youngest glacial-alluvial fills (Scott 1982).

The volcanic-canyon reach is characterized by a braided channel with a flood plain from 3 to 5 channel widths wide. Channel migration is somewhat confined by the canyon walls, but together, the flood plain and 1–foot terrace comprise a much wider valley bottom than in the terraced reaches above. Except for the 1–foot terrace, older terraces are very scarce and only exist in unusually wide areas. (Although not in the canyon proper, Conant Valley is a good example of this). Many of today's intermittent stream valleys have alluvial fills that are perched above the modern river about 10– to 15–feet. These perched valleys suggest that the river bed was higher when these valleys had perennial flows because perennial tributary alluvium is usually graded to the master stream. There are what look like strath terrace remnants near Heise and opposite the Burns Creek confluence, — and possibly another near Dry Canyon,— but I have not investigated them in detail except they are of different lithology. The Heise and Burns Creek remnants are basaltic, while the one near Dry Canyon is a Tertiary conglomerate (Staatz and Albee 1966).

Below the canyon, the river is finally unconfined by high terraces or canyon walls. Agricultural development has taken advantage of this fact. The river is much more braided here than anywhere else, although there is no obvious change in sediment size or confluence with large tributaries.

The river shows certain traits related to the landforms it helped shape and now traverses. In context to riparian vegetation, flood plain width is an important trait and is apparently related to bank resistance. High bank resistance is highly associated with the glacial terraces over much of the river's length, but not so much in the upper Jackson Hole basin or on the alluvial fan below Heise .

Perhaps the Jackson Hole anomaly can be explained by high bed load injections from Pacific Creek, Buffalo Fork, and Spread Creek, which are large headwater tributaries. Mills (1991) noted sediment accumulation near these large tributary confluences as well as increased braiding in reaches below the Jackson Lake dam. Some or all of the accumulation may be related to decreased peak flows due to operation of Jackson Lake dam (Marston 1990; Mills 1991). However, the tributary sediment loads are inherently high due to the erosive nature of the Harebell and Pinyon conglomerates in the tributary basins as evidenced by the tributaries' channel morphology. Because channel width-to-depth ratios tend to increase with high bedload (Wilcock 1971, Carson and Griffiths

1987), the braided channels may be unusually wide here to accommodate the unusually high bed load. Flood plain lood plain width is related to active meander amplitude (Wolman and Leopold 1957), while meander amplitude is related to channel width (Leopold and Wolman 1960). Although the Snake River channel is braided, an increased width would likely manifest itself in an increased flood plain width in a way similar to meandering rivers.

The large fan at the mouth of the volcanic canyon is the other area where the natural river was largely unconfined. There are glacial terraces here (Scott 1982), but the flood plain is much wider compared to the middle, terraced reaches. There are no large tributaries as in the Jackson Hole reach, so width would not be similarly affected. The Recent volcanics associated with the Menan Buttes or the confluence with the Henrys Fork may have an effect on slope, but a more regional approach and more detailed data are needed to understand why channel migration is less constricted here.

RECENT ALLUVIUM DEPTH AND COMPOSITION

River characteristics are related to sediment size distribution of the channel and banks. Although data is limited, channel bed material and channel deposits in the exposed flood plain and terrace bank look similar. Overbank deposits are typically sand dominated. Available data include recent pebble counts on flood plain and channel features, well borings for one channel cross section, and soil survey samples on terraces. Channel bed form shows in photographs of the nearly dry channel taken during dam closure (figures 40 and 42, p. 99 and 102) which are in chapter 3. Observations of channel features were also documented during dam closure.

Sediment size distribution of river bed and flood plain channel deposits – Using Wolman's (1954) method, I sampled the areal frequency distribution of bed surface particles to describe the general nature of bed material in terms of roughness. Bed locales were sampled. Sampling points were 1 foot apart along a 100 foot tape for a sample size of 100. Although Wolman's method is often used for a particle frequency distribution, it has considerable bias in frequency estimation because probability of selection is proportional to size, and there is no weighting to account for the uneven probability. A weighting factor as described by Leopold (1970) can eliminate most of the bias by weighting proportional to a particle's area. However, Wolman's method gives an unbiased estimate of the areal distribution of particle sizes on the bed, and this is the way my data is presented. Table 1 shows the particle sizes for commonly used percentiles. The percentiles represent the cumulative percent of bed area occupied by particles less than the size shown. A more complete description of the distributions as well as the sample locations are in appendix C.

Table 1. Sediment size distribution of selected channel and flood plain areas.

		Particle Size Percentiles		
Locale	D_{50}	D_{84}	D_{95}	Sample Size
Channel:				
Irwin gage	117	191	240	100
Heise gage	79	110	140	100
Flood plain:				
Newly vegetated*	43	72	97	55
Black Canyon Bar	61	92	120	100
Riley Ditch Bar	52	98	126	100

Explanation: D_{50} is the median particle size, D_{84} and D_{95} denote the 84th and 95th percentiles, respectively. The D_{xx} size means that xx % *of* the area has particles $\leq$ to the size indicated. Particle size is the intermediate diameter of a particle in millimeters (the b dimension as defined by Wolman (1954). * Patches of overbank deposits not included.

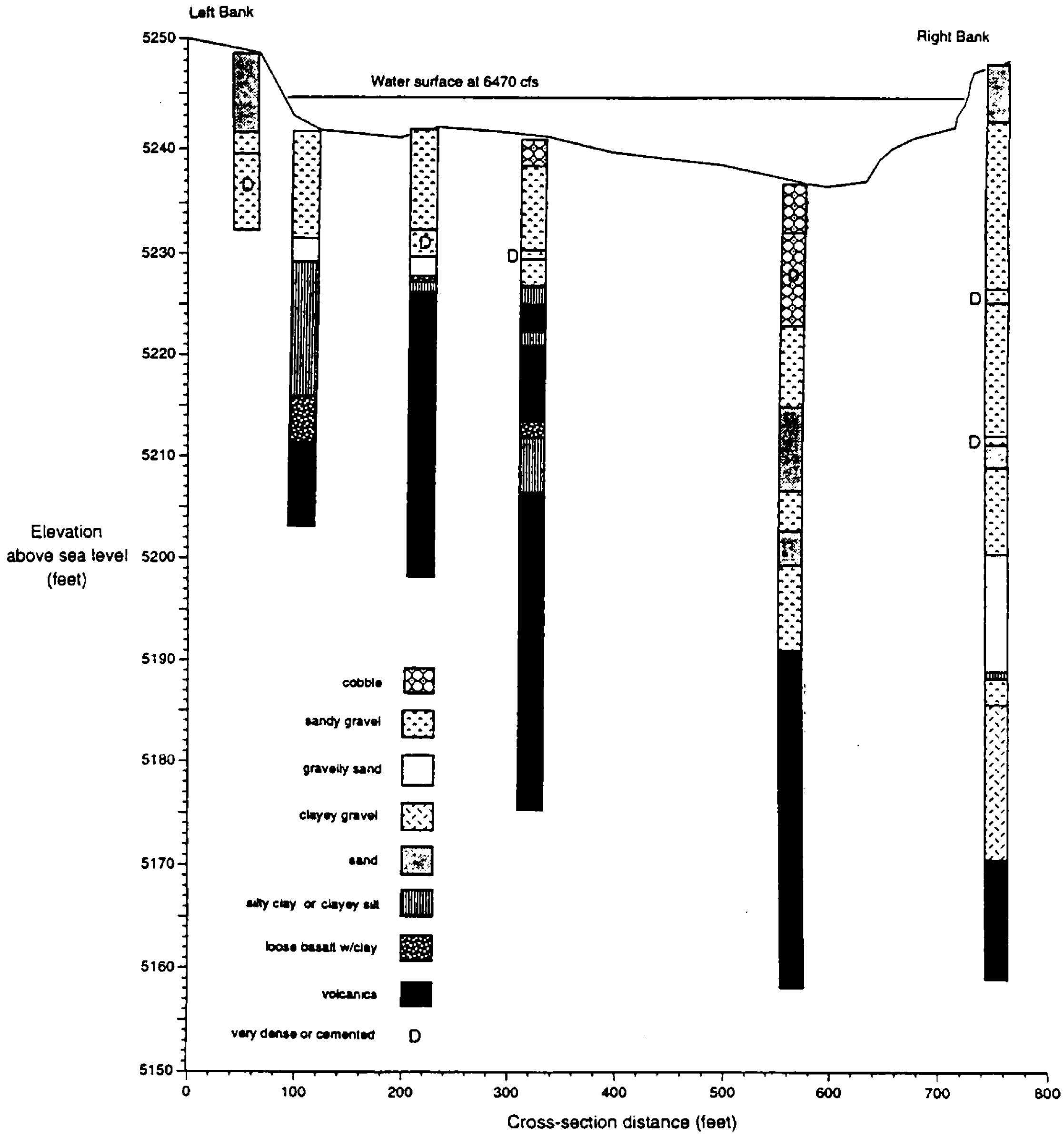
Channel area pebble counts were done during low flows and represent areas that may fill during high flows. Two locales are perpendicular with gage cross-sections; these locales are below the bankfull level and may scour slightly during receding flows (see chapter 3). The newly vegetated area is typical of young bars and have 6– to 8–year old riparian vegetation on them. The smaller particles (<2 mm) are probably over bank deposits, but were treated as channel deposits in field sampling. The flood plain areas have no overbank deposits on them. However, I suspect that the particle size distribution is roughly similar to those parts of the flood plain that are hidden by overbank deposits. This suspicion is based on visual inspection of about 500 shallow pits dug in a broad range of flood-plain materials and exposed bank cuts. The areas are shown on aerial photography and in 1941 appear similarly devoid of vegetation as today. The size of these areas has remained constant since 1941. Based on tree ages and the discharge record, these channel deposits probably stabilized around 1917.

The bed has features typical of cobble bed rivers, but the classic pool and riffle sequence (Leopold and Wolman 1957)) are somewhat muted and are drowned except during very low flows. Figures 40 and 43 (page 99 and 102) show straight reaches photographed during dam closure. A report describing the events and river during dam closure is filed in the Palisades powerhouse library maintained by the Bureau of Reclamation. The following passage is an anonymous observer's impression of the bed at this time:

> *One surprising feature of the exposed river bed was the almost continuous smooth appearance of the river channel, void of pot holes or deep ponds outside the main channel from the Dam to Palisades Creek, and to a lesser degree from Palisades Creek to the South Fork Bridge, eleven miles downstream.*

The reference to a "main channel" is curious because just as today, there was only one channel from the Dam to Palisades Creek during the 1950's and earlier. From what can be seen today, side channels generally show a more pronounced pool and riffle sequence — relative to width — than the main channel.

<u>Channel material composition and depth</u> – One channel cross section has been drilled to consolidated or otherwise very firm material. Figure 5 summarizes data from well boring and shows the depth and composition of material below the bed. Figure 1 (page 4) shows the Swan Valley bridge location.



Data collected by Idaho Department of Transportation in August 1978 at the alignment of the Swan Valley bridge built in 1981.

Figure 5. Depth and composition of material below channel bed.

Outward appearances of the channel near the Swan Valley bridge are typical of the braided reaches. However, this cross section is in the subsided portion of the graben valley, and depths here may not be representative of other reaches.

Terrace composition – The soils of the lower terraces and flood plain are described by Miles (1981). Table 2 shows the classification of flood plain and terrace soils found in the primary study area.

Table 2. Classification of soils found on terraces in the primary study area.

Soil Name	Family or higher taxonomic class	General location
Hobacker	Loamy-skeletal, mixed Pachic Cryoborolls	Swan Valley
Badgerton Variant	Sandy, mixed Typic Cryoborolls	Swan Valley
Harston	Course-loamy, mixed (calcareous) frigid Xeric Torrifluvents	canyon
Bock	Course loamy,mixed, frigid Calciorthidic Haploxerolls	alluvial fan
Bannock	Course loamy over sandy or sandy skeletal, mixed frigid Aridic Calcixerolls	alluvial fan
Heiseton	Course-loamy , mixed (calcareous) , frigid Aquic Xerofluvents	alluvial fan

The Hobacker and Badgerton soils were formed on the 10-foot terrace. The Bock and Bannock soils are formed on a terrace somewhat lower than 10 feet. One extensive area of Bock and Bannock soil overlies a basalt flat. This is the basaltic strath terrace area mentioned earlier. The strath terrace is similar in height to the 10–foot terrace of the upper reaches and both terraces may be correlated with great caution.

The Harston soil is so isolated that it is difficult to relate the terrace it is on with the other terraces. The Heiseton soil is scarce along the South Fork above Heise, and I am unfamiliar with it in the field.

Miles (1981) calls all of these soils "flood-plain soils", probably in the sense that these terraces were once flood plains. However, the distinction between the two terms is important in that the decreased flooding allows for differing soil genesis and edaphic factors on the terraces compared to the flood plain. All of these terrace soils were originally fluvents, but the presence of a mollic epipedon (names ending in "oll") suggests an age difference. The Harston and Heiseton soils, which lack a mollic epipedon, may be younger than the others because they have had less time to accumulate enough organic matter since becoming terraces.

Most of the terrace soils are presently cultivated or pastured. Remnant native vegetation and photographs taken before cultivation suggest that these were upland areas before settlement. Vegetation is discussed in more detail in chapter 4.

In addition, Miles (1981) describes two unnamed soils and classifies them to sub-order. These soils are found throughout the primary study area. The first is a complex of Aquic Cryoborolls–Typic Cryaquolls. The second is a Xeric Torrifluvent. The main difference between these soil types is the depth to the course gravels with the gravels being capped by a finer-textured top soil. The complex has a thicker (12 to 14 inches) top soil of silt loam to silty clay. The fluvent has a top soil about 10 inches thick composed of sandy loam to loam.Judging by the mapped locations and my experience, these two soils were formed on the 1–foot terrace and natural-flow flood plain and support (unless cleared) riparian vegetation. The fluvent typifies the flood plain, but the mapping is not detailed enough to always separate the terrace from the flood plain.

PRESENT CLIMATE AND RUNOFF PATTERN

The present climate of the upper Snake River basin can be generalized as having cold, snowy winters and short cool summers. Classification is difficult, being somewhere between maritime and continental (Barry and Chorley 1982). Total precipitation varies with location and elevation, being higher in the northwestern portion and at higher elevations. Based on weather stations, monthly precipitation is about evenly distributed in the lower elevations and towards the southern portion. The higher or more northerly areas receive a higher percentage of precipitation during the winter (Steele et al. 1983; Miles 1981; Young 1982). Average annual precipitation varies from about 60 inches in the higher mountains (Young 1982) to 9.35 inches at the Idaho Falls weather station which is about 20 miles downstream from Heise. The lower valleys are semi-arid and the mountains are humid.

The Snake River's discharge amount and timing, or runoff pattern, pattern is dominated by snowmelt. Figure 6 shows the snowmelt influence by relating energy flux, snow-pack water, and precipitation data from a mid-mountain, upper-watershed weather station, and runoff data from two Snake River gaging stations above Palisades Reservoir. The Moran station is just below Jackson Lake Dam. Jackson Lake Dam releases were minimal and constant due to the reservoir filling after 3 years of repairs.

LAND OWNERSHIP PATTERN

Public land comprises the vast majority of land area, especially in the upper portions, and is nearly all federal. Establishment of public ownership approximately coincides with European settlement in this area. Yellowstone National Park, which is partly drained by the Snake River, was established in 1872 (US GOVT 1872), while the Teton National Forest and the heart of the future Grand Teton National Park (GTNP) were born out of the Yellowstone Timber Reserve, set aside in 1891 (Pinchot 1947). The Bridger, Teton, Targhee, and Caribou National Forests, which are partly drained by the Snake River were established soon after. The mountainous portion of GTNP was separated from the Teton National Forest in 1929, and further expanded into the Jackson Hole basin in 1950, which until this time was private (US GOVT 1950). Much of the remainder of land was either homesteaded and converted to private ownership, or became Public Land administered by the Grazing Service in 1934 via the Taylor Grazing Act. These Public Lands are now administered by the Bureau of Land Management.

Until perhaps 1950, the type and intensity of public land use depended more on access and demand than regulations. Since this time, access improved, uses became more complex, demands increased, and regulations were enacted accordingly.

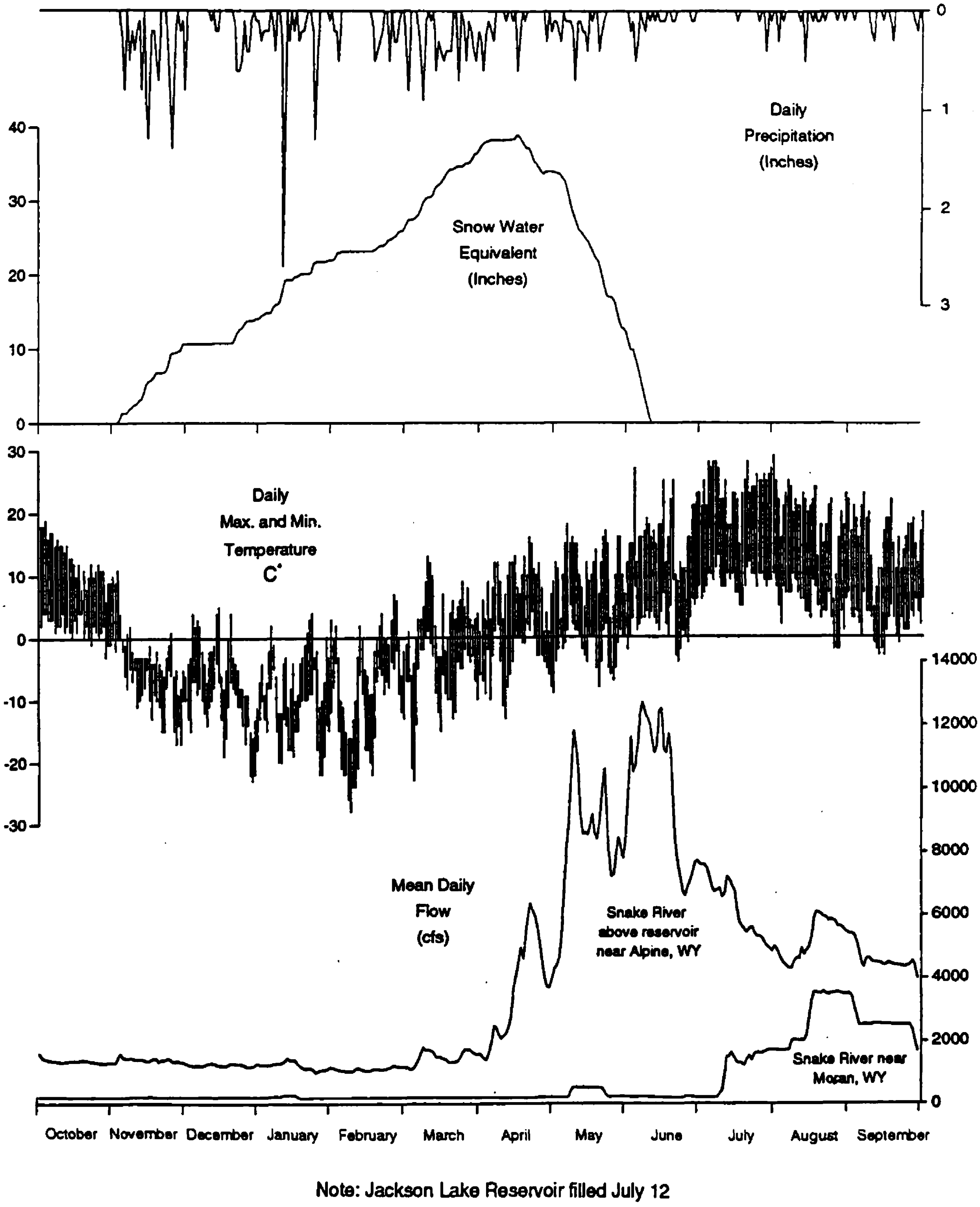


Figure 6. Seasonal pattern of energy flux, precipitation, snow-pack water and streamflow for 1989. Weather data is from Phillips Bench, Wyoming Station 10F23S. on the east slope of the Teton Range.

VEGETATION

The present native vegetation can be generalized as follows: The lower valleys slopes, basin floors, and lowest benches support (or supported) steppe (Hironaka et al. 1983), while a mosaic of conifer and aspen tree stands occur on the foothills and up to moderate elevations in the mountains (Steele et al. 1983; Mueggler 1988). Conifer-forb parklands are common in the subalpine zone (Gregory 1983), and herbaceous meadow or conifer savannahs dominate in the alpine zone. Upper timber line, including krummholz or stunted trees (Arno and Hammerly 1984) is about 11,000 feet above sea level.

Presently, the native steppe communities are typically dominated by big sagebrush (*Artemisia tridentata*), rabbit brush (*Chrysothamnus* spp.), Great Basin wild rye (*Elymus cinereus*), blue bunch wheat grass (*Agropyron spicatum*), and Idaho fescue (*Festuca idahoensis*). Much of the steppe on private land has been converted to pasture, small grain production, or residential development. Although agriculture started in the late 1880's in the lower country (Horton et al. 1989), large scale clearing for dry-land agriculture probably started in the 1930's, judging by early photographs and my conversations with local farmers. This conversion makes up a very small portion of the watershed, but these areas are often near the river or its tributaries. Many grain fields are unvegetated from fall to spring, while some fields are bare an entire year if in summer fallow. Summer thunderstorms on these bare fields causes much local erosion (Smart 1987 pers. comm.), and most of these fields are below the Palisades Dam, so sediment can enter the river via small tributaries. Suspended sediment in the Snake River is occasionally measured at the Heise gage, but only since 1977. Therefore, detecting changes in sediment regime due to farming is difficult. Sediment regime is discussed more in chapter 3.

The foothill and lower montane forests, which consists mainly of lodgepole pine (*Pinus contorta* var. *latifolia*) quaking aspen (*Populus tremuloides*), and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) stands, probably contributed more to changes in runoff characteristics than any other zone due to their dynamic nature and areal extent.

Historically, these forests burned with frequent, small fires, or catastrophically with stand-replacing fires (Loope and Gruell 1973). Since European settlement, and especially during the last few decades, conifer stands have been managed for timber production. Most of these stands are mature, and even-aged silvicultural systems are the norm with the clearcut method being most common (USDA FS 1985, USDA FS 1990). However, most effects of forest management do not reach the primary study area because the activity post-dates Palisades Dam and much of the managed area is upstream of the Palisades reservoir; the reservoir traps any increased sediment, and dam operation negates any changes in runoff. The amount of recent activity below the Dam and above the Henrys Fork confluence is probably negligible.

The conifer-forb parklands in the subalpine zone and the meadow/conifer savannah complex in the alpine zone have the most potential for affecting the runoff characteristics due to their combined areal extent and copious snow accumulations. However, the forests in these areas, which are primarily subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*), have not changed appreciably over the last century due to slower growth and a less frequent natural fire frequency (Gruell 1980b).

While the forest component has remained stable in a hydrologic sense, the herbaceous component may have been less so. Herbaceous species composition is a complex of tall mesic forbs, with Engelmann aster (*Aster engelmannii),* lovage (*Ligusticum filicinum),* horse mint (*Agastache urticifolia),* and meadowrue (*Thalictrum fendleri)* being the common dominants in the western and southern portions, while various graminoids mixed with low forbs are more common in the northern and eastern portions. Domestic sheep grazing is an important land use of these zones, and typical of western U.S. ranges (Clapp 1936), use was quite heavy in the early part of the century according to local sheep ranchers and land managers. Local legend tells how the sheepherders' progress in the mountains could be gauged from the valleys simply by watching the dust clouds raised by the sheep.

It is difficult to assess the impact of sheep grazing on sediment and water yield because there are few well-controlled studies on these impacts, especially for large watersheds. Graf (1988) summarizes these studies and suggests that for small areas (say 10 to 100 acres) heavy grazing can substantially affect runoff and sediment yield. For much larger areas, climactic factors far outweigh grazing effects, or at least the effect of grazing is masked by the complexity of the watershed.

One could logically extend the heavily grazed, small-area situation to a larger watershed and assume similar response but data for the local situation is limited and there is no control over climate. However, sheep grazing still occurs in this area, and recent experience may yield insight to past events. The "sheep dust clouds" occurred during the 1930's (Egbert 1990 pers. comm.) which coincided with droughty years. Droughty conditions occurred during the late 1980's, and several "fires" were reported in the area that were actually dust clouds from moving sheep. Sheep numbers were typically higher during the 1950's than today, but recent repeat photography of a typical Teton Range sheep allotment closed in 1960 shows only subtle changes in species composition in some areas, but no noticeable change in cover [1]. Even if there is a change in range condition (Dyksterhuis 1949), range condition is generally inadequate to directly assess the effect of grazing on hydrlogy (Gifford and Hawkins 1978).

As a result of a large flood on a grazed tributary in the region (but not quite in the drainage basin) during an intense summer thunderstorm, extensive watershed rehabilitation projects were done during the 1950's in the southern portion of the Teton Range. In this same area, a 10,000 acre sheep allotment was closed due to impact on soil (USDA FS 1985). Whether or not these events were sheep induced cannot be determined for reasons mentioned earlier.

Another factor which may contribute to natural erosion is the extensive mounds of bare soil due to pocket gopher (*Thomomys talpoides*) activity. Much bare soil is exposed as

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[1] Photographs on file at Targhee National Forest Headquarters, St. Anthony, Idaho.

gophers push out excavated soil to the surface. These mounds appear stable during small rains. Mounds may erode during intense convective storms, but I have not noticed this due to pre-occupation with the weather and possible electrocution. Gregory (1983) felt that gopher activity allowed some tall forb communities to change to an earlier successional status. In Gruel's (1980b) judgment based on early narratives, gopher activity levels have probably not changed appreciably since pre-European settlement.

FIRE

Fire can make a considerable difference in watershed response when there is enough moisture during normal periods to support vegetal cover that protects and holds soil, and drought periods to allow ignition of vegetation (Graf 1988). This situation fits the Snake River watershed reasonably well.

Watershed response after fire includes an increase in water and sediment yield. Water yield increases are mainly due to decreases in evapotranspiration loss; higher canopy reductions are correlated with higher yield (Troendle and King 1987). In order for noticeable increases to occur in main stem reaches, a large portion of the basin must be affected during a short time. Yield increases in watersheds managed for water as a commodity are typically small because only a small percentage of the basin is treated at a time (Zeimer 1987); this relationship may hold true in more natural watersheds such as the Snake River's. Sediment yield increases depend largely on changes in infiltration rate relative to precipitation and the nature of the sediment. If infiltration rate is less than precipitation input, overland flow occurs which can move sediment. An important aspect in fire's effect on infiltration rate is soil hydrophobicity, or water repellency (Debano 1981). Fire intensifies any repellency due to precipitates of waxes and other polymers that plant released to the soil.

As mentioned earlier, the montane vegetation was burned periodically and with varying intensity. Gruel's (1980a) repeat photography of W.H. Jackson's photos from the 1870's in the upper basin show large increases in the areal extent of conifer forests, especially on low-to mid elevation sites. My own repeat photography of photographs from the early 1900's show a similar change in the lower basin. The latter photography is presented in chapter 4, as well as fire history and associated vegetation dynamics.

Judging by the repeat photography and my knowledge of the region's forests, extensive areas burned during the late 1800's. The large fires in this region during 1988 were on the same scale. Whether or not the early large fires created a noticeable difference in water yield on the South Fork is hard to determine due to no control over the effect of climate. However, there is climate and runoff data for the Snake River above Jackson Lake to test the 1988 fire's effect on water yield, but there are potential problems with such an analysis. The temporal distribution of water yield is more important to river morphology than the overall increase. If yield increases coincide with climatically-induced peak flow, channel changes can be expected because peak flow magnitude and frequency largely determine channel morphology (Wolman and Miller 1960). Peak flow is not always well-correlated with total yield, and there are now just a few years of annual peak data to compare to the pre-fire condition. Although this type of analysis is of interest, the level of precision may be too low to yield useful results.

Fire-induced sediment yield increases in the Snake River watershed were investigated by Marston (1990) using simulated rainfall on field plots. He found a 35-fold increase in soil loss due to rainfall on burned versus unburned glacial till soils. In addition, most of the soil loss was due to rainfall splash, with minimal losses due to snowmelt. This difference has channel morphology implications. Rainfall -induced sediment delivered to the channel after the snowmelt peak is more likely to remain in the active channel until flushed out with more competent flows. This increased sediment supply may also allow overbank deposits to increase in thickness.

MINING

Some mining occurred along the Snake River and some tributaries. The Caribou Basin, at the head of McCoy Creek was the most productive area. Placer mining probably began about 1870 (Horton et al. 1989), with at least 1 million dollars in gold removed by 1890. Activity apparently declined quickly; only $58,000 worth was removed from 1915 to 1959. The effect on the Snake River sediment regime is unknown, but early photographs of the mouth of McCoy Creek indicate that additional sediment was slight.

Sporadic placer mining and panning occurred in the Snake River as well. These activities are not well documented, but some placer mining occurred at the mouth of Black Canyon, across from Table Rock, and Wolf Flat. Only the Table Rock area was notably productive (Spaulding pers. comm. 1993). Evidence of this activity is still visible, and from what I have seen at Black Canyon and Wolf Flat, the effects are very minimal. Panning was likely more widespread, but due to the dense sand and very fine gold dust, most places did not pan out.

WATER DEVELOPMENT

Development of the Snake River's water for agriculture followed the usual historical pattern, where water is first diverted into canals and ditches, followed by reservoir construction for primary irrigation storage — which is adequate for normal years — and finally by creating reservoirs for supplemental irrigation storage to hold water for the dry years.

The first irrigation canal built on the South Fork is the Anderson Canal, which was cut during 1879 and 1880 (Carter 1955). The Riley Ditch, the first ditch of appreciable length encountered below the Palisades Dam, was built during 1899 and 1900, and extended another 1000 feet in 1949 (Carter 1955). Several ditches and canals extend from the South Fork below the Riley and Anderson, many of which are tied to the Great Feeder Canal system. This system consists of a large headgate and a canal connecting the main river channel with a major anabranch called the Dry Bed. The Dry Bed was the main channel until 1893, when the main flow began to favor the present main branch (Carter 1955). Carter (1955) states that the Great Feeder headgate is the largest in the world . Below these irrigation works, the landscape is dominated by cropland, and for this reason and the complex of irrigation diversions, the primary study area ends near Heise, Idaho (figures 1, 71, and 72: p. 4, 203, 204).

About 121 river miles above Heise is Jackson Lake Dam, which increased the size of the natural Jackson Lake . The log dam built in 1905 with private funds was the first storage project on the entire Snake River, which promptly washed out (Palmer 1991). The log dam was replaced in 1907 by the Bureau of Reclamation, which washed out in 1910 and was again rebuilt in 1911, and then raised to 65.5 feet in 1916 (Palmer 1991). The total storage capacity since 1917 is 847,000 acre-feet (USGS 1973). Due to earthquake risk and its poor foundation, the dam was strengthened from 1986 to 1989, but the dam operated normally except for short-term, higher releases to reduce storage and vice versa.

Jackson Lake Dam operation affects Snake River flows, but the overall effect on riparian vegetation in the primary study area is not large, based on hydrographs and photographs dating from about 1910. This effect will be more completely explained in the next chapter, but interestingly, operation of Jackson Lake Dam changed dramatically once Palisades Dam was closed, the main change being reduction in annual peak flows (Marsten 1990). Levee construction in the Jackson, Wyoming area was contemporaneous with the Palisades Project; perhaps flood control rather than flow routing for irrigation was the main reason for this change. The effect of Jackson Lake Dam on downstream sediment regime is probably nil, because the natural Jackson Lake preceding it had the same sediment-settling effect as the dam-induced reservoir.

Soon after Jackson Lake Dam construction, other reservoirs were constructed on the Snake River, the largest being American Falls, built in 1906. Although American Falls Reservoir is well below the primary study area (figure 1), it has large implications for the South Fork due to western water law and development of the lower Snake River Plain for irrigated agriculture. These implications are briefly described in context to Palisades Dam below, and their effects shown in chapter 3.

Due to dry years in the 1930's, the need for supplemental water to irrigate existing lands on the Snake River Plain became apparent, and this was the main impetus for creating Palisades reservoir (Carter 1955, USDI BOR 1961). Initially authorized in 1941, the dam was constructed during 1951 to 1957 (USDI BOR 1961), and closed 11:43 A.M. on November, 3 1956 [2]. Full power generation began in May 1958 (USDI BOR 1961). Reservoir releases are delivered to the land with facilities in place before dam construction (USDI BOR 1961).

The dam is a zoned earthfill structure containing 13,571,000 cubic yards of locally excavated material (USDI BOR 1961); several borrow pits above and below the dam supplied the fill. One terrace area and one hillside area were the primary sources below the dam; no excavation for fill occurred in the channel below the dam except that associated with the stilling basin. A 10-foot wide trench was excavated in the river channel at the Irwin gage to facilitate low flow measurement during dam closure, but its long-term effect on the river is probably negligible. This trench is visible in figure 40 on page 99. Some above-dam pits appear to be in the channel, and activities associated with these pits and other items such as coffer dam and tunnel construction may have had a short-term effect on sediment regime below the dam. Photographs documenting construction activities are available at the Palisades power house library. The trench size is documented in US Geological Survey discharge measurement notes.

Palisades Reservoir is managed for irrigation storage, power generation, flood control, recreation, and fish and wildlife conservation (USDI BOR 1961). Active storage capacity is about 1,200,000 acre-feet and the average annual inflow is about 4 times this amount at 4,576,000 acre-feet. Irrigation storage management, which dominates reservoir

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[2] Report on file at the Palisades power house library, Palisades, Idaho.

operation, is quite complicated and the release pattern within a given water year (October 1 to September 30) varies according to holdover storage, and diversion and storage rights (Van Den Berg 1990 pers. comm.). Palisades reservoir often fills physically by early spring, but much of the water belongs in downstream storage or diversions because the water rights are far downstream from the study area (Van Den Berg pers. comm. 1990).

Hydropower operation, which can greatly effect downstream river morphology, (Kaplinski et al. 1992; Kaplinski et al. 1993) probably has little to no effect on the South Fork. Power peaking, which cause fluctuations in river stage, is the main cause of these effects (Kaplinski et al. 1992; Kaplinski et al. 1993), but power peaking is unusual in Palisades operation, and stage fluctuation within a 24 hour period is limited to 0.5 feet (Van Den Berg pers. comm. 1990). As inferred from recent fish habitat work (USDI FWS 1990), fluctuations become important for fish survival at flows less than about 1000 cfs because important habitat is alternately emptied and filled, resulting in stranded fish. Informal agreements prevent fluctuating flows during mean flows below 1200 cfs or if instantaneous flows drop below 1000 cfs (Van Den Berg pers. comm. 1990). However, the discharge record shows that fluctuations were common before Palisades dam during the snow-melt period. Since dam closure, elimination of large peak flows and sediment retention are the most obvious effects important to river morphology and riparian vegetation.

SUMMARY

The Snake River watershed above Heise, Idaho is a geologically diverse mountainous area, with a runoff pattern dominated by snowmelt, and a bed load dominated by coarse deposits of largely glacial origin.

Before the operation of Palisades Dam, flows were natural except for a slight effect from Jackson Lake Dam beginning in 1907. There were apparently no gross changes in runoff pattern inherent to the watershed from about 1900 to the present. However, an increase in tree cover in low- to mid-elevation zones may have had a subtle effect on base flows.

During the Pleistocene and early Holocene epochs, climate and sediment regime varied enough so that the river was not in a constantly graded condition. As a result, several terraces are extant along most of the river's course; most of these terraces are inset fills, which indicate cyclic rising channel beds and flood plains followed by downcutting.

The most recent and major change in runoff and sediment regime in the primary study area is due to the operation of Palisades Dam, which was closed in 1956. The physical effects of this change are discussed next.

CHAPTER 3

RIVER FORM AND PROCESS THROUGH TIME

OVERVIEW

In this chapter, changes in the South Fork below the Palisades Dam (figure 1) are described as well as probable reasons for these changes. River form is essentially what the river is made of and how it looks. River form can be defined with such attributes as channel pattern in plan-view, cross-sectional shape, sediment particle size distribution of the channel and flood plain, slope, type and spacing of bars, width, depth, and various combinations or ratios of some of these. River processes involve an interaction between energy and mass in the river system; water, sediment, gravity, and friction are the main ingredients. Process can be defined as how water and sediment move through the channel and flood plain system. River process and form are intricately related and are discussed together.

A river is an open system, usually in a dynamic equilibrium with the water and sediment entering from the drainage basin, which in turn depends on the climate and geology of the drainage basin. Considering the valley features as previously discussed, the South Fork was in equilibrium, or graded, in the recent past. Palisades reservoir operation is analogous to a change in climate and geology; the discharge pattern has changed to better suit human needs, and the reservoir traps nearly all of the sediment originating upstream. Given these changes in sediment and water regime, how has the river responded over the last 36 years in reaching a new equilibrium? What are the probable reasons or mechanisms for these responses? And finally, if the river is responding, what will it look like in the future? These questions are the central theme for much of this chapter. The last part of the chapter is more methods-oriented where the use and statistical aspects of hydraulic geometry are discussed. This latter information not only serves as a more detailed discussion of the procedures I used related to the study-area's hydraulic geometry, but should give more insight into the use and interpretation of hydraulic geometry in general.

Following various works of L. B. Leopold and his colleagues, channel form and process involves 8 variables which are flow regime (discharge), sediment load, sediment size, width, depth, velocity, channel roughness, and slope. The first three can be thought of as inputs or independent variables while the latter ones are response variables. Although there is considerable interaction between these variables, resulting changes in these variables are discussed in the above order. Interactions between these variables are discussed as well as the implication of the results. Amount of discussion depends largely on the data at hand rather than relative importance.

DATA SOURCES

Flow regime – Flow regime can be defined as the timing and magnitude of water volume within the channel and flood plain system. The water discharge record for the Snake River near Heise, Idaho is the primary source for the study area flow regime; this record was chosen because it best represents the flows in the study area and has the longest period of record, starting September 25, 1910. This data is published by water year (October 1 to September 30) by the US Geological Survey (USGS) until 1960 in various Water Supply Papers. An index to these papers is included in appendix A. After 1960, discharge data is published jointly by the USGS and the Idaho Department of Water Resources (IWR). This data contains mean daily discharge for every day of the year except for some winter days before 1925. Also, beginning in water year 1914, instantaneous maximum and minimum discharge for the year, period of record, and estimates of these before the record began are included. Discharge is in units of cubic feet per second (cfs). Monthly and yearly summaries of streamflow and other information pertinent to gage operation and location are also included. A sample of the discharge record and other details of Snake River gage records are in appendix A. Much of the above data is available on CD-ROM (Earth Info 1991), and mean daily discharge data from the CD-ROM was used to make hydrographs and check a regression used to reconstruct unregulated flows. Instantaneous discharges were gathered from the USGS or USGS/IWR publications. Reservoir inflow data was supplied by the Bureau of Reclamation via computer disc.

Mean daily discharge for the South Fork of Snake River near Lyon, Idaho gaging station was used to extend the period of record previous to the Heise gage record. Data is similar to the Heise record, but lacks instantaneous discharges and the record is not as continuous. The record begins April 21, 1903 and ends September 30, 1910. Although the record is not continuous and less accurate than the Heise record, it is the only record previous to Jackson Lake Dam. Only the daily gage heights are reported until 1909, but enough measured discharge and gage height data are reported to estimate unreported daily discharge. The data is published in USGS Water Supply Papers (see appendix A).

Mean daily discharge for the Alpine, Irwin, and Dry Canyon gages were used in conjunction with bed elevation dynamics. These gages have similar data attributes as the post-1914 Heise gage record, and mean daily discharge was obtained from the same CD data source as the Heise record (Earth Info 1991).

Sediment load – Suspended sediment load is measured sporadically at the Heise gage starting in 1977. Load is reported in mg/l, tons/day, and percent of load finer than 0.062 mm. This meager data is combined with hydraulic geometry analysis which is explained further in the methods section. There is no direct data for bed load.

Channel cross-sections – Cross section data for all gaging stations except Dry Canyon and Lyon are available from the USGS from about 1970 to present; this data is recorded on discharge measurement note form number 9-275-F. These notes only represent wetted channel, so to best show the full channel area, I chose the notes from the largest discharges since 1970. This same year's data was used to show scour and fill with changing discharge. Ground-level photographs of the river from the dam to the Swan Valley bridge were taken by a Bureau of Reclamation employee during dam closure in November 1956. For channel-change comparisons, I photographed these same places in November, 1992.

Hydraulic geometry and channel bed elevation dynamics – Data from five stream gaging stations were used for analysis. The station number, name, and their respective record period are as follows in downstream order:

13022500 **Snake River above reservoir near Alpine, Wyoming**
July 17, 1953 to present

13032500 **Snake River near Irwin, Idaho**
May 8, 1949 to present

no # **South Fork of Snake River near Lyon, Idaho**
May 24, 1904 to October 17, 1904; April 15, 1905 to November 15, 1905;
May 21, 1906 to June 12, 1906; June 17, 1908 to August 12, 1908;
April 1, 1909 to October 25, 1909; April 5, 1910 to September 26, 1910

13036000 **Snake River at Dry Canyon, near Swan Valley, Idaho**
May 9, 1934 to October 9, 1934; April 2, 1935 to November 6, 1935;
May 4, 1936 to November 3, 1936.

13037500 **Snake River near Heise, Idaho**
October 23, 1916 to present.

These gaging stations are referred to in the text with shorter names, such as "the Alpine gage" for the Snake River above reservoir near Alpine, Wyoming station.

For all stations except the Lyon gage, data on width, cross-sectional area, mean velocity, gage height, and discharge were obtained from photostatic copies of original discharge measurement summary sheets (form number 9 - 207) supplied by the USGS. These forms also have data related to method, channel condition such as ice effects, observer name, and measurement date. An example is shown appendix A. Data for the Lyon gage is published in Water Supply Papers (index in appendix A), and mean velocity is not reported after 1905.

Measurements are typically one month apart, except early in a record when the rating (gage height-to-discharge) curve needed quick defining. I grouped the data by water year, which is October 1 to September 30, except the November 3, 1936 Dry Canyon observation which was included in the 1936 water year.

Slope – The same two river surveys used in channel plan form (USGS 1932, USGS 1939) provide data on slope via profile measurement. Contour interval is 5 feet, the horizontal scale is 1 inch = 2640 feet, and the vertical scale is 1 inch = 20 feet.

Channel plan-form and width changes – I used two temporally separated sets of aerial photography; I chose these sets because they best represent the pre- and post-dam conditions and discharge was similar for each set. Table 3 shows pertinent information for each set.

Table 3. Aerial photography flight attributes

Agency	Flight Date	Nominal Scale	Film Type	Study area Coverage
ASCS	Sept. 10, 1941	1:12,000*	panchromatic	lower 3/4
BLM	April 22, 1987	1:12,000	color	entire

* The scale for the negative is 1:20,000; prints used are enlargements from the negatives.
The mean daily discharge was 6080 cfs on September 10, 1941 and 6420 cfs on April 22, 1987

Three maps are also used for visual comparisons to maps drawn from the above photography. The first is from General Land Office Survey work conducted during the 1890's, with a scale of 1 inch = 2640 feet. The other from two river surveys (USGS 1932; USGS 1939), each with a scale of 1 inch = 2460 feet.

METHODS

Flow regime - Two main approaches were used in conjunction with discharge magnitude to describe flow regime: time series and frequency distributions. Both mean daily discharge and annual peak discharge were used for each approach.

The hydrographs are plots of mean daily discharge over time. These plots show data directly from the Alpine, Irwin, Dry Canyon, and Heise gage records. For the Lyon gage, predicted mean daily discharges were used for the pre-1909 flows. I estimated mean daily flow with published daily gage heights and a regression of published gage height-to-discharge data. Hydrographs for the last two years of the Lyon record were plotted directly as in the other gages. Hydrographs are shown singly or as composites. Curve-fitting information is included in appendix B.

The time series of annual peak discharge, or annual flood series, are plotted from data files compiled from published discharge records. Published instantaneous discharges were used directly. To determine instantaneous annual peak discharge for the Heise record prior to 1914, I regressed instantaneous annual peak dischargeon the highest mean annual discharge corresponding to the remainder of the pre-dam period. A given pair of these variables occurred no more than one day apart — they often occurred on the same day. The complete statistics and plots for this fit are in appendix B. Instantaneous discharge for the Lyon record could not be calculated in the above way due to lack of data.

Flow duration curves show the frequency distribution of mean daily flows. I used the total-period method outlined by Searcy (1959) with a 500 cfs class interval. I constructed pre-dam and post-dam period curves for comparison. Due to the very large data sets (N = 16,802 and N = 12,381, respectively) and file handling convenience, the post-dam period includes the last 34 days of the pre-dam period. The flows during these 34 days are not unusual for the post-dam period, so results should not be noticeably affected.

The flood frequency curves use the highest instantaneous discharge for each year, or annual flood. Two methods were used to create two separate plots. The first is the US Geological Survey (USGS) method (Dalrymple 1960), using Weibull's equation for the plotting position. Although it can be biased (Cunnane 1978), the USGS method is commonly used, and I used it so that comparisons to earlier work in geomorphology and hydrology are possible. Weibull's contribution (1939) is not always clear in the literature. Weibull's equation is :

$$Pe = \frac{m}{N + 1}$$

Where: Pe = probability of an event being exceeded
m = rank, with 1 for the largest flood
N = total number of floods in th series

The plotting position can be either the probability or the recurrence interval. The inverse of the probability is the recurrence interval, (e.g., Pe = 0.02 is the 50 year flood). The recurrence interval is shown on the figures.

The other method uses a plotting position equation derived by Cunnane (1978). Cunnane's equation is less familiar than other equations, and using the previous symbols it is:

$$Pe = \frac{m - 0.4}{N + 0.2}$$

The main problem with Weibull's equation is that it is only unbiased for uniform distributions (Cunnane 1978). Flood frequency distributions are seldom if ever uniform (Reich and Renard 1981). Flood frequency analysis for the Heise annual flood series was approximated using techniques described by Reich and Renard (1981). Only the pre-Palisades Dam flow data is analyzed in detail; several distributions were tried but only the best fitting one is shown. The bankfull and mean annual flood values for the post-dam period are approximated directly from observed ranks.

The primary purpose of flood frequency analysis is prediction of flood magnitude, which is not very relevant under dam-regulated conditions. However, a more accurate description of flood history should result from the more precise, advanced method using the pre-dam data.

The flood control effect due to Palisades reservoir management was determined using the reservoir-inflow data and a regression. The reservoir inflow data closely represents the flow at Irwin as if it was unregulated. I used a regression to convert this unregulated Irwin flow to what unregulated flows would be at Heise. This regression used mean daily flows for Irwin and Heise gages from 1956. The regression output was checked for precision against actual flows at Heise in 1954. Predicted flows are within 10% of a given observed value. Curve-fitting information is included in appendix B.

Sediment load and size – Suspended sediment load data from the Heise station measured sporadically after dam closure was combined with the relationship between velocity and discharge to estimate changes in suspended sediment load. With a fixed water discharge, velocity increases with increases in suspended sediment load (Vanoni 1946; Vanoni and Nomicos 1960). This relationship is most apparent with channels having minimal bedform changes, moderate to high velocities, and larger suspended sediment size (Vanoni and Nomicos 1960). As described in chapter 2, the bed lacks dunes, and this may because of the large sediment size. There are theoretical reasons dunes rarely form if bed material size is larger than about 0.6 mm (Bagnold 1956). The sediment load data measured at Heise gives some insight into suspended sediment size distribution for post-dam flows. Comparing changes in the velocity discharge relationship over time at the Irwin station (just below dam) and at Heise 47 miles downstream give some indication of suspended sediment load recovery and sediment concentration in general. Comparing similar changes during the same time period at the Alpine station serves as a control. Sediment load–to discharge curves over time, or C–Q relations, are constructed and interpreted following Williams (1989).

Channel roughness can also be effected by channel bends (Leopold et al. 1960). However, this effect has probably remained constant during the analysis period. As shown later, the sinuosity of the South Fork has hardly changed, especially near the gages where the velocity-to-discharge relationship was measured. Vegetation in the channel and on the flood plain can also change roughness. However, there is minimal flood plain in the gaged reaches, and little apparent change in flood-plain vegetation since dam closure (figures 39 and 40, p. 98 and 99). There is no precise data on within-channel vegetation, except USGS notes indicate it was present in late summer during the record period.

To better detect changes, only the higher flow magnitudes were used for the relationship. Flows were limited to those above 15,000 cfs for Irwin and Heise, and above 13,000 cfs for Alpine, the latter station having proportionately lower flows. This limitation eliminates the potentially strong leverage effect of the lower flows on curve fitting, and suspended load is quite low below the cut-off value (personal observation).

Curve-fitting techniques were consistent for all data sets. The test for coincidence was based on a single combined model using a grouping variable; this method has more power than the separate line technique (Kleinbaum et al. 1988). The separate lines are shown because the differences are more intuitively obvious than with the single model. The models fit the least square assumptions reasonably well except the Heise 1957 to 1990 curve which had strong and statistically significant serial correlation. The time-corrected model is shown in the paired–plots, but because scales must be consistent, I had to use the uncorrected model to test for coincidence. Curve fitting information is in appendix B.

<u>Channel width</u> – Changes in width were compared for all of the South Fork covered by the two sets of aerial photography (table 3). Most of the canyon reaches are covered, starting near Conant Valley. Also, the width-to-discharge relation at the Irwin and

Heise gages give a more precise and continuous width change measurement, but they only represent areas having straight reaches. The same relation at Dry Canyon and Lyon gives an indication of conditions at these stations for their respective record periods.

Photo-interpreted width determination was based on the channel area of fixed reaches. Reach end-points were defined by permanent near-bank features common to both photo sets such as lone conifers and rock outcrops. Reaches were between 1.24 and 3.59 river–miles long and often included braided and single-channel sub-reaches. Channel area was measured on a digital planimeter to the nearest 0.001 square inches, which represents about 0.2 acres. Repeated measurements varied within about 3 percent for the moderate– to large– sized polygons. Slight scale differences between the photo sets were accounted for.

Depth, velocity, and channel roughness – Changes in the hydraulic geometry exponents for depth and velocity for the various stations and periods indicate channel adjustments in velocity and depth as well as channel roughness. Concomitant changes in width exponents are also included in this analysis.

Slope – Slope as measured in the 1930's is summarized from the river profile surveys, allowing comparisons to un-gaged South Fork reaches as well as general comparisons to other studies. Changes in slope are inferred from changes in bed elevation at gaging stations and sinuosity changes for pre- and post-dam periods. For bed elevation at a station, only periods having a constant cross-section location are compared.

Bed elevations for non ice–effected channels were determined from the USGS discharge measurement notes with the following equation:

$$\text{Bed Elevation} = \text{Datum} + \text{Gage Height} - \text{Mean Depth}$$

Datums for the Alpine, Irwin, and Heise gages are from surveys; the Lyon and Dry Canyon datums were estimated from topographic maps. The few changes in datum are accounted for, and there were no associated changes in cross–section location. An example of bed elevation calculations is included in appendix C.

Channel sinuosity for a given stream reach is the along-channel distance of the reach divided by the straight-line reach distance. There are several ways to measure sinuosity; I used Richards (1982) method which is more appropriate for braided streams, along with a slight modification to account for valley meanders as presented in Graf (1988). These two methods can be summarized as follows:

As outlined by Richards (1982), total sinuosity is the total channel length for all channels (main and anabranches) in a given reach divided by the straight-line–reach length. Along-channel length was measured along a channel's center line. I included the same wetted channels use in width measurement, except the branches with inlets blocked by sediment.

In Graf's method, the hydraulic sinuosity index is the percentage of total sinuosity due to hydraulic forces. Valley sinuosity was calculated using a weighted average of the valley sinuosities for two main sections which are separated by a major inflection point near Gormer Canyon.

$$HSI = [100\%(TS - VS)]/(TS - 1)$$

where:

HSI = hydraulic sinuosity index
TS = total sinuosity
VS = valley sinuosity

Hydraulic geometry – Channel width, depth, velocity, and suspended sediment load each vary with discharge. The relations between discharge as an independent variable and the four response variables is termed hydraulic geometry (Leopold and Maddock 1953). There are two main approaches to hydraulic geometry: at-a-station and downstream. The former uses data from a given station to examine the relations at that station. The latter, or downstream, uses the relation from several stations along a river course, and the changes in the response variables are related to a discharge of fixed frequency respective to each station. Each approach has its purposes. At-a-station hydraulic geometry lends much insight into channel stability, roughness, and sediment dynamics for the station and other sections represented by the station. Downstream hydraulic geometry gives insight into the spatial changes along the channel for the same factors.

The water development history of the Snake River greatly complicates the discharge frequency of many stations, so the downstream hydraulic geometry is not very meaningful. Therefore, I only used the at–a–station approach. A more detailed explanation of my methodology and relation to other studies is included near the end of this chapter.

For now, it is sufficient to say that I used ordinary least squares regression techniques for curve fitting with an emphasis on the slope parameter, which typifies hydraulic geometry studies in general. My analysis includes the usual width–, depth–, and velocity–to–discharge relations. Depth and velocity values are means for the cross-section during observation. I used the separate model approach (Kleinbaum et al. 1988) to detect shifts across periods for a given station. I accounted for serial correlation, and used several model formulations to find the most parsimonious model.

The same exact data sets were used for the bed elevation change analysis as for hydraulic geometry. As mentioned earlier, I included only non–ice–effected channel observations. There were also a few unusual observations that I changed using common sense and the fact that any one variable can be checked using the other variables, the cross–sectional area, or the discharge determined from gage height. Records with a missing value (usually width) were not included. The observations made during dam closure were not included because the measurement trench (see chapter 2) was not a natural channel. Deletions and changes are noted on the USGS data sheet copies on file at the University of Montana. Total non-inclusions and changes amounted to 135 out of

1416 total records, or about 10%. The great majority of this percentage is due to ice-effects. I changed less than 1% of the observations, and only if the value was clearly a mistake in original data recording. Outliers remaining after curve fitting were not removed.

Gaging station descriptions – Because so much data is drawn from the gaging stations, a description of the physical characteristics and history is useful for interpretation of the data. I have visited all the existing cross-sections. I found a cable remnant of the Dry Canyon gage, and know the general location (within a few channel widths) for the Lyon gage which is based on the published description.

All of these gage cross-sections are on straight reaches and have cobble beds. Current meter measurements are done from cables. Staff gages were read before 1913, after which water–stage recorders were installed. Bank characteristics and stream–side vegetation varies and this is summarized below. Left or right bank references are for downstream views.

The Alpine cross-section's left bank is steep colluvium while the right bank is the 10–foot terrace scarp which is steep. Many of the reaches above and below the gage are dominated by bed rock. The stream-side vegetation is mainly coniferous. The gage is about 9 river miles above the reservoir at full pool.

At Irwin, both banks are formed by the 10–foot terrace, which is somewhat lower and less steep than at Alpine. Scattered cottonwoods line the terrace scarp while the tread is dominated by steppe. The gage is located about 1.4 miles below the Palisades Dam, and has been at this location since 1950.

According to the published description for the Lyon gage, the right bank is high and steep. The left bank is overflowed and some of the flow bypassed the gage through a slough at very high stages. During its measurement history, the channel had a gravel bed, and it still does today. The right canyon wall is volcanic while the left is conglomerate. There was probably some alluvium bounding the channel on one or both sides. A photo of the chain gage shows sandbar willow (*Salix exigua*) nearby, and what appears to be riparian vegetation on the right bank, but the background is out of focus. The gage was moved in 1904, but the cross-section (ferry cable) was not..

The Dry Canyon cross-section best represents the cottonwood–dominated riparian area. The 1–foot terrace, which supports old-growth cottonwoods, forms the left bank. The right bank is colluvial basalt. Today's gaged reach is similar to the reach as measured in the 1930's based on historic photography from 1932 and 1941. The channel bend upstream of the gage has shifted, but there is no noticeable change at the cross–section.

The Heise gage has the longest measurement period but it is also the most complicated. The cross–section location was moved several times. Differing cross-section location can affect results, especially for width (Knighton 1975); hence the more limited use of the entire record. The control was effected by the Anderson Dam, a low rock crib structure that helped divert water into the Anderson canal. The dam washed out in the large floods of 1917 and 1918. Very low remnants of the dam still exist today. Periodic maintenance by a canal company effects the cross–section periodically when a low gravel bar is bulldozed out of the channel, temporarily decreasing the mean bed elevation. The USGS hydrographers noted this activity as well as the canal company in later years, and I used this information to separate natural from unnatural changes in bed elevation.

TheHeise cross–section location has not changed since 1953, perhaps before. The left bank is formed by the constructed berm of the Riley Ditch, and the right bank is a narrow flood plain area dominated by willow. The cross–section is just downstream from an outcrop of basalt which appears to be part of a strath terrace. The terrace tread is farmed, as well as the loess–covered bench above the Riley Ditch.

RESULTS

Flow regime – The amount and timing of water flowing past the Heise gage for the pre– and post–dam periods is summarized in table 4.

Table 4. Summary of discharge at the Heise gage for the pre– and post– Palisades dam periods.

Period	Mean Annual Discharge	Mean Annual Flood	Bankfull Discharge	Minimum MDF	Maximum MDF
Pre–dam (1911 to 1956)	6887	26445	21677	1500	51600
Post–dam (1957 to 1990)	7126	20300	18600	460	26700

Explanation: All discharges in cubic feet per second (cfs). MDF = mean daily flow
Bankfull discharge is the 1.5–year flood, mean annual flood is the 2.33–year flood, based on the standard Weibull formula.

The total flow history for the two periods is shown in the composite hydrographs in figure 7. The modal pattern as well as anomalies are visible at a glance.

The cumulative probabilities for the various flow magnitude classes are shown in the flow duration curve (figure 8). Essentially, this curve is similar to a flood frequency curve, except it includes all of the flows for every day in the record rather than just the annual peaks, and the probability is on a daily rather than yearly basis.

The time order of yearly maximum peak flows, or annual floods are shown in figure 9. The Lyon gage values are mean daily flow while the Heise values are instantaneous (15 minute interval). The two gages are still comparable, for there is little inflow between the gages (see figure 1). Also, maximum mean daily flows are about 1 percent less than corresponding instantaneous flows except for year 1927, which had an unusual flood called Gros Ventre.

The Gros Ventre flood occurred in May of 1927, when the natural dam impounding the Gros Ventre River suddenly washed out. This event shows up in figure 7 as a very sharp narrow peak over the 'a' in May, with a mean daily flow of 36,600 cfs; the instantaneous discharge was 60,000 cfs. This is the highest flow in the USGS record for the Heise gage. However, Army Corp of Engineer (COE) records indicate a flood of about 65,000 cfs in early June 1894. The USGS record for Heise, published after 1970, refers to the COE record for the 1894 flood only.

The flood frequency distributions for the pre-Palisades dam period are shown in figure 10. The log–normal distribution, which is shown, best fit the data. For any distribution that I tried, the Weibull or Cunnane formulas only affected the recurrence-interval value for a given flood magnitude, not the shape of the data scatter. This consistency is evident in figure 10.

Flood control effect due to Palisades reservoir management is shown in figure 11. In general, the flood-peak reduction depends on how much the unregulated flow exceeds about 25,000 cfs. Flood control guidelines call for flows not to exceed 20,000 cfs, or in the case of unusually large and unanticipated reservoir inflows, peaks are not to exceed 30,000 cfs at Heise (Van Den Berg 1990 pers. comm.).

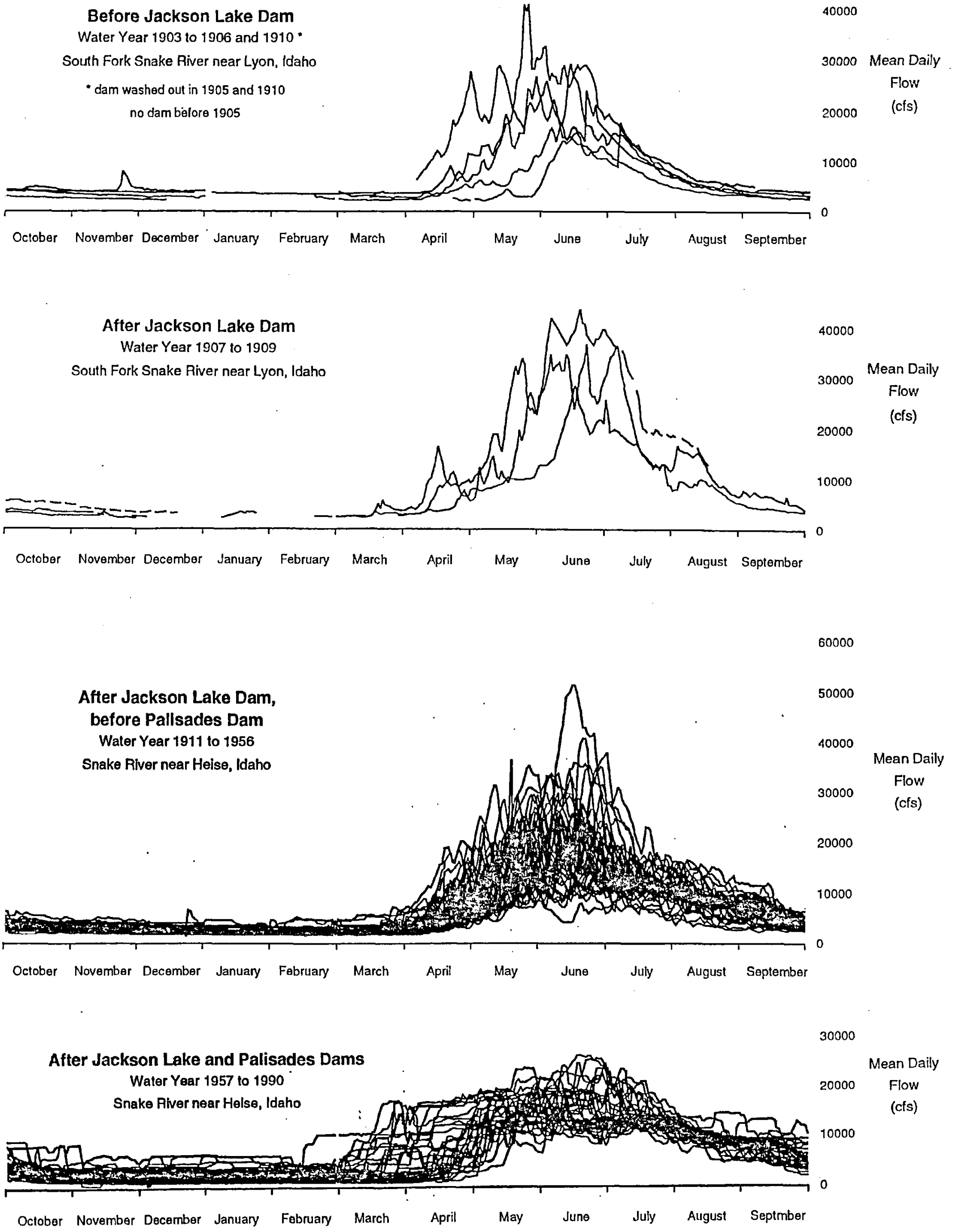


Figure 7. Composite annual hydrographs for pre- and post-dam periods. All graphs plotted on same scale

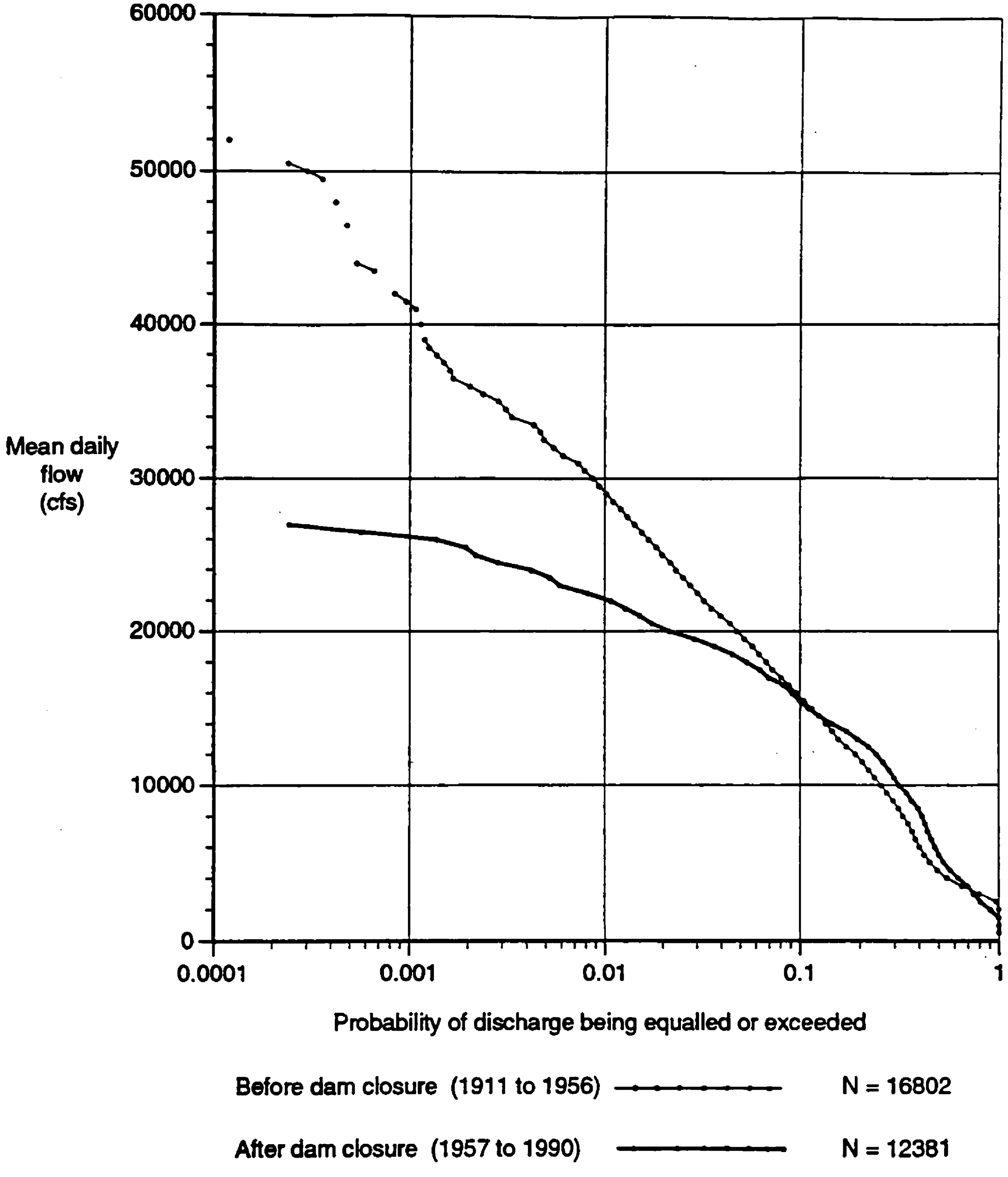


Figure 8. Flow duration curve for the Heise gage record. Points show 500 cfs–class boundaries; gaps show no observed flows within a class.

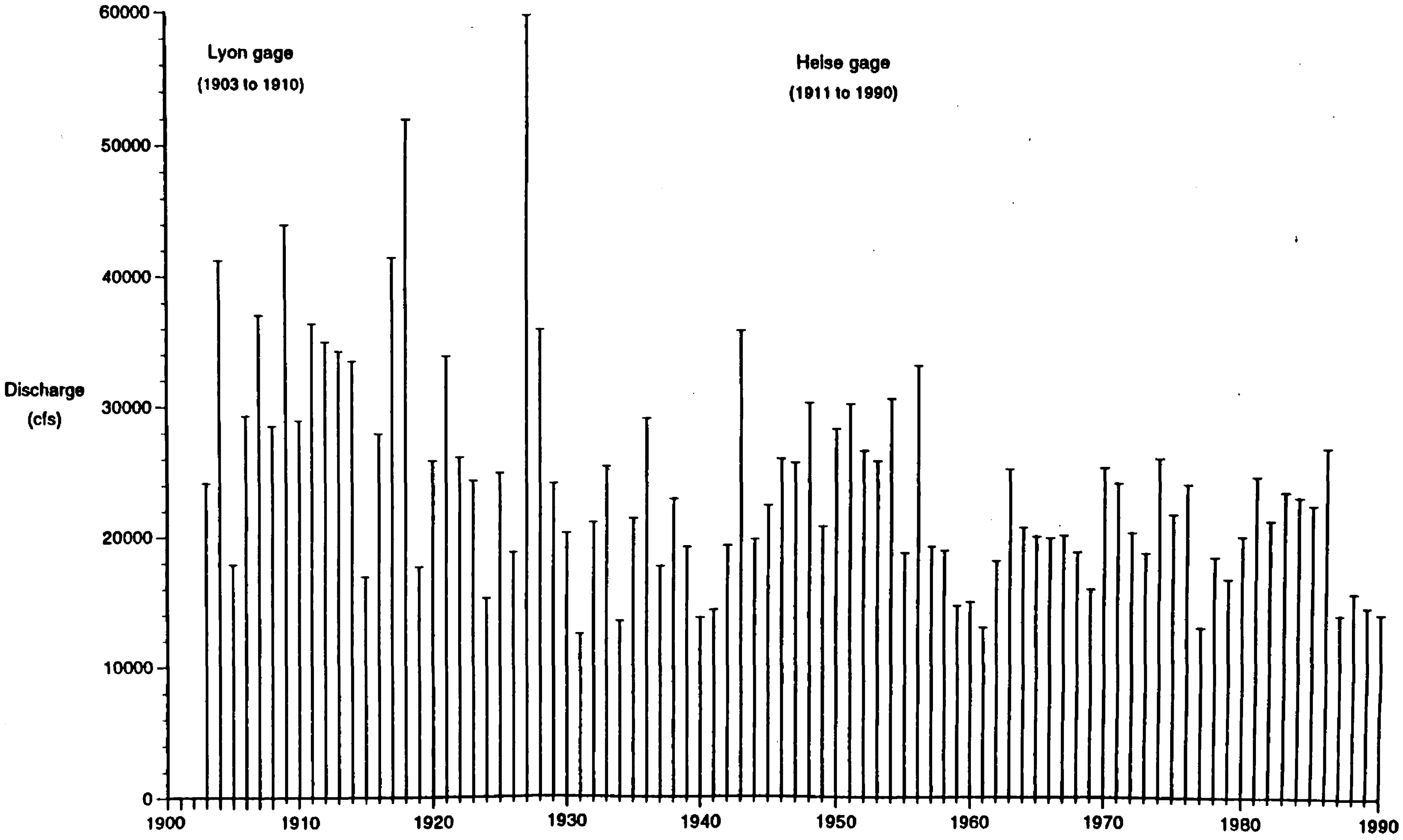


Figure 9. Time series of annual floods at the Lyon and Heise gages.

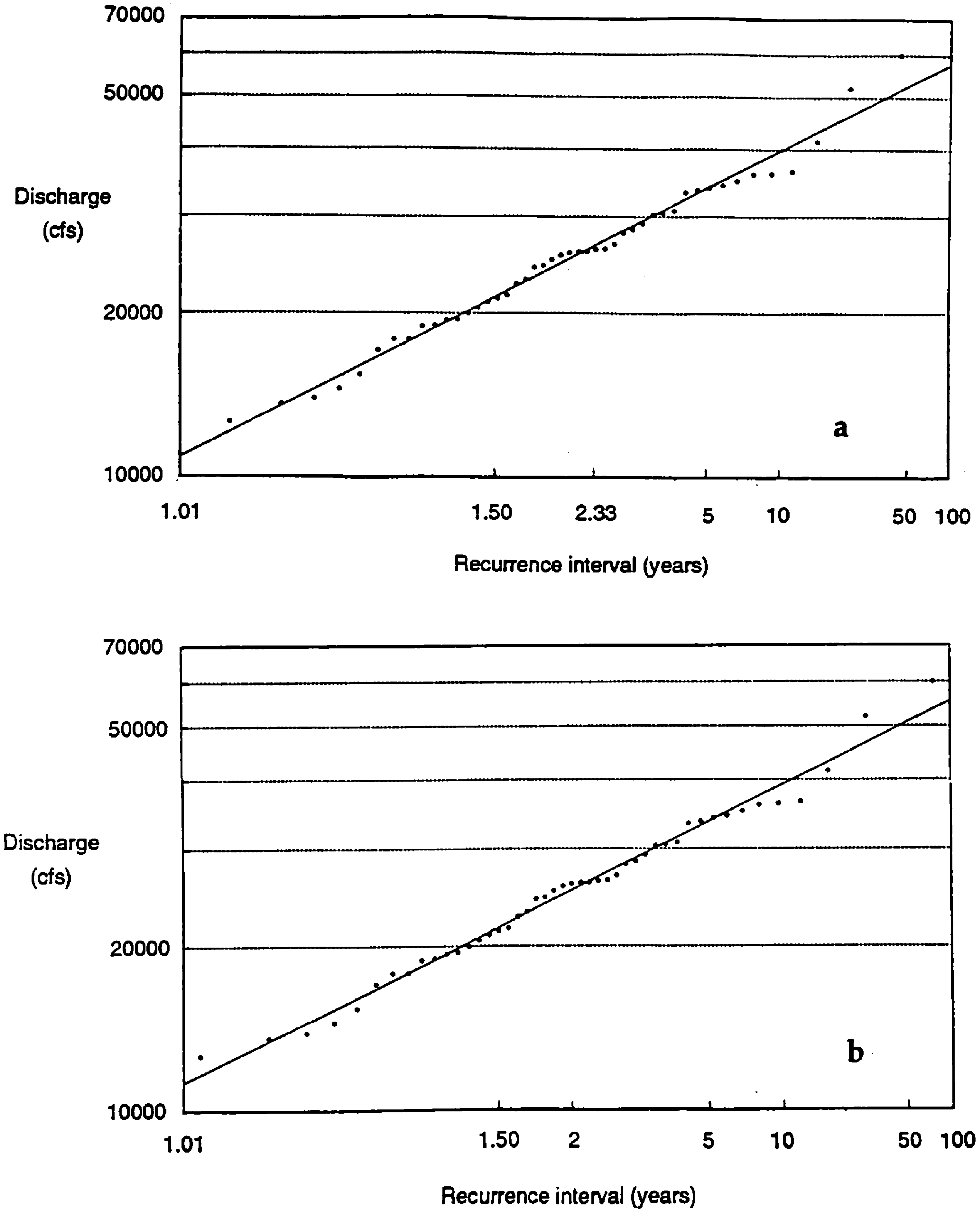


Figure 10. Annual flood frequency for the pre–Palisades dam period (1910 to 1956) at the Snake River near Heise, Idaho. Empirical probability determined with the Weibull (a) or Cunnane (b) formula. Both plots are log–normal.

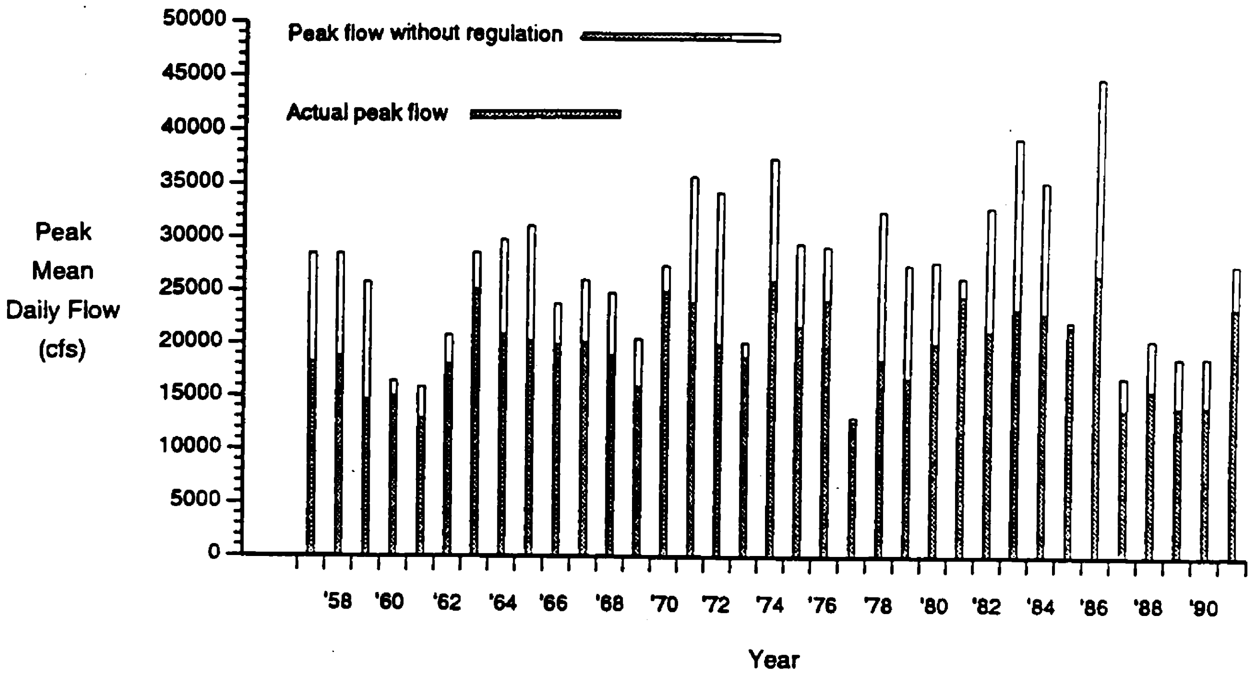


Figure 11. Flood control effect of Palisades dam at Heise.

Sediment load and size – With the closure of Palisades Dam, the sediment regime immediately below the dam changed from the pre-dam condition. No analysis is required to establish this change; nearly all sediment (except colloidal sized) that would naturally come into the the reach immediately below the dam is trapped by the still waters of the reservoir, which has never been empty since dam closure. The purpose of the analysis is to determine the amount of change in sediment regime due to reservoir trapping and predict changes.

Various suspended sediment load relations are shown in figures 12 to 14, starting with the basic total suspended sediment load-to-discharge relation. Suspended sediment concentration is separated into particles larger than very fine sand (> 0.062 mm) and silt and clay, and these separates are related to discharge in figure 13. The timing of discharge and suspended sediment concentration for years with the most complete record are shown in figure 14, as well as the corresponding concentration-to-discharge relations. The strong outlier in 1982 occurred on December 30; the unusually high concentration on a mid-winter day is difficult to explain. Without this outlier, the concentration-to-discharge slope would be similar to the other slopes.

Sediment relations are typically quite scattered, and the considerable scatter in the Heise data may be partly due to local influx of fine sediments from cropland erosion, which would be largely silt and clay. However, there is still much scatter in the suspended-sand-to-discharge relation shown in figure 13, suggesting that much of the variance is inherent to the river itself.

The final set of relations shown in figure 15 are a surrogate for suspended sediment load-to-discharge, and the longer record allows some inference to the pre-dam sediment regime. For a given discharge, velocity changes with a change in suspended sediment load. If there is a change in the relation, the slope or intercept parameters will change — either solely or in combination. The test for coincidence for the Alpine and Heise pairs were not statistically significant ($p > .10$). Although the Irwin pair is the most visually coincident, the coincidence test was statistically significant ($p = .0271$). The F-test used to test coincidence is sensitive to violations of assumptions, especially with disparate sample sizes. However, the Irwin pair fit the least square assumptions well, and sample sizes were similar; curve-fitting information is included in appendix B. Importantly, the direction of change is opposite to that expected with a supposed reduction in sediment load. Sediment load effects on viscosity are included later in relation to channel roughness.

There is no direct data for bed load. The pebble-count data presented in chapter 2 and appendix C gives an indication of typical sizes extant in the channel and flood plain, but the dynamics of specific particle sizes are empirically unknown. However, bed material still moves. The most direct evidence for this is the persistent reoccurrence of a gravel bar at Heise that is periodically bulldozed away, and bed scour and fill at the gaging stations. The latter is information is presented in the section on slope.

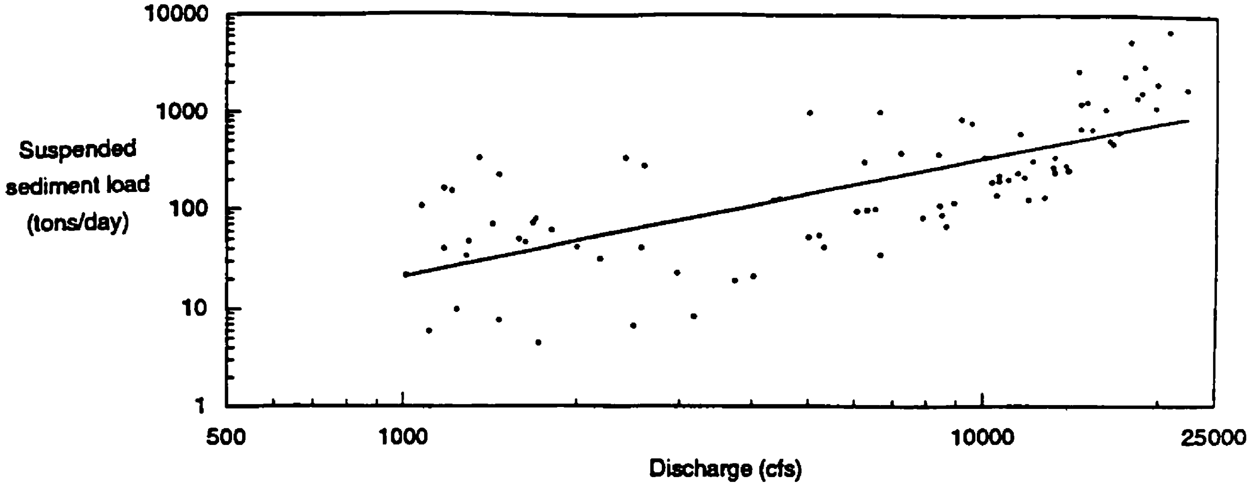


Figure 12. Relation of suspended sediment load to discharge at Heise for the period 1978 to 1992

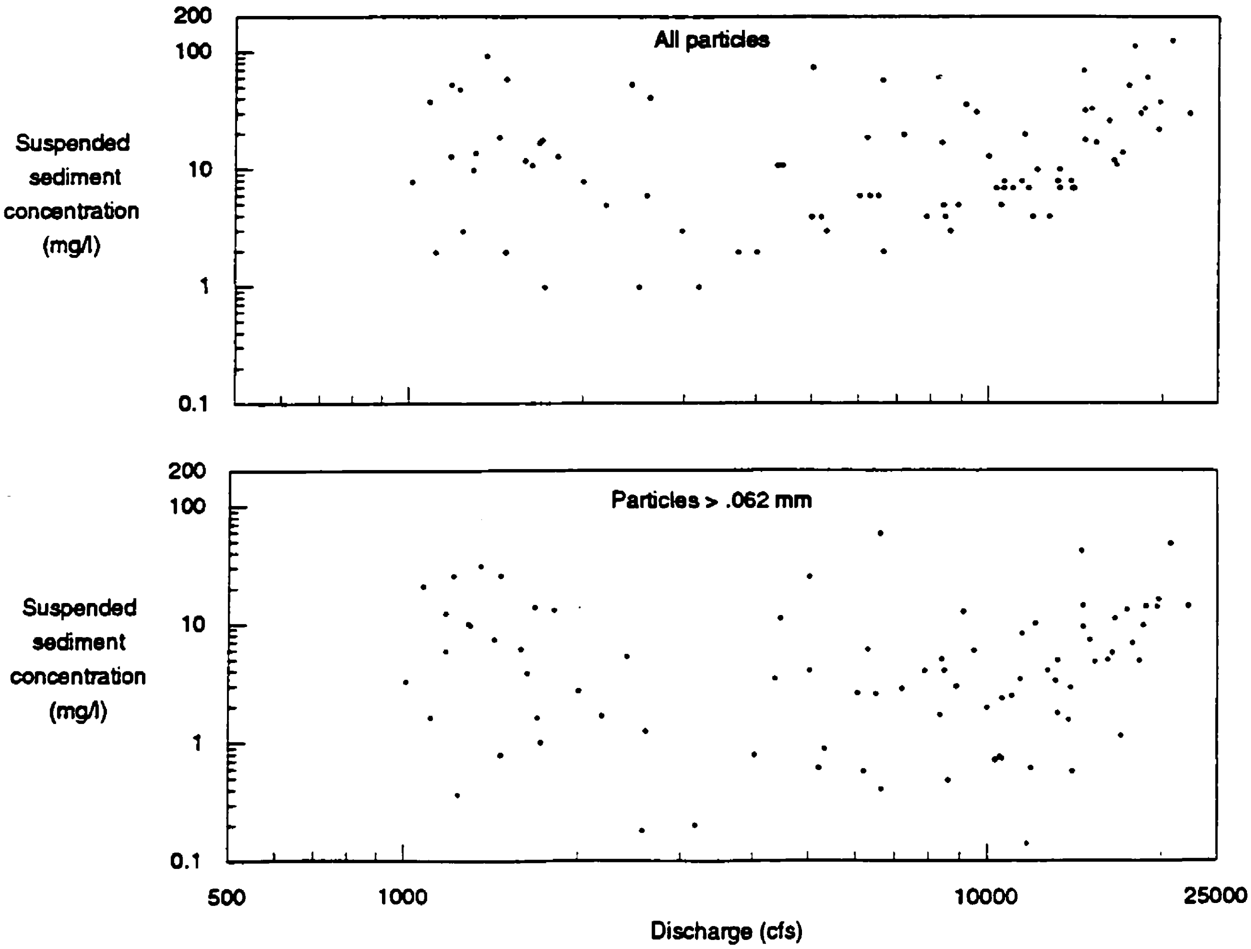
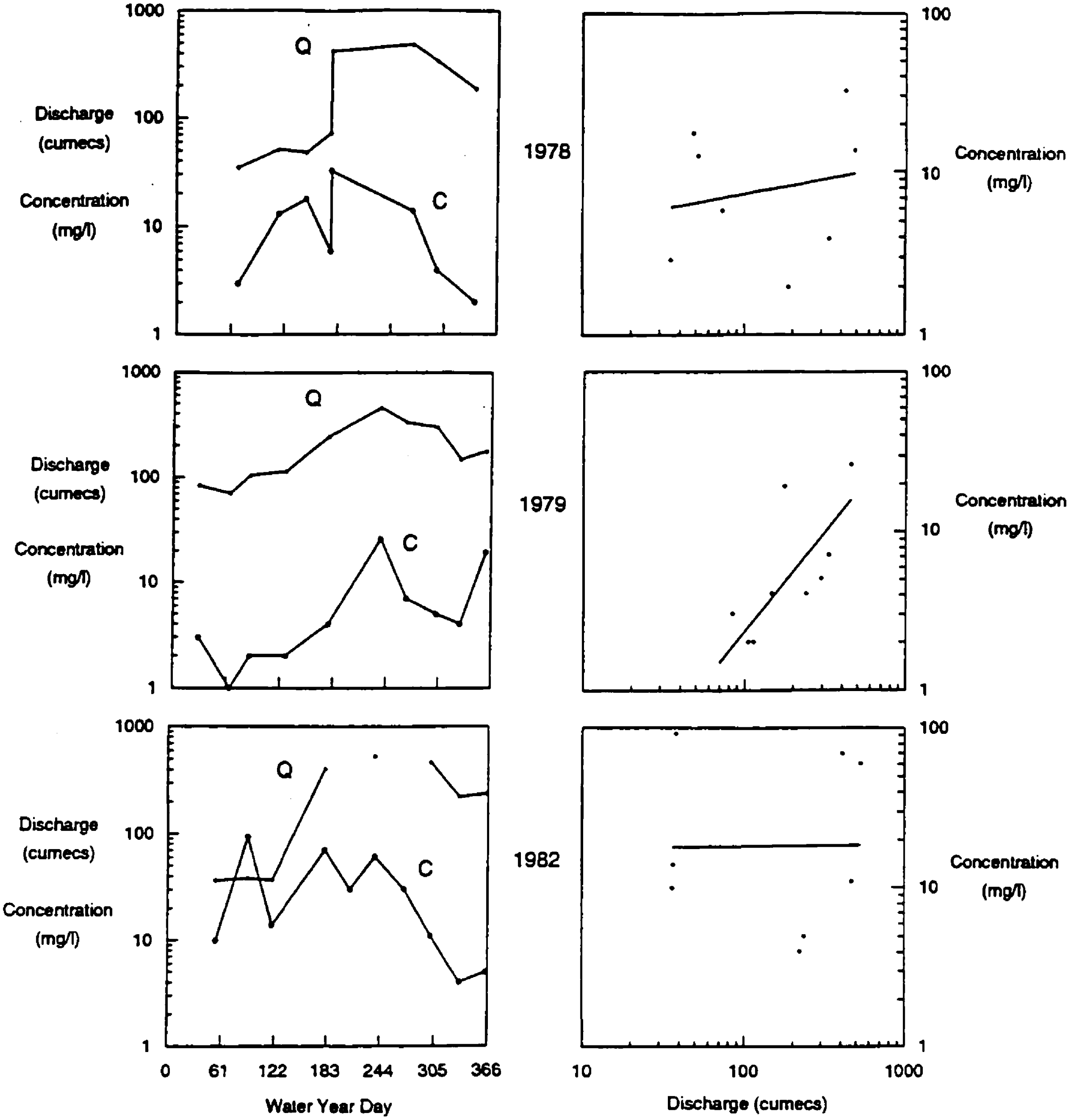


Figure 13. Relation of suspended sediment concentration to discharge at Heise for the period 1978 to 1992.



Note: Discharge (Q) units are cubic meter per second (cumecs).

Figure 14. Discharge and suspended sediment concentration over time and corresponding concentration-to-discharge relations.

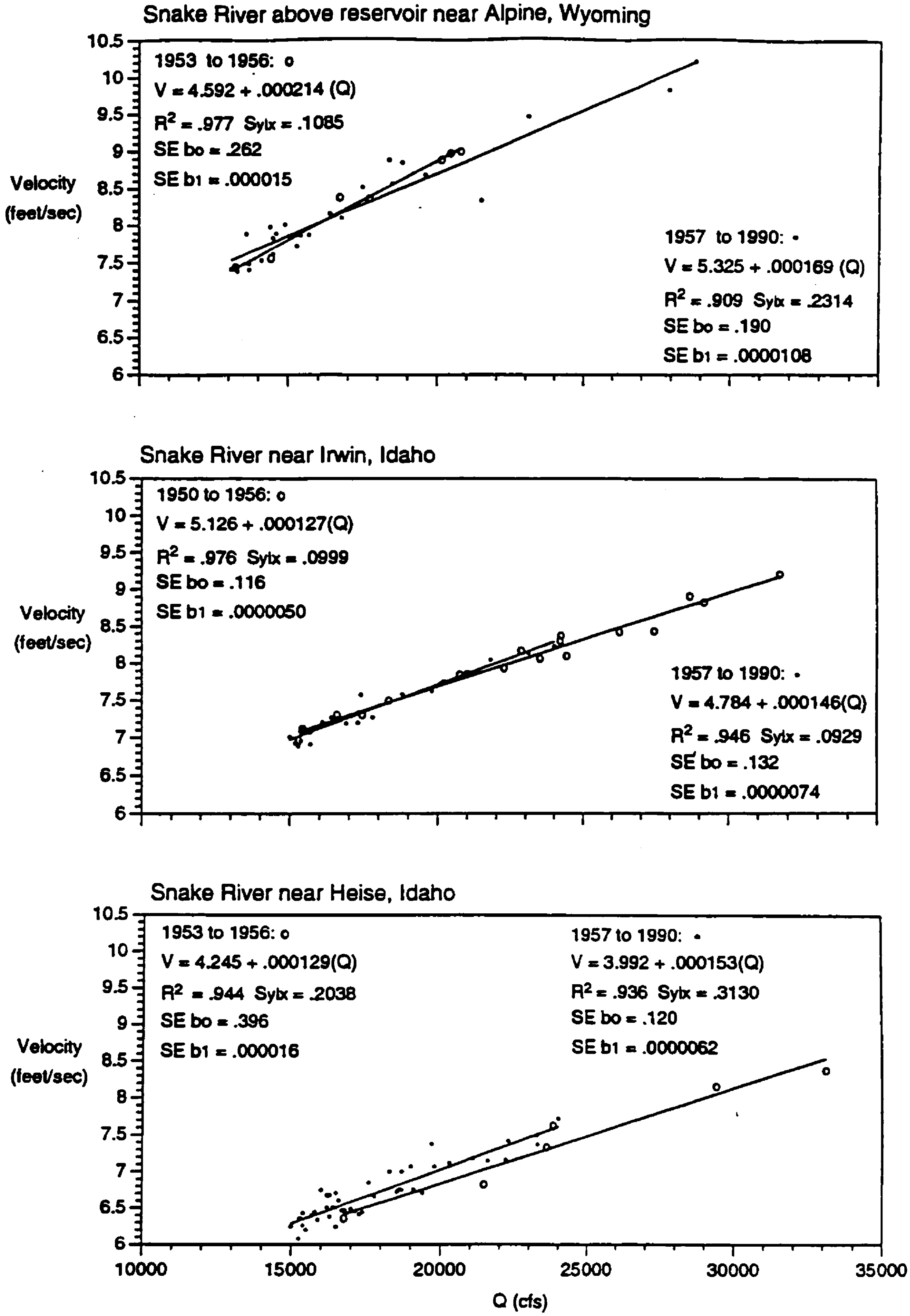


Figure 15. Relation of the higher velocities-to-discharge for the Alpine, Irwin, and Heise gages for pre– and post– dam periods.

Width, depth and velocity at gaging stations – These three parameters interact and adjust to changes in discharge and sediment regime. The changes in width, depth, or velocity as discharge changes allows inference into other factors such as channel roughness and competence in moving bed particles. The empirical relations between width, depth, and velocity to discharge is known as hydraulic geometry. The following equational nomenclature allows some insight into the hydraulic geometry results. Symbols and equations are those originally presented by Leopold and Maddock (1953), which have become standards.

w = water surface width

d = mean depth

v = mean velocity

Q = discharge

Mean depth is defined as the quotient of A/w, where A = cross-sectional area. Mean velocity can be defined as the quotient Q/A. Q is determined from several subsections, each with its own A and v, where v is the mean of 2 or 3 current meter observations (Corbett 1943).

The three equatons for hydraulic geometry are:

$$w = aQ^b$$

$$d = c\,Q^f$$

$$v = kQ^m$$

where a, c, k, b, f, and m are constants. The 3 equations are power functions, and b, f, and m represent the slope of the lines for the respective relations between width, depth, and velocity to discharge. The constants a, c, and k are the respective values of width, depth, and velocity at $Q = 1$.

Because $Q = \mathrm{A} \times v$, and $Q = w \times d \times v$, and $Q = aQ^b \times c\,Q^f \times kQ^m$,

$$Q = ackQ^{b+f+m}$$

so $$b + f + m = 1$$

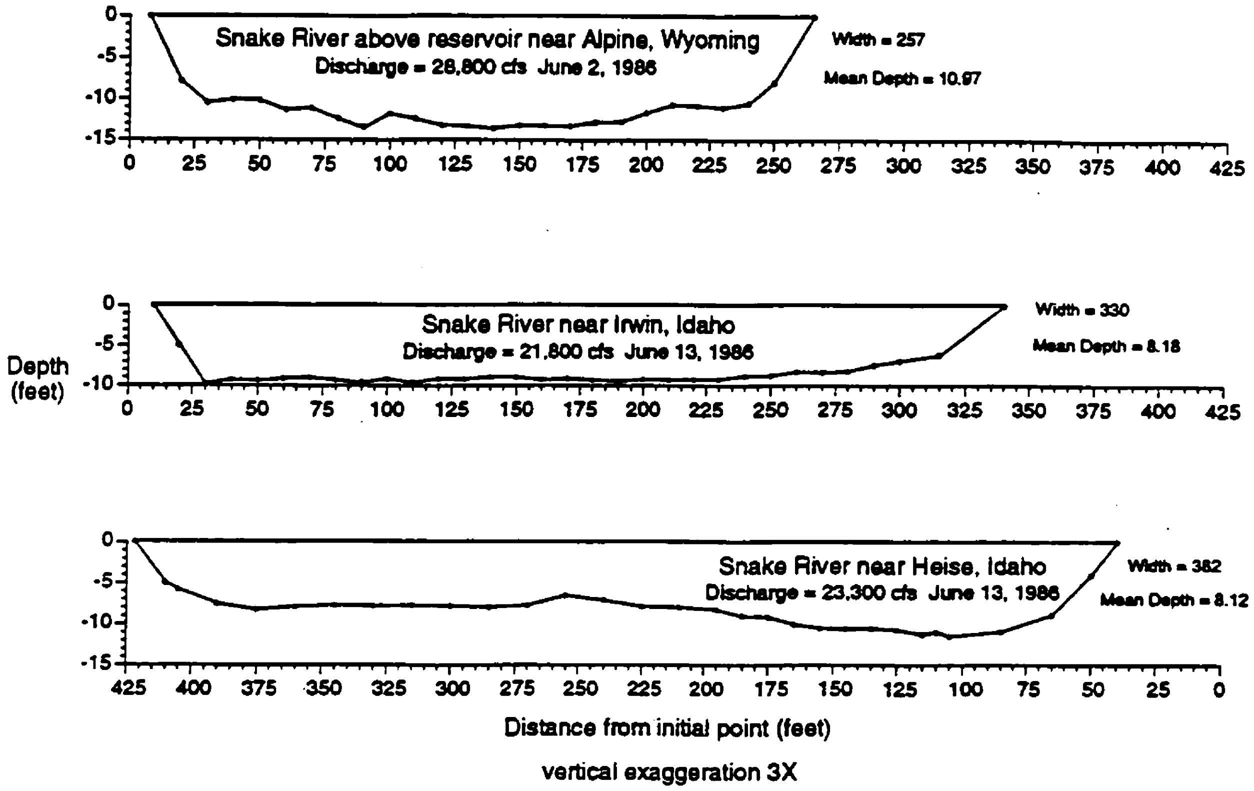
and $$a \times c \times k = 1$$

The continuity between the 2 sets of constants allows a cross-check on the precision of slope coefficients and intercepts. Each set should equal 1, using summation for slopes and multiplication for the intercepts. A summary of the constants for each station and period analyzed as well as the validity checks is presented in table 5. Stations are presented in downstream order. The slope coefficients are in bold type because of their greater importance in interpreting stream characteristics.

Table 5. Hydraulic geometry constants by gaging station and period.

Station /	Width		Depth		Velocity		Product	Sum
Period	*a*	*b*	*c*	*f*	*k*	*m*	*a*x*b*x*c*	*b*+*f*+*m*
Alpine:								
1953 to 1956	162.66	**.044**	.096	**.456**	.064	**.500**	.999	1.000
1957 to 1990	161.08	**.045**	.093	**.459**	.067	**.495**	1.003	0.999
Irwin:								
1950 to 1956	164.75	**.075**	.035	**.540**	.175	**.382**	1.009	.997
1957 to 1990	153.08	**.084**	.033	**.548**	.202	**.367**	1.020	0.999
Lyon:								
1904 to 1908	118.19	**.095**	.864	**.230**	.010	**.675**	1.021	1.000
1909 to 1910	145.53	**.071**	.976	**.230**	.007	**.701**	.994	1.002
Dry Canyon:								
1934 to 1936	146.28	**.092**	.070	**.470**	.088	**.450**	.901	1.012
Heise:								
1934 to 1936	260.64	**.044**	.143	**.405**	.028	**.548**	1.044	.997
1953 to 1956	265.28	**.042**	.038	**.530**	.098	**.430**	.988	1.005
1957 to 1990	149.82	**.100**	.074	**.458**	.090	**.442**	.998	1.000

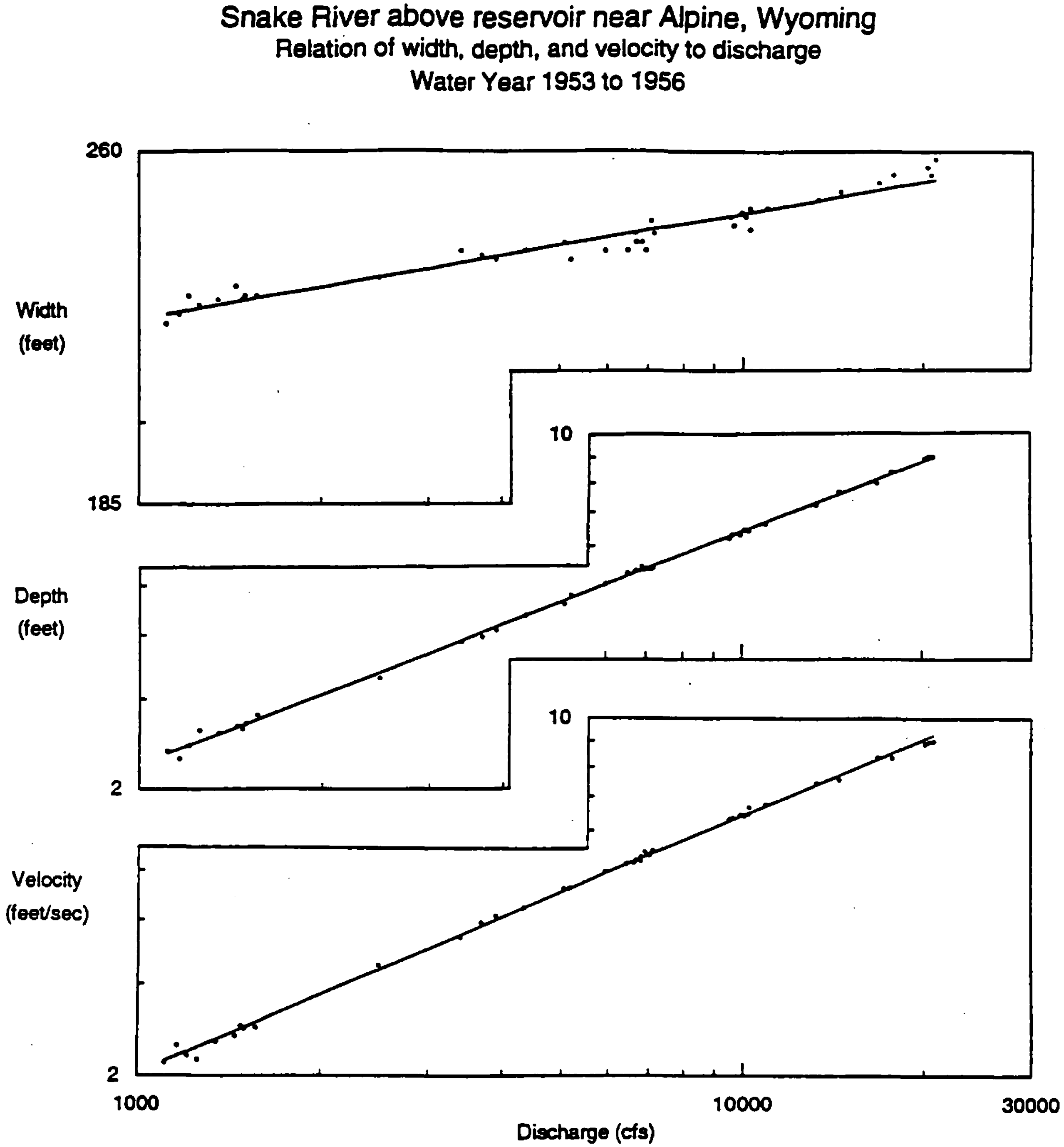
Figure 16 shows the channel shape at the gage cross–sections during the highest measured flows, which are near bankfull. The respective width-to-depth ratios for the Alpine, Irwin, and Heise stations are 23, 40, and 47. Plots are on the same scale.



Note: all views are downstream; Heise width values are reversed because initial point is on right bank

Figure 16. Gaging station cross-sections at high flows.

Figures 17 to 25 are the hydraulic geometry scatter plots and regression fits for the stations and periods shown in table 5. The constant values are shown in the equations. There was serial correlation in many data sets and the constants are from time-corrected regressions. Although the plotted line is based on uncorrected data, differences in constant values from corrected regressions were very slight except for at the Lyon gage during 1909 to 1910. The effect of serial correlation on regression coefficients is discussed later. Plot sets for a given station are on a common scale.

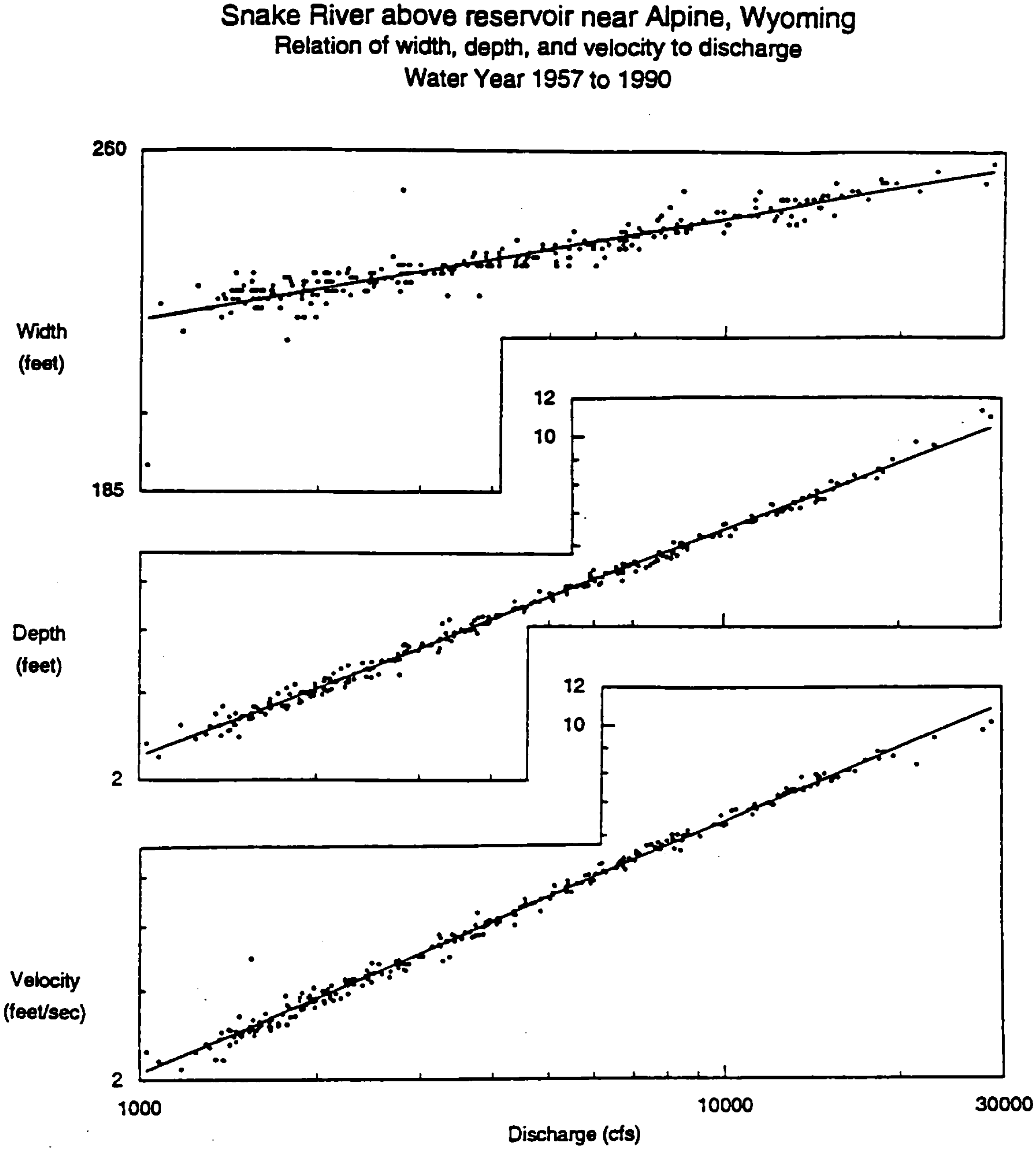


$$w = 162.662Q^{.044}$$

$$d = .096Q^{.456}$$

$$v = .064Q^{.500}$$

Figure 17. Hydraulic geometry at the Alpine gaging station during 1953 to 1956.

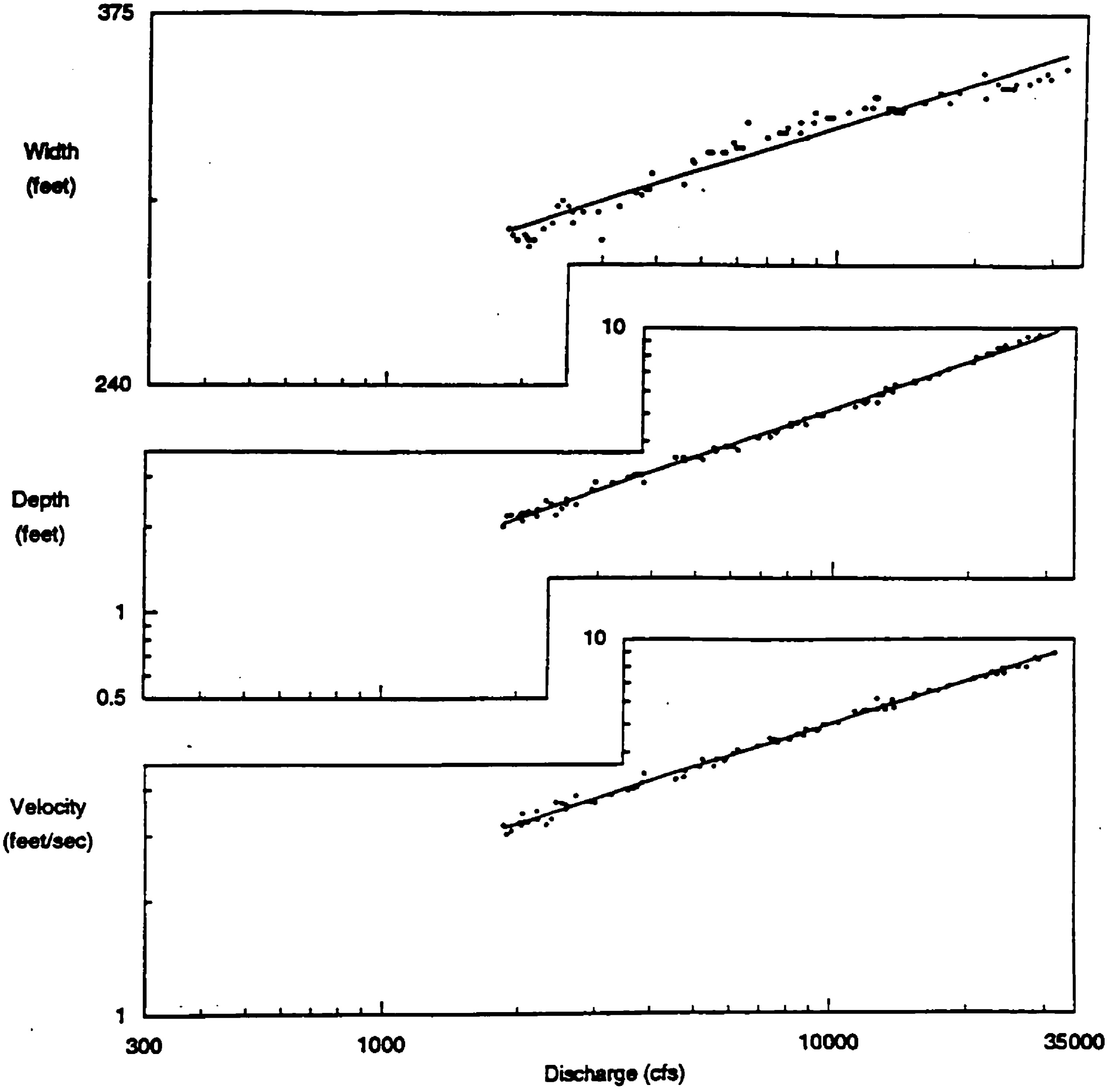


$$w = 161.08Q^{.045}$$

$$d = .093Q^{.459}$$

$$v = .067Q^{.495}$$

Figure 18. Hydraulic geometry at the Alpine gaging station during 1957 to 1990.



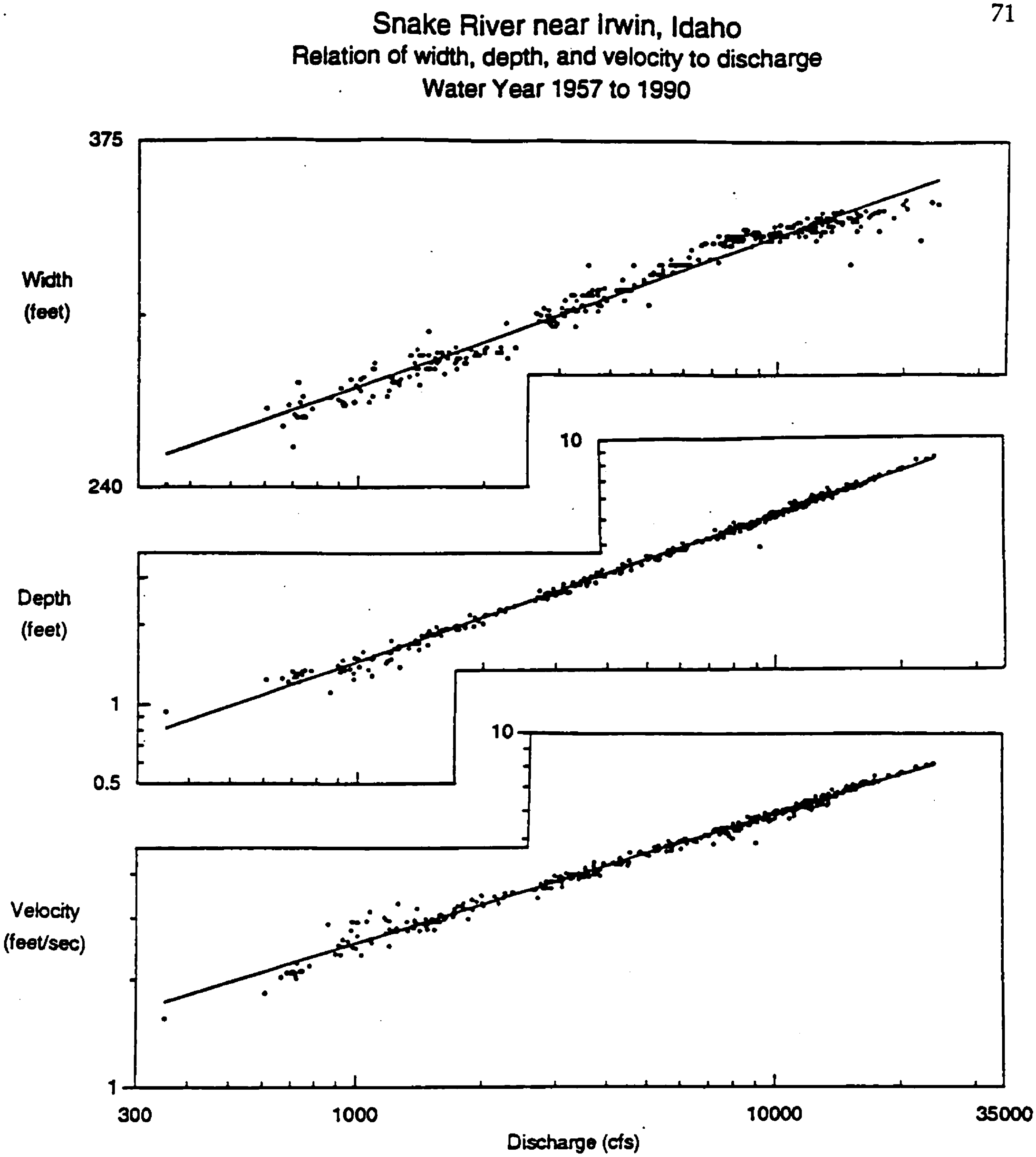
Snake River near Irwin, Idaho
Relation of width, depth, and velocity to discharge
Water Year 1950 to 1956

$$w = 164.75Q^{.075}$$

$$d = .035Q^{.540}$$

$$v = .175Q^{.382}$$

Figure 19. Hydraulic geometry at the Irwin gaging station during 1950 to 1956.

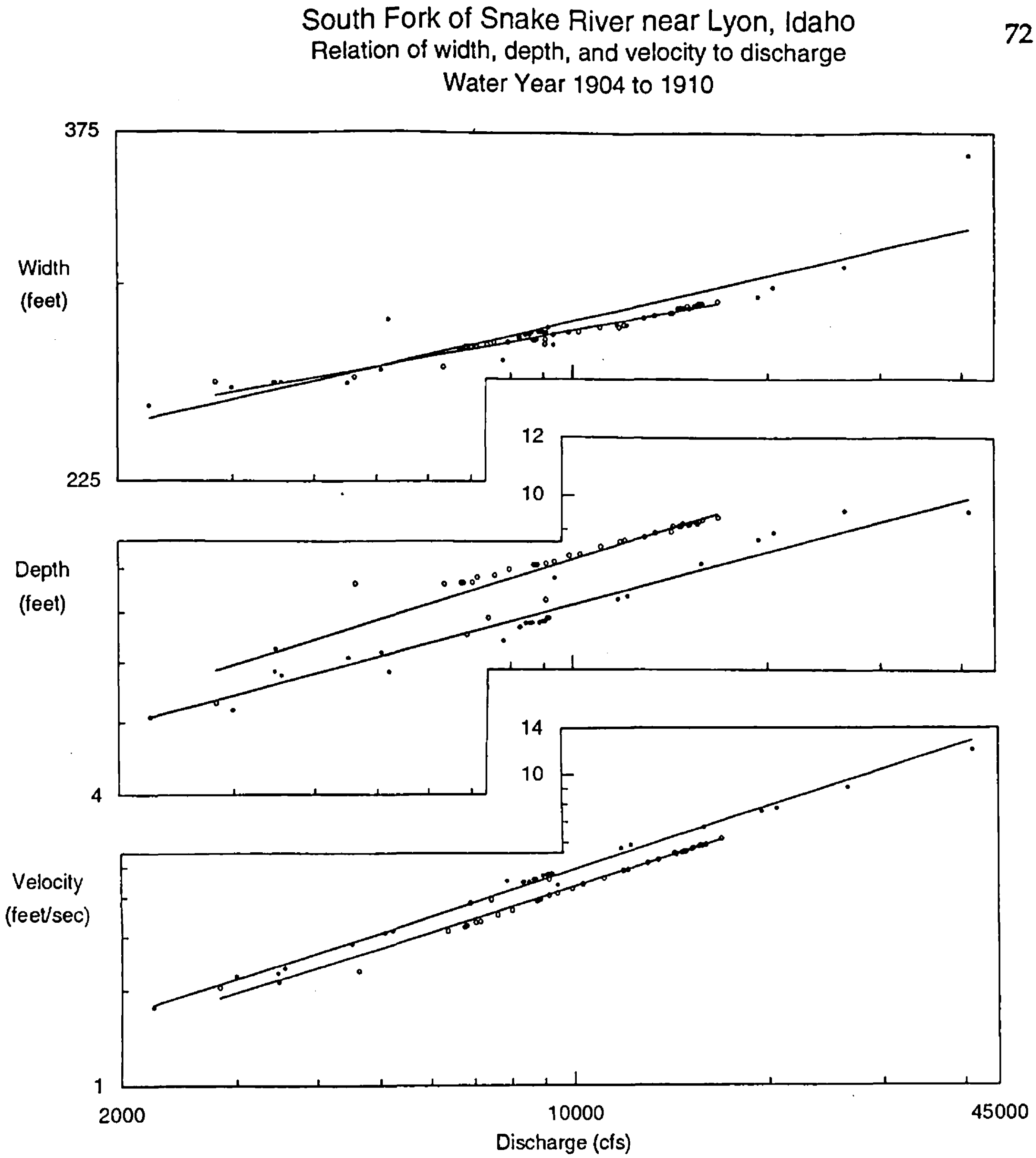


$$w = 153.08Q^{.084}$$

$$d = .033Q^{.548}$$

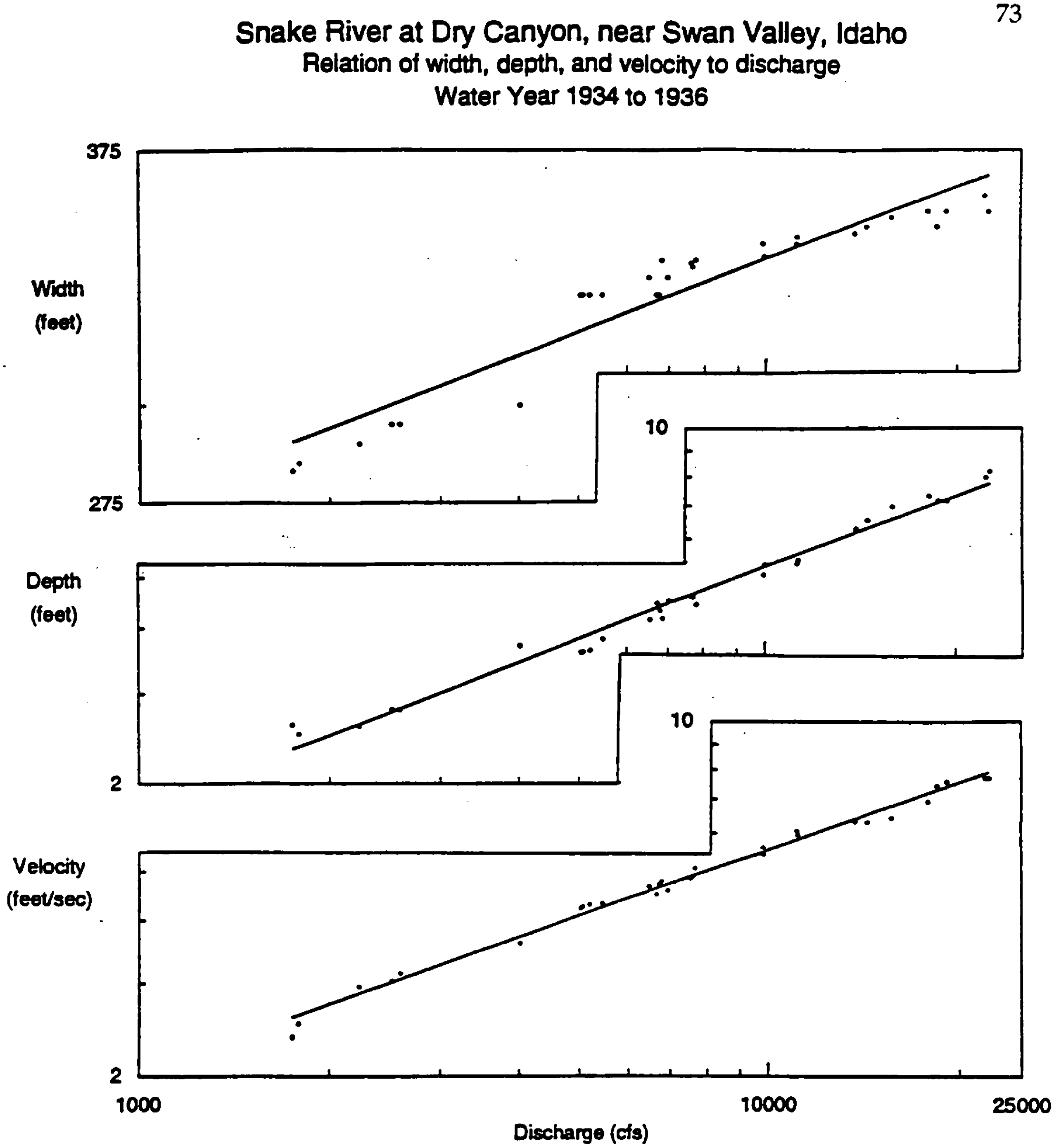
$$v = .202Q^{.367}$$

Figure 20. Hydraulic geometry at the Irwin gaging station during 1957 to 1990.



1904 to 1908 •	1909 to 1910 ○
$w = 118.19Q^{.095}$	$w = 145.53Q^{.071}$
$d = .864Q^{.230}$	$d = .976Q^{.230}$
$v = .010Q^{.675}$	$v = .007Q^{.701}$

Figure 21. Hydraulic geometry at the Lyon gaging station during 1904 to 1910.

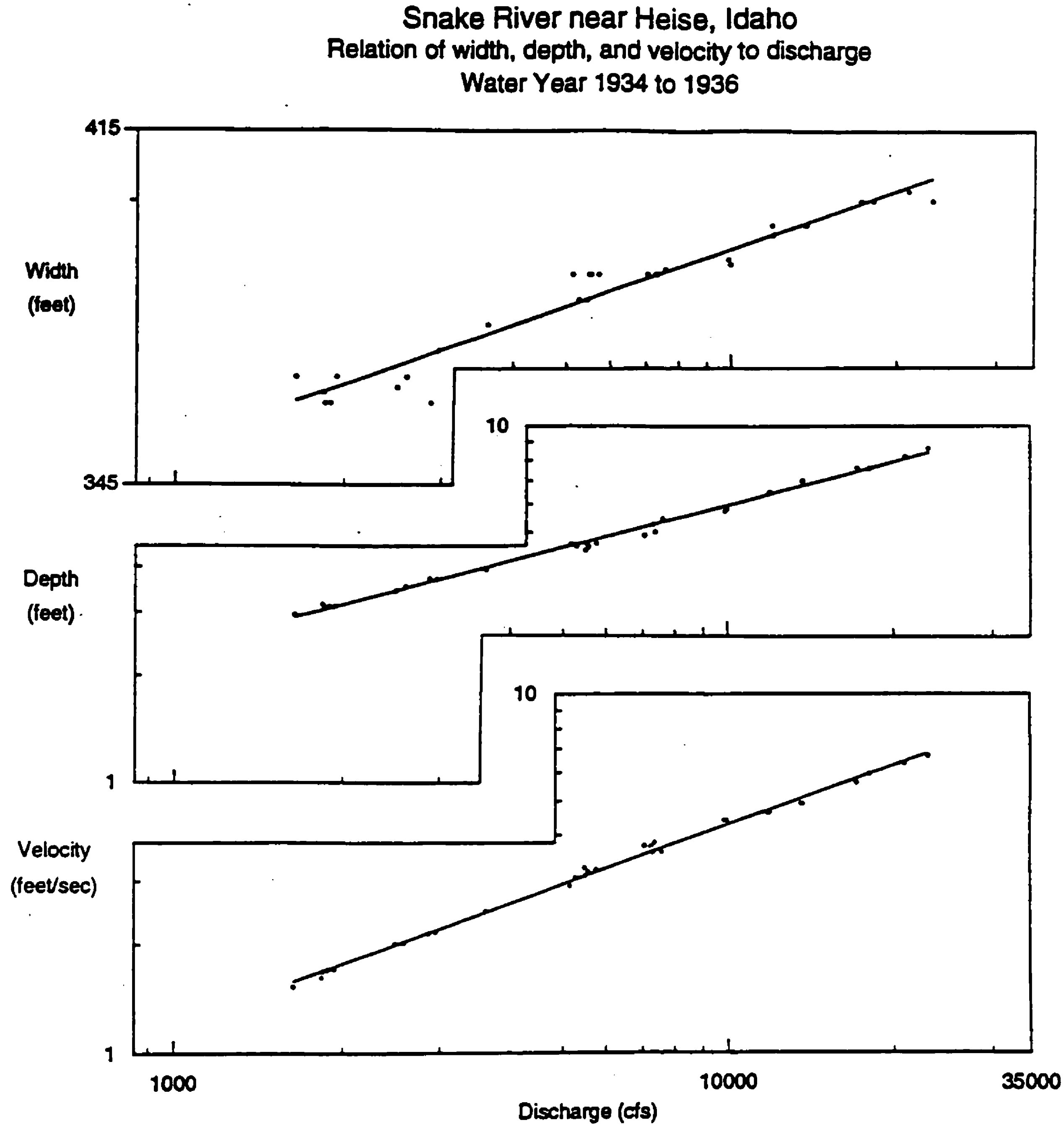


$$w = 146.28Q^{.092}$$

$$d = .070Q^{.470}$$

$$v = .088Q^{.450}$$

Figure 22. Hydraulic geometry at the Dry Canyon gaging station during 1934 to 1936.

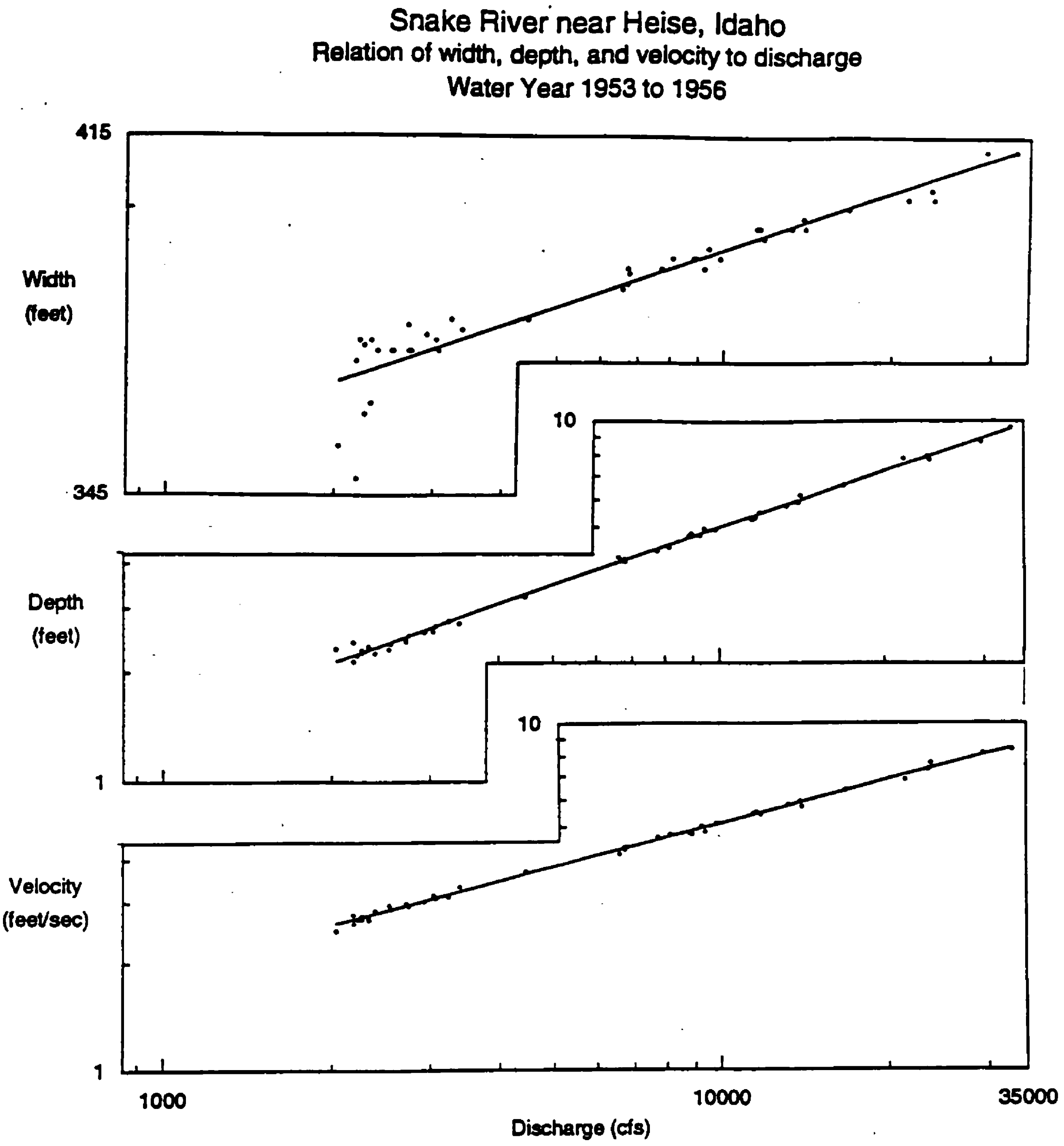


$$w = 260.64Q^{.044}$$

$$d = .143Q^{.405}$$

$$v = .028Q^{.548}$$

Figure 23. Hydraulic geometry at the Heise gaging station during 1934 to 1936.

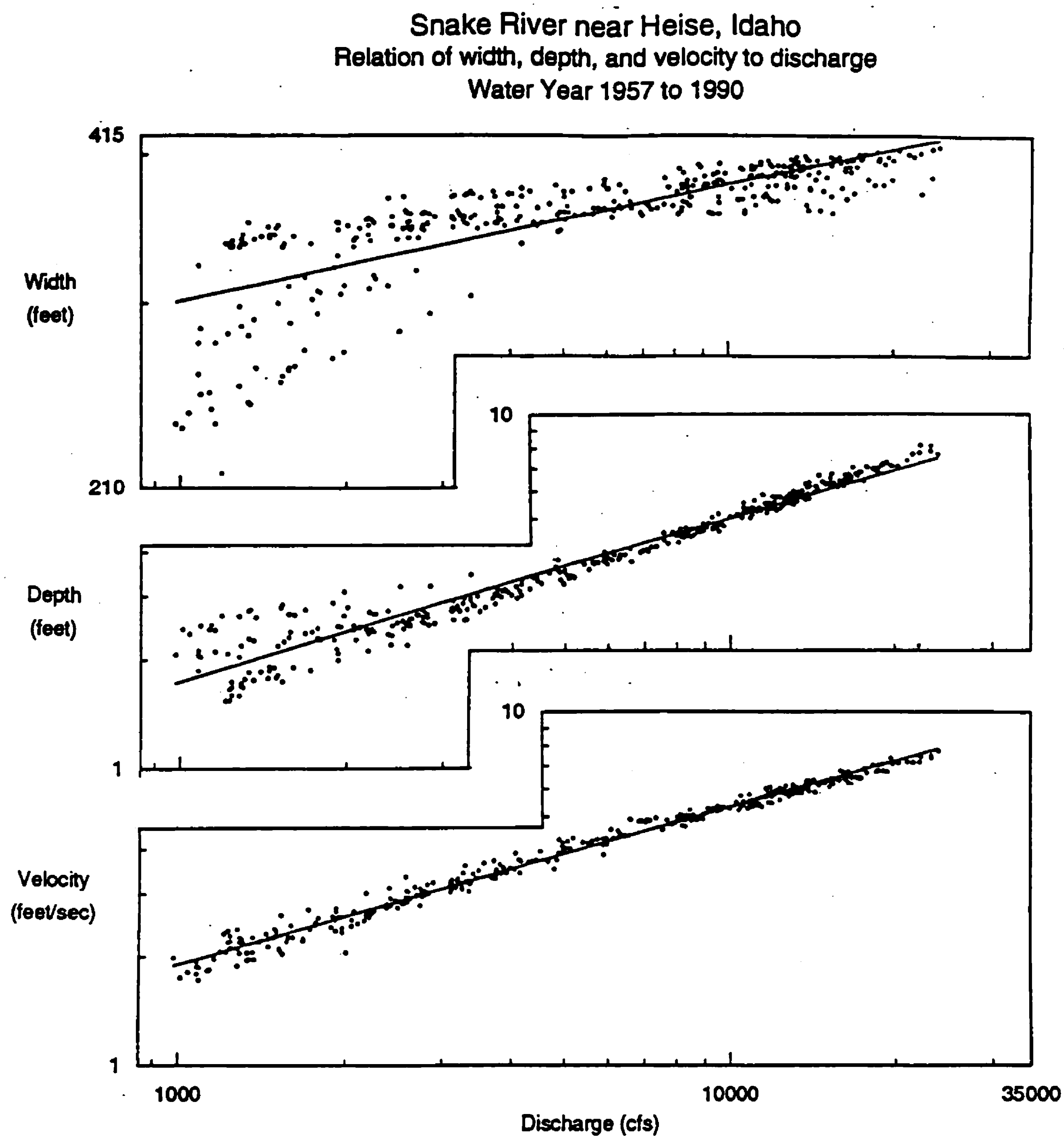


$$w = 265.28Q^{.042}$$

$$d = .038Q^{.530}$$

$$v = .098Q^{.430}$$

Figure 24. Hydraulic geometry at the Heise gaging station during 1953 to 1956.



$$w = 149.82Q^{.100}$$

$$d = .074Q^{.458}$$

$$v = .090Q^{.442}$$

Figure 25. Hydraulic geometry at the Heise gaging station during 1957 to 1990.

Given the available record, there are several combinations of periods and stations that could be compared. However, the analysis is limited to sets of stations across meaningful periods. These sets are: 1) pre- and post-dam (dam was closed 1956) for the three stations having the inclusive record length, 2) the temporal overlap between the Dry Canyon and Heise records (1934 to 1936), and 3) the Lyon pair.

The Alpine station serves as a control, and the Irwin and Heise station exponents are compared to Alpine within and between the pre- and post-dam periods. The Dry Canyon gage best represents the wider flood plain reaches, and the Heise exponents are compared to those of Dry Canyon as well as the later Heise-period exponents. Comparisons of the early Heise gage period exponents is confounded by changes in channel control and cross-section location. The large floods during 1917 and 1918 are of interest, but any affects on the channel are difficult to interpret because of the Anderson dam washing out, which caused slight shifts in control. The Lyon gage relations changed after the 1909 flood, hence the split comparison before and after this large flood.

All of the stations have low *b* exponents, which is due to the high bank angle. Most stations are located in areas having stable banks except the Lyon station and presumably the Dry Canyon station. At Lyon, the channel shifted slightly with the passage of a large flood in 1909 (USGS 1911). The Dry Canyon station is bounded by an old alluvial bar showing considerable channel migration in the past, but the record only includes moderate peak flows and channel characteristics were relatively stable during the record period.

Because the exponents (slope coefficients) sum to 1, they can be located on a ternary plot. Figure 26 shows the exponents for the various stations and periods. Changes over time within a station and differences between stations are readily apparent. The statistical error associated with the coefficients can be roughly assessed if one considers that, except for Lyon and Dry Canyon, a symbol's space represents the 95% confidence interval. The temporally-spaced exponent sets for a given station are meaningful for assessing changes over time, and the further apart the symbols, the less likely that a station's geometry between periods is the same.

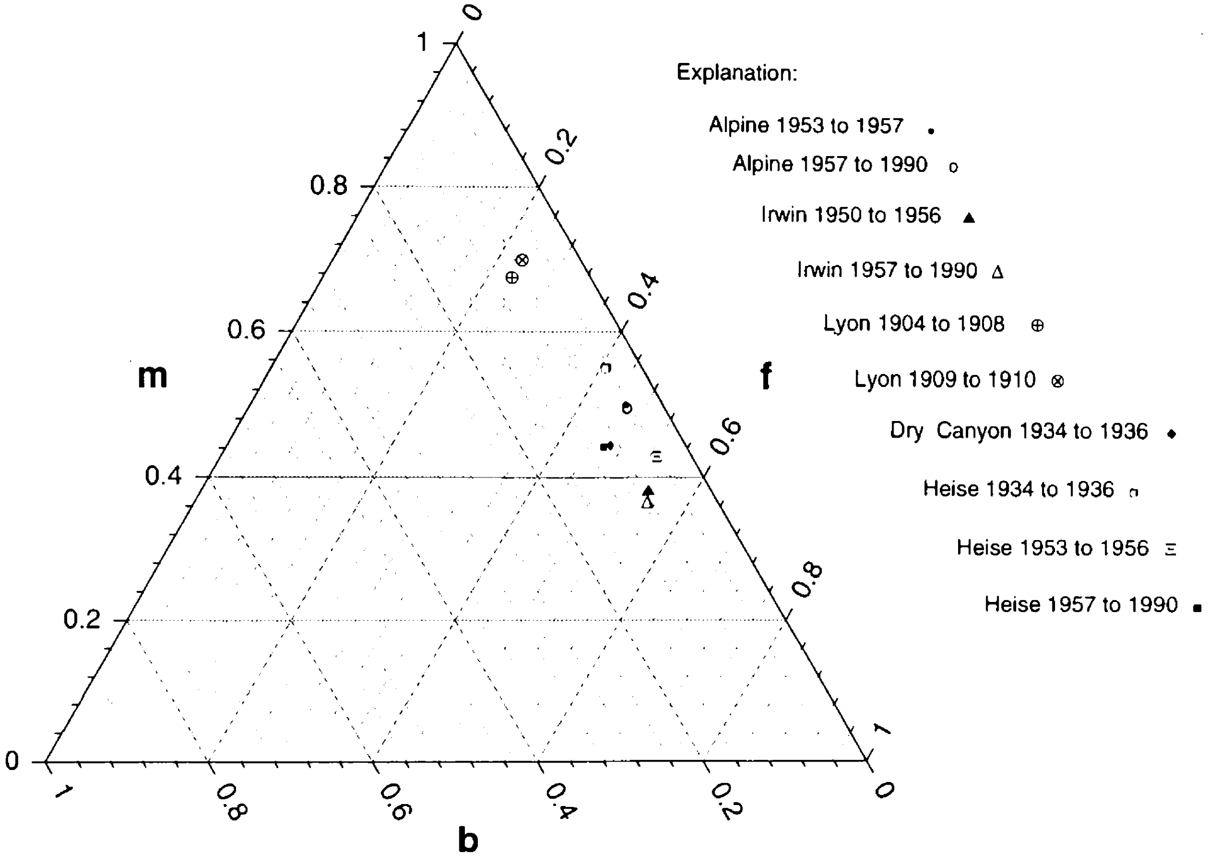


Figure 26. Ternary plot of hydraulic geometry exponents of each station and period.

For the Alpine station, which has the closest exponent set between periods, only the width (*b*) difference was not statistically significant ($p = .409$). All the other exponent set differences for Alpine and Irwin are statistically significant ($p < .01$); those for Heise have $p < .001$. The exponent differnces for Lyon are difficult to test due to inconsistent transformations, but there are large shifts in the constants *b*, *c*, and *m* (figure 21). More detailed statistics are given later in table. 7.

Although statistically significant differences give insight into precision, whether the differences are meaningful in a practical sense is also important. The plotted location of the exponent sets allows inference into channel dynamics. Rhodes (1977) introduced a ternary plot with subdivisions based on reasonably well established hydraulic relationships. This subdivided plot is called a b-f-m diagram, and the subdivision lines are based on rates and directions of change in width-to-depth ratio, competence, Froude number, velocity-cross-sectional area ratio, and slope-roughness ratio (Rhodes 1977).

Figure 27 is the b-f-m diagram, showing the same exponent sets as in table 5 and figure 26. A brief characterization for the stations based on the diagram follows shortly. A full interpretation is included in the discussion, where other channel characteristics can be related.

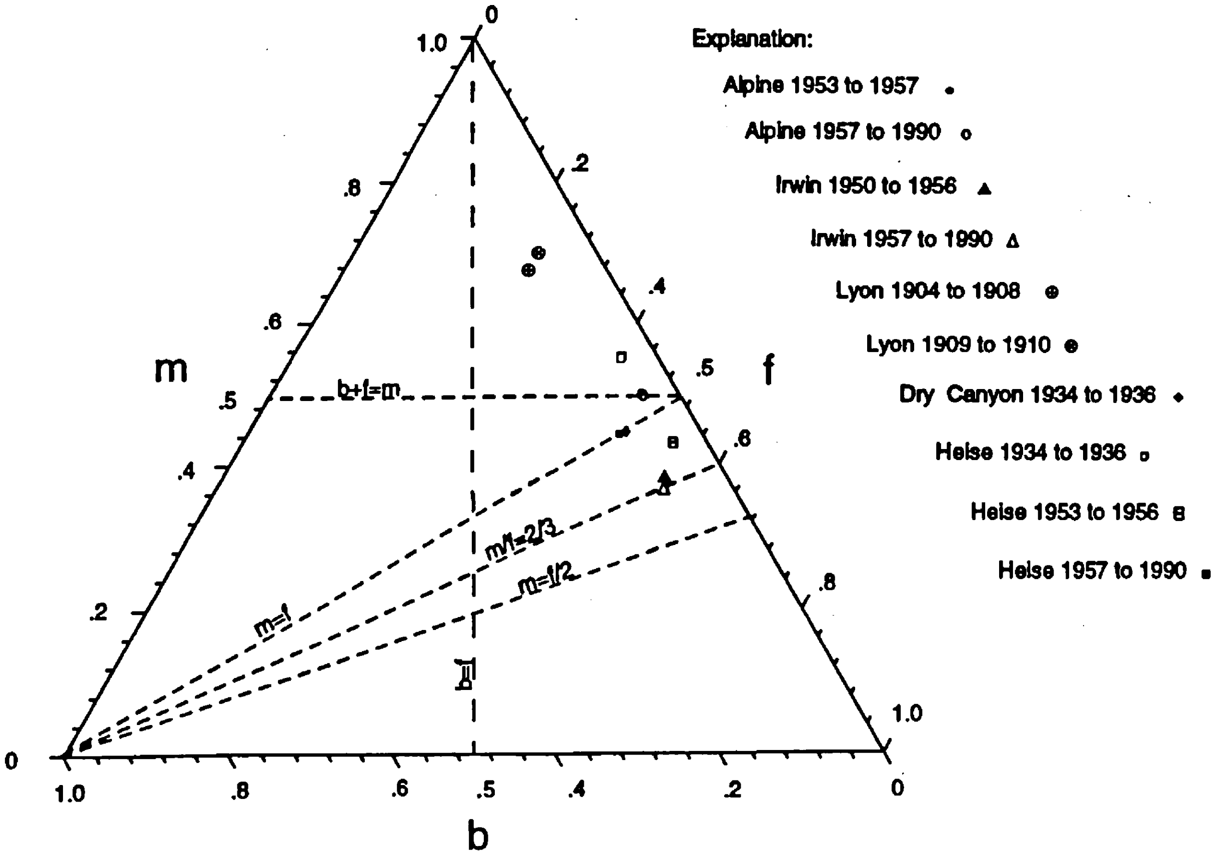


Figure 27. b-f-m diagram of hydraulic geometry exponents by station and period.

Considering the b-f-m diagram subdivisions, the most consistent grouping of exponent sets , or symbols, is their location to the right of the $b = f$ line. This line separates channels that have increasing or decreasing width-to-depth ratios with increasing discharge. Although the cross-sections have high w/d's (figure 16), the b values are much less than the f values, which means the w/d decreases with discharge. The implications of this decreasing ratio is that the banks are more stable than the bed, the banks are steep, and station reaches have relatively low bed load transport rates. The transport rate is based on the shear stress formula.

The subdivision $m = f$ also has sediment transport implications. Stations plotted above this line have increasing competence with discharge because velocity increases at a higher rate than depth. Most of the points hover near this line, but the Irwin station points are consistently below while those for Lyon are far above. The points for Heise are about evenly split, with the 1930's cross-section having the higher competence. The cross-section location during the 1950's was different from the 1930's cross-section, which may explain some of the spread. Velocity– and depth–rate increases are equal for the post-dam closure period, while the pre-dam period had a faster depth increase, which implies even lower competence. The cross-section location has been consistent since at least 1953.

Related to the above is the $b + f = m$ subdivision, where $m = .50$. Station values plotting above this line represent channels that have very rapid increases in velocity with discharge. Rhodes (1977) used Richards' (1973) empirical work to arrive at the .50 limit. Perhaps the region above this line can be viewed as a more extreme condition of the $m > f$ condition. The Lyon station values are far above this line, and the Heise station during the 1930's fits this condition to a lesser extent.

One aspect of hydrodynamics is the relative balance between gravitational force on water and the inertial resistance of the water itself or obstacles in the channel. The Froude number indicates which is higher; at unity, the forces are balanced. Gravitational force exceeds inertial force when the Froude number exceeds one and vice-versa. Flows with Froude numbers > 1 are known as supercritical, and upper-regime or supercritical flows at high discharges are required to transport large sediment particles (Fahnestock and Haushild 1962, Rhodes 1977). The line $m = f/2$ separates channels that have increasing or decreasing Froude numbers with increasing discharge. Stations with exponents above this line have increasing Froude numbers. This relationship only gives insight into the potential for supercritical flows, not whether the flows are actually supercritical. All of the stations have this potential. However, the spread at Heise is particularly interesting and may be due to the varying effect of the Anderson dam remnants on channel control, because the cross-section locations were different in respect to the remnants. The relationship is counter-intuitive though, because the 1930's cross-section was closer to the remnants than today's cross-section, and one would expect lower Froude numbers for the section closest to the remnants.

Finally, the subdivision $m/f = 2/3$ is related to roughness. This relationship is based on the well-known Manning equation, which is empirical, and denotes a change in slope-to-roughness ratio. If one assumes that slope does not change (or very little) with discharge, then roughness decreases with increasing discharge for stations with exponents above the line. Rhodes (1977) considered this relationship as speculative. Although roughness itself is not directly measurable, it can be inferred from other relationships such as the immediate one and others. Based on the b-f-m diagram, all stations except Irwin have decreasing roughness with increasing discharge. The pre- and post-dam Irwin channel has very little change. More results involving roughness are presented later.

Width changes along reaches – Width is the most responsive and reliable parameter to changes in sediment or water discharge (Leopold and Wolman 1957; Andrews 1982). Although the b values for the various stations show how width changes with discharge and how this relation has changed over time, the stations may only represent straight reaches and much of the river has curved or braided reaches. To better represent any width changes over time, I measured width changes at a fixed discharge representing two important time periods — pre– and post–Palisades dam. Table 6 summarizes the changes in width for contiguous reaches covered by sequential aerial photography. Pre-dam conditions are represented by the 1941 flight while the 1987 flight represents post-dam conditions. Flows during these two periods were 6080 and 6420 cfs, respectively.

Table 6. Channel width changes between pre– and post–Palisades dam conditions.

Reach	Up-river endpoint River Mile	Reach Length Miles	W_{1987}/W_{1941}
1	878.97	2.57	1.014
2	876.40	2.06	1.183
3	874.34	2.50	1.002
4	871.84	1.98	.994
5	869.86	1.76	1.017
(About 1/2 river mile is missing from 1941 photo coverage between reach 5 and 6)			
6	867.09	2.64	1.115
7	864.45	1.46	1.083
8	862.99	3.59	1.054
9	859.40	2.90	1.035
10	856.50	2.90	.958

The photo-compared reaches, which are contiguous except the one gap, start in Conant Valley and end about 300 feet upstream of the Heise station. Of the six primary reaches described in chapter 2, this is the volcanic- canyon reach.

The ratio W_{1987}/W_{1941} is the channel area change for a reach length common to both periods. Width varies slightly along channels, and the channel area represents an integration of channel widths; a change in area corresponds to an overall width change for the reach. The ratio shows the direction and magnitude of change, and most reaches have increased widths. There is some measurement error, but a change greater than about 5% is probably real. Most reaches have straight and braided sections, and there is no apparent trend in width change and channel pattern. The overall width change for the measured reaches balances out to 1.042, which means the 1987 channel is about 4% wider than the 1941 channel, assuming no measurement error.

Width change in the terraced reach in Swan Valley is represented by the Irwin station. Using the width equations (figure 19 and 20) and similar discharge, (6000 cfs), the mean predicted width during 1950 to 1956 is 316 feet, the same type of prediction for the 1957 to 1990 period is 318 feet. However, based on field visits and land-based photography taken during dam closure, there is noticeable bank erosion immediately below the dam at Sheep Creek. Some bank erosion is to be expected, but in comparison to banks downstream in the terraced reach, this erosion appears unusually high and the width may have increased here. Also, adjacent channel bed material is unusually coarse with many large boulders showing today in contrast to 1956. Figures 42 and 43 show the contrasting bed material; the width change is difficult to assess in the photos, but apparent in the field.

Even though channel alignment may change, channels maintain their widths over time when the water and sediment regime remain stable. This relationship will be discussed more fully later, but in light of this, figures 28 to 30 show reaches with varying degrees of width change. The figures are presented in downstream order and are for reaches 2, 3, and 10 (table 6). These reaches are braided and have undergone some alignment changes. The channel plan form as surveyed in the 1930's is shown for comparison to the measured plan form during 1941 and 1987, and the channel as mapped in 1893 is shown for reach 3. Although not shown, straight reaches typically have little alignment change as well as low width change.

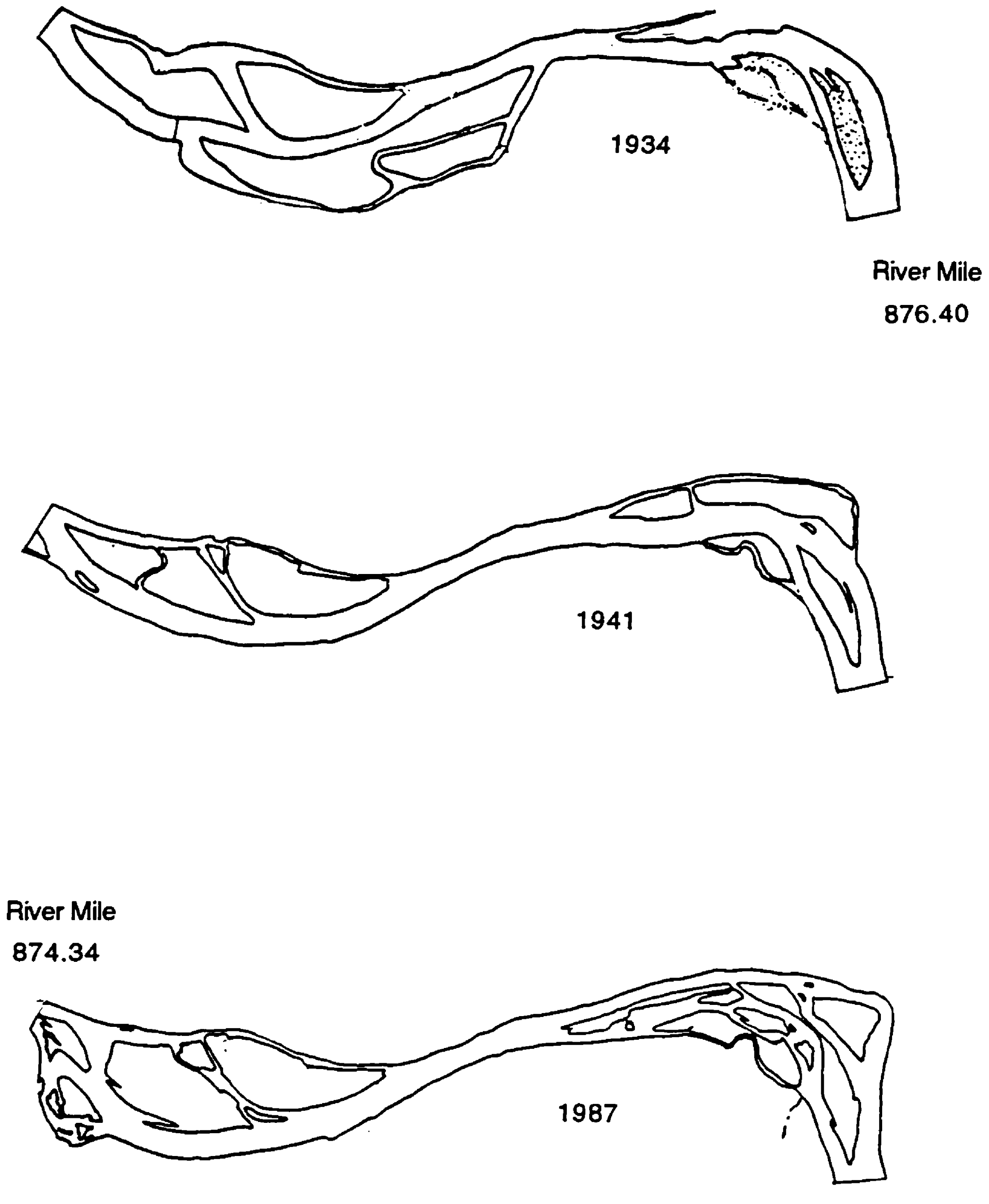


Figure 28. Channel alignment and width change, reach 2.. W_{1987}/W_{1941} = 1.183

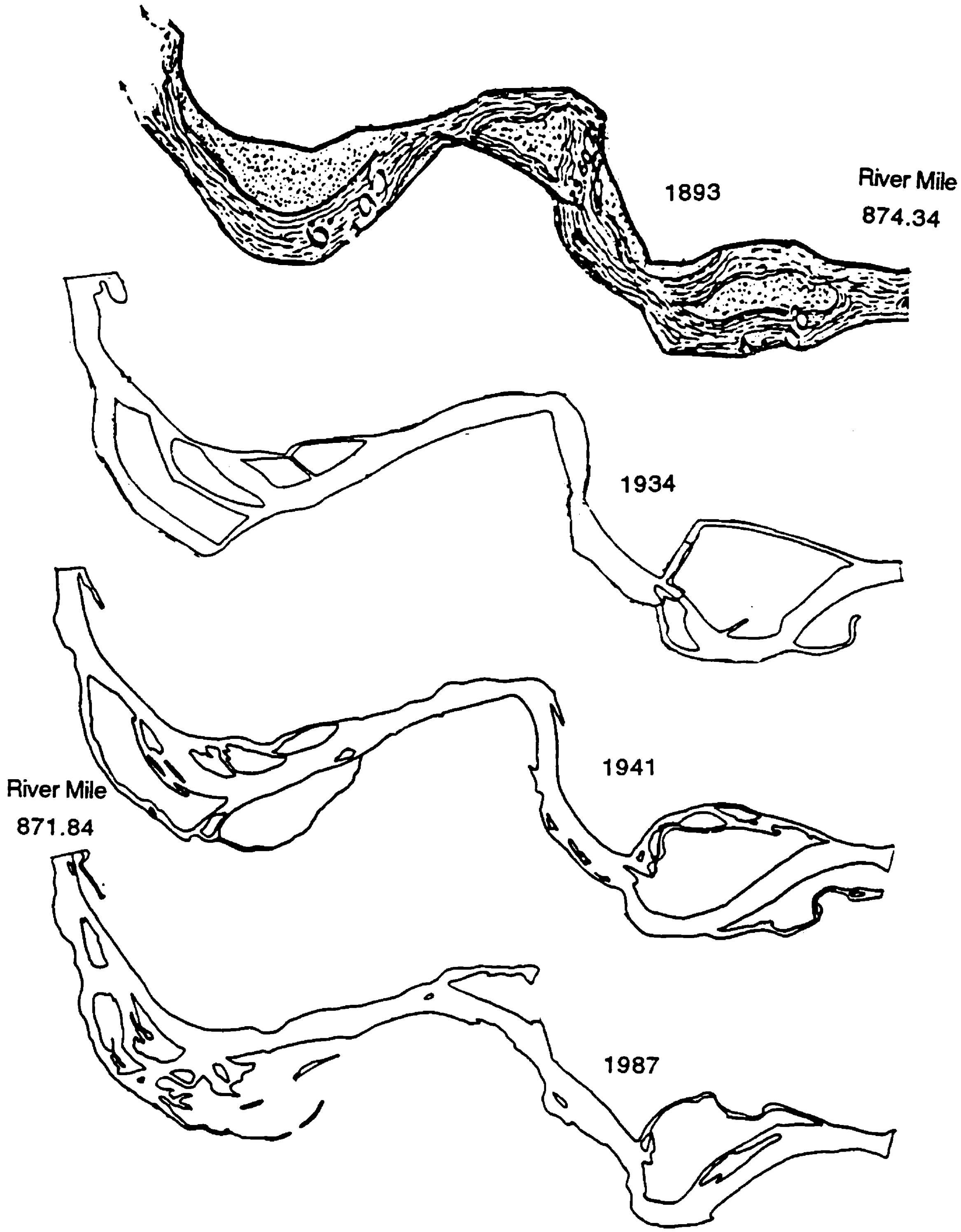


Figure 29. Channel alignment and width change, reach 3. W_{1987}/W_{1941} = 1.002

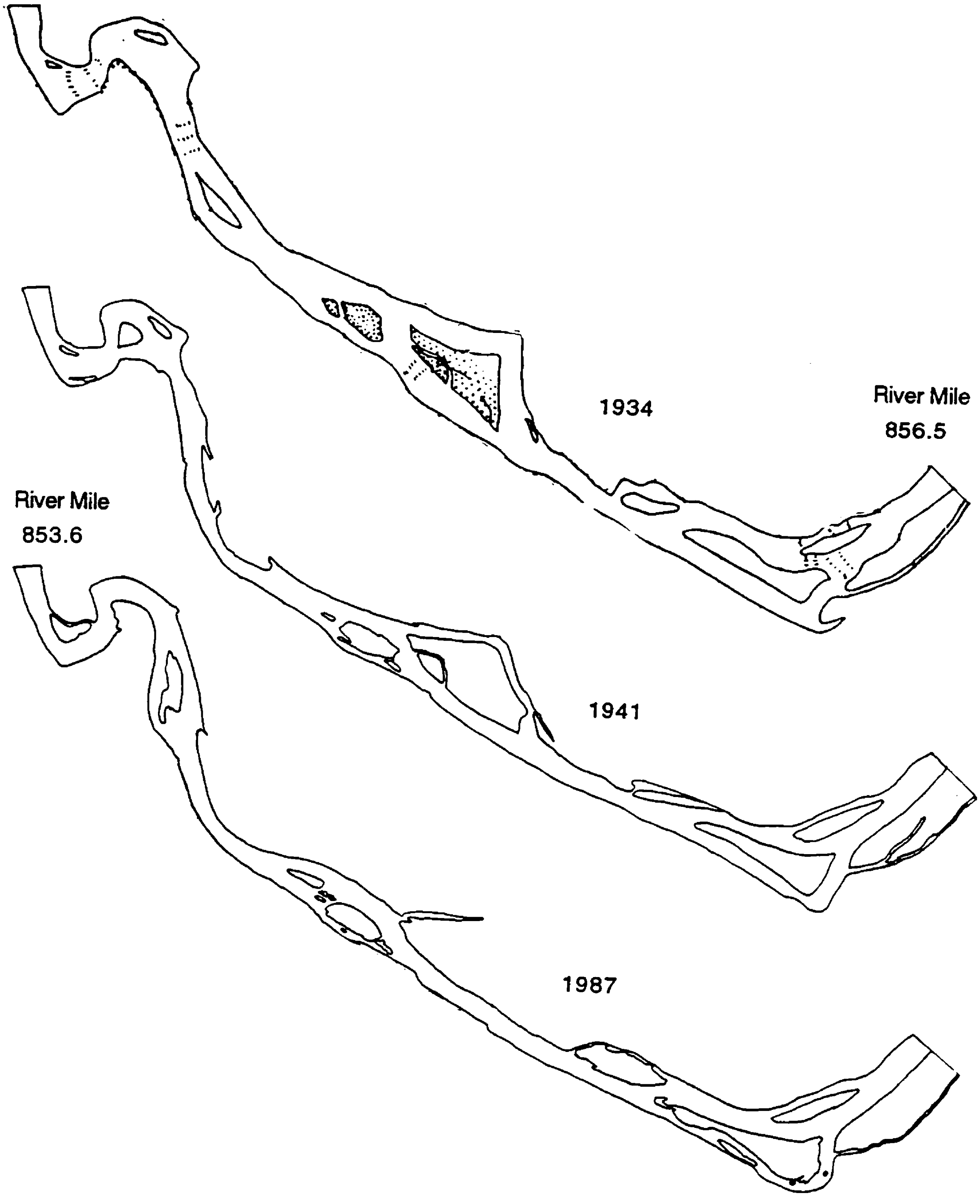


Figure 30. Channel alignment and width change, reach 10. $W_{1987}/W_{1941} = 0.958$

Channel roughness – Flow resistance in channels, or channel roughness, is an important variable but is not directly measurable. Because of this, channel roughness is inferred from other relationships, some of which are already reported. This section briefly brings these inferences together along with more evidence.

As presented by Leopold et al. (1964), roughness is composed of two main components: skin resistance, which is the friction caused by channel boundary material, and internal distortion resistance (form resistance), due to channel features such as dunes, bars, and bends. Two minor components are spill resistance and viscosity. Spill resistance, which is related to sudden reductions in velocity as in behind an obstruction, occurs when the higher-velocity water must spill into lower velocity areas. Higher Froude numbers indicate the onset of spill resistance (Leopold, et al. 1960), but available data for the South Fork is lacking in respect to spill resistance. Viscosity can change with water temperature or suspended sediment load, the latter being more important but still minor in overall effect.

Of the above, the most important component in total roughness change since dam closure is skin resistance. As will be reported shortly, there has been little change in channel sinuosity, so channel bend resistance has probably remained stable across the two periods. Addition of obstructions is limited by the scarcity of mass-wasting, and the possible effect of sediment on viscosity, which has already been established, is very slight at best.

For turbulent flow, skin resistance can be estimated in terms of relative roughness which involves the flow depth (d) and the height of the larger bed particles. If there is a change in be particle size distribution, the roughness will change. The channel just below the dam is the most likely place for a change in roughness to occur, since the smaller particles are likely to be washed away and not replaced, therefore increasing the relative roughness. I investigated roughness change two ways. Both use velocity as a surrogate for roughness.

The Darcy-Weisbach friction factor "*f*" is proportional to depth and velocity in the form d/v^2 if slope is constant(Richards 1973). Figure 31 shows the friction factor and discharge relation at the Alpine, Irwin, and Heise stations before and after dam closure. A change in bed particle size distribution will change the relative roughness, which should be more noticeable at low depths or discharges if all other factors remain constant.

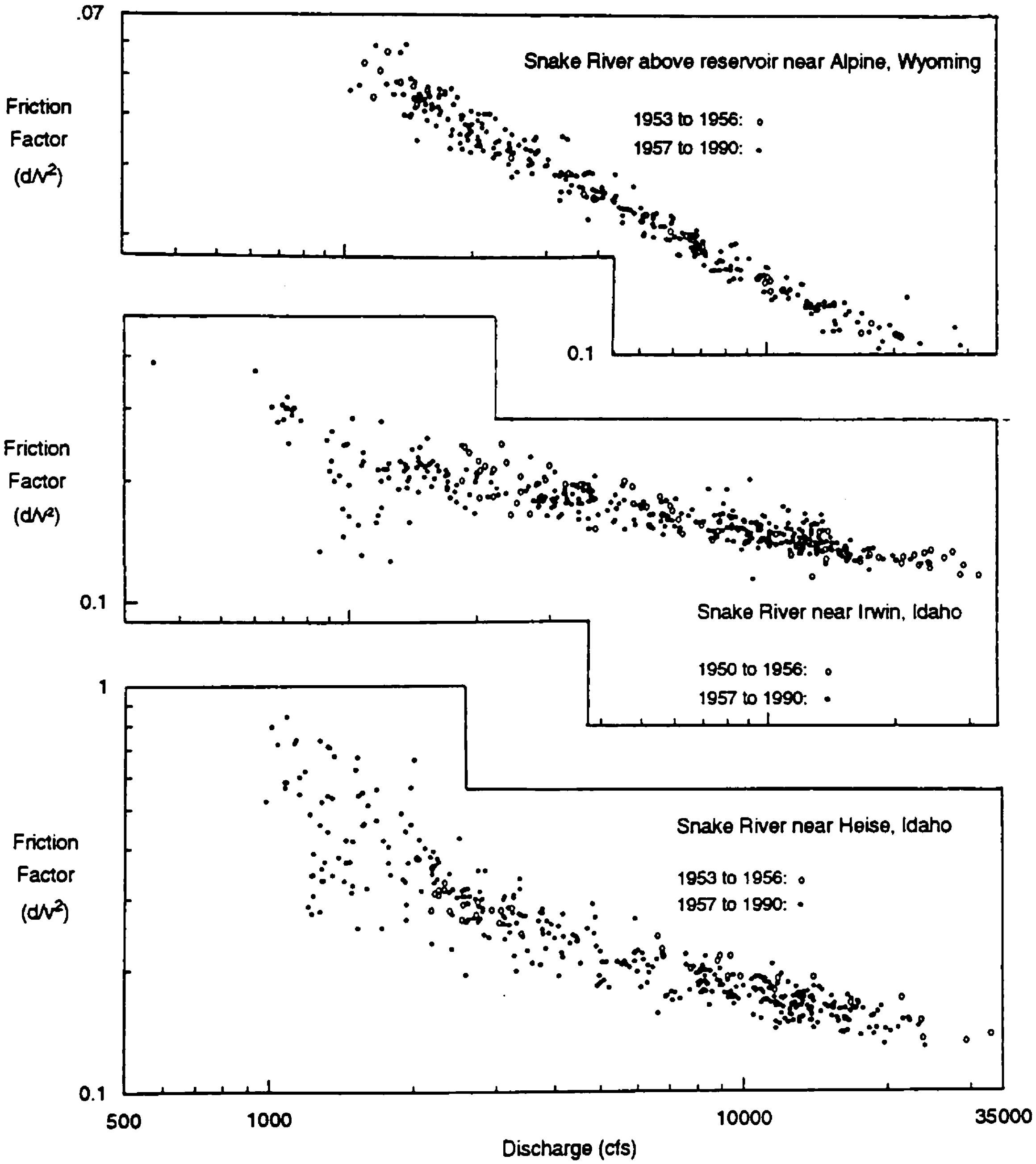


Figure 31. Friction factor changes with discharge at the Alpine, Irwin, and Heise gaging stations during the pre– and post–Palisades dam periods.

At the Irwin and Heise stations, the wider variance at lower discharges during the post–dam period is particularly interesting, and this fan-shaped pattern shows up in other relationships at these two stations. Due to reservoir management, storage is always high during high discharges, but storage varies considerably during low flow events. Jacobson (pers. comm. 1992), says there is a noticeable difference in the velocity–to–discharge relation at Irwin during low flows due to changing reservoir storage. In the regression residual plot for velocity vs. discharge at Irwin (Appendix B), the variance is fanned-out at low flows during the post–dam period. Other stations and periods show a similar fan shape, but only about 1/3 the amount at Irwin and Heise. I checked the effect of hydraulic head on velocity at Irwin by regressing velocity on discharge and reservoir surface elevation. The slope for the third variable does not indicate a hydraulic head effect for post-dam flows (see Appendix B). The hydraulic head difference is a less plausible explanation for the variance pattern at Heise, due to the great distance from the dam. The intermittent mid-channel bar at Heise may explain it, but I did not investigate this in detail.

The friction factor change over time fluctuates with discharge, becoming less with higher discharges in the spring and early summer. As in above, this pattern follows that from the earlier-mentioned hydraulic geometry relation, where velocity changes at a faster rate than cross-sectional area, or $m > b + f$. There is no apparent time trend in this relationship for the Alpine, Irwin, and Heise stations having common cross-sections. The same can be said for the slope-to-roughness ratio based on the Manning equation.

As shown earlier in figure 15, the velocity for a given discharge at Irwin increased slightly, which is unexpected for a decrease in sediment load due to the reservoir. The difference in hydraulic head is a plausible hypothesis for this increase, where the head is always higher at the higher discharges during the post–dam period, which would increase velocity for a given discharge. High discharges at low head after dam closure are needed to test this, but they do not exist.

There is one time trend that may be related to a roughness change at the Irwin station, where the velocity–to–discharge relation shifted during the period immediately before the dam. Figure 32 shows the time trend in the residuals from the regression relating these two variables. Although many relations at various stations had time trends, or serial correlations, only the pre-dam-Irwin relation had this consistent trend. As will be shown later in figure 35, the Irwin channel aggraded during this period, but other stations that aggraded do not show this consistent trend.

However, the trend may be related to a change in slope due to aggradation, and the sample sizes may not be large enough to define the pattern in the other aggrading situations. If the trend at Irwin is due to a change in roughness and not slope, it is probably associated with sediment load increases during dam construction, which occurred during this time. Relative roughness may also have changed with sediment load increases, but it is not detectable in the other relationships examined.

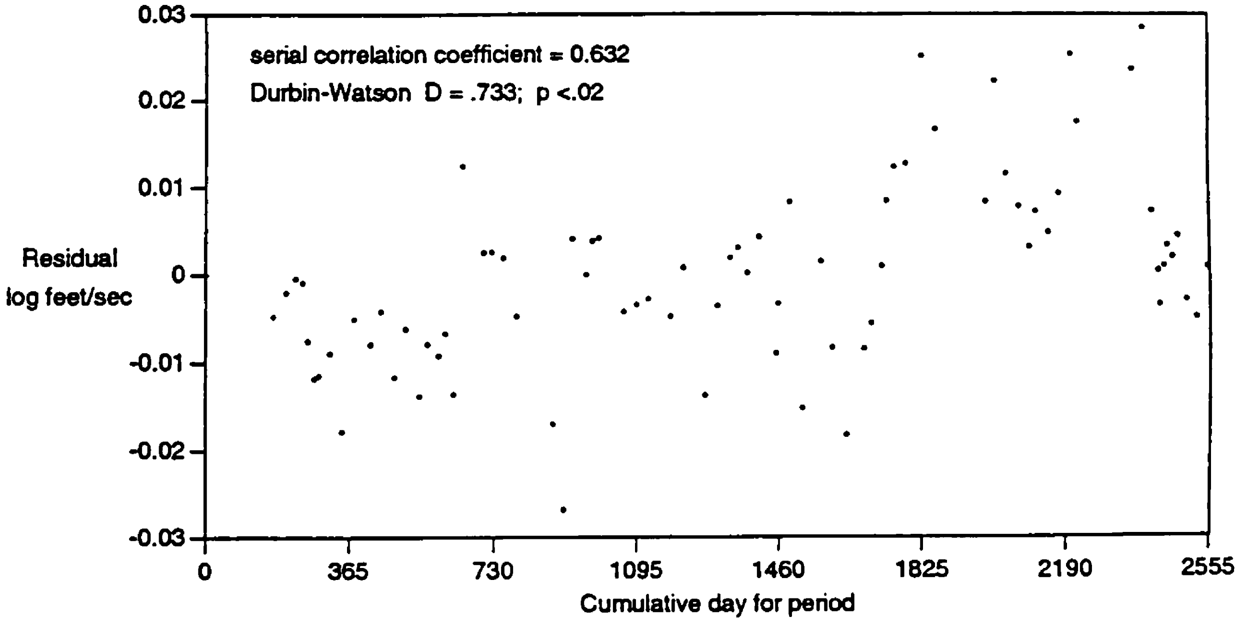


Figure 32. Time series of residuals for the velocity–to–discharge regression at the Irwin gaging station during 1950 to 1956.

In order to equate a change in roughness with a change in any of the velocity relations, slope must remain constant. Of course, an overall change in slope or longitudinal profile would probably cause drastic changes in velocity relations, but a local change in slope due to scour or fill may also confound the relationship.

In summary, there is little evidence of roughness change after dam closure at the gaging stations. The only detectable change in velocity relation occurred during dam construction activity and was temporary.

<u>Slope</u> – The change in elevation along a horizontal channel distance is the most common measure of slope or longitudinal profile. River response is very sensitive to slope changes, or conversely, slope responds to changes in water and sediment regime, but the change is usually slow, small, and difficult to measure.

Although there is no precise, temporally-spaced slope data, changes in slope can be detected by changes in sinuosity and channel bed elevation dynamics at gaging stations, which are presented.

The river profile as measured in the 1930's is shown in figures 33 and 34 to give context to the information presented. The river mile values are standardized to the Heise gage and do not coincide with some USGS maps due to an 8 mile error. Channel bed elevation dynamics for the Alpine, Irwin, and Heise stations for periods where cross-section locations were consistent are shown in figure 35. Detailed scour and fill dynamics with discharge at the Alpine, Irwin, and Heise stations are shown for 1986 in figures 36 , 39, and 40. The dynamics at Lyon and Dry Canyon are for their entire record period (figure 37).

For a more visual and possibly more intuitive presentation of channel characteristics through time, photographs of reaches immediately downstream from Palisades dam during dam closure and Autumn 1992 are shown in figures 40 to 43.

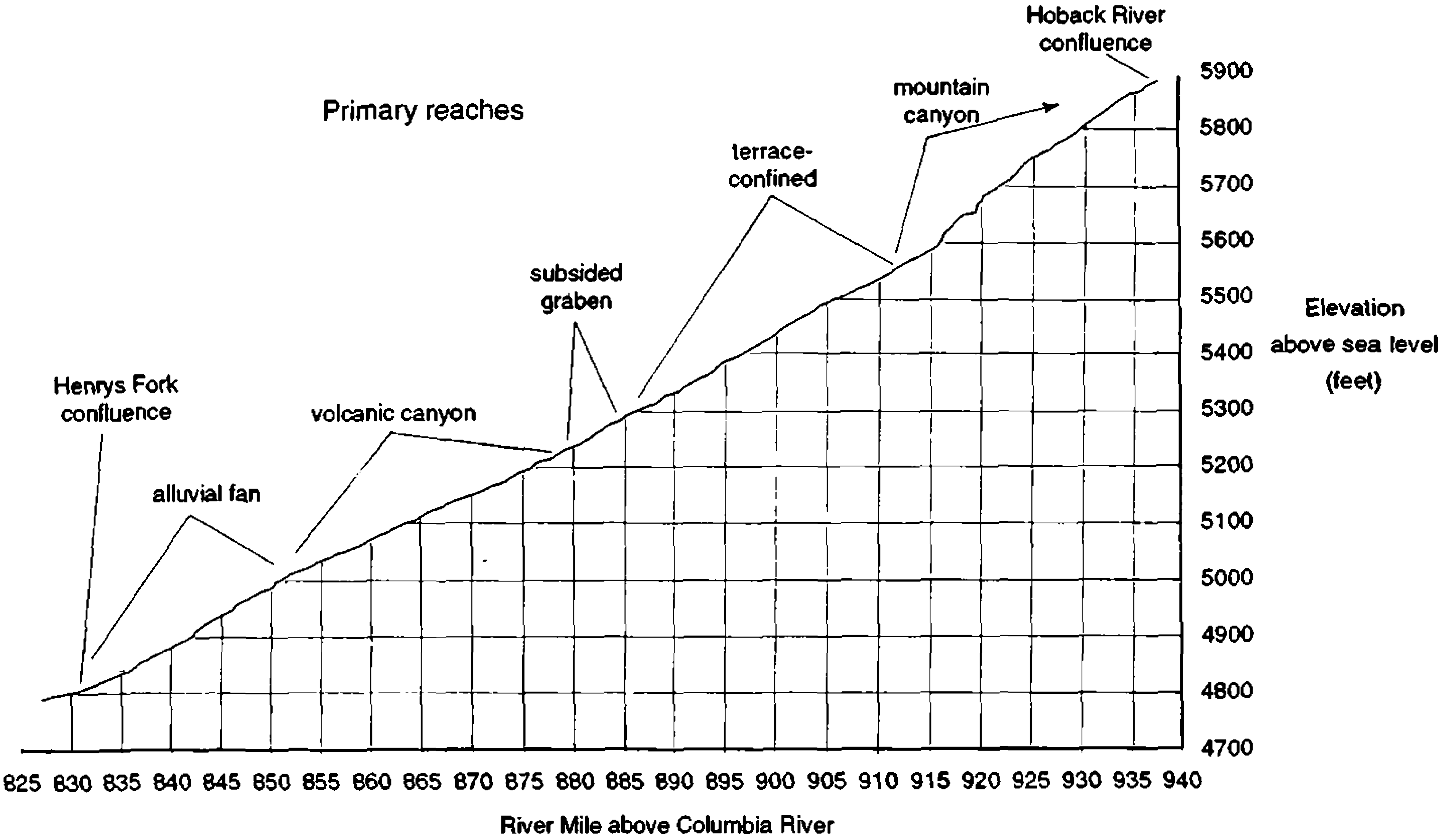


Figure 33. Longitudinal profile of Snake River from the Henrys Fork to Horse Creek.

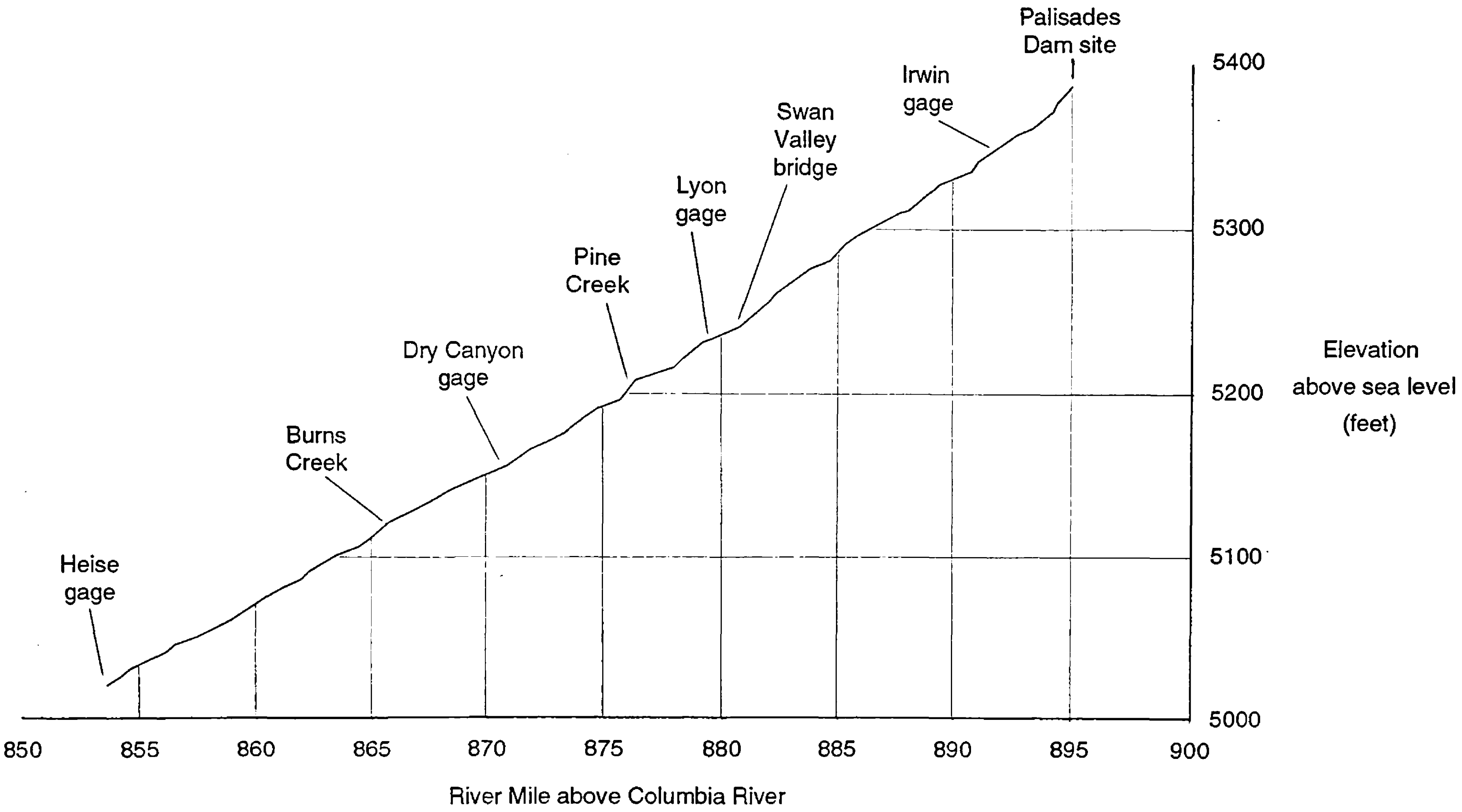


Figure 34. Longitudinal profile of South Fork Snake River from Heise to Palisades Dam site

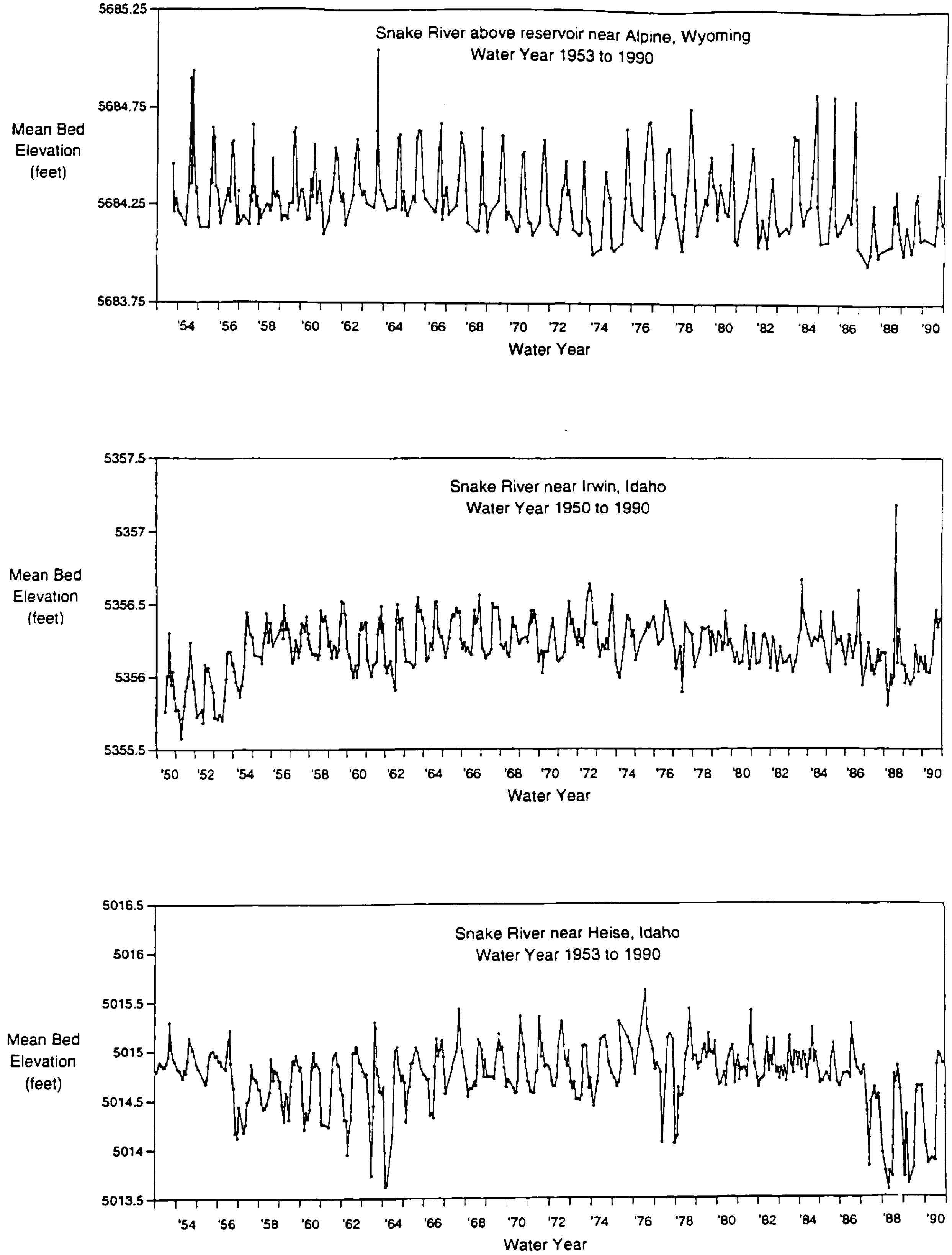


Figure 35. Channel bed elevation dynamics at the Alpine, Irwin, and Heise gaging stations.

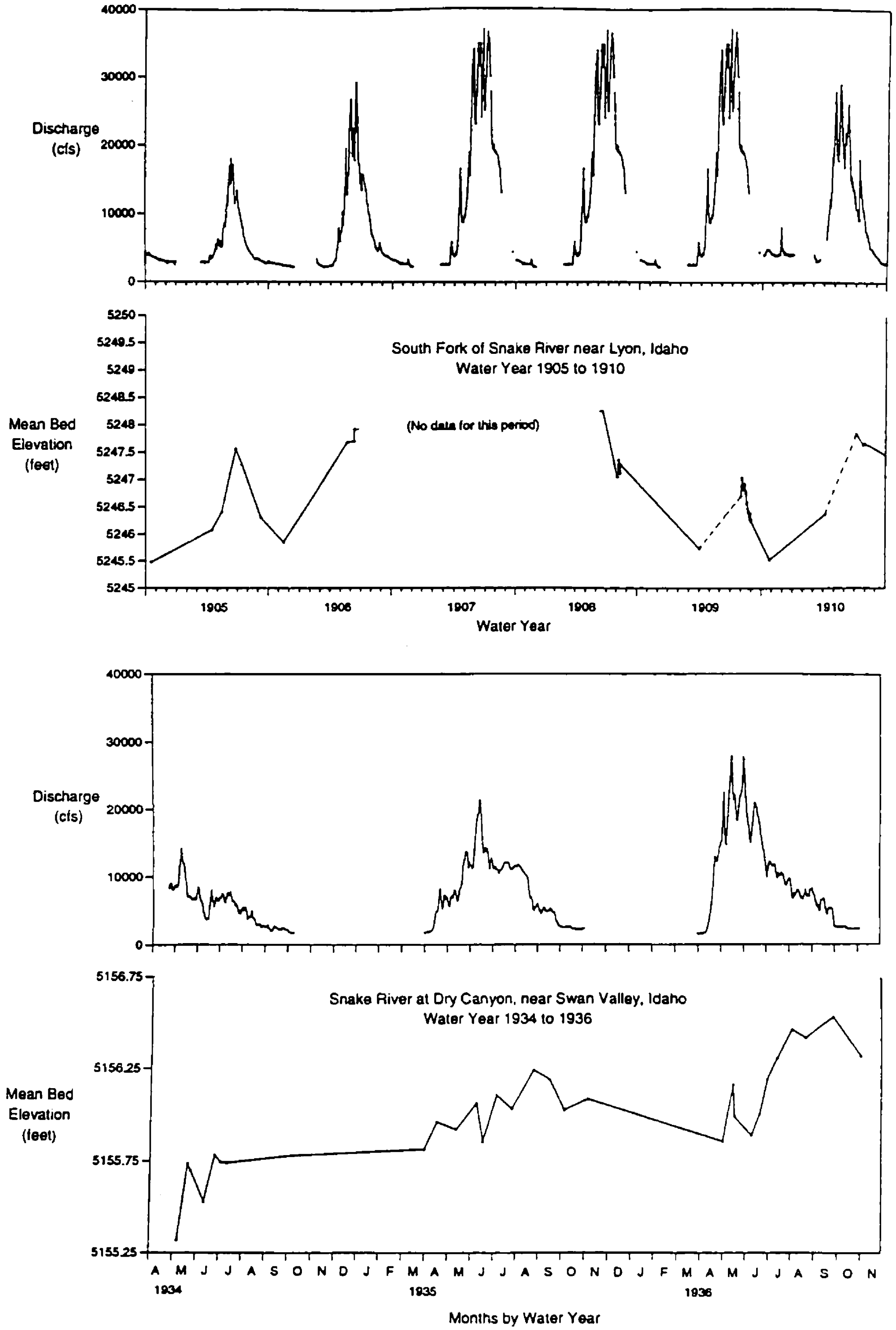
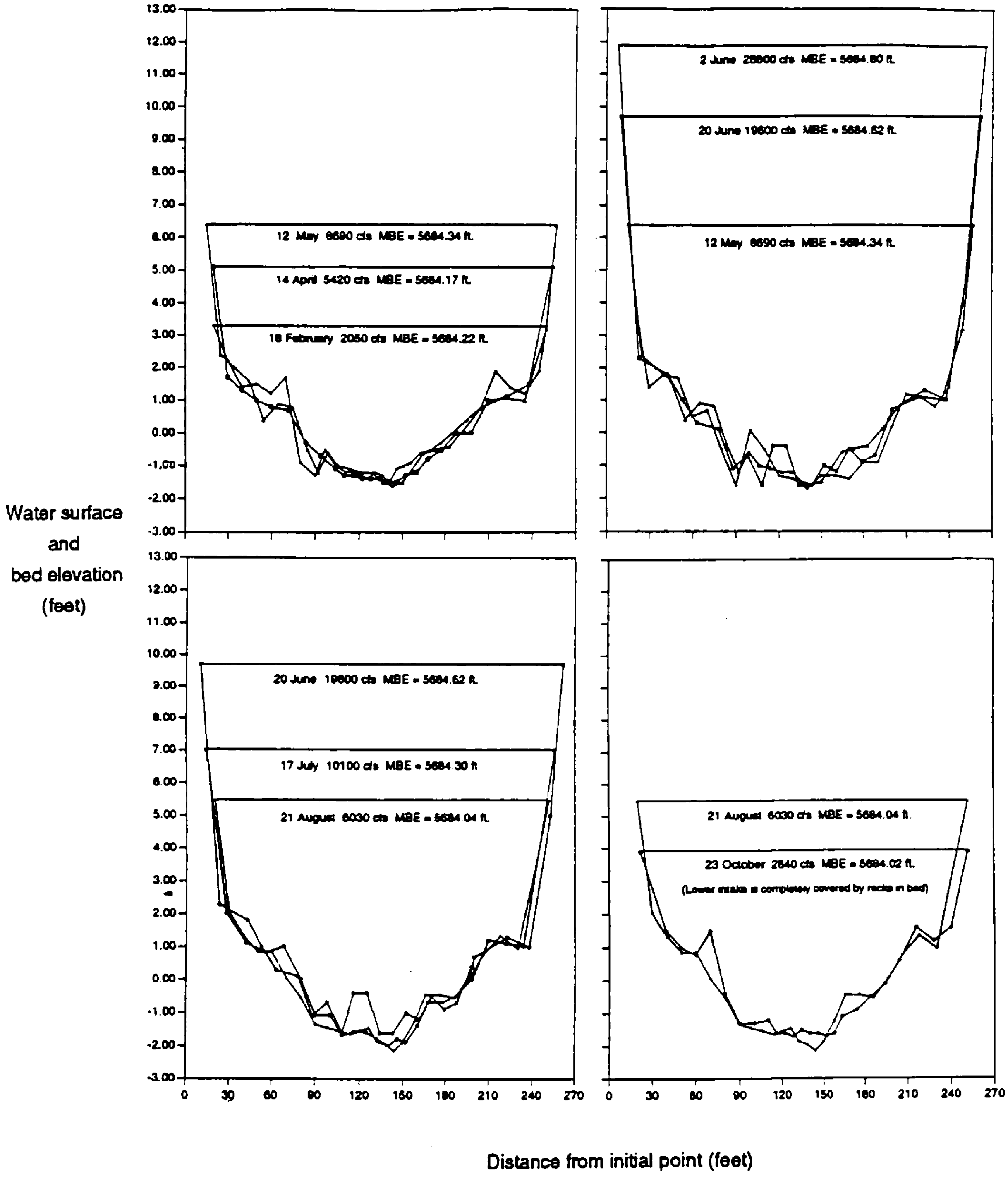
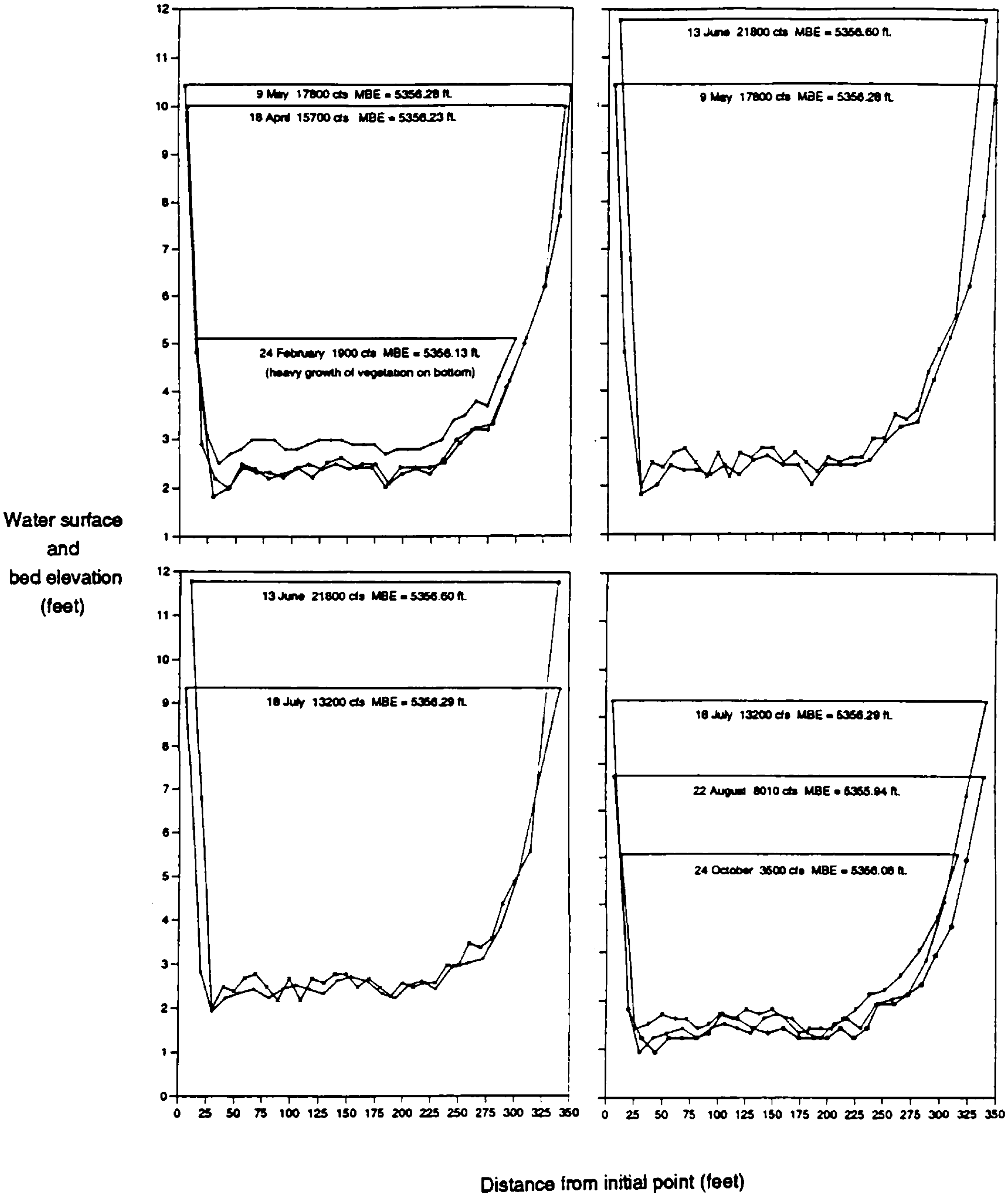


Figure 36. Channel bed elevation dynamics at the Lyon and Dry Canyon gaging stations.



Datum = 5683.90 ft. MBE = Mean bed elevation

Figure 37. Scour and fill with discharge at the Alpine gaging station during 1986.



Datum = 5353.00 ft.   MBE = Mean bed elevation

Figure 38. Scour and fill with discharge at the Irwin gaging station during 1986.

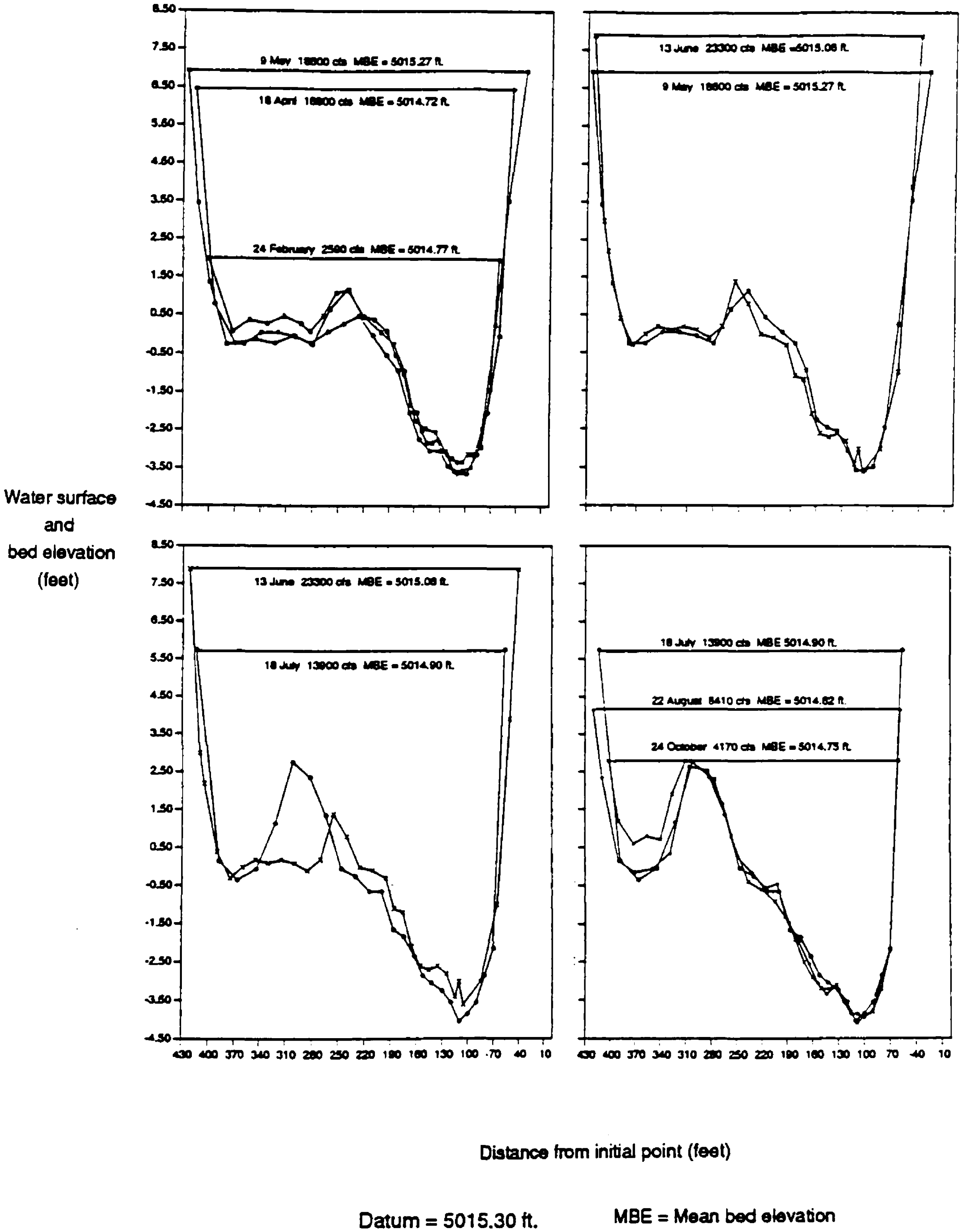


Figure 39. Scour and fill with discharge at the Heise gaging station during 1986.

Figure 40. Upstream view of channel from the Irwin station during Palisades Dam closure, November 8, 1956. Flow is 19 cfs. U.S. Bureau of Reclamation (P. Merritt #3801)

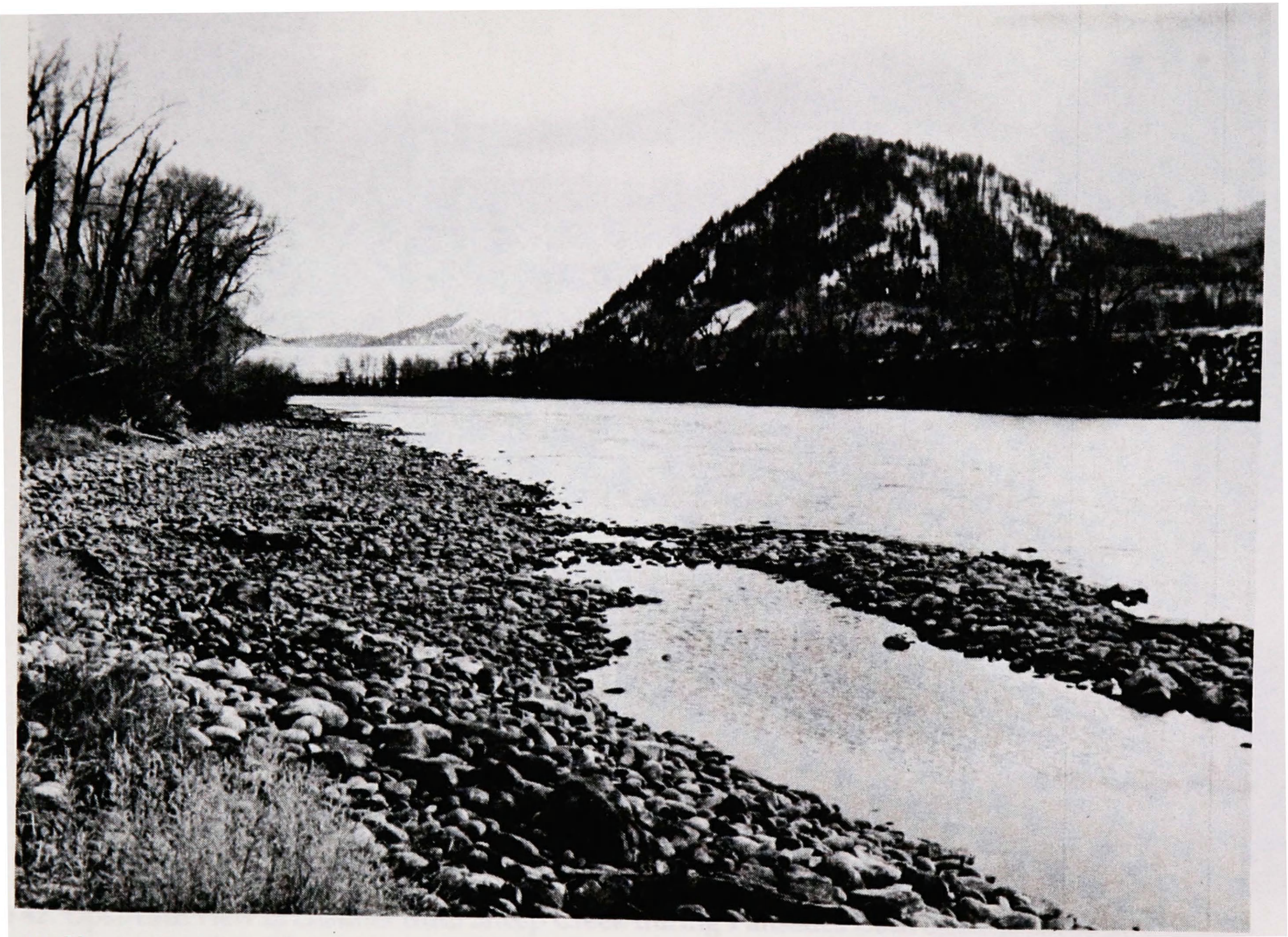


Figure 41. Upstream view of channel from the Irwin station, November 20, 1992. Flow is 1220 cfs.

Figure 42. Upstream view of channel from Sheep Creek during Palisades Dam closure, November 8, 1956.
Flow is 19 cfs. (U.S. Bureau of Reclamation P. Merritt # 3795)

Figure 43. Upstream view of channel from Sheep Creek, November 20, 1992. Flow is 1220 cfs.

Although slope or energy grade line is extremely important in river processes and these results are not direct measures of this, there are patterns in the data that suggest that slope has changed little in between the two periods. But first, a brief summary of the river profile follows.

The overall slope a shown in figures 33 an 34 show the usual concave-upward shape. The sharp dips are typically associated with the larger bends , where slope must increase to counter-act the increased roughness. Not surprisingly, the mountain canyon reach with its bedrock knick points has the steepest and most irregular slope. The terraced-confined and subsided reaches have similar slopes which are less than the mountain canyon's overall slope. Although the volcanic canyon reach is quite sinuous, its overall slope is less than that of the terrace-confined reach, where the channel is quite straight (figure 2; p. 5). The slope steepens again along the alluvial fan, where the channel is highly braided and sinuous. However, upon reaching the Henrys Fork, the slope lessens drastically and remains so beyond what is shown in figure 33. There is no apparent change in sinuosity here, but there is a noticeable change to smaller bed particle size below the Henrys Fork, which could be a reason for the reduction in slope (Mackin 1948; Leopold and Maddock 1953). However, this particle size difference may be a remnant of the Teton Dam failure in June 1976, which discharged considerable water (1.7 million cfs near St. Anthony, Idaho) and presumably high amounts of sediment into the Snake River.

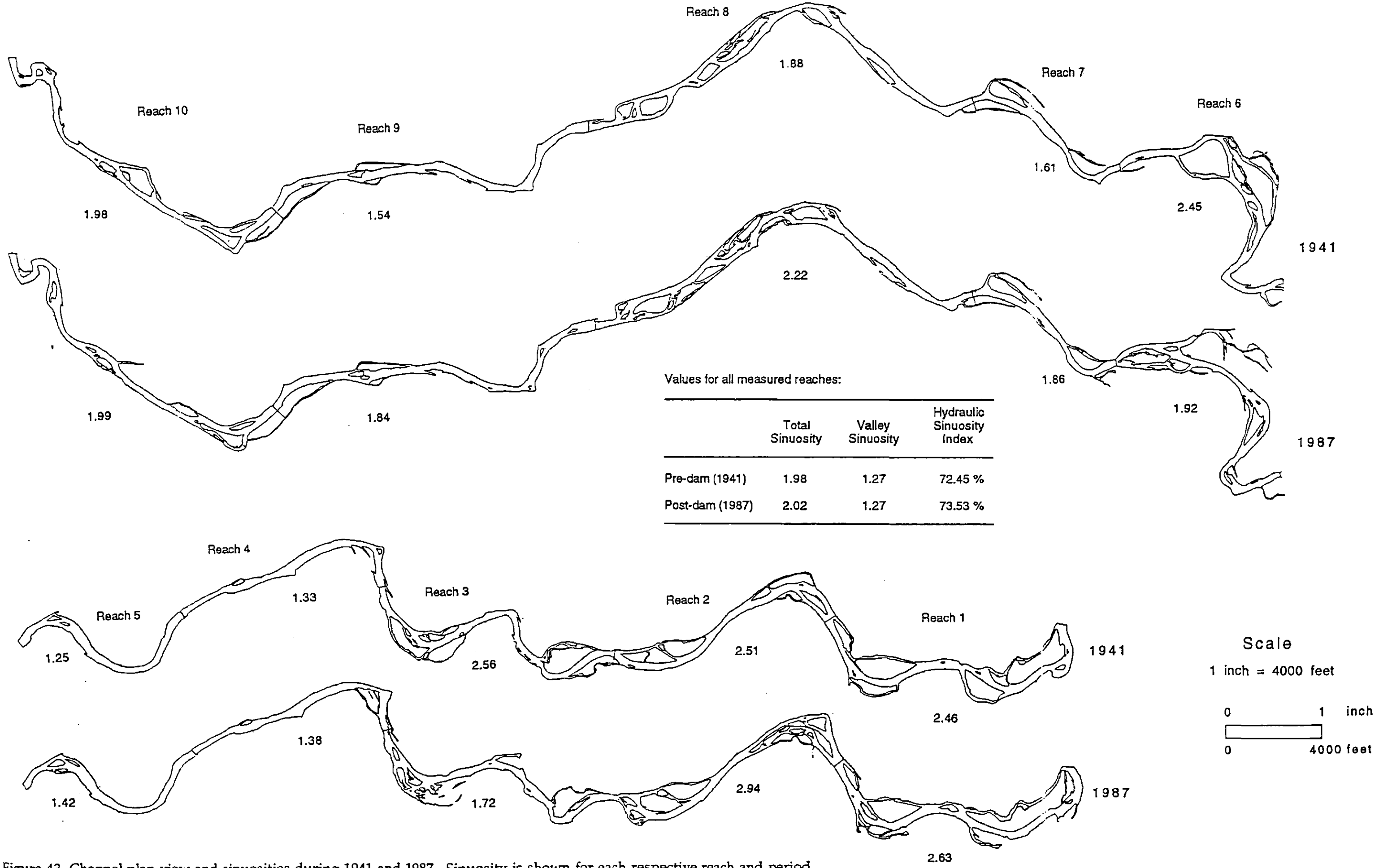
After dam closure, the only bed load source between the dam and Palisades Creek is from the river reach itself and a few very small tributaries. Because of this, channel degradation is most likely here, and the Irwin gage cross-section serves as a fixed measure through time of bed elevation dynamics. The bed elevation at Irwin has seasonal variation , but a fairly stable bed elevation over the last 40 years (figure 35). As mentioned earlier, the Irwin channel aggraded during the dam construction period, but has been in a steady-state equilibrium since then. Other stations, including the control at Alpine above the reservoir, generally show a similar steady-state pattern. The occasional large drops at the Heise cross-section are due to periodic maintenance by a occasional large drops at the Heise cross-section are due to periodic maintenance by a canal company. This involves bulldozing an intermittent gravel bar, thereby decreasing the mean bed elevation. The Geological Survey and canal company records of this activity correspond with these sharp drops.

The change in mean bed elevation (MBE) with discharge at the various gaging stations (figures 35 and 36) is complicated by channel shape itself. Unless there is no change in width with discharge, even a bed that neither scours or fills will show "fill" during higher discharges because of the gain in channel elevation along the sloping bed as the water surface rises. However, if MBE is reduced during higher discharges, then the bed has definitely scoured, but to an uncertain extent. The sloping-bed effect is less important with steeper banks (a low *b* hydraulic geometry exponent), but slight filling and scour with changing discharge can be masked by this effect.

Others have used the same method of tracking bed elevation (e.g. Anderson 1979) as in this study, and I have discussed this method with hydrographers, but neither have mentioned the sloping-bed effect. Only simple geometry is required to see this effect, but I did not realize the effect for a long time. Future work involving this method should consider this.

Although the South Fork banks are steep, scour and fill is slight enough at the Alpine, Irwin, and Heise gages (figures 37 to 39) for the above effect to become important in interpreting figures 35 and 36. When viewing these figures, consider that discharge returns to a similar base level each year and any significant drop or rise after a season represents true scour or fill. Another less intuitive (but more precise) way to show mean bed elevation dynamics (MBE) is shown in appendix C, where mean bed elevation was regressed on gage height and the residual is plotted against time and gage height. If there is truly no change in channel shape due to scour and fill, MBE and gage height would show a perfect fit (not necessarily linear), barring measurement error. Errors on these plots show similar time trends and magnitudes as in figure 35. Trends are difficult to assess for the Lyon gage due to clustering of gage height values, but the shift at Dry Canyon is apparent. Therefore, some of the change in MBE is due to scour and fill, but there is undoubtedly some measurement error. Judging by the data pattern and field measurement precision, deviations greater than .2 feet around a central tendency probably represent scour or fill.

Another indicator for slope change is channel sinuosity. Channel sinuosities during the pre– and post–Palisades dam periods, as measured on 1941 and 1987 aerial photography, are presented in figure 44. The values are for the entire channel length common to both aerial photography flights, which is the majority of the volcanic-canyon reach. There has been little change in sinuosity between the two periods for the entire measured area, but some reaches show considerable change. Changes can be in either direction, and are largely due to additions or subtractions of anabranches due to past channel evulsions or cut-offs. The additions and subtractions of side-channels are apparently balanced, but there is a tendency towards shorter and more numerous anabranches.



Values for all measured reaches:

	Total Sinuosity	Valley Sinuosity	Hydraulic Sinuosity Index
Pre-dam (1941)	1.98	1.27	72.45 %
Post-dam (1987)	2.02	1.27	73.53 %

Figure 43. Channel plan view and sinuosities during 1941 and 1987. Sinuosity is shown for each respective reach and period

DISCUSSION

Considering the results, the South Fork's form and process has changed little over the last 36 years since dam closure. This lack of change is due to three main reasons: 1) the inherently stable nature of the river during low peak flows, 2) the source, size, and movement patterns of bed load, and 3) the similar magnitude of the bankfull discharge during pre- and post-dam periods. However, some factors have changed with dam closure, the most important being a drastic reduction in bed load below the dam and elimination of the moderate and high peak flows or floods.

To better explain how the South Fork will respond in both form and process to changes in these important factors as well as some minor ones, the natural river before Palisades dam will be described, followed by the expected response due to damming. The underlying reasons for the expected response will also be presented. So that the South Fork can be viewed in context to other rivers, some comparison to situations on other dammed rivers are given. The composition of the flood plain and terraces and nature of the drainage basin were discussed in detail previously and will only be related in general terms here. As well, riparian vegetation will be related in general but described in more detail in chapter 4.

The natural river - Since at least the last 150 years, the South Fork can be characterized as a perennial, stable-braided, cobble-bedded river with a discharge largely driven by snowmelt having a low sediment load. In general, the size of the river channel and its flood plain are related to the discharge while the pattern is largely due to the composition of bed load and channel deposits, which are similar.

The perennial status of the South Fork during early-settlement times (1890's) has been challenged by some descendants of the area's pioneers. They state that "the river was dry in 3 out of 5 years" and travel was possible in the channel during dry times. If this were true, it has great implications for interpreting past events, but there is considerable evidence to the contrary. The stream flow record shows continuous flow during years of continuous measurement, which began during 1903 at Lyon, Idaho. Some winter flow calculations are complicated by ice and some of these situations are shown as gaps in figure 7 (page 56), but the records show estimated flows during these ice periods. Thus, the river has been perennial since at least 1904. For such a large river to be dry as stated, there would have to be a drastic difference in climate during at least the late 1800's as compared to the period of streamflow measurement. Native vegetation and the extent of summer snowfields between the two periods would reflect such a change. Early accounts from the trapping era during the mid-1800's (Haines 1955), early government surveys (Hayden 1873; Hayden 1879), and various photographs, especially those of W. H. Jackson taken during the 1870's, do not reflect such a drastic climate change. Also, winter flows are typically lowered due to Jackson Lake dam operation beginning in 1905, but again, flows are still perennial since this time.

The braided pattern of the river shows in early survey maps as well as on aerial photography taken before dam closure; some of these plan views are shown in figures 28 to 30 (p. 84 to 86) and figure 44. There are several types of braided rivers and the various patterns and dynamics are due to several processes (Smith 1973; Fahnestock 1963; Fahnestock and Bradley 1973; Schumm 1981; Ashmore 1991). In general, bank erosion resistance, sediment particle size distribution, and sediment load relative to channel capacity, either singly or in combination are the main factors involved in braiding. Although an excess sediment load relative to a channel's capacity to move the sediment, or in other words an aggrading stream, is an oft-stated reason for braiding, it is not a necessary requirement (Leopold and Wolman 1957; Fahnestock 1963).

The direct physical sedimentary cause for braiding according to Ashmore (1991) is local aggradation and loss of competence in lateral flow expansion, and the initiation and maintenance of braiding are often triggered by local short-term pulses in bed load supply. However, pulsing or uneven distribution of sediment in time and space is common to every alluvial river, and the noting of this phenomenon is common in the literature (e.g. Gilbert 1914; Langbein and Leopold 1968; Leopold and Emmett 1976; Andrews 1979; Reid, Frostick, and Layman 1985; Carson and Griffiths 1989). The "piling up" or concentration of sediment so common in streams is largely explained by kinematic wave theory.(Langbein and Leopold 1968). In this theory, concentrations of particles in dunes, riffles, and other wave bed forms results when moving particles become too closely spaced and interact, thereby reducing the effectiveness of the ambient water to move them. The underlying reason for this or the generally uneven flow of fluid is not understood.

The braiding pattern and process found in nature is continuous from the wide, shallow, rapidly-shifting, almost infinite-channeled river , to the very stable, multi-channeled river with deeper, narrower channels with one main channel. The very stable type is called anastomosed by some (Smith 1973; Schumm 1981); the distinction is due to process. The "true" braided rivers have relatively high bed load to suspended sediment load ratios, while the anastomosed type have the opposite. Stability is enhanced by the binding action of finer-textured sediments (Schumm 1960; Smith 1973; Schumm 1981). The South Fork falls more towards the latter end of the spectrum (figure 44). Although the channel is usually stable as evidenced by pioneer vegetation patterns, it is not anastomosed as defined because of the low suspended sediment load. The coarse channel material shown in figures 40 to 43 (pages 99 to 102) is typical since at least 1877, judging by the descriptions of Hayden (1879) and field evidence (see chapter 2 and appendix C). Given the above, there is a paradox between channel pattern, sediment composition, and channel stability on the South Fork. Some of this will be explained later, but future work will cover it in more detail.

The natural flow regime reflects the usual snowmelt pattern, except diurnal fluctuations found on smaller streams are much dampened, evidenced by the similar magnitude of instantaneous and mean daily discharges (appendix B). Peak runoff timing varies year to year, but is modal around mid-June (figure 7; p. 56)). Many annual hydrographs have 2 or 3 higher peaks; the Alpine and Lyon hydrographs typifies this (figures 6 and 7; p. 29 and 56). Based on my own observations and data shown in figure 6, the multiple peaks are largely due to alternating warm and cold periods rather than direct precipitation events. Basin-wide rain-on-snow events are rare; frontal storms nearly always result in snow in the higher mountains. Rain on an existing snowpack results in high flows when the snowpack is thin enough to melt rapidly (Harr 1981). This situation, which is common in maritime climates, is most likely to occur in the study area during the autumn and early winter; however, autumn and winter discharge is consistently low during the record period (figure 7; p. 56). Because of the nature of snowmelt, where precipitation is absorbed by soils with no splash impact, erosion is low over much of the drainage basin most of the time. The work of Marston (1990) discussed in chapter 2 supports this.

Channel cross-sectional area is largely due to the higher, less frequent discharges (Leopold and Wolman 1957; Wolman and Miller 1960; Schumm and Lichty 1963; Dury 1973; Hickin and Sichingabula 1988). In other words, floods determine channel shape and width is usually the most responsive. The bankfull discharge, which typically occurs every 1 or 2 years, performs much of the work in moving sediment over longer time frames, such as decades (Wolman and Miller 1960). The bankfull discharge is also closely related to incipient movement of channel material (Keller 1971; Andrews 1979; Andrews 1982). Scour and fill on the South Fork as measured at the various gaging stations follows the same pattern, where mean channel shape shifts with passage of discharges near bankfull (figures 37 to 39; p. 96 to 98).

Even if this relation of bankfull discharge to sediment dynamics is true, it does not tell the whole story behind channel morphology. Although it is clear that discharges much below bankfull do little work, the role of catastrophic floods in channel and flood plain morphology is equivocal. Some river reaches change little with very large events (Dury 1973; Platts et al. 1985; Hickin and Sichingabula 1988), while others change considerably (Schuum and Lichty 1963; Stewart and LaMarche 1967; Scott and Gravlee 1968; Platts et al. 1985; Hickin and Sichingabula 1988). Width change and channel migration rates have large implications for riparian vegetation dynamics, and future work will address this issue in detail. Based on the evidence presented so far, channel migration rates and width changes were slight (figure 44, table 6) from 1941 to 1987. Only a few larger floods occurred during this time (figure 9; p. 58). The general stability of the hydraulic geometry during the period of only moderate floods (figures 9, 17 to 20, 22 to 26;

pages58, 68 to 71, 73 to 78) and the shift during a large flood (figure 9 and 21) also point to channel stability below a certain threshold.

Bed load movement rate can be inferred from figures 35 to 39, which show the mean bed elevation dynamics and shape changes. Some of these changes may be due to the differing heights of individual cobbles, but scour and fill definitely occurs, especially at Alpine and Heise. The changes at Irwin are slight and it is hard to say if bed load still moves here, although a significant change occurred as late as 1988 (figure 35). The Irwin station is only 23 channel widths below the dam, but despite evidence of bed load movement, the channel has not degraded since dam closure (figures 35, 40, and 41). The 1.5 mile reach between the dam and the station has provided enough sediment to replenish any scour at the Irwin cross-section since dam closure through at least 1990. This 1.5 mile reach has only 3 very small tributaries, with Sheep Creek being the largest (figure 1; p. 4). Apparently, bed load moves short distances .

The natural suspended sediment characteristics are difficult to reconstruct from the data, but a gross characterization is possible. By combining the work of Vanoni (1941), Vanoni (1946), Vanoni and Nomicos (1960), sediment data at Heise, aerial photography flown during natural flows, and field observations, the natural suspended sediment regime in the South Fork can be approximated.

In order to reconstruct the natural sediment regime, the dam release condition, which is essentially clear water, is compared to the pre-dam condition at the Irwin station. Changes in skin- and internal distortion-resistance can complicate this comparison, but their effect appears similar across the two conditions, even at low discharges (figure 31; p. 88). With a constant bed configuration, channel flow resistance is reduced with increasing suspended sediment concentration (Vanoni 1941; Vanoni 1946; Vanoni and Nomicos 1960).

Suspended sediment concentration and load measured at the Heise station since dam closure are low (figures 12 and13; p. 62) compared to some other natural rivers (Williams 1989), which have concentrations 4 to 100 times higher than the present South Fork's. The natural sediment concentration was undoubtedly higher at the Irwin station as compared to dam releases due to the trapping of sediment in the reservoir, but the natural concentration still may not have been very high. Typical increases in velocity of sediment-laden water compared to clear water can be between 4 and 11 percent (Vanoni 1941; Vanoni 1946). In this same work, the corresponding decreases in the friction factor were about 10 and 20%. These changes are associated with modest sediment concentrations ranging from 1200 to 3300 mg/l. The more complete work of Vanoni and Nomicos (1960) show similar relations of velocity and friction with increasing sediment, their most important addition being the control over the effect of bed forms. Their results show a decrease in the friction factor between 5 and 28% with corresponding sediment concentrations between 3640 and 8080 mg/l as compared to the friction factor with clear water. Unlike many investigations involving sediment, Vanoni and his colleague's results are quite precise and should be reliable enough for the following comparison.

Aerial photography taken September 14, 1951 shows a river with clearly discernable bottom features. The discharge was 7410 cfs, which is near the mean annual flow (table 4). This discharge fills about 1/3 of the total channel capacity (Leopold et al. 1964). In contrast, the river is opaque and presumably higher in suspended sediment on July 14, 1952 with a discharge of 13,700 cfs. The South Fork is quite opaque with suspended sediment even after dam closure, but concentrations still only reach about 100 mg/l (figure 13; p. 62). After dam closure, the South Fork's friction factor relation to discharge at Irwin is similar to the pre-dam condition (figure 31; p. 88). Although no great precision can be claimed for the South Fork friction factor relations, the similarity of the relation before and after dam closure at the Irwin station indicates that natural sediment concentrations were probably not much higher than 8000 mg/l. Beyond this level and with similar variance, there would likely be a noticeable shift in the relation at Irwin resulting in higher friction factors for a given discharge after dam closure. Also, the slope for the velocity-to-discharge relation would be lower at Irwin after dam closure but the opposite effect has occurred (figure 15; p. 64). As discussed earlier, the velocity increase is likely due to an increase in hydraulic head associated with reservoir storage.

The hydraulic geometry at the various stations (figure 27; p. 79) characterize a channel with stable banks, low bed load transport rate, low roughness, and moderate competence. The high width-to-depth ratio also implies a higher bed load as compared to suspended sediment load (Leopold and Maddock 1953; Wilcock 1971; Carson and Griffiths 1987). These characteristics derived from station data cohere with those derived from other data sources mentioned earlier.

<u>The river after damming</u> - Alluvial river channels downstream from dams change their form over time. These changes are complex and difficult to predict. The following discussion describes the changes in the South Fork since dam closure and attempts to predict long-term changes.

If a channel is in equilibrium with water and sediment discharge and if one or both of these factors change as is usually the case upon dam closure, some change in morphology can be expected. The most common change examined is channel degradation, where the bed elevation is lowered due to scour of bed materials with no subsequent replacement. As explained by Petts (1979, 1980) and Williams and Wolman (1984), channel changes are not limited to degradation and include aggradation, channel widening or narrowing, increasing or decreasing roughness, changes in planform such as braided to meandering and the related sinuosity, and reduced or increased channel migration rate (Bradley and Smith 1984). Riparian vegetation usually responds to these channel changes, especially changes in channel shape, and channels can also respond to these vegetation changes (Graf 1978; Crouch 1979a; Williams and Wolman 1984; Hereford 1991).

The direction and rate of channel changes depends on the initial channel condition and the changes in sediment and water discharges with dam operation. There are many documented case studies, many of which are reviewed by Petts (1979) and Williams and Wolman (1984). From these case studies and their own investigations, rates of channel changes can be roughly predicted, but the direction of change is much more difficult. For example, observed channel degradation rates follow a similar pattern, but whether a channel will degrade or aggrade is difficult to predict before dam operation, especially if tributaries enter below the dam. Even if channel erosion is reasonably certain, whether a channel will widen or deepen is difficult to predict; this depends on the relative resistance to scour of the bed and banks which can be subtle and difficult to measure or judge. Part of the prediction problem is the lack of documentation of sediment and water discharge regimes and important channel characteristics such as bed and bank particle size distributions prior to dam construction.

With the operation of Palisades dam since 1956, most suspended sediment load and all the bed load that would otherwise pass through the reach immediately below the dam is eliminated. Because of the few large tributaries below the dam (figure 1; p.4), much of the sediment load for the primary study area was supplied by the South Fork reaches above the dam site. In turn, the upper South Fork gained its sediment from the terrace scarps (which are quite high where the channel impinges on the older terraces) and the various tributaries. As shown in figures 7 to 10 (pp. 56 to 59) and table 4 (p. 54), the bankfull discharge has changed little with dam operation.

Given the above scenario of reduced sediment load and similar bankfull discharge, one would expect the South Fork channel to be eroded, either through widening, degradation, or both. In fact, both are occurring, but the rates of widening and degradation are small compared to other studied rivers. For example, channel degradation is often on the order of feet or meters, and occurs within 10 years on many documented cases (Williams and Wolman 1984). The ratio of post-dam width to pre-dam width (W_t/W_0), either decreasing or increasing, follow the same temporal dynamics and are on the order of $W_t/W_0 = .039$ to 4.45 for individual cross-sections (Williams and Wolman 1984). These ratios correspond to about a 96 percent reduction and 445 percent increase in width, respectively. However, width changes are not systematic in a downstream direction as in degradation. Bradley and Smith (1984) noted channel degradation of 1.5 meters and a 25 percent width decrease on the Milk River below Fresno dam, but time dynamics are not reported.

So far, the only sign of channel changes on the South Fork are shown in figures 42 and 43 (pp. 101 and 102), where a coarsening of bed material after dam closure is obvious and an associated channel degradation is likely. Widening was apparent in the field, but is not as clear in figure 43. A short distance downstream, a continuous record of channel bed elevation shows no consistent trend in degradation (figure 35; p. 94) since dam closure. This lack of change is not due to lack of bed load movement; bed scour and fill still occurs (figures 35 and 38) and filling occurs with the passage of peak discharge (figure 38; p. 97). Bed elevation dynamics at the Heise and Alpine gages are similar to the Irwin station's (figure 35).

In contrast to bed load movement which appears small, width change can be potentially large if channel banks are cut without the usual accretion on the opposite side. Usually, a channel simply migrates laterally, maintaining its width if erosion and deposition of channel material is equal. A channel will widen if erosion is higher than accretion. The width at the Irwin gage has not changed (figures 19 and 20; p. 70 and 71), but the banks are formed in a Pleistocene terrace and are quite stable here (see chapter 2). Because of this bank stability, any channel adjustment due to sediment depletion is more likely to occur in the vertical direction, but as mentioned above, none has occurred except some temporary aggradation during dam construction (figure 35; p. 94). Channel width over most of the study area has also remained essentially constant, despite channel migration (table 6, figure 44; p. 82 and 106). Much of the channel migration occurred during the pre-dam period, but some has occurred since, judging by channel positions shown on 1960 and 1987 aerial photography.

When individual pre- dam (1941) and post-dam (1987) reaches are compared, both narrowing and widening has occurred as well as the constant width condition (table 6, figure 44). Reaches 2 and 6 have the highest width increase since 1941, and these reaches also show a higher degree of channel pattern change. This correlation between channel migration and width increase may not be a real trend, however; 6 out of the 10 measured reaches have either significantly reduced widths or have remained unchanged, but still had pattern changes. A significant increase or decrease is defined here as being greater than 4 percent. This percentage is equal to Williams and Wolman's (1984) arbitrary cutoff value. The net increase in width for all reaches of about 4 percent may reflect the discharge history 5 years before the aerial photography times. Referring to figure 9 (page 58), the peak discharges were moderate to low from 1937 to 1941, with none higher than 23,100 cfs in 1938. The same time interval before the 1987 flight includes higher discharges, with the 1986 peak discharge being the highest since dam closure at 27,000 cfs, and the other years at least 21,400 cfs. The width increase may be due to the higher peak discharges immediately before the 1987 photography.

There are some subtle changes that can be expected due to dam closure and these include an increase in relative roughness due to increasing particle size distribution, an additional increase in friction due to a reduction in suspended sediment which has already been discussed, change in competence due to a reduction in the density of the water-suspended sediment mixture, and less ice.

Channel roughness could increase primarily due to a change in relative roughness or skin resistance, which is in turn due to a likely shift in bed particle size distribution as the smaller particles are winnowed away. With constant channel boundary dimensions and an increase in skin resistance, the velocity for a given discharge is reduced, and the reduction is more easily detected at low depths or discharges. However, although there is no noticable change in channel shape (figure 40 and 41; p. 99 and 100), there is still no indication of an increase in skin resistance since dam closure at the Irwin station, where it is most likely to occur (figure 31; p. 88). In fact, some low discharges since dam closure have a slightly increased velocity, but this may be due to higher hydraulic head when the reservoir is fuller. Low flows during very low reservoir capacity are more comparable to the pre-dam condition, but I did not make this comparison, for there are vaery few observations.

The velocity-to-discharge relation for the higher flow regimes, where suspended sediment would have the most effect, does not reflect the expected increase in friction (figure 15; p. 64). The details behind roughness changes are explained previously, but there is apparently no change in roughness since dam closure, except perhaps near Sheep Creek (figures 42 and 43; p. 101 and 102) and during dam construction (figure 32;). The density of the sediment-water mixture is probably lower after dam closure, especially near the dam. This decrease in density may lower the flow competence for a given discharge. For cobble bed material, Pemberton and Lara (1984) show about a 17 percent reduction in tractive force for clear water vs. water and colloidal silts. However, they do not give densities for any sediment mixtures so their information is difficult to apply. In light of the similarity of bed scour magnitudes before and after dam closure, density changes on the South Fork are probably minor in context to stream competence.

Winter temperatures are cold enough to freeze the river to a varying extent. Dam releases during winter may warmer than pre-dam flows, because denser, warmer-than-freezing water is apt to be at the the deepest stratum of the reservoir (water density is highest at 4° C) and the outlet works are near the dam's bottom. For the pre-dam period, hydrographers notes often mention severe icing, with the river being gorged with ice for several days or weeks. The more recent notes are less specific about degree of icing, but according to a local resident, the river does not gorge with ice very often since dam closure (Spaulding pers. comm. 1993). The gage record does not show high water surface heights during winter (figure 7; p. 56). Spaulding says that water occassionally backs-up, but does not remember torrents due to rapid ice-break up. My own experience concurs with this: I spent many winter days during the 1988/1989 winter which had unusually high ice amounts. Even though the channel was about 95 percent frozen, the ice melted slow and I saw no evidence of torrents. Fishery research the following year experienced heavy ice too, but the modest spring flood (23,000 cfs) had the only notable effect on channel boundaries (Schrader pers. comm. 1992). However, there is an account of a "big bang" and a channel change during March 1901, near the Great Feeder head gate's Diversion Dam (Carter 1955).

With a change in channel boundary shape or bed particle sizes, the rates of change of width, depth, and velocity with changing discharge, or the hydraulic geometry (Leopold and Maddock 1953) should change accordingly. The hydraulic geometry relations can be thought of as the "pulse" of a river; a change in the exponents indicates a change in river form and process. Indeed, after closure of Hoover dam, the hydraulic geometry relations on the Colorado River at Yuma, Arizona, which is 350 miles below the Dam and where channel boundary changes were large, show drastic changes in hydraulic geometry (Leopold and Maddock 1953). On the South Fork, the before- and after-dam exponents have changed slightly at Irwin, and the width exponent at Heise has the highest deviation (table 5; p. 66 and figure 26; p. 78). At the Lyon station, the depth and velocity exponents changed moderately after a passage of a large flood (figure 21; p. 72), but the record ends soon after this event so a possible recovery to the previous relation is undetectable. Time will tell if the slight shift at Irwin represents an effect of the dam or is a natural deviation. As mentioned earlier, the stable banks at Irwin restrict width-increases somewhat, so one would expect any channel changes to show in the depth and velocity exponents. The minimum variance theory of Langbein (1964) tested by Williams (1978) predicts that channel adjustments shown in the exponents will be spread evenly and minimized among the exponents. Considering the channel at Irwin before and after dam closure and given a fixed width, coarsening of bed material, and reduction in slope, one would expect the depth exponent (f) to increase at the expense of velocity (m). This trend, however small and perhaps meaningless, is apparent in the data (table 5,figure 26). The opposite trend occurs at Heise after dam closure, but the remoteness of this station from the dam and periodic modifications from a canal company complicates interpretation.

One more indication of a change in channel process is sinuosity, which is usually defined as the ratio of channel length to valley length. Sinuosity also represents the ratio of channel slope to valley slope; with a constant valley slope, a change in sinuosity indicates a change in channel slope. As in width change for the same periods, some reaches have sinuosity changes either in a positive or negative direction (figure 44; p. 106). These positive or negative changes mainly reflect channel avulsions or closures, respectively, and in a sense, sinuosity may represent horizontal channel stability (Mills 1991). The overall sinuosity for all reaches between the two periods (1941 and 1987) has remained essentially unchanged; the creation of new and the filling-in of old channels is apparently balanced. However, there is a tendency towards smaller islands and shorter, more frequent anabranches since dam closure (figure 44; p. 106).

The very slight change in channel sinuosity on the South Fork is in contrast to that in the upper Snake River below Jackson Lake dam. Mills (1991) compared the Snake River's sinuosity for various periods and found much larger changes. Although we used similar methods (his total sinuosity index is the same as the total sinuosity I show in figure 44 — the hydraulic sinuosity index is an extra step — see methods section), Mills' (1991) results for sinuosity measured during a similar time period is 1.73 and 2.21. The South Fork's values are 1.98 and 2.02. Although Mills (1991) does not show control over discharge at the times of photography as done here, some or all of the difference in sinuosity change between the two study reaches may be due to sediment dynamics. As explained more fully in chapter 2, peak discharges were reduced below Jackson Lake after closure of Palisades, but the sediment load remained the same below Jackson Lake. The South Fork has undergone a reduction in the larger peak discharges and sediment is trapped by the reservoir

Increased braiding (and therefore total sinuosity) can occur with higher flood events, but an increase can occur with excessive sediment loads (Mills 1991), which is the "textbook" case of aggrading, braided rivers.

The South Fork's remarkable lack of change is only remarkable in context to most other rivers that have been studied, especially in their response to damming. A majority of these rivers have fine-textured channel boundaries, and once dislodged, sediment particles have low enough fall velocities to be entrained long distances. Such is not the case for the South Fork.

Although gravel- and cobble-bed rivers can have proportionately larger loads of sands in their bed loads as compared to what is seen on the bed (Leopold and Emmett 1976), I don't think sand makes up a very large proportion of the South Fork's bed load. Even considering bed particle size distribution fining with depth (Bagnold 1968), channel degradation would be higher as the sand would be moved great distances as the cobble layers are unravelled during high shear stresses, thus reducing the local sediment volume with resulting degradation.

The East Fork River, where Leopold and Emmett (1976) first accurately measured bed load, has much higher exposed sand on its bed than even the pre-dam South Fork. This comparison is based on descriptions of the East Fork River in Andrews (1979), my own visits to the East Fork study reaches, and pre-dam photography of the South Fork bed, some of which are included here (figures 40 and 42; p. 99 and 101).

Given the process changes due to Palisades reservoir and the slight morphology changes so far, it is logical to ask what the long-term changes in the South Fork will be, especially in relation to riparian vegetation. However, in view of the difficulty in predicting long-term channel morphology trends in dammed alluvial rivers (Petts 1979, Williams and Wolman 1984) and the disparate nature of the South Fork as compared to other studied rivers, I will use two approaches to predicting changes: extrapolation of present trends, using Hutton's uniformitarianism concept (Thornbury 1954), and a field situation analogous to the South Fork's.

The local widening, bed-particle coarsening, and likely degradation 0.5 river miles below the dam at Sheep Creek (figure 42 and 43; p. 100 and 101), indicates channel boundary erosion. The lack of such erosional evidence 1.5 river miles below the dam (figures 35, 40, and 41; p. 94, 99, and 100) indicates very slow channel boundary enlargement. With this enlargement and coarsening the channel becomes more stable due to lower velocities for a given discharge and increasing bed particle sizes. Once enlargement begins at the Irwin station, the downstream migration of enlargement, or marching rate, can be somewhat estimated. But until this happens, one can only say the rate is at the most about 200 feet per year. As this enlargement process slowly marches downstream, riparian vegetation that depends on fresh, moist, bare mineral soil for establishment will slowly disappear as old individuals die. The cottonwood is one of these species at risk. With increased peak discharges similar to the pre-dam period, the marching rate may even increase.

This eminent change in channel morphology will eventually be a death-knell to the riparian forest as we know it today, but 'how long is eventually?'. To help answer this question, a comparison to a natural stream channel that has existed for many decades or even centuries, with a sediment source and flow regime similar to the dammed South Fork is required. Such a channel exists; it is a Snake River tributary below Jenny Lake, in Grand Teton National Park, Wyoming, aptly named Cottonwood Creek.

There are many other creeks that are below lakes in the drainage basin, but the very gradual transition of Jenny Lake's surface to Cottonwood Creek is especially helpful. Because the moraine surrounding Jenny Lake is much lower than the other Pinedale-aged, piedmont lakes (see chapter 2), channel dynamics immediately below the lake are not complicated by the steeper slope of the moraine front. Jenny Lake is analogous to a reservoir with a spillway equal to the height of the channel below. The lake has trapped all bed load since the late Pleistocene, and Cottonwood Creek is bounded by the 30-foot, Pinedale-aged terrace (see chapter 2).

The width of Cottonwood Creek is unusually large for the first 0.5 miles below the lake (figure 45), the depth appears greater than downstream reaches, and the velocity is so slow it is difficult to see where the Lake stops and the Creek begins. Nevertheless, the cottonwood riparian forest gradually increases beginning where the width constricts and the velocity and depth recover to what would be expected for creeks of similar discharge in the region. Cottonwood Creek has its own tributaries, but most have a lake a short distance above their confluences with Cottonwood Creek, so sediment loads are probably low in in these tributaries with lakes (figure 45). Moreover, the cottonwood forest begins above the first large tributary.

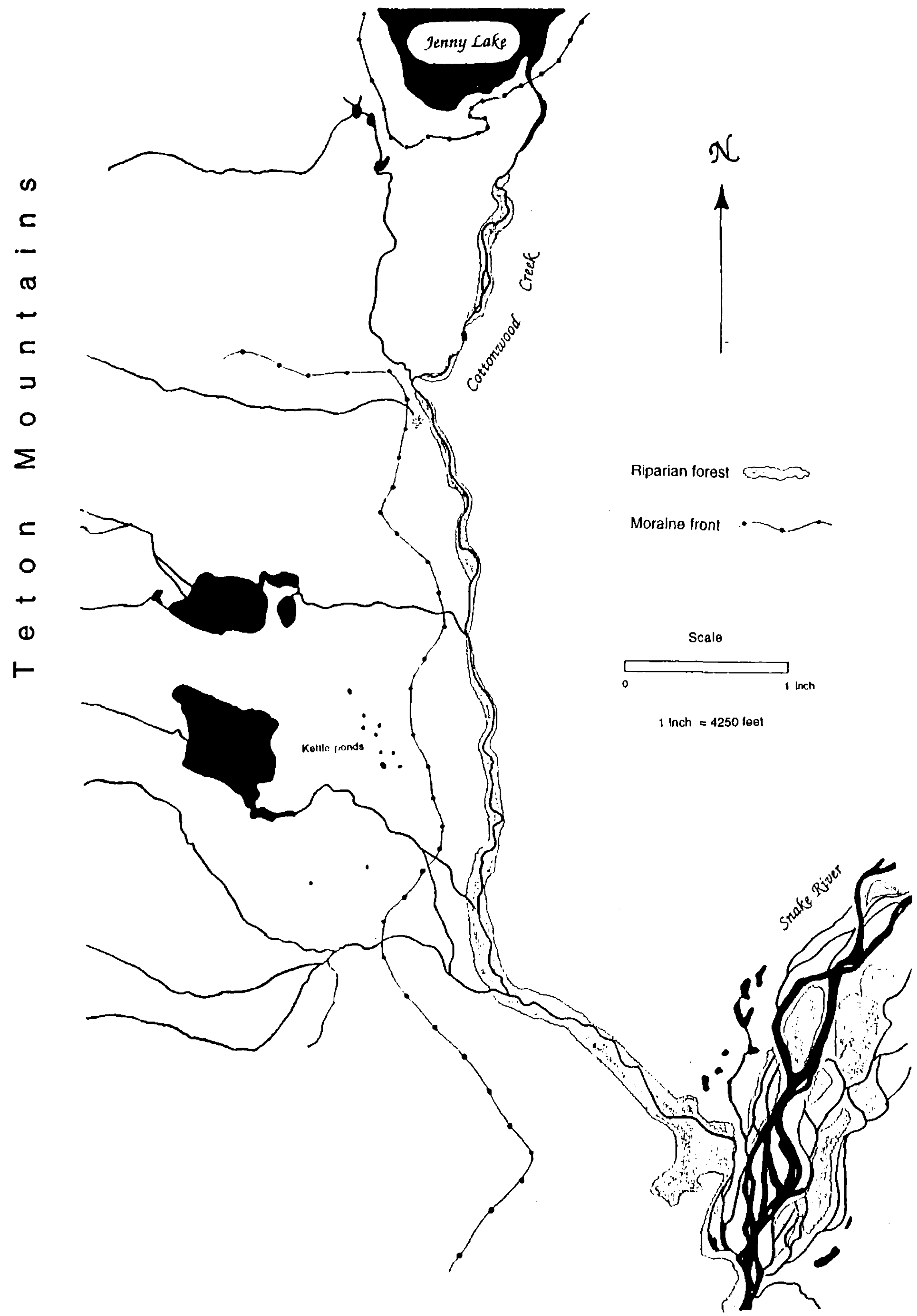


Figure 45. Plan view of Jenny Lake and Cottonwood Creek and extent of riparian forest.. Map compiled from 7.5′ USGS topographic maps (Jenny Lake, WY and Moose, Wy), orthophoto maps in Young (1982), and field visits.

Cottonwood Creek, like the Snake River, has cut into the old flood plain now making up the 30-foot terrace, but convergence of the present channel grade and terrace tread is opposite from the usual situation: the maximum deviation occurs at the downstream-end of Cottonwood Creek. Even though the channel has degraded, perhaps over the years bed load has been recruited from the increasingly higher banks formed in the terrace.

Based on the evidence so far on the South Fork and the working model of Cottonwood Creek, the South Fork channel is likely to continue to degrade and increase in width as it has just below the dam, and these changes will migrate downstream. It may take several decades or even centuries before large changes occur downstream of the terraced reach (see chapter 2) on the South Fork.

SUMMARY

The morphology of the South Fork has changed little since Palisades dam closure in November 1956, especially when compared to the more drastic changes occurring on other dammed rivers. However, with dam closure some processes have changed and they are just beginning to manifest themselves as changes in morphology. Two main processes that have changed due to Palisades reservoir management are a drastic reduction in bed load and the elimination of peak flows larger than the 3-year flood. The natural suspended sediment concentration and load estimates are low, and there is no apparent difference in the velocity-to discharge relation due to a change in suspended sediment concentration.

To date, changes in morphology most clearly related to impoundment are an obvious coarsening of bed sediment, a likely decrease in slope, and local increases in width within the first river mile below the dam. These changes are likely to migrate slowly downstream as the smaller bed load particles are moved downstream and are not replaced. Bed particles apparently move very short distances with each annual peak discharge. Evidence of this slow movement rate is the lack of channel degradation 34 years after dam closure at the the Irwin gaging station 1.5 river-miles below the dam. Some scour and fill probably occurs at all measured stations, but no measurable degradation or aggradation has occurred since dam closure.

For a constant discharge, the 1987 channel width is a net 4 percent larger than in 1941. This slight increase may reflect discharge history immediately before the respective years. Channel migration has occurred during the same period, indicating that bank erosion and accretion are still in balance. Total sinuosity, considering all anabranches, has also remained similar, being 1.98 in 1941 and 2.02 in 1987, indicating that slope and horizontal channel stability have hardly changed since dam closure.

The at-a-station hydraulic geometry for 3 stations, including 1 station above the reservoir, show statistically significant but very slight changes. The shift in exponents since dam closure for the station just below the dam indicate a slight increase in channel roughness. However, the friction factor at low flow shows no trend.

Based on Snake River results and an analogous but older situation on a tributary, I predict the Snake River below Palisades Dam will undergo a gradual increase in width and reduction in velocity for a given discharge. These changes will slowly migrate downstream with a predicted rate of at most 200 feet per year.

SOME ASPECTS OF HYDRAULIC GEOMETRY

The hydraulic geometry for the various Snake River gaging stations was an important component of the primary analysis and the most pertinent results are already presented. This section serves as a more detailed and complete analysis of the geometry at the Snake River stations including curve fitting technique, Snake River channel behavior, and the geometry and behavior of other rivers. The two main themes are model building and interpretation.

MODEL BUILDING

Definition and approach - Model building is defined here as fitting a line through observed bivariate data, or a regression. The approach in this study is purely empirical, and line equation parameters for a given station and period have a unique mean and variance and are treated as such. No attention is given to theoretical, most probable equations as some have (e.g., Langbein and Leopold 1964; Rhodes 1977).

Model formulation - The equations presented thus far are power functions, which are the traditional way of fitting hydraulic geometry data. Data having a power function distribution will plot as a straight line on double-log paper. Figures 17 to 25 show the data plotted on a base-10 log scale in the original units.

Because power functions are linear in base-10 logarithms, I log-transformed all variables for regression analyisis. As an example for width, w and discharge, Q:

$$w = a\,Q^{b} \qquad \text{(power function)}$$

$$\log w = \log a + b(\log Q) \qquad \text{(log-linear)}$$

The power function exponent has the same value as the log-linear model's slope parameter, which in the above example is b.

Although power functions are commonly used for hydraulic geometry, there is no *a priori* reason that they should represent hydraulic geometry relations (Richards 1973). In fact, the relations between discharge and width, depth, and velocity do not always conform to a power function or the equivalent log-linear model. Because of this, two other forms have been proposed and used. One is the log-quadratic model (Richards 1973) and the log-piecewise linear model (Bates 1990). The former is especially useful when the log-transformed relationship is curved rather than straight, the latter is better when these relations have more than one linear section, with each section having a different slope. As with the power function or log-linear model, both of these newer models have a continuity relationship between the parameters. In this study, only the log-linear (LLM) and log-quadratic (LQM) models were used and compared. Patterns in the South Fork data did not warrant the increased complexity of the log-piecewise model (LPM), so the LPM was not used. Simple linear and quadratic models using the original units yielded poor fits.

Using width and discharge again as an example, the basic form for the log-quadratic model is:

$$\log w = a + b_1(\log Q) + b_2(\log Q)^2$$

If the slope parameter b_2, is 0, then the model simplifies to the log-linear model. The continuity relationship between the parameters is:

$$(b + f + m) + 2(b_2 + f_2 + m_2)\log Q = 1$$

where b_2, f_2 , and m_2 are the respective quadratic terms for the width, depth and velocity equations.

Identifying channel changes over time was an important aspect of this study. A variation of conventional hydraulic geometry is unit hydraulic geometry, which is based on unit discharge and has greater application in defining channel changes (Williams 1987). Unit discharge, $q' = Q / W$, leaves just two relations: $d = c'Q^{f'}$ and $v = k'Q^{m'}$. Although this method detected channel changes in other rivers (Williams 1987) which are similar to the South Fork, changes on the South Fork were no more apparent than with the conventional method. Figure 46 shows the unit hydraulic geometry at the Irwin gage.

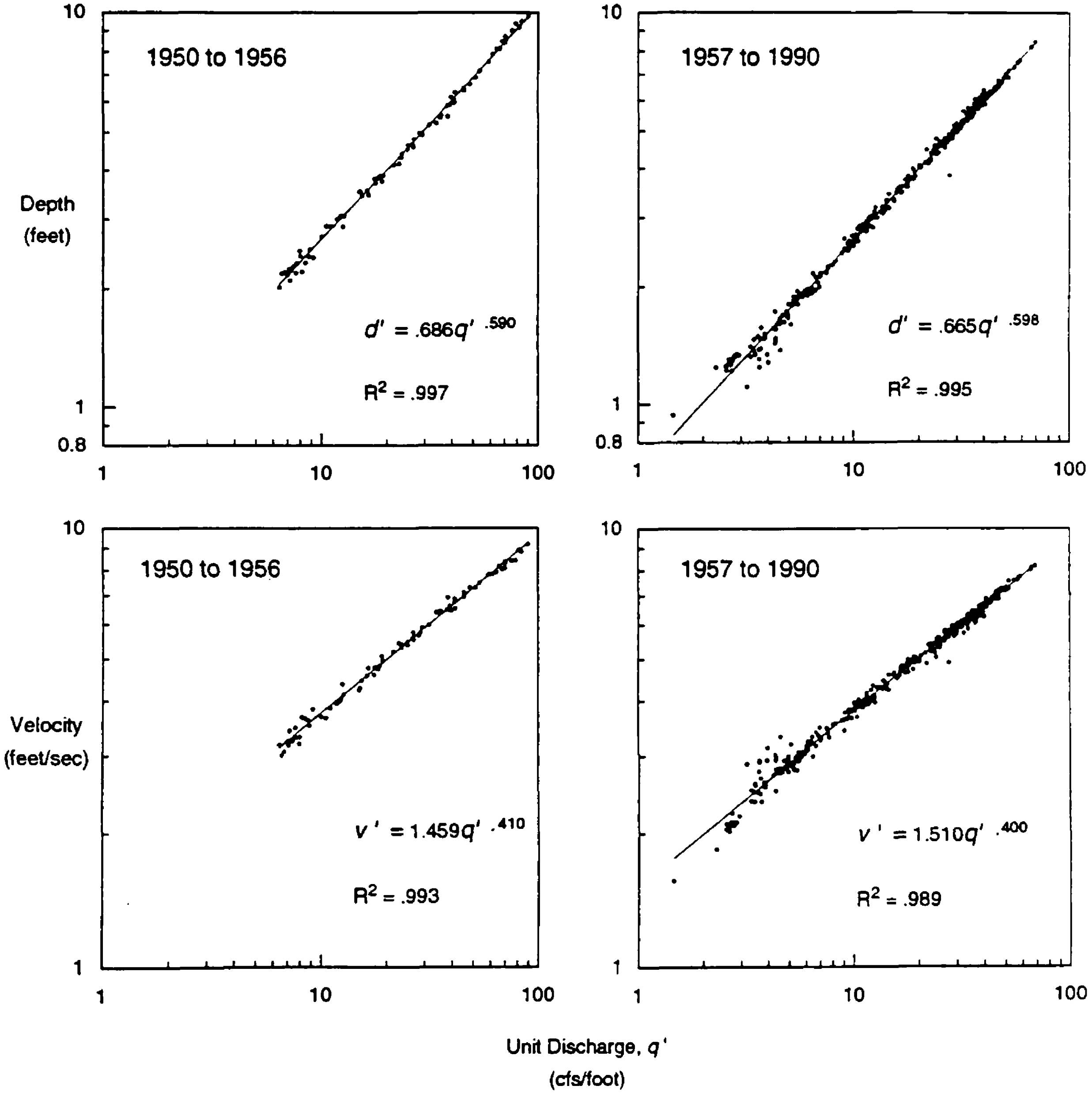


Figure 46. Unit hydraulic geometry for Snake River near Irwin, Idaho.

Model assessment - I used two criteria for model assessment. The first was the degree in which a model met the least square regression assumptions. The second criteria was the sizes of the standard error of the estimate(Sylx) and standard error (SE) of slope coefficient(s). The smaller these errors, the better.

The least squares assumptions are: 1) constant variance of a dependent variable (w, d, or v) for any observed value of the independent variable (Q); 2) errors are independent, normally distributed, with a mean of 0; and 3) the independent variable (Q in this study) is fixed and not random. Methods and decisions involving the first two assumptions are simpler and better definedcompared to those for the third assumption. A short description of my assessment procedure follows.

I assessed constancy of variance visually by plotting the regression residual against the estimate and Q. As well, the degree of correlation between residual absolute values and the estimate and Q is measured with Spearman's rho. Independence was assessed by testing for serial correlation with the Durbin-Watson test (two-tailed). A serial correlation coefficient (r) gives the degree or strength of the time dependency. Models having strong serial correlation (arbitrarily defined $r > 0.5$) were transformed using the Cochrane-Orcutt procedure (Neter, et al. 1989). Time series plots of resisiduals were also examined. I used the Wald-Wolfowitz Runs test (Siegal 1956) to determine if a sequence of positive or negative residuals (runs) unusual enough to be considered more than a random occurrence. A better-fitting line will have fewer runs, yielding a higher p-value. The test statistic was generally negative, indicating clustering rather than a regular, systematic pattern. I assessed normality by plotting the residual values against their corresponding percentage points of a standard normal variable; normal distributions plot as a straight line. I tested whether the standardized residuals were normally distributed with the Lilliefors test (Conover 1980; Wilkinson 1986). Low p-values indicate non-normality.

Another least squares regression assumption is that the independent variable is fixed and not random, or in a more practical sense, Q is measured without error. This precision issue is common to any model, and the following discussion pertains to whether the data conforms to the assumption.

Because the slope parameters are of primary interest in hydraulic geometry, the primary purpose of regression in this study was describing the slope parameter of the various equations and comparing some of these slopes. If errors are present and the above purpose is in mind, the closely related functional analysis technique should be used to avoid bias (Mark and Church 1977). However, if the coefficient of determination (R^2) is close to one, the results from ordinary least squares and functional analysis coincide (Mark and Church 1977). Such is generally the case here, where R^2 for the various regressions are between .662 and .999, with 11 out of 54 fits lower than .900 (table 7 to 9). Another way of looking at the validity of ordinary least squares is the slope parameter formula in functional analysis (Mark and Church 1977), which is:

$$b_f = \{(b_r{}^2/R^2 - \lambda) + \sqrt{[(b_r{}^2/R^2 - \lambda)^2 + 4\lambda b_r{}^2]}\}/2b_r$$

where:
b_f = functional analysis slope parameter
b_r = ordinary least squares slope parameter
λ = (error in y)^2/(error in x)^2

and x is the independent variable and y is the dependent variable.

For the Snake River hydraulic geometry data, discharge is the independent variable, while width, depth, and velocity are the dependent variables. However, discharge error depends on the error of velocity and cross-sectional area (A) from which it is determined in the field. This is an odd circularity which may make an already difficult situation intractable. Nevertheless, an error estimate follows.

In the field, velocity is measured to the nearest 0.01 feet/sec and depth to the nearest .1 foot for each section of channel. The total channel cross sectional area is rounded to the nearest 1 square foot, but may contain up to about 5 % error due to depth errors. Width is measured to the nearest foot, so mean depth as calculated here from A/width is about 0.02 feet, although this assumes no error in A.

The probable violation of the error assumption is at a maximum in the width relations, where R^2 is typically the lowest. Considering that the hydraulic geometry exponents *b*, *f*, and *m* summed very close to 1, (table 5 and 7), it is unlikely that the exponent values are biased much. This is more clearly the case with curve fits having a high R^2, typified by depth and velocity. For those with a lower R^2, λ must be large for bias to be small. It follows that for large λ, the error in the independent variable, *Q*, must be small. Even if *f* and *m* have little bias, a large bias in the width exponent, *b*, would not allow close summation to 1. Summation to 1 is not an artifact of the circularity of measurement; based on many studies, exponent sums can deviate largely from unity (Rhodes 1977). Therefore, although the precision of *Q* is not truly known, it is probably high enough to meet the least squares regression assumption.

MODEL PERFORMANCE

The following tables summarize the statistics related to model assessment represented by 88 separate regressions, which includes the iterations to correct for serial correlation. Printed outputs for each regression, showing the ANOVA tables and the various plots, are on file at the University of Montana. I used SYSTAT version 3 (Wilkinson 1986).

Table 7. Mean and standard error of hydraulic geometry slope parameters.

Station: Period/ Model	b (SE) b_1 (SE) b_2 (SE)	f (SE) f_1 (SE) f_2 (SE)	m (SE) m_1 (SE) m_2 (SE)	Continuity
Alpine: 1953 to 1956				
log linear	.044 (.0017)	.456 (.0028)	.500 (.0033)	1.000
log quadratic	-.076 (.0294)	.385 (.0567)	.690 (.0599)	.999
	.016 (.0040)	.010 (.0078) NS	-.026 (.0082)	
Alpine 1957 to 1990				
log linear	.045 (.0011)	.459 (.0022)	.495 (.0026)	.999
log quadratic	.030 (.0253) NS	.313 (.0365)	.601 (.0584)	1.008
	.002 (.0034) NS	.020 (.0049)	-.014 (.0080) NS	
Irwin 1950 to 1956				
log linear	.075 (.0020)	.540 (.0051)	.382 (.0040)	.997
log quadratic	.378 (.0342)	.136 (.0655)	.457 (.0655)	1.003
	-.039 (.0044)	.053 (.0086)	-.010 (.0085) NS	
Irwin 1957 to 1990				
log linear	.084 (.0081)	.548 (.0021)	.367 (.0021)	.999
log quadratic	.207 (.0140)	.362 (.0391)	.422 (.0406)	.999
	-.017 (.0019)	.026 (.0054)	-.008 (.0057) NS	
Lyon 1904 to 1908				
log linear	.095 (.0082)	.230 (.0124)	.675 (.0129)	1.000
log quadratic	-.421 (.1276)	-.048 (.2403) NS	1.462 (.2043)	.993
	.065 (.0161)	.035 (.0304) NS	-.100 (.0258)	
Lyon 1909 to 1910				
log linear	.071 (.0031)	.230 (.0231)	.701 (.0220)	1.002
log quadratic	-.873 (.1870)	.372 (.5705) NS	.802 (.5476) NS	1.069
	.127 (.0243)	-.017 (.0744) NS	-.014 (.0716) NS	
Dry Cyn. 1934 to 1936				
log linear	.092 (.0056)	.470 (.0118)	.450 (.0080)	1.012
log quadratic	.610 (.0777)	-.513 (.1714)	.853 (.1406)	1.006
	-.068 (.0102)	.128 (.0227)	-.053 (.0186)	
Heise 1934 to 1936				
log linear	.044 (.0020)	.405 (.0067)	.548 (.0059)	.997
log quadratic	.116 (.0458)	-.100 (.1154) NS	.841 (.1080)	.993
	-.010 (.0061) NS	.066 (.0153)	-.039 (.0144)	
Heise 1953 to 1956				
log linear	.042 (.0023)	.530 (.0058)	.430 (.0040)	1.002
log quadratic	.111 (.0570) NS	.480 (.0966)	.393 (.0642)	1.000
	-.009 (.0074) NS	.006 (.0126) NS	.005 (.0083) NS	
Heise 1957 to 1990				
log linear	.100 (.0045)	.458 (.0074)	.442 (.0030)	1.000
log quadratic	.706 (.0780)	-.520 (.0956)	.824 (.0517)	.994
	-.082 (.0105)	.132 (.0129)	-.052 (.0070)	

NS: the test for $b_j \neq 0$ is not significant at $\alpha = .05$

Table 8. Curve-fitting statistics for width-on-discharge regressions.

Station: Period/ Model	adj. R^2	Sylx	Spearman's rho	Runs p	Serial Corr. r	D W p	Normal p	n
Alpine: 1953 to 1956								
log linear	.945	.0042	.163	.294	.240	>.05	.514	39
log quadratic	.962	.0035	-.185	.335	.174	>.10	.446	39
Alpine 1957 to 1990								
log linear	.852	.0063	-.123	.007	.024	n>100	<.001	268
log quadratic	.852	.0063	-.132	.015	.026	n>100	<.001	268
Irwin 1950 to 1956								
log linear	.945	.0067	.065	.198	.357	<.02	.009	78
log quadratic	.973	.0047	-.140	.075	.365	<.02	.221	78
Irwin 1957 to 1990								
log linear	.969	.0062	-.075	.001	.184	n>100	.218	347
log quadratic	.974	.0057	-.250	.028	.114	n>100	.010	347
Lyon 1904 to 1908								
log linear	.827	.0124	.138	.170	-.164	>.10	<.001	29
log quadratic	.890	.0099	.530	<.001	.063	>.10	<.001	29
Lyon 1909 to 1910								
log linear	.937	.0043	-.010	.044	.081	<.02	.030	36
log quadratic	.870	.0037	.318	.006	.431	<.02	<.001	36
Dry Cyn. 1934 to 1936								
log linear	.902	.0096	-.361	.066	.314	<.10	.331	30
log quadratic	.962	.0060	-.637	.352	.318	>.10	.147	30
Heise 1934 to 1936								
log linear	.942	.0038	-.311	.457	.081	>.10	.104	30
log quadratic	.945	.0037	-.379	.877	.061	>.10	.458	30
Heise 1953 to 1956								
log linear	.887	.0056	-.603	.212	.256	>.10	<.001	43
log quadratic	.889	.0056	-.608	.173	.270	<.10	.001	43
Heise 1957 to 1990								
log linear	.570	.0617	-.320	.030	-.230	NT	<.001	371
log quadratic	.631	.0550	-.374	.036	-.013	NT	<.001	371

NT : not testable; $D > D_L$ but Durbin Watson tables only to n=100

Table 9. Curve-fitting statistics for depth-on-discharge regressions.

Station: Period/ Model	adj. R^2	Sylx	Spearman's rho	Runs p	Serial Corr. r	D W p	Normal p	n
Alpine: 1953 to 1956								
log linear	.999	.0069	-.138	.841	-.129	>.10	.752	39
log quadratic	.999	.0068	-.225	.841	-.110	>.10	.313	39
Alpine 1957 to 1990								
log linear	.994	.0213	-.028	.043	-.130	NT	.052	267
log quadratic	.994	.0217	-.064	<.001	-.135	NT	.488	267
Irwin 1950 to 1956								
log linear	.993	.0294	.102	.575	-.051	>.10	.540	77
log quadratic	.995	.0322	-.134	.070	-.142	>.10	.226	77
Irwin 1957 to 1990								
log linear	.995	.0164	-.286	<.001	.297	<.02	.010	347
log quadratic	.995	.0160	-.313	<.001	.300	<.02	.077	347
Lyon 1904 to 1908								
log linear	.924	.0187	.085	.007	.160	>.10	.001	29
log quadratic	.925	.0186	-.017	.010	.025	<.02	.001	29
Lyon 1909 to 1910								
log linear	.738	.0401	-.357	<.001	.400	<.10	<.001	36
log quadratic	.754	.0358	-.400	<.001	.300	<.02	<.001	36
Dry Cyn. 1934 to 1936								
log linear	.982	.0202	-.209	.010	.470	<.02	.918	30
log quadratic	.990	.0276	-.227	.347	-.128	>.10	.545	29
Heise 1934 to 1936								
log linear	.992	.0247	-.154	.015	.243	<.10	.964	29
log quadratic	.996	.0092	.281	.003	.490	<.02	1.000	30
Heise 1953 to 1956								
log linear	.995	.0236	-.292	.216	.137	>.10	.432	42
log quadratic	.995	.0236	-.244	.062	.140	>.10	.234	42
Heise 1957 to 1990								
log linear	.941	.0918	-.242	.405	.009	NT	<.001	371
log quadratic	.954	.0829	-.258	.219	.001	NT	<.001	371

NT : not testable; $D > D_L$ but Durbin Watson tables only to n=100

Table 10. Curve-fitting statistics for velocity-on-discharge regressions.

Station: Period/ Model	adj. R^2	Sylx	Spearman's rho	Runs p	Serial Corr. r	D W p	Normal p	n
Alpine: 1953 to 1956								
log linear	.998	.0080	-.032	.269	-.032	>.10	.901	39
log quadratic	.999	.0072	-.149	.697	-.039	>.10	.329	39
Alpine 1957 to 1990								
log linear	.992	.0147	-.110	<.001	.338	<.02	.001	268
log quadratic	.992	.0146	-.106	<.001	.345	<.02	.001	268
Irwin 1950 to 1956								
log linear	.992	.0226	-.245	.565	-.122	>.01	.046	77
log quadratic	.992	.0229	-.253	.301	-.127	>.01	.055	77
Irwin 1957 to 1990								
log linear	.988	.0166	-.313	<.001	.385	<.02	.001	347
log quadratic	.988	.0166	-.272	<.001	.383	<.02	.001	347
Lyon 1904 to 1908								
log linear	.990	.0194	.180	<.001	.466	<.02	.001	29
log quadratic	.993	.0158	-.213	<.001	.362	<.02	.026	29
Lyon 1909 to 1910								
log linear	.967	.0384	-.221	.001	.391	<.02	<.001	36
log quadratic	.966	.0354	-.405	<.001	.400	<.02	<.001	36
Dry Cyn. 1934 to 1936								
log linear	.991	.0244	.148	.090	.119	>.10	.383	29
log quadratic	.993	.0233	-.144	.038	-.093	>.10	.785	29
Heise 1934 to 1936								
log linear	.997	.0250	-.246	.370	.351	<.10	.699	29
log quadratic	.997	.0161	.137	.090	.335	<.10	.690	30
Heise 1953 to 1956								
log linear	.997	.0183	-.123	.616	.069	>.10	.292	42
log quadratic	.996	.0182	-.153	.616	.086	>.10	.722	42
Heise 1957 to 1990								
log linear	.983	.0418	-.190	.195	-.104	NT	<.001	371
log quadratic	.988	.0187	-.184	.795	-.148	NT	<.001	371

NT : not testable; $D > D_L$ but Durbin Watson tables only to n=100

Table 11. Effect of serial correlation (r) on slope parameters (b, f, m), log linear model.

Station: Period	b	(r)	f	(r)	m	(r)
Alpine: 1953 to 1956						
uncorrected	.044	(.240)	.456	(-.129)	.500	(-.032)
corrected (r < .5)						
Alpine 1957 to 1990						
uncorrected	.045	(.024)	.456	(.540)	.495	(.338)
corrected (r < .5)			.459	(-.130)		
Irwin 1950 to 1956						
uncorrected	.075	(.357)	.545	(.646)	.380	(.632)
corrected (r < .5)			.540	(-.051)	.382	(-.122)
Irwin 1957 to 1990						
uncorrected	.084	(.184)	.548	(.297)	.367	(.385)
corrected (r < .5)						
Lyon 1904 to 1908						
uncorrected	.095	(-.164)	.230	(.160)	.675	(.466)
corrected (r < .5)						
Lyon 1909 to 1910						
uncorrected	.076	(.501)	.267	(.650)	.657	(.653)
corrected (r < .5)	.071	(.419)	.230	(.400)	.700	(.391)
Dry Cyn. 1934 to 1936						
uncorrected	.092	(.314)	.470	(.470)	.439	(.549)
corrected (r < .5)					.450	(.119)
Heise 1934 to 1936						
uncorrected	.044	(.081)	.400	(.676)	.556	(.731)
corrected (r < .5)			.405	(.243)	.548	(.351)
Heise 1953 to 1956						
uncorrected	.042	(.256)	.535	(.624)	.423	(.672)
corrected (r < .5)			.530	(.137)	.430	(.069)
Heise 1957 to 1990						
uncorrected	.098	(.628)	.458	(.675)	.445	(.637)
corrected (r < .5)	.100	(-.023)	.458	(.009)	.442	(-.104)

Table 12. Effect of serial correlation (r) on slope parameters (b_j, f_j, m_j), log quadratic model.

Station: Period	b_1	b_2	(r)	f_1	f_2	(r)	m_1	m_2	(r)
Alpine: 1953 to 1956									
uncorrected	-.076	.016	(.174)	.385	.010	(-.110)	.690	-.026	(-.039)
corrected ($r < .5$)									
Alpine 1957 to 1990									
uncorrected	.030	.002	(.026)	.345	.015	(.561)	.601	-.014	(.345)
corrected ($r < .5$)				.313	.020	(-.135)			
Irwin 1950 to 1956									
uncorrected	.378	-.039	(.365)	.191	.046	(.735)	.427	-.006	(.638).
corrected ($r < .5$)				.135	.053	(-.142)	.457	-.010	(-.127)
Irwin 1957 to 1990									
uncorrected	.207	-.017	(.144)	.362	.026	(.300)	.422	-.008	(.383)
corrected ($r < .5$)									
Lyon 1904 to 1908									
uncorrected	-.420	.065	(.063)	-.048	.035	(.025)	1.462	-.100	(.362)
corrected ($r < .5$)									
Lyon 1909 to 1910									
uncorrected	-.212	.036	(.534)	1.088	-.104	(.593)	.124	.068	(.610)
corrected ($r < .5$)	-.873	.127	(.431)	.372	-.017	(.413)	.802	-.014	(.400)
Dry Cyn. 1934 to 1936									
uncorrected	.610	-.068	(.318)	-.488	.126	(.569)	.873	-.057	(.581)
corrected ($r < .5$)				-.513	.128	(-.128)	.853	-.053	(-.093)
Heise 1934 to 1936									
uncorrected	.116	-.010	(.061)	-.100	.066	(.490)	.988	-.057	(.592)
corrected ($r < .5$)							.841	-.039	(.335)
Heise 1953 to 1956									
uncorrected	.111	-.009	(.270)	.459	.010	(.619)	.437	-.002	(.668)
corrected ($r < .5$)				.480	.006	(.140)	.393	.005	(.086)
Heise 1957 to 1990									
uncorrected	.808	-.096	(.613)	-.628	.147	(.682)	.822	-.051	(.647)
corrected ($r < .5$)	.706	-.082	(-.013)	-.520	.132	(.001)	.824	-.052	(-.148)

The salient points evidenced in tables 7 to 12 are that on balance, the log-linear model (LLM) is the most parsimonious, the depth and velocity relations had the least scatter, serial correlation does not have a great effect on estimating the slope parameter with the LLM, and close summation of exponent values to 1 does not clearly indicate lack of bias. Finally, most of the models meet the least squares assumptions reasonably well. However, improving those that do not would add complexity, making comparisons even more difficult.

The LLM is the most parsimonious, or yields the most precision with the least complexity. The log-quadratic model (LQM) typically yields a lower Sy|x than the LLM (tables 8 to 10), but the improvement is generally very small. Likewise, the adjusted R^2 increased (improved) slightly with the addition of the quadratic term. For the LQM, the standard errors for the slope parameters are substantially higher than with the LLM — even with similar slope magnitudes. Normally, these higher standard errors for the LQM slopes would further detract from the LQM's utility, but problems related to collinearity are affecting the calculations. These problems can be alleviated with scaling techniques discussed later, but the additional effort will add little improvement. Again regarding the LQM, the slope parameter tends to be much more sensitive to transformations that reduce serial correlation (tables 11 and 12).

The depth and velocity relations to discharge had much less scatter than the width relations. Velocity was particularly precise. Documented velocity relations are nearly always more scattered, mainly because of uneven roughness from dune, bed planation, and antidune formation with increasing discharge (Vanoni 1946; Simons and Richardson 1966). Sediment concentration-discharge relations also can show hysterisis, (Leopold and Maddock 1953; Williams 1989), due to roughness decreases with decreased turbulence (Vanoni and Nomicos 1960). The South Fork stations' good fits for velocity are probably due to more consistent roughness characteristics.

With the LLM, the slope parameter values did not change much after correcting for serial correlation, with most differences being between 0.001 and 0.005 which is in the range of the 95 percent confidence interval (95% CI). The differences after correction are the greatest for Lyon during 1909 to 1910, with the change in f after correction slightly exceeding the 95% CI. This is not too surprising since the channel had shifted after a large flood and may have been re-adjusting during 1910. Except for Irwin during 1950 to 1956 (figure 32; p. 90), time series plots show no consistent trend across years; generally, the error fluctuates within a season. Serial correlation in these cases is probably due to slight changes in roughness as aquatic vegetation grows and is later scoured away. A reason for serial correlation at Irwin in the early period has already been discussed.

The slope parameters summed very close to one for every regression in each model type (table 7). However, considering the large shifts in values after serial correlation correction in some of the LQM regressions (table 12), one obviously cannot assume no bias in the estimates if they sum to 1. This last point may contradict the reasoning in the section on estimating the precision of Q. Reconciling this possible contradiction is beyond the scope of this study. However, one possibility is the effect of the Q^2 term on calculations. The log-transformed Q has a short enough range that $\log Q$ and $\log Q^2$ are nearly collinear, and collinearity can affect computer program algorithm calculations. An indicator of this problem is inflated slope coefficient standard errors, and the standard errors for the log-quadratic models are much higher than the comparable log-linear model. Another indication is that the variance inflation factors (not shown) were also very high for the slope coefficients in the LQM.

There are problems with some regressions as revealed in tables 8 to 10. The most glaring one is statistically significant serial correlation, even after "correction" with $r < 0.5$. Also, some of the residuals are not normally distributed. The first problem can be solved with more iterations, but I chose not to after considering how little the values changed with just one (table 11 and 12), indicating little bias. Non-normality is not so much a problem because most of the tests used in inferences are robust to moderate deviations from normality, especially if the sample sizes are large, say n > 25 (Pearson and Please 1975; Kleinbaum et al. 1988). The 1909-1910 Lyon fits are the worst in regard to sample size and deviation from normality, and inferences involving this data should be viewed with caution.

The assumption of constant variance was met well in all the fits except for width at Heise. The width error varied because of the intermittent gravel bar (figure 39; p. 98). When the few observations after channel maintenance were removed, very little improvement in fit occurred. The natural scour and fill of this bar has a large effect on the width at low flows (figures 24 and 25; p. 75 and 76).

Spearman's rho (table 8 to 9) indicates the degree of constancy, with lower values indicating a more even fit. Figures 17 to 25 (pages 68 to 76) show the general pattern of variance for the log-linear fits that are uncorrected for serial correlation. The corrected ones are similar.

The fit of any of the separate regressions can be improved with techniques such as weighted least squares to improve variance constancy (and most likely non-normality) and as mentioned earlier, further transformations to correct for serial correlations. However, techniques or transformations must be consistent for data sets to be compared. For this reason, I had to accept lower precision in some cases in order to make comparisons and vice versa. Finally, Ridenour and Giardino (1991) recommend compositional analysis (rather than standard regression as used here) for hydraulic geometry data because of the continuity, or "unit-sum constraint" of the exponents. I did not use compositional analysis because it requires special software and the basis for comparison, logratio mean- and logratio covariance-vectors, are not comparable to other hydraulic geometry studies. Also, I could not relate these vectors to real streams.

The collinearity problem in the LQM can be alleviated using orthogonal polynomials or re-scaling Q (Kleinbaum et al. 1988). Due to unequal spacing of data points, the former technique would require a program that calculates orthogonal polynomials. SYSTAT version 3. does not do this. Re-scaling is much easier but is not always effective (Kleinbaum et al. 1988). Both of these techniques would make comparisons more difficult, which is one reason I chose not to do them. However, there is a comparison that indicates the degree of improvement of the LQM over the LLM, and this influenced my decision as well. The Sy|x (and all corresponding sums of squares) for a model fit with natural (raw data) polynomials will be the same as for a model fit with orthogonal polynomials (Kleinbaum et al. 1988). Therfore, the small improvement in Sy|x in most cases (tables 8 to 10) may not warrant the extra effort.

Precise estimates of exponents are only one aspect of hydraulic geometry, what these exponents mean is another. Current knowledge of stream behavior as related to hydraulic geometry is quite cloudy, and as will be seen shortly, great precision increases are as effective as looking into fog with binoculars.

INTERPRETATION OF HYDRAULIC GEOMETRY

The rates of change in width, depth, and velocity with discharge represented by b, f, and m may indicate changes in channel form and process. Form changes in themselves are more easily detectable while process changes are not. Of course, form changes are associated with process changes, but the cause-and-effect relation is often unclear. What follows is a guide to interpreting hydraulic geometry in context to cobble-bed stream behavior, with an emphasis on sediment movement, based on the South Fork data, the work of others on various streams, and theory. I use "guide" loosely, for there is little consistency between exponent values and stream behavior in general. I continue despite this deficiency for two reasons: 1) the basic ingredients of hydraulic geometry relations also form an important way we look at streams conceptually and operationally, and 2) persistent anomalies often lead to new discoveries and increased understanding.

Channel form - The cross-sectional shape and the size of *b* have the most direct relationship and allow the easiest interpretation: a small *b* means steep bank angles, with $b = 0$ for vertical banks and flat bed.

If steep banks are considered stable, then a smaller *b* indicates higher bank stability for a given W/D ratio. Bank stability, as measured by the percentage of silt and clay (M), has been related to W/D in the field (Schumm 1960), with high W/D with lower M, but Rosgen (1993) erroneously relates width-to-depth (W/D) ratio with *b*, where "*...channel width increases faster than mean depth, with increasing discharge in high width/depth ratio channels. The opposite is true in low width/depth ratio channels*". A simpler way to say the first phrase is: W/D ratio increases with discharge. This can obviously only occur when $b > f$ (Rhodes 1977). However, bank steepness (*b*) and W/D ratios are not necessarily well-correlated. For example, the South Fork stations have high W/D ratios (figure 16; p. 67) but *b* is much lower than *f* (table 5; p. 66), clearly showing the relationship between width/depth ratio and bank angle (or channel stability) as indefinite. Moreover, the correlation between M and W/D (Schumm 1960) was poor for channels with gravel or cobble beds. Despite this, W/D ratio is commonly used in stream stability evaluations (Pfankuch 1975). Of course, high W/D channels with low bank angles occur and are perhaps common, but basing bank stability on W/D is subject to error.

Sediment transport - Channel cross-sectional shape may be related to bed stability or bed load transport, and naturally-wide channels seem to have higher proportions of bed load (Mackin 1948; Leopold and Maddock 1953; Schumm 1981). However, the relation between sediment load transport capacity and channel width was still not clear for many years even on a qualitative level. Based on evidence and opinion, notions varied from decreased capacity as channels narrowed to the opposite of this as well as increases and decreases about some optimum width. Carson and Griffiths (1987) considered these conflicts and concluded that bed load transport capacity is maximized at an optimum width. Carson and Griffiths (1987) admit that their work is less applicable to natural streams, but combining their work with Wilcock (1971) and Bagnold (1977), the notion that wider channels move more bed load is apparent in natural streams. Assuming the above is true, changes in the a constant lend insight to bed load transport capacity changes, but any comparisons would have to be made with similar bank stability (b) and similar flood magnitude history at least. A more precise way is to use $w = aQ^b$ (instead of a) to yield width at bankfull discharge, because a represents width at $Q = 1$ which implies great extrapolation.

Both suspended sediment and bed load transport are related to hydraulic geometry. The following quotations, (Leopold and Maddock 1953) based on several flume and field observations, give the general idea of their tentative findings:

At a constant discharge, an increased velocity at a constant width is associated with an increase of both suspended load and bed load in transport. At constant velocity and discharge, an increase in width is associated with a decrease in suspended load and an increase in bed load in transport.

The relationship between the increase in suspended load with discharge is reasonably clear as demonstrated by Leopold and Maddock (1953), and it is a function of:

$$\frac{\text{the rate of increase of velocity with discharge}}{\text{the rate of increase of depth with discharge}}$$

or m/f. With a higher m/f ratio, the rate of increase of suspended sediment load with discharge increases too.

However, the above relations are based on streams and flumes with sand beds, where the suspended sediment is more easily derived from bed scour. The field settings were snowmelt streams in the semi-arid western United States with high sediment loads derived from tributaries or at least upstream from the measuring stations. This is important in context to the following discussion which concentrates more on bed load movement patterns and the ratio m/f.

Along lines of inquiry specific to bed load, Rhodes (1977) related the shear stress formula:

$$\tau = \frac{K\,\partial v}{\partial y}$$

where: v = velocity, y = height above bed, K = viscosity coefficient

and Du Boys' shear stress formula: $\tau = \lambda dS$, where λ is fluid density, d = depth, and S = slope of energy grade line. Slope influence can be equated to velocity if other factors are held constant.

From these equations, it is evident that depth and velocity play a direct role in moving bed load particles, or competence. When velocity (or slope) and depth are higher, competence increases.

Channel morphology is not constant longitudinally at a given discharge. Width narrows and widens, and there are often pools (deeps) and riffles (shallows), the latter usually coinciding with the former. With the mutual adjustment of width, depth, and velocity with changing morphology and constant discharge, some channel sections may have higher competence than others. Likewise, the morphology differences may originate with an underlying property of water itself.

Anyone who has waded streams below flood stage notices that the current is stronger in riffle areas than pools, yet these areas appear to accumulate bed particles, contradicting the above equations. This apparent contradiction is resolved when sediment and water movement in time and space are considered. What follows is an explanation stream waders and hydrologists alike may appreciate, emphasizing channels with coarse bed particles.

The following phenomena appear common to every alluvial channel: Riffle and pools tend to be regularly spaced and stay in their longitudinal positions through several seasons, despite concurrent bed load movement. Bed particles scoured off riffles are replaced by other particles later, and riffle surfaces typically have larger particles than pools during low flows. These phenomena have been observed and documented many times, and Leopold et al. (1964), Richards (1982), and Graf (1988) summarize these. The stalling of bed particles and bed load movement in pulses, mentioned earlier, reflects a difference in competence in time and space, and the pool and riffle dynamics may be reflecting this as well. In essence, there seems to be a wave-like or oscillating property to sediment movement.

The velocity reversal process (Keller 1971) lends insight into these phenomena, where at low flow, velocity near the bed (bottom velocity) is less in the pool than in adjacent riffles, but with increasing discharge, the bottom velocity in pools exceeds that in adjacent riffles. On a coarse-textured foothill stream, Keller (1971) found that pool and riffle bottom-velocities converged near the bankfull discharge, after which pool bottom-velocities likely exceeded adjacent riffle bottom-velocities. During peak flow, particles scoured out of pools tend to stall on the riffles, where competence is relatively less. During falling stages, flow over riffles becomes relatively more competent than pools, and particles scoured off riffles land in adjacent pools. In hydraulic geometry terms, m near the bed is higher in pools than riffles. The distinction between bottom velocity and the usual mean velocity is important, because velocity is unevenly distributed in a cross-section at a given time, and mean velocity is poorly correlated with bottom velocity (Rubey 1937).

A similar pattern emerges in a coarse-textured mountain stream, where competence tended to increase only when m equals or exceeds f, especially when b is small (Wilcock 1971). If $f > m$, the reduction in competence is minimized by large increases in width with discharge (large b). This latter point is in agreement with the relation of width to bed load movement discussed earlier. Rhodes (1977) incorporated both of these points in his b-f-m diagram rationale.

Considering the varying channel shapes in cross-section along a stream, the pools and riffles, and the hydraulic geometry for these sections -- especially the relation between m/f and competence -- relating bed load transport behavior at specific channel locales with their hydraulic geometry is tempting. Not surprisingly, others have been tempted, and a summary of their work specific to this follows.

Bed scour occurs at some channel cross-sections with the passage of floods. For channels with fine bed particles, most or all of the bed can scour as discharge and competence increase, returning to its former level later with lower flows washing in sediments from tributaries (Leopold and Maddock 1953; Leopold et al. 1964; Leopold et al 1966). In these situations, pools and riffles alike showed simultaneous scour and the relative values of m and f bore no consistent relation to local scour and fill dynamics. The suspension of bed particles during high flows may explain the high sediment concentration and bed scour during rising stages. For channels with predominately large bed particles such as gravel and cobbles, continuous scour along a channel during a season may be less likely but seems to occur (Leopold et al 1964). This last point contradicts the general pattern of pool and riffle dynamics and velocity reversal discussed earlier. This contradiction disappears when the shorter time intervals involved with velocity reversal are considered along with the longer ones associated with sediment replenishment from tributaries.

The intensively studied East Fork River provides much insight into channel morphology changes occurring with water and sediment discharge. The sediment budget, water and sediment discharge patterns, channel morphology, and hydraulic geometries of an appreciable length of this river were incorporated into a unique study (Andrews 1979). The dynamics of scour and fill with discharge and its relation to local hydraulic geometry is especially pertinent to the present discussion.

The East Fork River is a snowmelt stream with a bed of gravel and sand. Like the examples reviewed above, the channel bed was generally lower after the snowmelt period, and the bed reached its early spring position the following spring. Late-season sediment supply came from a major tributary which injected mainly sand. Even though net scour occurred during the entire snowmelt season, there were local accumulations and depletions of bed sediment during peak flow. Andrews (1979) measured 11 closely-spaced sections. Some sections scoured during peak flow (scouring sections) while at the same time, others filled (filling sections). Pool and riffle characteristics were not generally apparent; only one section represented each type. As expected, the pool scoured and the riffle filled during peak discharge. During falling stages, most filling sections were scoured below their early-spring position, while scouring sections filled only slightly or remained the same. In other words, there was net scour after the snowmelt period. When re-measured the following year, bed elevations at all sections had returned to their early-spring levels.

The East Fork sections had respective hydraulic geometry quite consistent with the relation between *m* /*f* and competence. As usual, Andrews (1979) used mean depth and mean velocity for his relations. Figure 47 shows the hydraulic geometry of the scouring and filling sections.

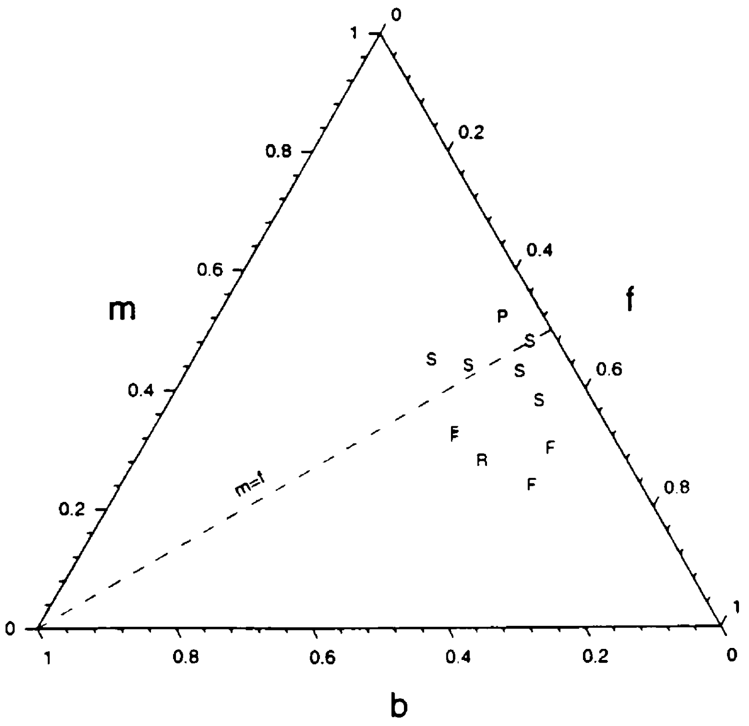


Figure 47. b-f-m diagram for East Fork River, Wyoming showing scour and fill behavior.

The relative plotted positions of the scouring (S) and pool (P) sections versus that of the filling (F) and riffle (R) sections coheres well with the concepts related to pool and riffle dynamics. Also, their separation about the $m = f$ line fits the rationale presented by Rhodes (1977), which is based on empirical observations and theoretical formulas.

Unfortunately, filling sections do not always plot below the $m = f$ line, or even below scouring sections, and vice versa. The East Fork situation seems to be a special case. As mentioned earlier, the exponent values for the rivers Leopold and Maddock (1953) examined do not consistently conform to the simple $m/f > 1$ = higher competence notion. For convenience, the South Fork b-f-m diagram is repeated and modified in figure 48 to show the lack of coherence between exponent values and behavior. The same is done for the rivers examined by Leopold and Maddock (1953).

The bed elevation dynamics with discharge for the southwestern Rivers are probably complicated by large changes in sediment concentration during then snowmelt events. Leopold and Maddock (1953) thought that channels would adjust to differing suspended loads, and their data shows this. This phenomenon should be kept in mind when interpreting bed scour and fill dynamics from hydraulic geometry.

In contrast to the above, the Snake River stations do not have the added complication of high suspended sediment load originating in tributaries or the main channel itself. However, the magnitude of scour and fill with changing discharge is small and the general pattern is more difficult to see, especially at Irwin. Still, the lack of coherence between m/f ratio and scour/fill behavior is obvious. The Irwin section is the only station that fits if Irwin is actually filling during high discharges. The Lyon cross-section may also fill during high discharges; if so, it is the most drastic anomaly. However, the banks were less steep at Lyon, and as explained earlier, the sloping-bed effect is more pronounced with higher b exponents.

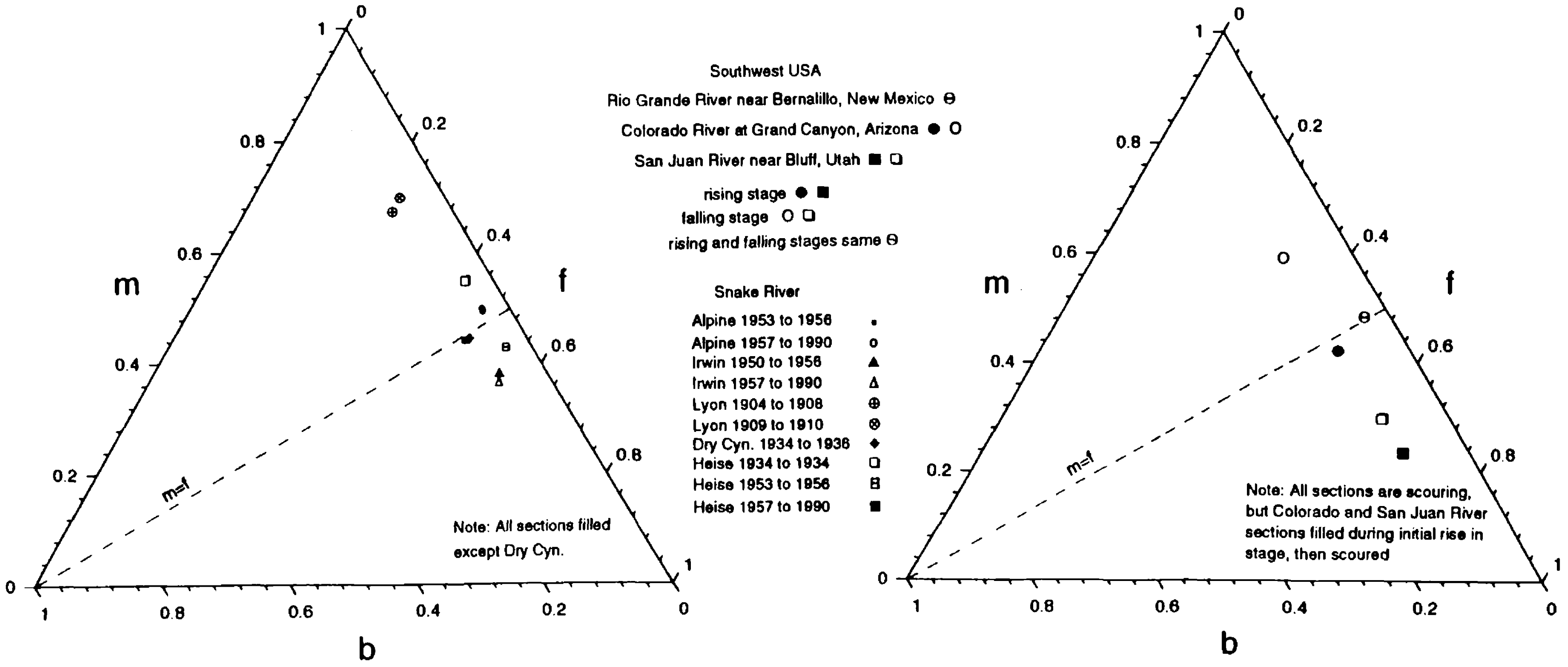


Figure 48. b-f-m diagrams for Snake and southwestern USA rivers, showing scour and fill behavior. Snake River stations on left.

It is now obvious that prediction of channel fill or scour during a flood event is not always possible using the *m* /*f* ratio alone. This ratio may still indicate competence in some way, but without information from adjacent areas, relative competence of adjacent sections is unknown.

Given the inconsistent correlation of the *m* /*f* ratio with scour and fill dynamics, and that the underlying reasons for scour and fill are fundamental to fluvial landforms, there is an incentive to explore other relationships that may better explain these dynamics. A full exploration is beyond the scope of this study, and available data is inadequate to find a relation that always works. However, some plausible hypotheses come to mind quickly and these are presented now.

Consider again the well-known Du Boys equation for shear stress: $\tau = \lambda dS$. Assuming constant skin resistance density, and discharge, slope is proportional to velocity. In wide channels, depth is very close to the hydraulic radius R, and d is substituted for the more formal usage of R. The Froude number: $F = v/\sqrt{gd}$, where g is acceleration due to gravity, incorporates the actual velocities and depths rather than the rates of increases that *m* and *f* afford. The Froude number also is related to competence. By using the depths and velocities at various discharges for the Snake River stations, Froude numbers as well as the Du Boys equation's basic idea of competence are incorporated in the curves shown in figure 49.

Like the *m* /*f* ratio, the relation of Froude number and discharge lends no insight into whether a section will scour or fill during peak discharge. The Dry Canyon station is the only example of a scouring section, yet its curve is buried amongst the others represented by filling sections. However, there are some interesting points in respect to figure 49. The Froude numbers are moderate and represent subcritical flow. Rhodes (1977) subdivision at $m = f/2$ was based on critical flows at $F = 1$. Station exponents plotting above the subdivision can reach supercritical flow ($F > 1$), but discharge would have to be very high before supercritical flow becomes widespread on the South Fork. In defense of the of velocity reversal hypothesis, Keller (1972) argued that Froude number has little bearing on pool and riffle dynamics. The South Fork data lends support to his argument.

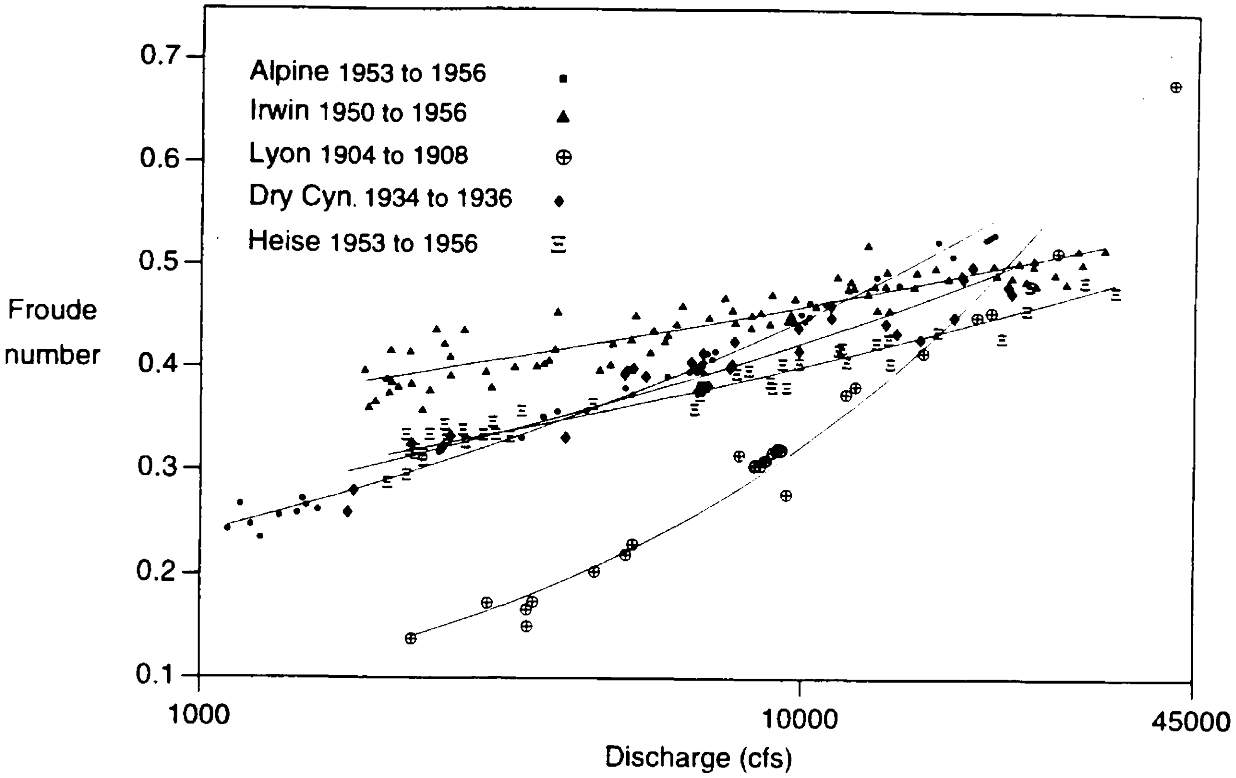


Figure 49. Relation of Froude number and discharge for Snake River gaging stations.

The approaches so far are inadequate for predicting scour and fill behavior, but these are the obvious, easy ones. At least two more ways of looking at scour and fill dynamics are available. One is using bottom velocity rather mean velocity. Wilcock's approach (1971) incorporated the uneven distribution of velocity with depth. Leopold and Maddock (1953) recognized the possible deficiency of mean velocity, but this is the usually available form. If bottom velocity proves deficient, the kinematic wave theory may apply. Perhaps the piling up of bed particles is not related to the way we measure velocity, and the observed velocity differences are due to the piles themselves. In respect to this last point, Langbein and Leopold's (1968) simple flume experiment with glass beads is intriguing.

SUMMARY

The usual power function or log-linear model (LLM) fit the data best with the least amount of complexity. Also, current knowledge allows for some interpretation of LLM's; even if other models such as log-quadratic (LQM) and log-piecemeal fit better, the results cannot be interpreted without more research. The LQM was also more sensitive to serial correlation, where in some regressions, slope parameters changed in sign and magnitude after correction, further complicating interpretation. The standard errors for the slope parameters (SE b_j) in the LQM were larger than the (SE b_j) for the LLM. Regarding the LQM, the sensitivity to serial correlation and the inflated standard errors are likely due to collinearity between the independent variables logQ and $\log Q^2$. Collinearity, which affects calculations, can be alleviated but the extra effort required would yield a very small increase in precision — at least for the South Fork data. The independent variable, discharge, is calculated from the two of the three dependent variables. This quasi-independence may violate the independence assumption for least squares regression.

Although the LLM results are easier to interpret, there are still problems. Scour and fill behavior and *m/f* ratio, which has shown good consistency on one river, has not on others. More empirical work is needed to understand sediment movement and water discharge dynamics.

CHAPTER 4

VEGETATION OF EARLY-SETTLEMENT AND MODERN PERIODS

OVERVIEW

In this chapter, the respective vegetation of the earliest documented periods and most recent years are compared, focusing mainly on vegetation most closely associated with South Fork channel processes. Vegetation that is directly dependent on river processes and at the same time has an affect on the river is riparian vegetation. Upland vegetation is not dependent on the river, but it has an affect on the river by influencing streamflow and erosion. Vegetation is the way plant species are distributed in space and time, and is a reflection of the physical environment, flora, disturbance, and time. The physical environment has already been discussed, at least in a broad sense, in chapter 2 and 3. There will be some discussion in context to specific plant species, but the present study deals mainly with flora, physiognomy, disturbance, and time. Flora is simply a list of plant species, while physiognomy is the outward-appearance or general structure of plants growing together. There are numerous types of disturbance that affect plants, in this case the more likely sources are animals, fire, water, and sediment. Time itself, of course, has no direct effect on plants, but it implies changes will occur in vegetation as plants respond to past disturbance or as other factors affecting plant growth and survival change with time. Nothing is truly static, and river environments are usually very dynamic. The main idea behind this look back through time is to assess the pre-settlement South Fork environment, which can serve as a baseline for present and future comparisons. The assumptions and limitations of such a baseline are explained later, but in essence this baseline is merely a snapshot, which implies that presettlement conditions were static.

As discussed in chapter 3, the South Fork channel form and process have changed slightly and will continue to change as a result of Palisades reservoir management. Of the many factors that can affect South Fork riparian vegetation, changes in flood frequency and magnitude are the most important physical ones, while changes in flora and fauna are the more important biological ones. Because plants respond to changes in physical environment and fauna, one would expect some changes in the vegetation associated with the South Fork over time. Likewise, rivers respond to changes in vegetation.

Considering that post-American Indian settlement occurred around 1890, bringing with it fire suppression, exotic plant and animal species, and water development, how has the South Fork vegetation responded to changes in physical and biological factors over time, and which factors are responsible for any vegetation changes? What are some implications of any or potential changes? These questions are the main guide of inquiry.

DATA SOURCES AND METHODS

Flora - Accounts from two surveys conducted by the U.S. Geological Survey make up the bulk of the pre-settlement flora. F. V. Hayden led both of these surveys, the first in 1872, the other during 1877. The earlier work provides most of the flora data, which was directed by J. M. Coulter, with help from T. C. Porter. G. Vasey and S. T. Olney determined the Gramineae and Cyperaceae species respectively. The listed species were collected, but in case one is curious about examining these specimens, I found only a hint of a depository: collected specimens were compared with those at the "Agriculture Department" collection, to which Vasey was associated. Another hint for a depository is Anderson (1961) examined a specimen (*Phalaris arundinacea*) from the United States National Museum collected by G. Vasey in 1884. Many individuals are responsible for the information in these survey reports, and the person responsible is named if evident in the overall report. In general, these two survey reports are cited as Hayden 1873 and Hayden 1879.

One earlier account by Osborne Russell gives fragmentary data on the various plants and animals he saw during 1834 to 1843, which represents the mid- to late trapping era for this region. Russell's journal was edited by A. Haines, and although the original prose is evident and the contents depicted as accurately as possible, the work is cited here as Haines 1955 (Haines gives the sordid history of Russell's earlier publications). Trappers are notorious for tall tales, but this was Russell's motivation for writing his journal for he wanted the frontier presented as truthfully as possible.

The present flora was determined during an investigation of the extensive cottonwood forest in the primary study area (see chapter 1). I collected most of the plants from mid-May to the end of October during 1992 and 1993. Many species were saved for voucher specimens, especially those that were difficult to identify or are uncommon. Voucher specimens are deposited in the Idaho herbarium at the University of Idaho in Moscow. Difficult species were compared with herbarium mounts at the University of Montana herbarium.

Although I used plots for some of the investigation, I collected plants as I found them whether they were in plots or not. This approach and the long season insures a more complete collection. I chose specimens in anthesis if possible. Very wet areas are not as well-represented as the rest of the alluvial sites, and I only collected one aquatic species. No plants were collected from uplands and my reference to this area is based on past experience and familiarity with upland flora.

The method is a simple comparison of the two floras with some elaboration on the more important species, especially those thought to be introduced (non-native). The early flora list is compiled from Hayden's larger list encompassing the survey area, which includes parts of Wyoming, Idaho, Montana, and Utah. I only included the species Hayden denoted with "Snake River Valley". The Hayden Reports do not always clearly state what constitutes the Snake River Valley. Judging by the collection dates, travel routes, and names for nearby places, the Snake River Valley roughly coincides with the valley extending from the Salt River confluence to the Henrys Fork. This more limited Hayden list still probably includes species found on the very old terraces (chapter 2), but I only collected from the flood plain and 1-foot terrace, which are wetter, and from only the Swan Valley area down to Heise. In respect to the wetter area flora, the Hayden list is probably not as complete as the new list, and I try to account for these inconsistencies.

Plant species nomenclature changes over the years, so I used standard synonymy to reduce confusion. In the tables, I show Hayden's original names and more recent synonyms if necessary. Synonymy is mostly from Vascular Plants of the Pacific Northwest (Hitchcock et al. 1969) and Flora of the Pacific Northwest (Hitchcock and Cronquist 1973). The study area has a Great Basin influence, and most species not covered by the primary flora key were covered by Vascular Plants of Wyoming (Dorn 1988), sometimes with further verification through the Intermountain Flora (Cronquist et al. 1977). I do not use the most recent taxonomy (Barkworth et al. 1983) for wheat- and rye- grasses (*Agropyron* and *Elymus*); the traditional names are well-known. In some respects this is a deficiency, and this is discussed later.

Vegetation - Landscape scenes shown in early-settlement- period photography and General Land Office (GLO) cadastral survey notes on vegetation are the main sources for reconstructing natural vegetation. The photographers were various US Geological Survey workers, and prints from the original negatives were enlarged at the USGS Photo Library in Denver, Colorado. Each photo has a credit, date, and river discharge for the day if known. The original GLO notes are for several section lines crossing the river and flood plain in the primary study area. I chose lines that are about 2 miles apart, and that had early notes associated with them. In the notes, the size and species of bearing and witness trees are described as well as the general vegetation along the lines. Most notes are from the 1870's to about 1910. I followed Galatowitsch's (1990) method for interpreting the GLO notes. Although more fragmentary, the accounts from the Hayden surveys and Russell's journal give clues to pre-settlement period vegetation.

The present vegetation is described and compared to the early vegetation. The basis for this description is repeat photography and my observations during field work in the study area.

During repeat photography, I made every effort to find the original photo point at a time and season to match the early image. However, this was not always possible and some slight mental adjustment is necessary when viewing a few scenes. I used black & white film in a 35 mm camera. A wide-angle lens assured capturing the whole original scene. The new image was cropped during darkroom enlargement by projecting the new image on the old one until fixed features common to both images coincided. The images here are photostatic copies of half-tone versions of the original prints. There is some loss of detail and contrast with each step compared to the original prints, and some sky has been cropped out of some scenes.

A repeat photography set is on file at The University of Montana, the Bureau of Land Management Idaho Falls District, and the Idaho Nature Conservancy Field Office in Ketchum, Idaho. All sets are from the original negatives, and the prints are about 8 X 10 inches.

My observations occurred during the field work as mentioned in the flora section above. I was already familiar with Hayden's and Russell's accounts, and I paid particular attention to present situations related to them.

As with the flora, the comparison is simple, but I bring in as much information from the literature and my field visits as possible so that the data is more useful. Although people familiar with the present vegetation can interpret the photographs with little explanation, I give brief ones for those that are unfamiliar. Pertinent geologic features are also mentioned.

Time considerations - The two main comparison periods, early-settlement and present, are chosen to possibly show any effects of Euro-American (hereafter called "white" for simplicity, although there were a few people other than Caucasian) habitation and use of the upper Snake River region, with emphasis on the South Fork valley. This simplistic approach has some drawbacks. One is the difficulty in separating white causes (both direct and indirect) from natural ones. Another is the american Indians' influence, which is discussed later. Also, due to the available data, the characterization of the earliest vegetation is static, but due to climate changes and various disturbances, the vegetation was probably very dynamic before white influence, so my somewhat static view is a mis-representation of the complete picture. I tried to account for this deficiency, and future work will be more representative, but for now it is more important that the reader is aware of the drawbacks if not already so. Noss (1985) outlines procedures for characterizing presettlement vegetation and elaborates on the above., and my approach follows his closely.

Defining the pre-settlement period is not absolute, and my use of "early-settlement" is yet another indication of the gradual white influence. The following is a brief outline of the settlement pattern in the upper Snake River area, gathered from Sanborn (1978), and Horton et al. (1989). The former deals mainly with the Snake River in Wyoming. The latter source incorporates much of the earlier historical work on Bonneville County.

The earliest whites were explorers and trappers, attracted to the plentiful beaver. The first, John Colter came through in 1808, primarily to win the goodwill of the Indians for trappers that were soon to follow. The Astorians did follow, passing through the region during 1810 on their way to the Oregon coast and returning back to St Louis in 1813. Both Colter and the Astorians skirted the South Fork, primarily exploring the Jackson Hole and Henrys Fork areas. Trapping activity ceased soon after the War of 1812, and resumed about 1822, reaching its heyday during the 1830's. By the mid-1840's, large scale trapping ceased due to declining markets and the greater attraction of gold. Judging by the documented trapper travels, the South Fork was not heavily trapped and is usually only mentioned in passing by Russell (Haines 1955). Trapping pressure is discussed further in relation to beaver habitat and herbivory. Local mining activity is discussed in chapter 2.

The upper South Fork valleys, called Grand, Swan and Conant (chapter 2), as well as the adjacent benches, were first settled and farmed about 1890. Many of today's farmers are descendents of the original homesteaders. The earliest homesteads were quite scattered, but many more arose during the 1920's. The scale of agricultural land clearing seen today probably began in the late 1930's. Aerial photography from 1941 shows tilled fields at a similar extent as today. Livestock grazing coincided with settlement, but I can only find vague references to the extent. The effect of livestock grazing is inferred from the data.

Now it should be clear that a sharp line between pre-settlement and settlement periods cannot be drawn, and the many comparisons to follow are accordingly blurred. This is important to keep in mind because due to the nature of the data, many questions are necessarily answered with yes or no (if at all), but we are actually dealing with gradual influences.

Defining natural - The idea of 'natural' looms large in most investigations dealing with the environment. Everyone probably has their own definition or feeling as to what is natural, and the following is only meant to clarify what I mean by natural.

Natural is a condition or entity that is uninfluenced by human technology beginning with fire. Although this definition, taken to the extreme, precludes the North American landscape since at least the Pleistocene as being natural, there is a matter of degree of human influence. Clearly the Indians used fire, hunted, and gathered, thereby affecting plant and animal distributions. But I assume that their numbers were small enough to have little affect on vegetation compared to climate, lightning fires, and wildlife. This assumption is explored later and is supported to some degree by the data.

However, like the white settlement pattern, the Indian influence is also gradual, but in the opposite temporal direction. By about 1865, most of the region's Indians were moved to reservations, but even if we assume an abrupt removal, the white influence in technology in the form of horses, guns, metal knives, etc. probably occurred before written records or at least since their contact with trappers.

So again, like defining settlement, the idea of natural is nebulous. Although there is strong philosophical support for us being natural, I use the strict demarcation for convenience. Hoerr (1993) and Anderson (1991) explore and define naturalness and the idea stated here is the essence of their work. In general, consider the pre-settlement period as natural, but there will be specific references to Indian influences.

RESULTS

Flora - The vascular plants that the Hayden Survey collected from the Snake River Valley are listed with remarks in table 13. This represents pre-settlement conditions, but it is likely a partial list, because collecting was mostly near the stage route. Introduced species were noted in the Hayden list, but these species were restricted mainly to the Ogden, Utah area, and no Snake River Valley species were denoted as introduced. Spelling, capitalization, and statements are verbatim. This understood, the reader is spared the use of "sic" for every mis-spelling, etc. I could not find synonymy for some species, and this is denoted with a "?". The author abbreviation, such as L. for Linnaeus, which is included in Hayden's list, is not included in table 13 unless it is important for determining synomyny.

Current vascular flora found on recent South Fork alluvial sites are listed in table 14. For comparison, species listed in the Hayden Survey report are shown in bold type. Also, current species that are listed in the Hayden Report for areas near and similar to the Snake River Valley are mentioned in the remarks. An asterisk (*) means there are voucher specimens, which are deposited at the University of Idaho herbarium in Moscow.

There are several native species common today that Hayden did not collect in or near the Snake River Valley, but most were collected somewhere along their route and I did not find any glaring omissions.

The Hayden list includes many species that are found on drier, non-riparian or upland sites as well as those found in stable wet areas, which Hayden refers to as "swamps".

These two environments are poorly represented on the more recent alluvial deposits that the present flora represents. Presently, the higher, sandier places support some species found on uplands, and the quiet back-water areas and filled-in channels support some "swamp" species. A safe assumption is that the site requirements for the various species has not changed over time. To better connect the recent flora with the old, gross site requirements are listed for some species in table 14. These species-site relations are based only on observation, and I restricted any relations to patterns that seemed repeatable. The lack of a close coincidence of species between the periods is probably due more to bias in collection than large changes in flora except the herbaceous layer — especially the grasses. The forage grasses *Bromus inermis, Dactylis glomerata,* and *Phleum pratensis* (table 14) are quite common today and are definitely introduced species. *Poa pratensis* is even more common, and together with *Agrostis alba* var. *stolonifera* form a dense canopy on mesic sites by late July. These two species are likely introduced as well.

Of the various riparian grasses, the presence of *Phalaris arundinacea* (reed canary grass) during both periods is probably the most interesting. Anderson (1961) considers this a native North American species, and mentions introductions to the southern continents. Apfelbaum and Sams (1987) state that the species is now more widely represented through introductions in agricultural areas, using Anderson(1961) as a source. This species, or especially the form *P. arundinacea* f. *picta* is planted for hay. I have not encountered the *picta* form, which is easily distinguished. Anderson (1961) did not see the *picta* form in naturally occurring stands of the *arundinacea* form. Perhaps, as Apfelbaum and Sams (1987) state, *P. arundinacea* is a problem species invading wetland sites. In context to the South Fork, this issue will be discussed later, but it is reasonably clear that this species is native to the South Fork.

Two other grass species from Hayden's list (table 13), *Triticum repens* and *Triticum glaucum* are particularly interesting . The present synonymy for these is *Agropyron repens* (quack grass) and *Agropyron intermedium*,(intermediate wheatgrass) respectively. Both of these latter species are considered introduced; the former a "bad weed" while the latter is a forage grass (Hitchcock and Cronquist 1973). *A. repens* was also found in the Yellowstone area, which had been seldom visited before. I doubt that the Hayden party encountered what would be called *A. repens* and *A. intermedium* today. The confusing taxonomy for the wheat grasses due to hybridization and subtle distinguishing features may be a reason for Hayden's unlikely encounter. I found what looks like *Agropyron smithii*, other material that looked more like *Agropyron intermedium*, as well as *A. intermedium* seeded on adjacent uplands. *Agropyron dasystachyum* (thick-spike wheatgrass) is another similar native species that is similar to *A. smithii* and *A. repens* (Hitchcock et al. 1969)

Two other common introduced species are the small forb *Trifolium dubium* (suckling clover) and *Cirsium arvense*(Canada thistle). The former is nearly ubiquitous today except in shaded or wet sites, while *C. arvense* , which is a noxious weed, has a more sporadic distribution. Both of these species occur on islands that have not been grazed by domestic livestock for decades (Spaulding pers. comm. 1993) as well as currently grazed areas.

There are essentially no exotic woody species, with *Elaeagnus angustifolia* (Russian olive) being the only exception. This species is practically nonexistent upstream of Table Rock Creek, but is much more common near and below Heise, even on new alluvial bars. The closely related *Elaeagnus commutata* (silverberry) is very widespread today and is native to the Rocky Mountain area (Hitchcock and Cronquist 1973) but it was not collected by Hayden. This species is rare in Idaho, (Spahr, et al. 1991) and the South Fork supports the only large population in the state (Moseley 1990, pers. comm.).

The flora's tree component may have changed slightly since the late 1800's, for there are a few more conifer species now. *Juniperus scopulorum* (Rocky Mountain juniper) is the most common today, and the Hayden survey collected it nearby on the Henrys Fork, where it still exists. Other than *Juniper*, there are presently very few conifer individuals, and these occur in widely scattered locales with *Pseudotsuga menziesii* (Douglas-fir) being the most common, followed by *Picea pungens* (blue spruce). Interestingly, *Picea engelmannii* (Engelmann spruce) is very common along the tributaries and on subalpine sites, but I found none along the South Fork. Likewise, *P. pungens* is scarce where *P. engelmannii* is found. Based on morphology, there is little to no sign of hybridization. Steele et al (1983) encountered the same pattern. The other conifers of the recent flora, *Abies lasiocarpa* (subalpine fir) and *Pinus contorta*(lodgepole pine) are very scarce, with only a few of each found. I only encountered 2 young *P. contorta* trees, and curiously, there were no mature individuals in sight. Considering how scarce most of these conifers are along the River today, and how common they are in the mountains, it is not surprising that the Hayden Survey did not collect them along the South Fork.

The Hayden collection has three species that are normally found in higher elevations today. The three are *Frasera speciosa, Clematis hirsutissima,* and *Salix arctica* (table 13). The first two usually inhabit mid-montane to subalpine areas, while *Salix arctica* usually occurs near timberline. I cannot think of morphologically similar species that could be confused with these species. If the climate was cold enough to support *S. arctica* in the valley, it is unlikely that the many warm-site species would have been found with it. Perhaps the collection location is mistaken. Conversely, Hayden collected some low-land species at high (10,000 feet) elevations (e.g., *Amelanchier alnifolia, Lonicera involucrata*), but based on today's plant distributions, these finds are more conceivable than the *Salix arctica* find.

Due to the changing taxonomy and somewhat subjective nature of plant identification, there is possibility for greater overlap between the two flora lists, especially for species that are similar but not synonymous. In other words, the same plants may exist during both periods, but the taxonomy and human judgement may obscure this similarity. Of course, the best way to reconcile possible similarities is to use the original material, and anything short of this is second-guessing. However, where possible commonalities have been obscured due to mis-identification from myself, the Hayden workers, or nebulous taxonomy, I comment to this effect in table 14.

Perhaps the possibility of mis-identification is highlighted by Coulter's find of *Pinus ponderosa* in the Tetons, which he considered common (Hayden 1873). This long-lived, fire-resistant species does not occur within at least 200 miles of the study area today. Older *Pinus contorta* trees can have quite orange bark reminiscent of *P. ponderosa*; this may be the source of error if trees were viewed from a distance. Errors in my work are most likely associated with the wheatgrasses.

Finally, the forb *Chrysopsis villosa* has a very confusing taxonomy. My primary source for plant names, Hitchcock and Cronquist (1973), uses only *Chrysopsis* for the goldenaster group. Recent work by Semple and others (1980) split and arranged the various goldenaster sections into three genera. This lumping/splitting has ecological implications: via Semple et al. (1980) *Heterotheca* is a long-lived herb with a large taproot, while *Chrysopsis* is weakly-taprooted and very short-lived. Semple et al. (1980) also used genetic differences in their arrangement of goldenasters. I used *Chrysopsis* for consistency reasons, but *Heterotheca* may be more appropriate for the goldenaster found in the Snake River region.

Table 13. Vascular flora collected in the Snake River Valley during 1872.

Species (Hayden name)	Current name (if different)	Remarks
Trees:		
Populus angustifolia		Along the streams of the Teton Basin, common everywhere in Northwest, in the lower altitudes
Populus tremuloides		Common everywhere in the west on foot-hills and following the courses of streams
Shrubs:		
Artemisia tridentata		The common form all over the West
Salix arctica		Snake River Valley, August; Teton Mountains, elevation 12,000 feet, July
Salix cordata var. *augustata*	*Salix lutea*	
Spiraea Millefolium	*Chamaebatiaria millefolium*	
Symphoricarpus montanus	?	
Symphoricarpus occidentalis	*Symphoricarpos occidentalis*	
Forbs:		
Achillea millefolium		very abundant everywhere on the route
Allium stellatum	?	
Amerantus albus	*Amarathus albus*	Remarkably red for the species
Anemone multifida		
Angelica Breweri	?	Swamps in Snake River Valley, July

Table 13. Vascular flora collected in the Snake River Valley during 1872.— continued.

Species (Hayden name)	Current name (if different)	Remarks
Forbs, continued:		
Antennaria dioica	*Antennaria microphylla rosea)*	
Aphyllon fasiculatum	*Orobanche fasiculatum*	
Aplopappus suffruticosus	*Haplopappus suffruticosus*	
Arenaria conjesta		
Arenaria laterifolia		
Artemisia discolor michauxiana		
Artemisia dracunculoides	*Artemisia dracunculus*	
Asclepias speciosa		
Astragalus hypoglottis	*Astragalus dasyglottis*	
Astragalus tegetarius		
Astragalus junceus	*Astragalus convallarius*	
Barbarea vulgaris		
Campanula rotundifolia		
Chenopodium album var. *leptophyllum*	*Chenopodium leptophyllum*	
Cicuta maculata	? (probably *Cicuta douglasii*)	
Claytonia Chamissonis	*Montia chamissoi*	Spray flower of the lower falls of the Yellowstone, August; Snake River Valley, July
Clematis Douglasii	*Clematis hirsutissima*	Teton Mountains, elevation 10,000 feet, July; Snake River Valley
Cordylanthus ramosus		

Table 13. Vascular flora collected in the Snake River Valley during 1872.— continued.

Species (Hayden name)	Current name (if different)	Remarks
Forbs, continued:		
Dracocephalum parviflorum	*Dracocephalum nuttallii ?*	
Epilobium tetragonum	?	
Epilobium paniculatum		
Equisetum scirpoides		
Erigeron Bellidiastrum	?	
Eriogonum cernuum var. *tenue*		
Eriogonum heracleoides		
Eriogonum microthecum		
Eriogonum ovalifolium		
Eritrichium augustifolium	?	
Eritrichium Californicum	*Plagiobothrys scouleri*	
Eritrichium leiocarpum	?	
Erysimum cheiranthoides		
Eupatorium purpureum	*Eupatorium maculatum*	
Euphorbia serpyllifolia		
Frasera speciosa		
Gaura parviflora		
Gilia congesta		

Table 13. Vascular flora collected in the Snake River Valley during 1872.— continued.

Species (Hayden name)	Current name (if different)	Remarks
Forbs, continued:		
Gilia floccosa	*Eriastrum sparsiflorum*	
Gilia leptomeria		
Gilia pungens var. *squarrosa*	*Leptodactylon pungens*	
Hieracium Scouleri		
Hypericum Scouleri	*Hypericum formosum* ssp. *scouleri*	
Iva axillaris		abundant in Snake River Valley, July 26; near hot springs along the Yellowstone, August
Lepidium montanum		Very abundant. A dwarf form was found near Fort Hall, Idaho
Lychnis Drummondii		
Myrrhis occidentalis	*Osmorhiza occidentalis*	
Obione argentea	*Atriplex argentea*	
Oenothera biennis		
Oenothera scapoidea		
Orobanche multiflora	? (probably *Orobanche ludoviciana*)	
Oxytheca dendroidea		Grows in great abundance in Snake River Valley, July
Orthocarpus Tolmiei	?	
Oxytropis Lamberti	*Oxytropis sericea*	
Paonia Brownii		Every specimen found had but two carpels instead of 3 - 5
*Pentstemon confertus*var. *caerlo-purpurens*	*Penstemon procerus*	

Table 13. Vascular flora collected in the Snake River Valley during 1872.— continued.

Species (Hayden name)	Current name (if different)	Remarks
<u>Forbs</u>, continued:		
Physostegia parviflora	*Draccephalum nuttallii*	
Plantago Patagonica var. *gnaphaloides*	*Plantago patagonica*	
Polygonum aviculare var. *latifolium*	*Polygonum erectum*	
Polygonum tenue	?	
Polygonum tenue var. *latifolium*	*Polygonum douglasii*	
Ranunculus aquatilis var. *trichophyllus*	*Ranunculus aquatilis*	
Rumex pausifolius		
Rumex venosus		
Sisymbrium junceum	?	A form (?)
Spiranthes Romanzoffiana		
Stachys palustris		
Stephanomeria exigua		
Typha latifolia		
<u>Graminoids</u>:		
Agrostis scabra		
Alopecurus glaucus	?	

Table 13. Vascular flora collected in the Snake River Valley during 1872.— continued.

Species (Hayden name)	Current name (if different)	Remarks
Graminoids, continued:		
Brizopyrum spicatum	*Distichlis spicata*	
Elymus condensatus Presl.	? (probably *Elymus cinereus)*	
Eriocoma cuspidata	*Oryzopsis hymenoides*	
Glyceria pauciflora	*Puccinellia pauciflora*	
Hordeum pusillum		
Hordeum jubatum		
Melica bulbosa		
Phalaris arundinacea		Marsh Valley , Idaho, June; Snake River Valley , July; Upper Canon of the Madison, August. "Known as 'crazy grass', from its reputed injurious effect on horses." Watson.
Spartina gracilis		Snake River Valley, July; found in both Geyser Basins, August.
Triticum repens	*Agropyron repens*	Port Neuf Canon, Idaho, July; Snake River Valley. It is known as "bluejoint" and is valuable for hay and grazing. Found also in the Upper Geyser Basin.
Triticum glaucum, Desf. (?)	*Agropyron intermedium*	
Vilfa cryptandra	*Sporobolus cryptandrus*	

Table 14. Vascular flora collected on the South Fork riparian zone during 1992 and 1993.

Species * = voucher specimen	Abundance C=common S=scarce V=very	Remarks
Trees		
Abies lasiocarpa	VS	common at high elevations, Hayden collected in Yellowstone Park
Juniperus scopulorum	C	Hayden collected along the Henrys Fork
Picea pungens	VS	common along Snake River in Jackson Hole area
Pinus contorta var. *latifolia*	VS	very common at mid-elevations
Populus acuminata	C	
Populus angustifolia	VC	
Populus tremuloides	VS	found in very old channels, common on adjacent uplands
Psuedotsuga menziesii	S	common on adjacent uplands,Hayden collected in Teton Mountains
Pyrus malus	VS	found near old homesteads
Shrubs		
Acer glabrum	VS	common on upland ravines
Acer grandidentatum	VS	common on upland ravines
Alnus incana	S	Hayden collected in Teton foothills
* *Amelanchier alnifolia*	S	Hayden collected in Teton mountains at 10,000 feet
Artemisia tridentata	VS	very common on adjacent uplands
Berberis repens	VS	very common on adjacent uplands in conifer stands
Betula occidentalis	C	Hayden collected in Port Neuf Canyon, Idaho
Chrysothamnus viscidiflorus	VS	found with *Artemisia tridentata*

Table 14. Vascular flora collected on the South Fork riparian zone during 1992 and 1993 — continued

Species * = voucher specimen	Abundance C=common S=scarce V=very	Remarks
<u>Shrubs</u>, continued:		
Clematis ligusticifolia	C	Hayden collected in Port Neuf Canyon (a vine)
Cornus stolonifera	VC	Hayden collected in swamps of Teton River
Crataegus douglasii	S	
Elaeagnus angustifolia	VS	non-native
* *Elaeagnus commutata*	VC	missing from Hayden's complete list
* *Lonicera involucrata*	S	Hayden collected in Teton mountains at 10,000 feet
* *Pontentilla fruiticosa*	S	Hayden collected in Teton Basin
Prunus virginiana	VS	Hayden collected near Marsh and Malade Valleys, Idaho
Ribes lacustre	C	Hayden collected in upper Teton Canyon
Ribes aureum	VS	
Rhus trilobata	S	more common near Heise and below
Rosa woodsii var. *ultramontana*	C	
* *Salix bebbiana*	VS	few individuals found, occurs in very old channels
* *Salix exigua* ssp. *melanopsis*	VC	Hayden collected along Henrys Fork
Salix geyeriana	VS	found only in one locale, more common along large tributaries
Salix lasiandra	VS	
* ***Salix lutea***	C	
Symphoricarpos albus	S	common on nearby uplands in conifers
* ***Symphoricarpos occidentalis***	VS	common only at the *Salix geyeriana* locale

Table 14. Vascular flora collected on the South Fork riparian zone during 1992 and 1993 — continued

Species * = voucher specimen	Abundance C=common S=scarce V=very	Remarks
Forbs		
* ***Achillea millefolium***	S	
Actaea rubra	S	Hayden collected in upper Teton Canyon; found on moist, very old alluvium — especially old channels
* *Anemone cylindrica*	S	
* ***Anemone multifida* var. *multifida***	S	
Angelica arguta	VS	found with *Actea rubra*, this may be Hayden's *Angelica Breweri*
* ***Antennaria microphylla***	S	found on dry, stony sites
* *Anthemis cotula*	VS	non-native, sporadic occurrence on young alluvial bars
* *Arabis holboellii* var. *collinsii*	VS	
* ***Arenaria laterifolia***	S	
* *Arnica longifolia*	VS	Hayden collected in Grand Canyon of Yellowstone
* ***Artemisia dracunculus***	VS	found on sandy, dry sites
* *Artemisia ludoviciana*	S	Hayden collected in Port Neuf Canyon, Idaho
Asclepias speciosa	S	
* *Astragalus canadensis*	S	Hayden collected in Port Neuf Canyon
* *Astragalus tenellus*	S	found on stony, dry sites
* ***Campanula rotundifolia***	S	well distributed but not dense
Carduus nutans	S	non-native, noxious weed
* *Castilleja miniata* var. *miniata*	S	

Table 14. Vascular flora collected on the South Fork riparian zone during 1992 and 1993 — continued

Species * = voucher specimen	Abundance C=common S=scarce V=very	Remarks
<u>Forbs</u>, continued:		
Castilleja pilosa var. *longispica*	S	(identified with Dorn 1988)
* *Chrysopsis villosa* var. *villosa*	S	common only on dry, stony sites. Hayden collected from Henrys Fork
Cirsium arvensis	C	non-native, noxious weed
Convolvulus arvensis	VS	non-native, noxious weed
* *Corallorhiza wisteriana*	VS	
* *Euphorbia esula*	VS	non-native, noxious weed; more common on uplands with no trees
* *Equisetum laevigatum*	VC	well distributed except on stony, dry sites
* *Erigeron glabellus* var. *glabellus*	C	Hayden collected *Erigeron glabellum* in Teton Basin
Erigeron speciosa var. *macranthus*	VS	Hayden collected *Erigeron macranthum* in wooded canyon of Teton River. *E. macranthus* is synon. with *E. speciosa* var. *macranthus*
* ***Eriogonum heracleoides* var. *heracleoides***	VS	common on uplands in grass-lands
* *Fragaria virginiana* var. *glauca*	S	Hayden collected in Teton Basin
* *Galium triflorum*	S	Hayden collected the similar *Galium trifedum* on the Henrys Fork
Gentiana affinis	S	Hayden collected along the Henrys Fork
Geranium richardsonii	VS	Hayden collected along the Henrys Fork
Geum macrophyllum	VS	Hayden collected along the Teton River
* *Gilia aggregata* var. *aggregata*	S	Hayden collected in Teton Basin
* *Glycyrrhiza lepidota*	C	Hayden collected at and Creek, Idaho

Table 14. Vascular flora collected on the South Fork riparian zone during 1992 and 1993 — continued

Species * = voucher specimen	Abundance C=common S=scarce V=very	Remarks
<u>Forbs, continued:</u>		
* *Grindelia squarossa* var. *serrulata*	VS	this variety is introduced; Hayden collected an unknown variety in Port Neuf Canyon
* *Habenaria hyperborea*	S	Hayden collected in upper Teton Canyon
* *Heracleum lanatum*	VS	Hayden collected in upper Teton Canyon; found in moist, old channels
* *Hippuris vulgaris*	S	aquatic sites, Hayden collected on Henrys Fork
* *Lupinus argenteus*	S	common on adjacent, grassy uplands
Lychnis alba	VS	non-native
Lysimachia ciliata	VS	Hayden collected on Henrys Fork
Medicago sativa	VS	non-native (alfalfa) Hayden collected at Fort Hall, Idaho
Melilotus alba	S	non-native, more abundant in 1992
Melilotus officinalis	S	non-native, more abundant in 1992
Mentha arvensis	S	Hayden collected on Henrys Fork
* *Myosotis scorpioides*	C	non-native, restricted to wet areas (unusually small flowers)
Osmorhiza chilensis	VS	Hayden collected at upper Teton Canyon. Common upland forest species.
* *Penstemon angustifolius* var. *caudatus*	VS	Identified using Dorn 1988
Potentilla glandulosa	VS	Hayden collected on Henrys Fork
Potentilla gracilis	VS	Hayden collected on Henrys Fork
* *Prunella vulgaris* var. *lanceolata*	VS	Hayden collected on Henrys Fork, Teton Basin
* *Pyrola asarifolia* var. *asarifolia*	VS	

Table 14. Vascular flora collected on the South Fork riparian zone during 1992 and 1993 — continued

Species * = voucher specimen	Abundance C=common S=scarce V=very	Remarks
<u>Forbs, continued:</u>		
Rudbeckia occidentalis	VS	Hayden collected in Teton mountains and Snake River Plains
Rumex crispa	S	non-native, found on young alluvial bars
* *Sedum lanceolatum* var. *lanceolatum* ??	S	found only on stony, dry sites
* *Senecio indecorus*	C	this may be *Senecio debilis*, a very similar species
Senecio hydrophilus	S	Hayden collected at Henrys Lake. Found on young alluvial bars
Sium suave	VS	found in standing water. Hayden collected *Sium lineare* in Port Neuf Canyon, Idaho (*Sium suave* has very narrow leaves)
* *Silene menziesii* var. *viscosa*	S	
* *Smilacina stellata*	VC	Hayden collected at 10,000 feet in Teton mountains.
* *Solanum dulcamara*	VS	non-native, found in one locale (Wolf Flat)
* *Solidago canadensis*	VC	Hayden collected the similar *Solidago gigantea* along the Henrys Fork
* *Solidago occidentalis*	C	very ephemeral, often inconspicuous
* *Sonchus ugilinosus*	S	non-native, found on young alluvial bars
* *Sisyrinchium angustifolium*	C	a spring-time ephemeral. Hayden collected *Sisyrinchium Bermudiana*, which is likely the same species, along the Henrys Fork
Taraxacum officinale	VS	non-native, surprisingly scarce
Thalictrum sp.	VS	Hayden collected *Thalictrum fenderli* along the Henrys Fork
Tragopogon dubius	S	non-native
Trifolium dubium	C	non-native
Typha latifolia	S	found on wet, silty sites

Table 14. Vascular flora collected on the South Fork riparian zone during 1992 and 1993 — continued

	Species * = voucher specimen	Abundance C=common S=scarce V=very	Remarks
	Forbs, continued:		
	Urtica dioica	VS	Hayden found in Teton foothills
	Verbascum thaspus	VS	non-native
*	*Veronica anagallis-aquatica*	VS	Hayden collected along Teton River
*	*Vicia americana* var. *truncata*	S	Hayden collected near Marsh Valley, Idaho
*	*Viola canadensis*	S	common in mid-elevation conifer forests
	Xanthium strumarium	VS	non-native. Associated with heavy trampling and animal-bedding areas
	Graminoids		
	Agropyron cristatum	VS	non-native, restricted to disturbed and seeded areas
*	*Agropyron smithii*	C	a variable species; this may be Hayden's *Triticum glaucum*.
*	*Agropyron spicatum*	VS	common in upland grasslands
*	*Agrostis alba* var. *stolonifera*	VC	Hayden collected *Agrostis scabra* (table 13).
*	*Bromus anomalus*	VS	
*	*Bromus inermis*	C	non-native
	Carex nebraskensis	VS	
*	*Carex rostrata*	S	found in old wet channels. Hayden collected in Yellowstone
	Dactylis glomerata	S	non-native, sporadically abundant
*	*Eleocharis palustris*	S	found in old wet channels.
*	*Elymus canadensis*	S	

Table 14. Vascular flora collected on the South Fork riparian zone during 1992 and 1993 — continued

Species * = voucher specimen	Abundance C=common S=scarce V=very	Remarks
<u>Graminoids</u>, continued:		
Elymus cinereus	VS	common in upland grasslands
* *Elymus virginicus*	C	
Festuca idahoensis	VS	common in upland grasslands
* *Glyceria grandis*	S	usually found with *Carex rostrata*. Hayden found *Puccinellia pauciflora* (table 13), a similar species.
* *Hierochloe oderata*	VS	found along old, clear, spring-like channels
* *Hordeum depressum*	VS	found on young alluvial bars
* ***Hordeum jubatum***	S	found on disturbed areas
* *Juncus longistylis*	S	restricted to moist old channels
* *Muhlenbergia asperifolia*	S	Hayden collected along Henrys Fork
* ***Oryzopsis hymenoides***	S	restricted to stony, dry sites.
* ***Phalaris arundinacea***	C	very dense on many young alluvial bars
Phleum pratensis	S	non-native
Poa nervosa	VS	restricted to dry, stony sites. Identification uncertain.
* *Poa juncifolia*	VS	found with *Poa pratensis*
* *Poa palustris*	VS	non-native. Found on very old, moist channel bottoms.
* *Poa pratensis*	VC	non-native
Scirpus americanus	VS	
Scirpus validus	S	
* *Stipa comata* var. *intermedia*	S	

Vegetation - For the pre-settlement period, the general environment is characterized by various short references to the Snake River area by Osborne Russell during his travels in the 1830's and 1840's (Haines 1955) and the Hayden Surveys of 1872 and 1877. These early references are important and short enough to state below, and are numbered for future reference. If a place name has changed, the new one follows in brackets, except 'Lewis Fork' equates to the South Fork Snake River. The lead-in sentences put the quotes in a broader context. The quotes are exact, including spelling, punctuation, and italics. My additional comments are in brackets.

From Osborne Russell's journal (Haines 1955):

After entering the Snake River valley via the Salt River on May 3, 1834 . . . . .

1) "This is a beautiful valley covered with green grass and herbage surrounded by towering mountains covered with snow spotted with groves of tall spruce pines which from their vast elevation resemble small twigs half emersed in snow, whilst thousands of Buffaloe carelessly feeding in the green vales contribut to the wild and romantic Splendor of the Surrounding Scenery."

On June 21, 1834, Russell's party crossed the Snake River, probably near Fall Creek . . . .

2) "Here we were obliged to cross Lewis Fork which is about 300 yds. wide and might be forded at low stage of water, but at present was almost overflowing its banks running at the rate of about 6 mls per hour. We commenced making a boat by sewing two raw Bull hides together which we stretched over a frame formed of green willow branches. . . ."

After a hazardous crossing with a loss of one life, Russell describes the camp area . . . .

3) "Lewis' fork at this place is timbered with large Cotton wood trees along the banks on both sides."

Beginning on January 27, 1839, Russell trapped beaver and hunted near Heise; his first camp was likely near the Heise hot springs . . . .

4) "next morning I found 4 large fat Beaver in my traps and on the 2nd Feby. we returned to camp with 12 beaver. Feby. 10 Moved with the camp up river to where we had caught the Beaver and encamped. Lewis Fork comes thro. this kanyon for about 12 Mls. where the rock rises 2 or 300 feet forms a bench and ascends gradually to the Mountain which approaches close on the Nth side and on the South is about 3 or 4 Mls distant and an occasional ravine running from the mountain to the river thro the rocks on the Nth side forms convenient places for encamping as the bench and low Spurs are well clothed in bunch grass. Here we found imense numbers of Mountain Sheep which the deep snows drive down to the low points of rocks facing the river"

The following comments from the Great Plains region about buffalo, grass, and cottonwoods highlight the possible differences to the South Fork Snake River area.

In the Yellowstone River valley near the confluence of Clarks Fork of the Yellowstone, November 11, 1836 . . . .

5) "The bottoms along these rivers are heavily timbered with sweet cottonwood and our horses and mules very fond of the bark which we strip from the limbs and give them every night as the Buffaloe have entirely destroyed the grass throughout this part of the country"

On the Powder River, February 7, 1838 in the present Natrona County, Wyoming . . . .

6) "The bottoms along Powder river were crowded with Buffaloe insomuch that it was difficult keeping them from among the horses who were fed upon Sweet Cottonwood bark as the buffaloe had consumed everything in the shape of grass along the river"

From John M. Coulter's general description of the plains area encompassing Ogden, Utah to the Teton Basin, Idaho (Hayden 1873):

7) "On all these plains an entire absence of trees is noted, except a few of stunted growth along the larger streams; while the mountain-ranges are sparingly timbered with *Coniferae* from base to summit, intermixed along some foothills with "bitter cottonwood". ....[remarks on salty areas near Ogden].... Farther back, towards the mountains, the higher types [in a taxonomic

sense, compared to Chenopods] appear again, and with a greater richness of color than seems possible in such soil. Of course the Artemesias are common everywhere, and especially *A. tridentata*, completely covering the plains and far up the mountain slopes."

Frank H. Bradley, a geologist, describes the Snake River valley from upper Grand Valley to Swan Valley, on October 6, 1872 (Hayden 1873):

8) "At two points [one is Van Point] this rock descends nearly to the water's edge; but the valley soon opens out again, with broad bottoms on the east for several miles, to opposite the mouth of Fall Creek, where basalt appears upon the eastern side as it had done on the western some miles higher up. The upper part of this valley-flat is covered with sage-brush, but the lower half is full of the richest pasturage, except only such portions as are occupied by beaver-dams and bayous. Along these water courses, large thickets of black-haws [*Crataegus*] were most thickly covered with ripe fruit, but the crop of service-berries was almost an entire failure in all this region. At several points we noticed the abundant rose-bushes covered with hips, which were so soft when ripe as to have a translucent appearance of berries and to be very pleasant eating. [extended comments about fruit ripeness and reasons why] All through the cãnon, as well as along this lower valley, we noticed innumerable young plants of the lupines, which abound in the region, prepared to make vigorous growth as soon as the short summer opens."

The geologist Orestes St. John's describes the lower valley of the Snake (Hayden 1879), beginning with the Conant Valley area. (The Conant Valley area is shown in figures 58 to 61)

9) "Just above the little recess at Butte [Garden] Creek, which is shut off by a low butte capped by trachyte, we regain a larger bottom tract which reaches a mile or two along the stream on the south side, extending back to the foot of the mountain, which is here denuded of volcanics; the north side of the stream still showing a bluff of volcanic rock, underlaid by lighter colored deposits. This bottom is made up of gravel, which forms a bar-like ridge between the stream and a low, marshy tract inland, and is further molded into low terraces. The turbid, swift-flowing river is filled with low islands, covered with willow and cottonwood, and dense copses of wild rose."

St. John describes the Conant and Swan Valley areas in general . . . .

10) "Many beautiful views are gained from the trail passing over the high benches, stretches of wide bottom plain, through which the gleaming river winds in majestic curves, its surface studded with beautiful islands and the banks lined with tall cottonwoods, here bordered by mural bluffs of volcanic rock, fringed with dark-foliaged pine and fir, and the whole bounded

by rugged mountain walls, which stretch away in long lines of perspective until lost in the distant windings of the valley"

After passing through lower Swan Valley, St. John first describes the upper, terraced portion of Swan Valley and then Grand Valley (see chapter 2). These areas are shown in figures 50 to 56:

11) "Above the latter locality low bluffs of dark basaltic rock approach the southwest margin of the river, along which narrow tracts of alluvial bottom land border this side of the stream, which on the opposite side expand into the gravelly sage-covered plain of the lower basin. Higher up the valley the sedimentary mountains on either side approach nearer, the volcanic benches becoming higher and crowded into a narrow space, where they form a line of quite prominent bluffs [the Palisades Bench] on the northeast side, the bottoms being crowded to the opposite side, where they were found to be composed of coarse, water-worn materials, built into low, well-defined terraces 10 to 25 feet above the present level of the stream."

12) "A marked change at once takes place on entering the upper basin of the valley [Grand Valley]. If ever the volcanics extended farther than the narrows, they have been entirely swept out of the upper basin, which is occupied by a fine bottom tract based on a deposit of water-worn pebbles and alluvial matter, arranged in a series of much more prominent terraces than any occurring in the lower basin [Swan Valley], the highest which do not exceed perhaps 50 feet, while the lowest is only a few feet above the river level; the valley is narrower, but the alluvial terraces occupy the whole space intervening between the foot of the abrupt mountain borders. Numerous small streams debouching from the hills have swept down quantities of *debris*, which is piled in low-spreading accumulations like the tailings of a sluice-way; the waters often spread over the level bottoms, where they to-day form extensive areas of miry soil, but which will one day be converted into invaluable meadow tracts."

For the early-settlement period, the vegetation and environment are depicted in the following repeat-photography sets (figure 50 to 72) and vegetation descriptions summarized from early cadastral survey notes (table 15). The photographer and photo number are cited for the early photographs, which are all US Geological Survey. The photo sets and the notes are presented in a downstream direction. Keep in mind that the the study area is not evenly represented by the photographs; there ia a bias towards the more accessible places. The notes are for section lines that are about 2 miles apart.

Figure 50. Upper Grand Valley from Van Point, 1911. Most of the conifers are Douglas-fir *(Psuedotsuga menziesii)*, and the upland deciduous trees are aspen *(Populus tremuloides)*. Note short, wider-areas of flood plain dominated by cottonwood (*Populus angustifolia* and *P. acuminata*). Some terrace scarps are apparent. (A. R. Schultz #606)

Figure 51. Upper Grand Valley from Van Point, October 15, 1992. Conifer coverage has increased on the lower foothills. Active storage is 117,226 acre-feet, or about 10 percent of total active storage.

Figure 52. Lower Grand Valley from Van Point, 1911. Bear Creek enters on middle-left. Calamity Point is prominent at left-center, and Palisades Bench with bluffs is to right. River is more strictly confined by the 10- and 30-foot terraces in Swan Valley below Calamity Point. Boulder is rhyolitic welded tuff which caps the Tertiary conglomerate. Calamity Point and Palisades Bench are andesite. (A. R. Schultz #605)

Figure 53. Lower Grand Valley from Van Point, October 15, 1992. Note increase in conifer coverage on lower foothills. Hillside in foreground was recently trampled by domestic sheep; the low shrub is likely mountain snowberry *(Symphoricarpos oreophilus)*. Aspen is on hilltop in foreground, with Douglas-fir to right.

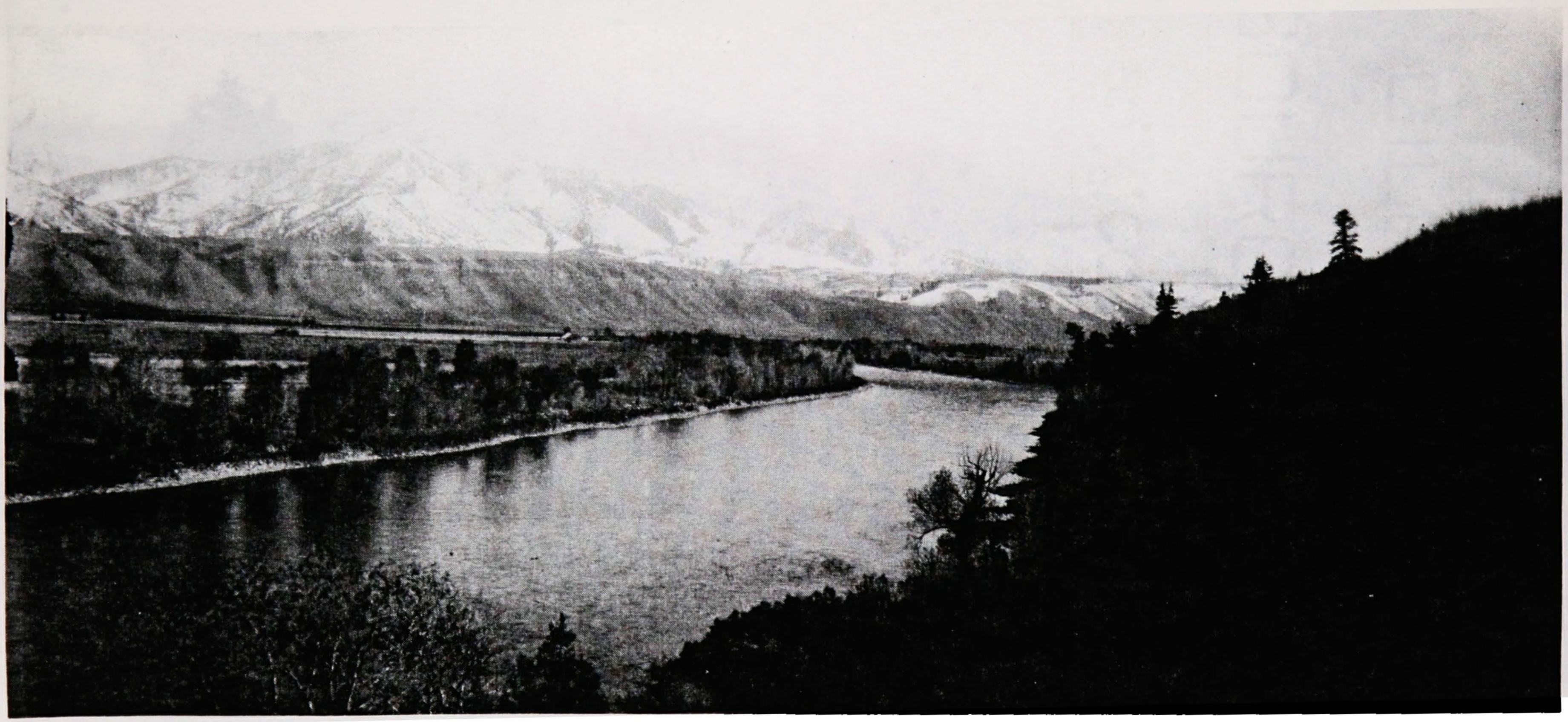


Figure 54. Upstream view of South Fork in Swan Valley, from near Indian Creek, 1911. Vegetation on river-right bank is on 10-foot terrace scarp, and steppe community dominates the terrace tread. Bushy conifers are rocky mountain juniper *(Juniperus sopulorum)*; tall Douglas-fir are among aspen on right hillside. (R. W. Richards #210)

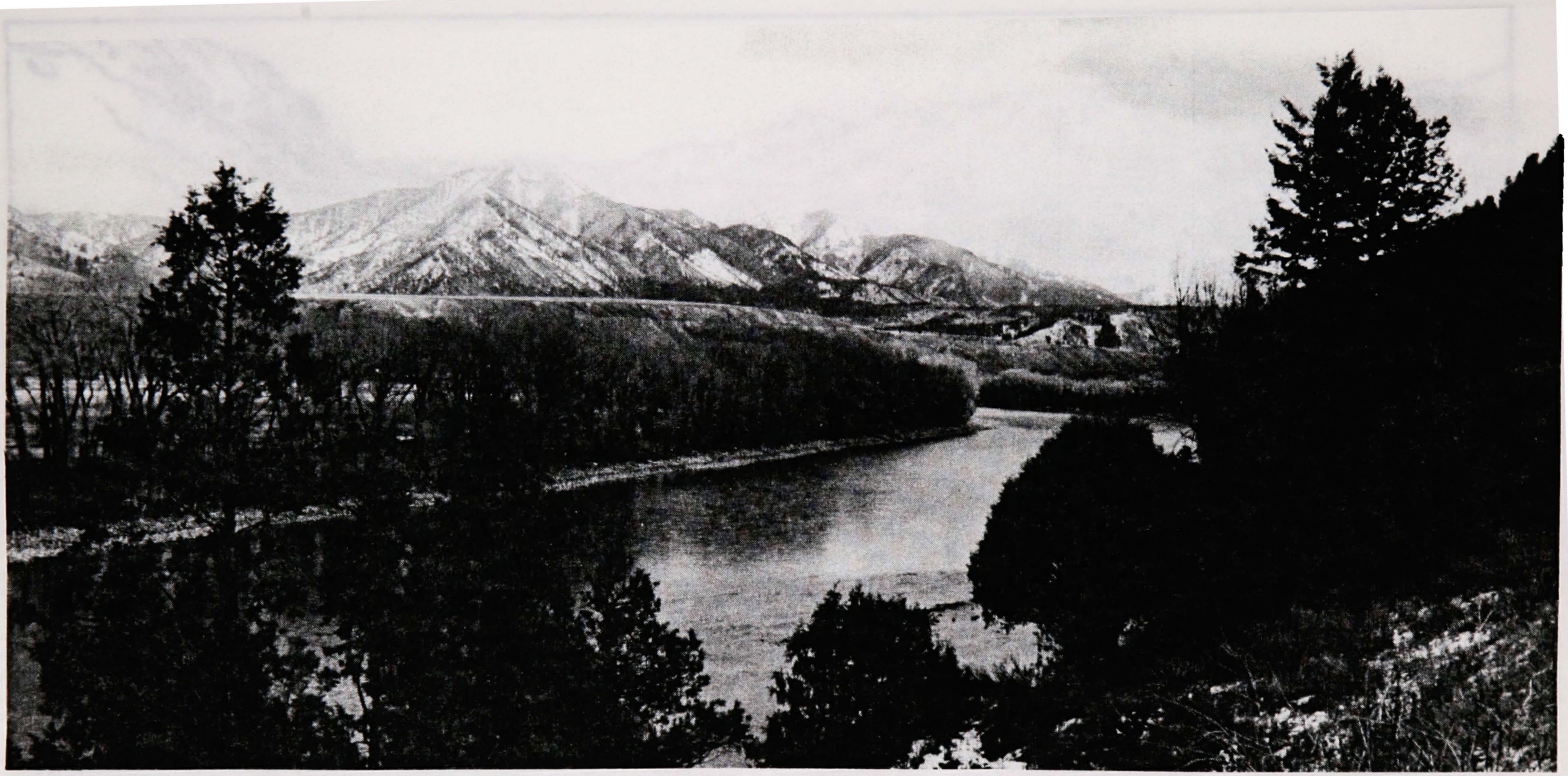


Figure 55. Upstream view of South Fork in Swan Valley, from near Indian Creek, November 20, 1992. Note increase in conifers on lower foothills. Tall conifer in right-foreground is Douglas-fir, tall one on left and bushy ones are rocky mountain juniper. Cottonwood dominates terrace scarp. Snake River Range (9000 -10,000 feet) is behind Palisades Bench. Flow is 1220 cfs.

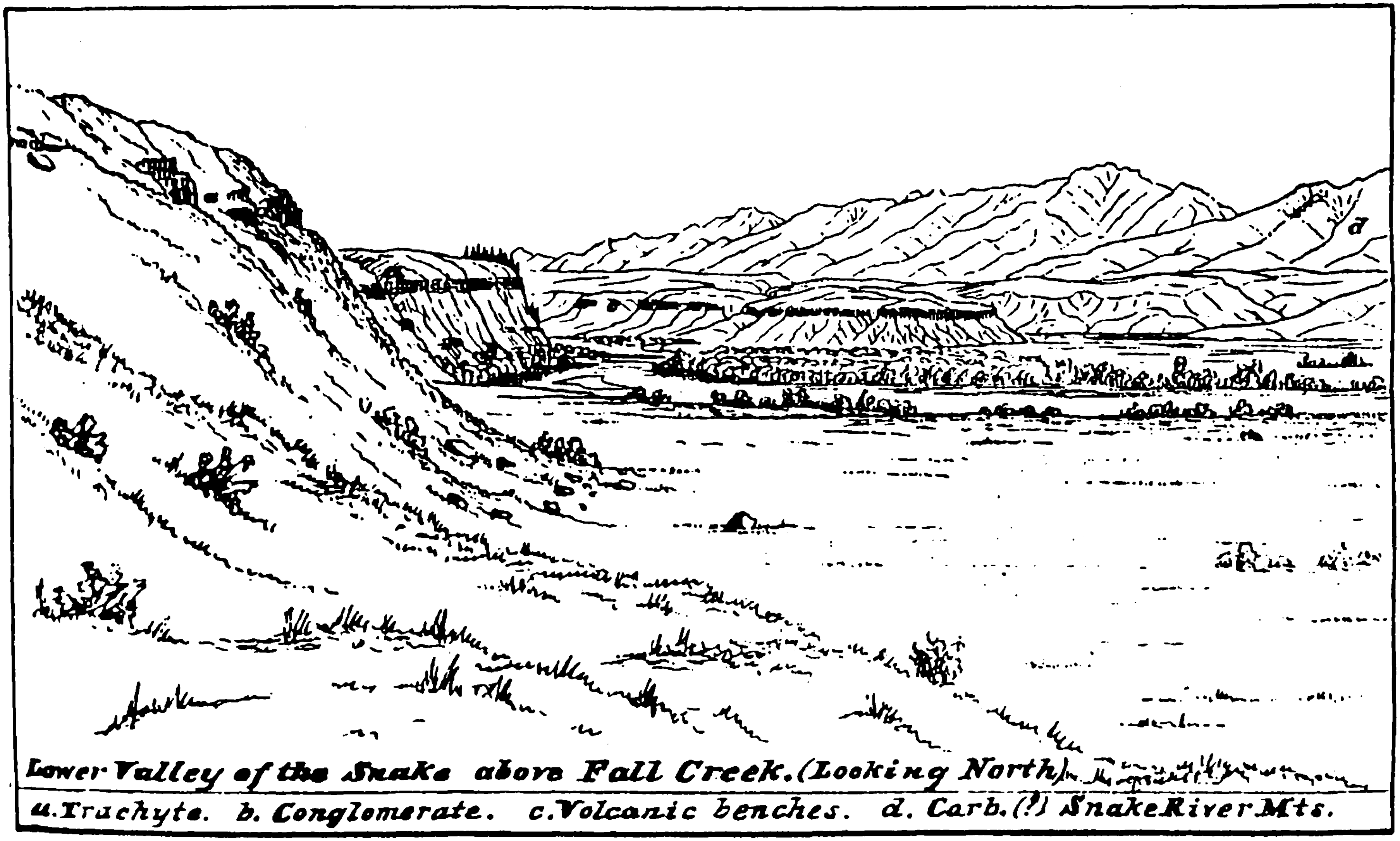


Figure 56. Downstream view of South Fork above Fall Creek in Swan Valley, 1877. Squaw Creek enters at left between bluffs, which are Tertiary conglomerate capped by rhyolitic welded tuff. Stouts Mountain (8600 feet) prominent in right-background, behind Pine Creek Bench. (Anonymous, from Hayden 1879)

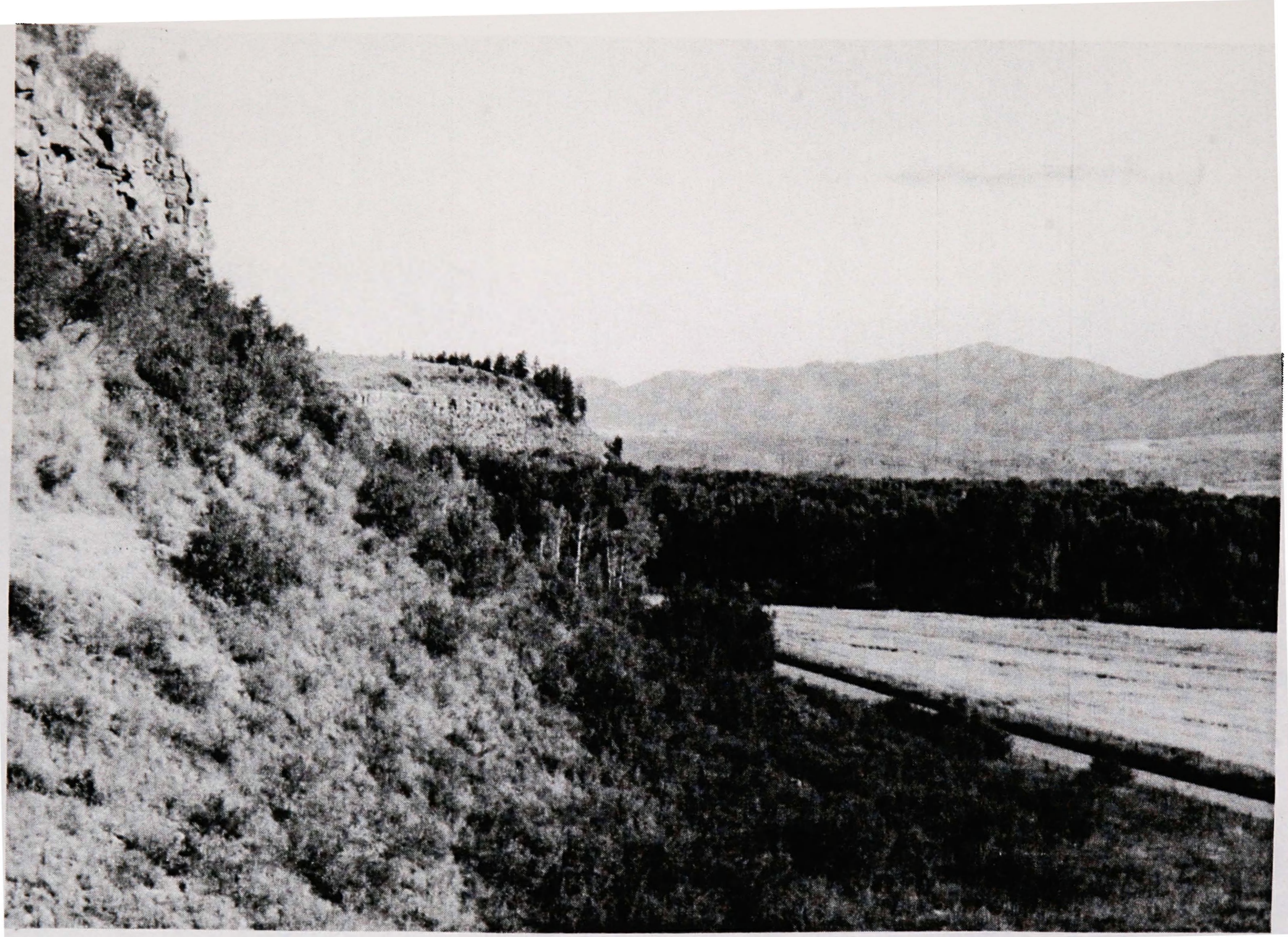


Figure 57. Downstream view of South Fork above Fall Creek in Swan Valley, August 19, 1992. Main river channel is behind the now-tall cottonwoods. Taller shrubs are mostly chokecherry (*Prunus virginiana*), with some young aspen. Low shrubs are mostly mountain snowberry, three-tipped sagebrush (*Artemisia tripartita*), rabbitbrush (*Chrysothamnus viscidiflorus*) , and bitterbrush (*Purshia tridentata*). Crop on the terrace is barley.

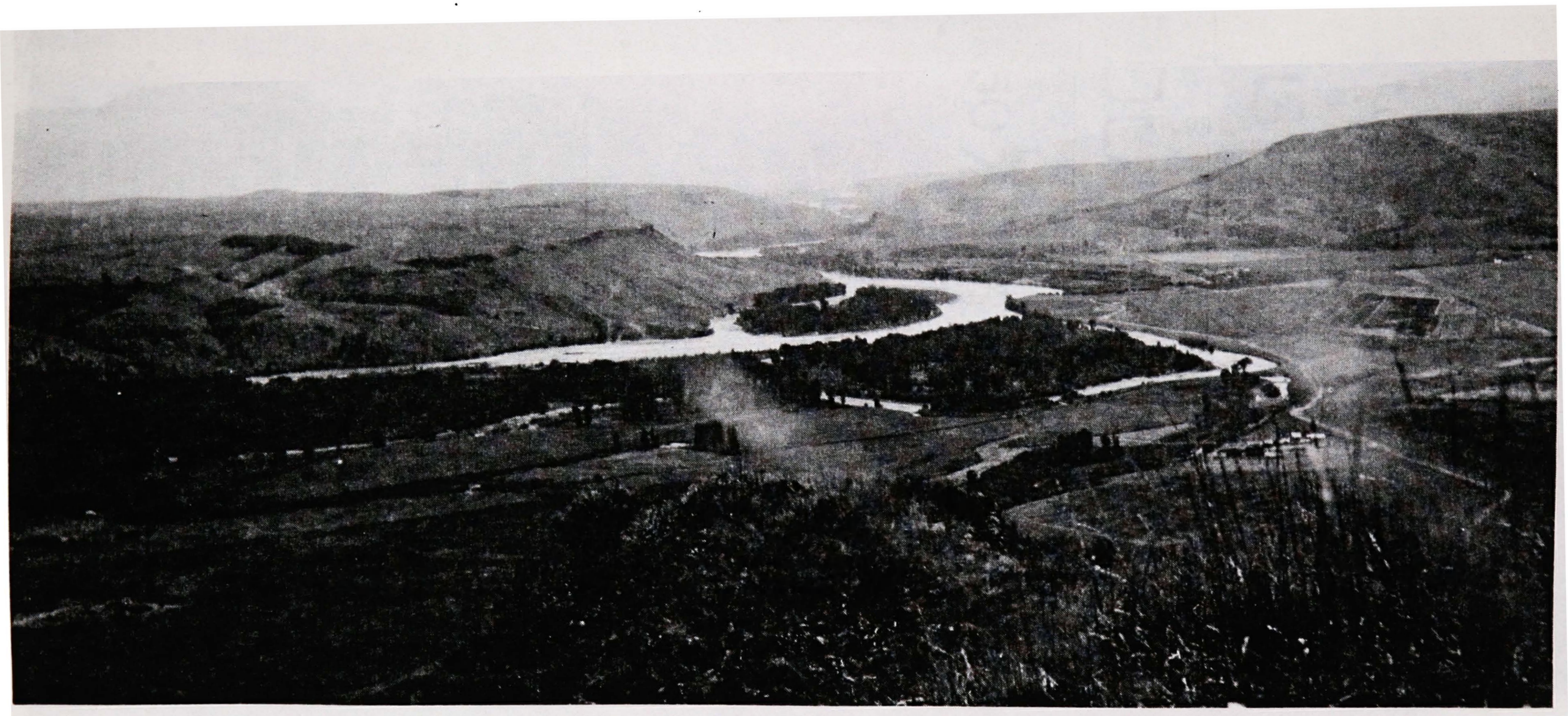


Figure 58. Upper Conant Valley from near Garden Creek, circa 1908 to 1911. Pritchard Creek enters in the middle-right, Pine Creek Bench is in the middle-left. This area was homesteaded around 1897. The grass in foreground is likely Great Basin wild rye *(Elymus cinereus)*. Cottonwood dominates the flood plain. (W. B. Heroy #31)

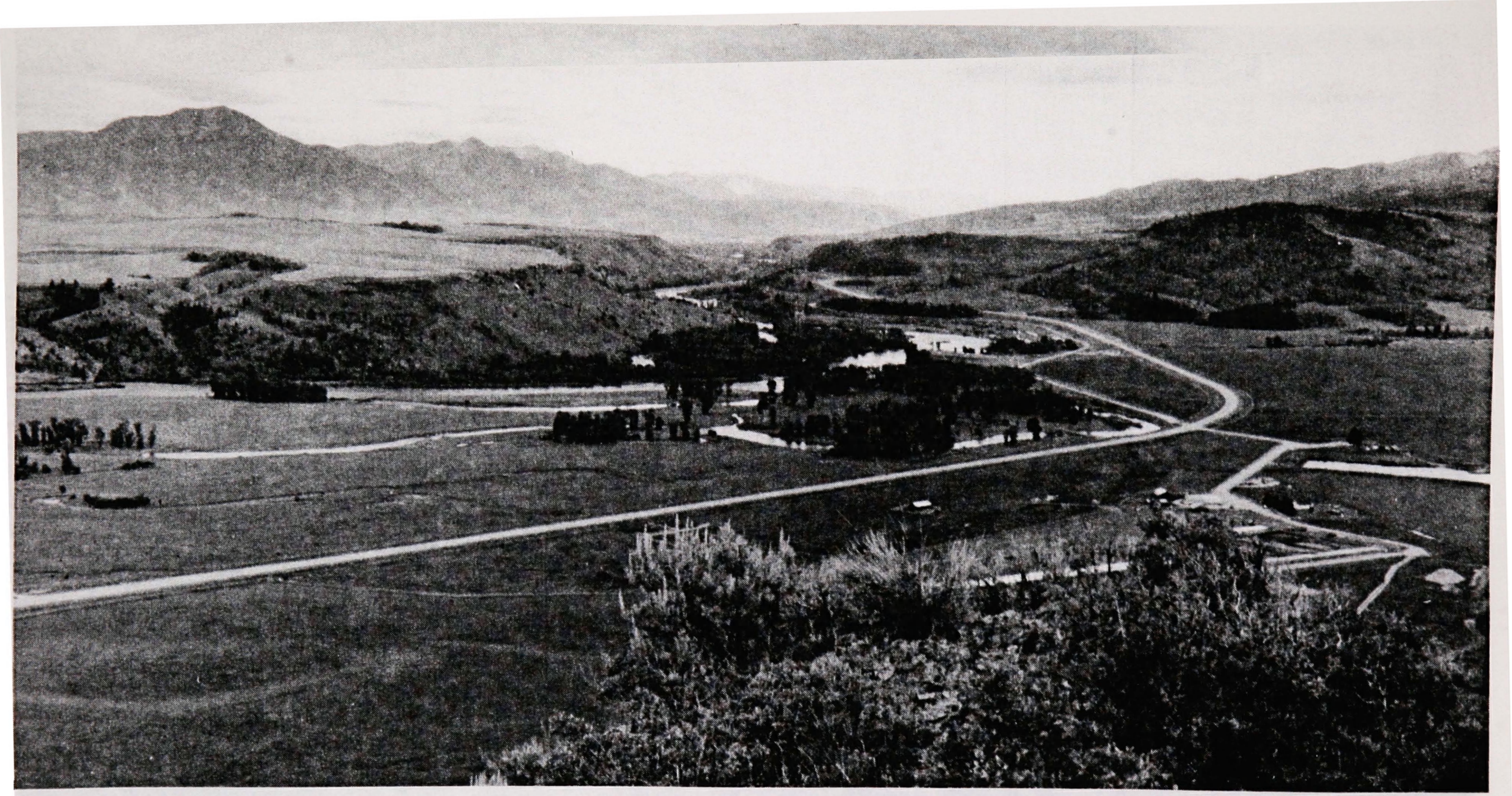


Figure 59. Upper Conant Valley from near Garden Creek, June 29, 1992. Some of the riparian forest has been cleared (during 1950's), and various forage grasses dominate the pasture with scattered hawthorn (*Crataegus douglasii*). Pine Creek Bench is dryland farmed; the slope facing the river is sagebrush steppe with scattered junipers and Douglas-fir. Most shallow draws and the hillside facing Pritchard Creek support aspen. Flow is 12,245 cfs.

Figure 60. Lower Conant Valley from near Garden Creek, circa 1908 to 1911. Stouts Mt. on left (with scratch), Pine Creek at center. This scene starts just below that of figure 58, and shows the entrance to the volcanic canyon, bordered by Pleistocene basalt and tuff benches. Note young vegetation on large bar to the right of center. (W. B. Heroy #32)

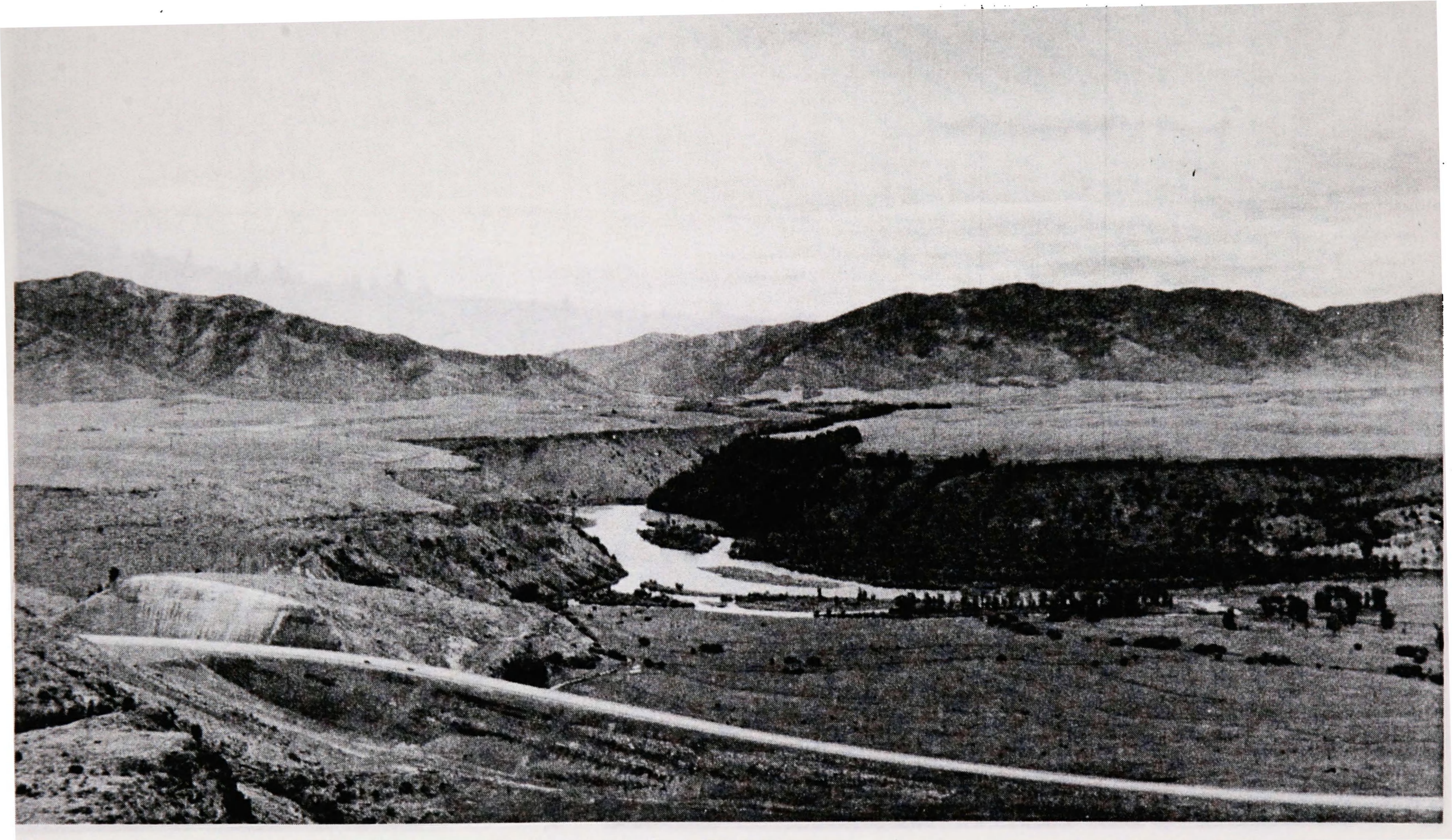


Figure 61. Lower Conant Valley from near Garden Creek, June 29, 1992. Extent of grain and alfalfa fields to mountain front apparent. Note cleared cottonwoods at base of Douglas-fir stand, which has matured. In pasture, most shrubs are hawthorn, and other riparian shrubs are now gone. Cottonwood has matured on large bar right of center. Though not obvious, pasture adjacent to highway is seasonally wet. Flow is 12,245 cfs.

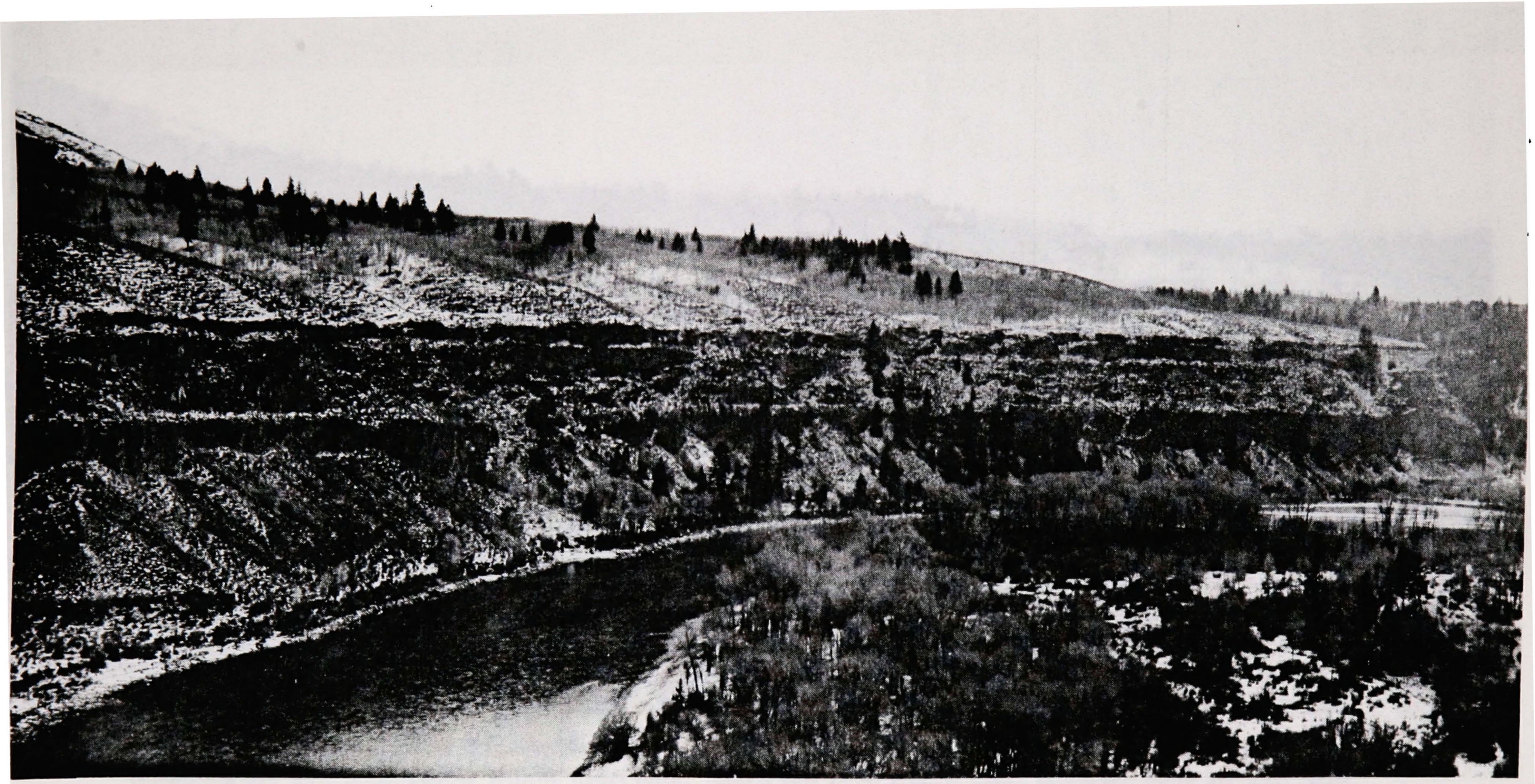


Figure 62. South Fork near Dry Canyon, 1932. Dry Canyon at extreme right. This is a typical volcanic-canyon reach. Canyon walls are Pleistocene basalt, which are overlain by colluvium and loess. More open area to right of cottonwoods is an abandoned channel. Dry Canyon stream gaging station was placed near lower-center of photo. Note lack of damage 5 years after the 60,000 cfs Gros Ventre flood. (G. R. Mansfield #984).

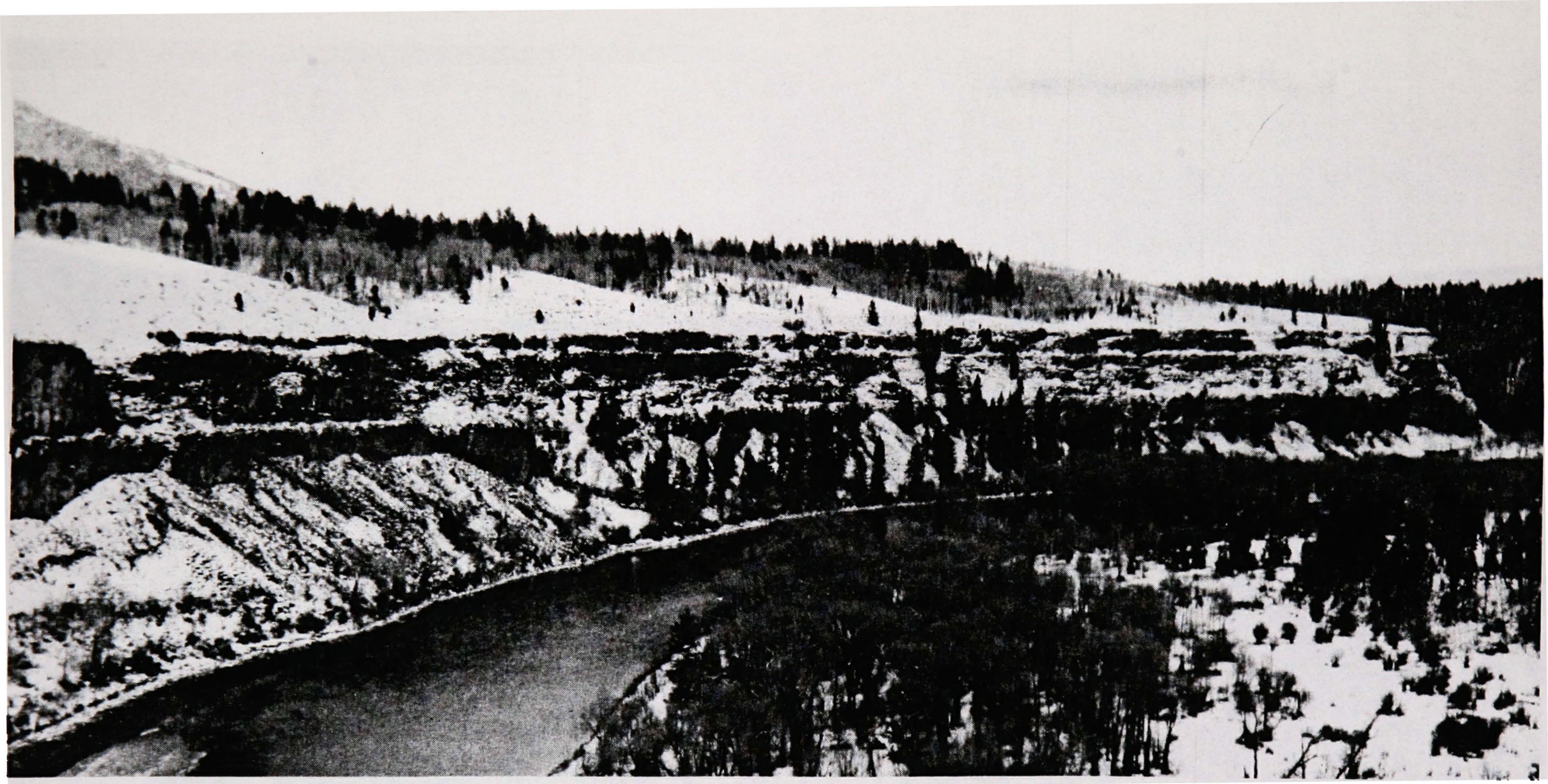


Figure 63. South Fork near Dry Canyon, November 10, 1991. Shrubs in old abandoned channel have been reduced, those remaining are hawthorn, yellow willow (*Salix lutea*) and a few Bebb willow (*Salix bebbiana*); there are also large, dead aspen on the ground. Note addition of cottonwood-dominated bar near right edge. Snow obscures upland steppe, which is sagebrush, rabbitbrush, bunchgrasses, and juniper in open areas. Upland forest is aspen and Douglas-fir, with common snowberry (*Symphoricarpos albus*) and serviceberry (*Amelanchier alnifolia*) dominating the understory. Gently-sloped and flat areas were recently grazed by cattle. Flow is 2,113 cfs.

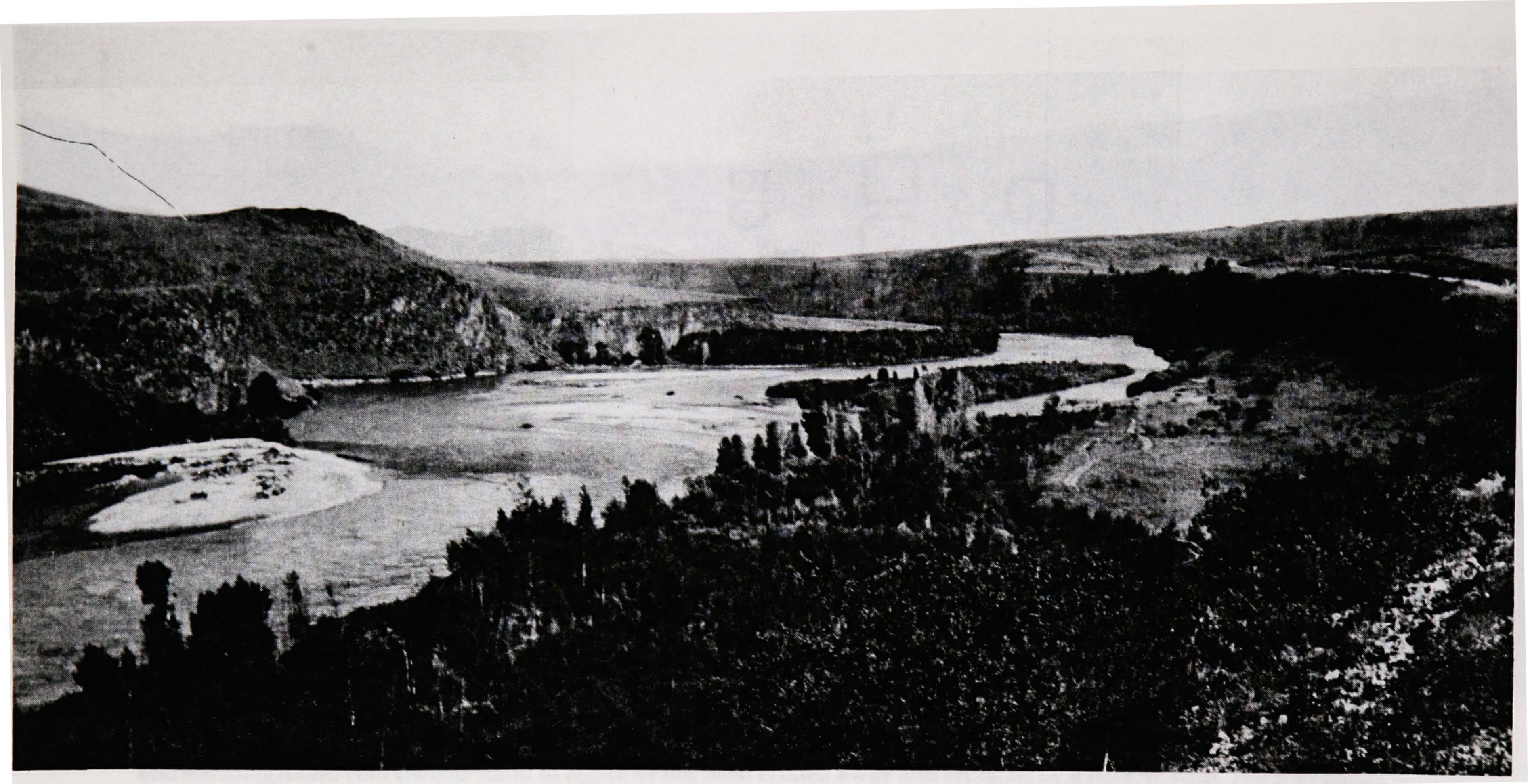


Figure 64. South Fork near Riley ditch headgate, circa 1908 to 1911. This is a typical lower-volcanic-canyon reach. Conant Valley is below distant mountains. The two higher, steep bluffs on left are Tertiary rhyolite, other cliffs are Pleistocene basalt. Cottonwoods dominate the flood plain. Note shrub-filled channel near the road, and mostly bare bars in center. View is upstream. (W. B. Heroy #28)

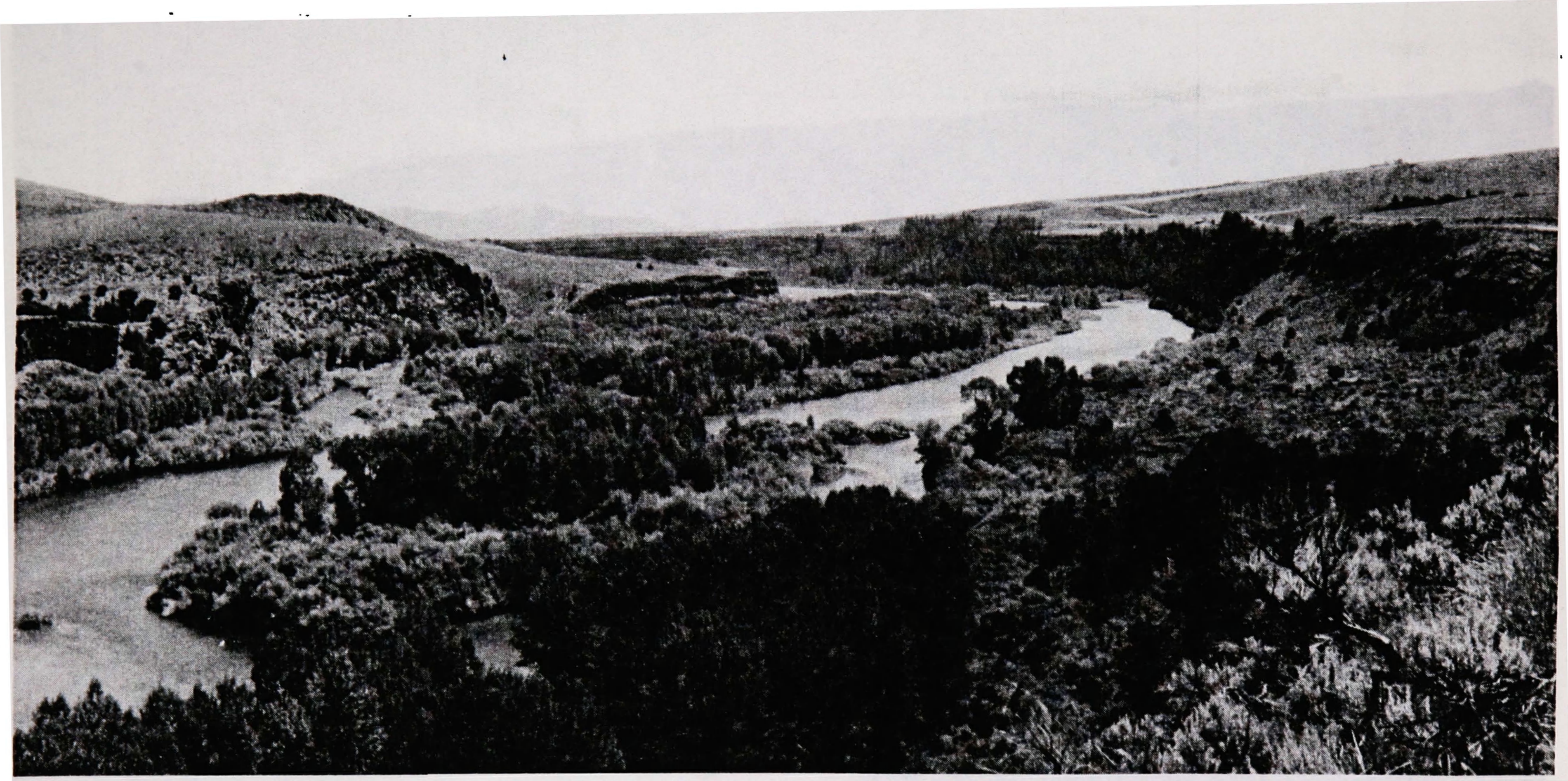


Figure 65. South Fork near Riley ditch headgate, June 18, 1992. As in other scenes, mature cottonwoods have increased. There has been considerable channel migration and bar shifting; the previously shrub-filled channel (figure 64) is now active, and the foreground cottonwood stand in figure 64 has been eroded away and replaced by a narrow strip. The previously bare bars now have mature cottonwoods. Side channel on left is partly filled with sandbar willow *(Salix exigua)*, and the shrubs fringing the cottonwoods are sandbar willow, yellow willow, red-osier dogwood *(Cornus stolonifera)*, and silverberry *(Elaeagnus commutata)*. Note conifer invasion in right-foreground, and increase in low upland shrubs on older alluvium in middle-right. Small cottonwood clumps (right-center) line the Riley ditch. Flow is 11,340 cfs.

Figure 66. South Fork near Riley ditch headgate, 1914. This scene is just below that of figures 64 and 65, which was taken from further upstream. The bare bar is in the same place as the bare bar just below the low basalt cliff in figure 64. The rounded bluff is the left-most rhyolite one shown in figure 64, and the downstream end of the shrubby, mid-channel bar of figure 64 shows here. The River flows to the left. (R. W. Stone #693)

Figure 67. South Fork near Riley ditch headgate, September 10, 1925. The scene is essentially the same, but the perspective is slightly different because it was photographed from further upstream. The bare bar has grown and is now vegetated. The taller plants on the right, back part of the shrubby bar are cottonwood. Flow is 5950 cfs. (W. C. Alden #1606)

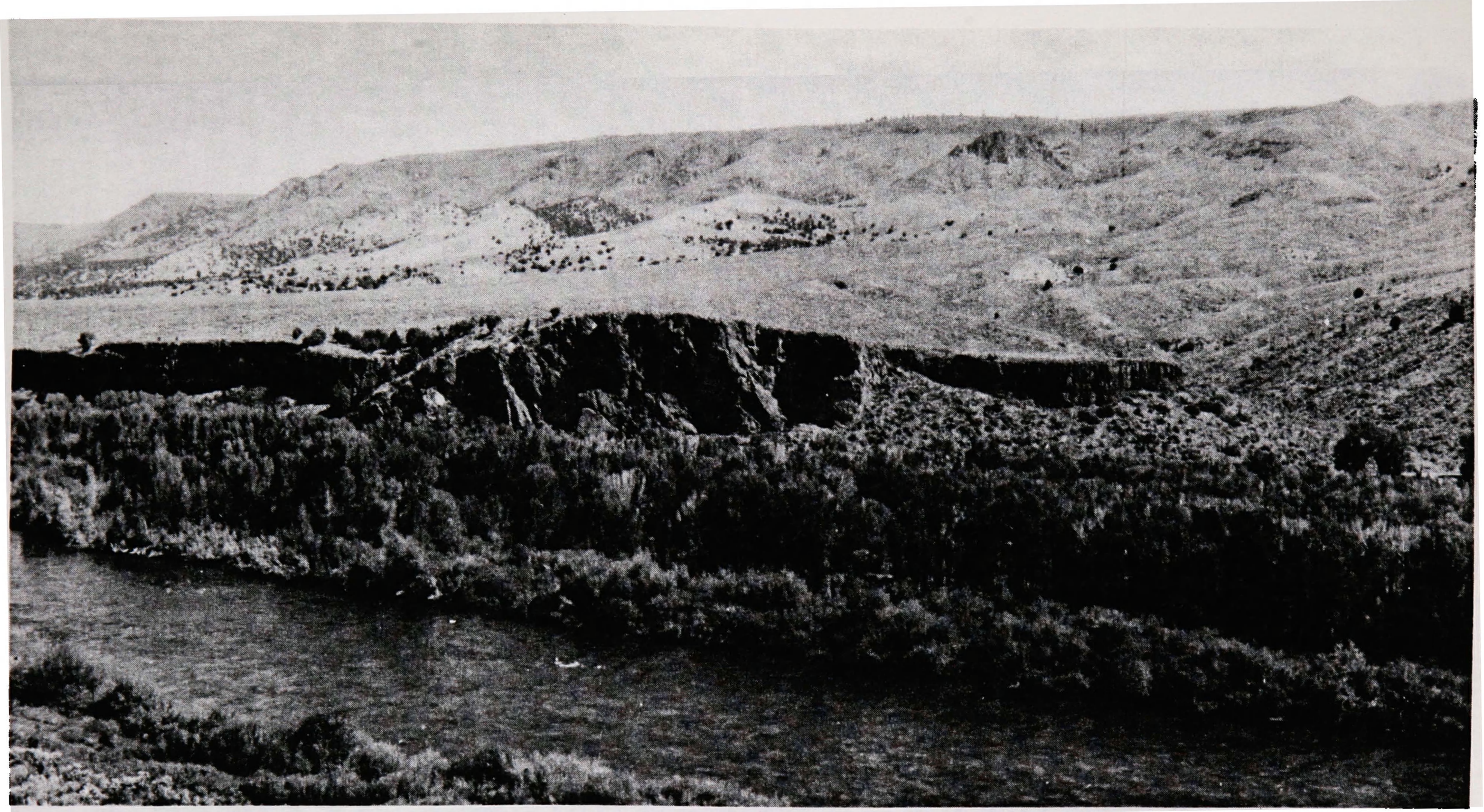


Figure 68. South Fork near Riley ditch headgate, July 13, 1992. The photo point is the same as on figure 66. The bar now supports mature cottonwood, fringed by the mixed shrub community described in figure 65. The front, right-third of the cottonwood forest are the ones on the shrubby bar in figures 64, 66, and 67. Junipers have increased on the foothills. The Pleistocene basalt flow surrounds the older, Tertiary bluff of rhyolite. This lithology attracted the early photographers. Flow is 10,965 cfs.

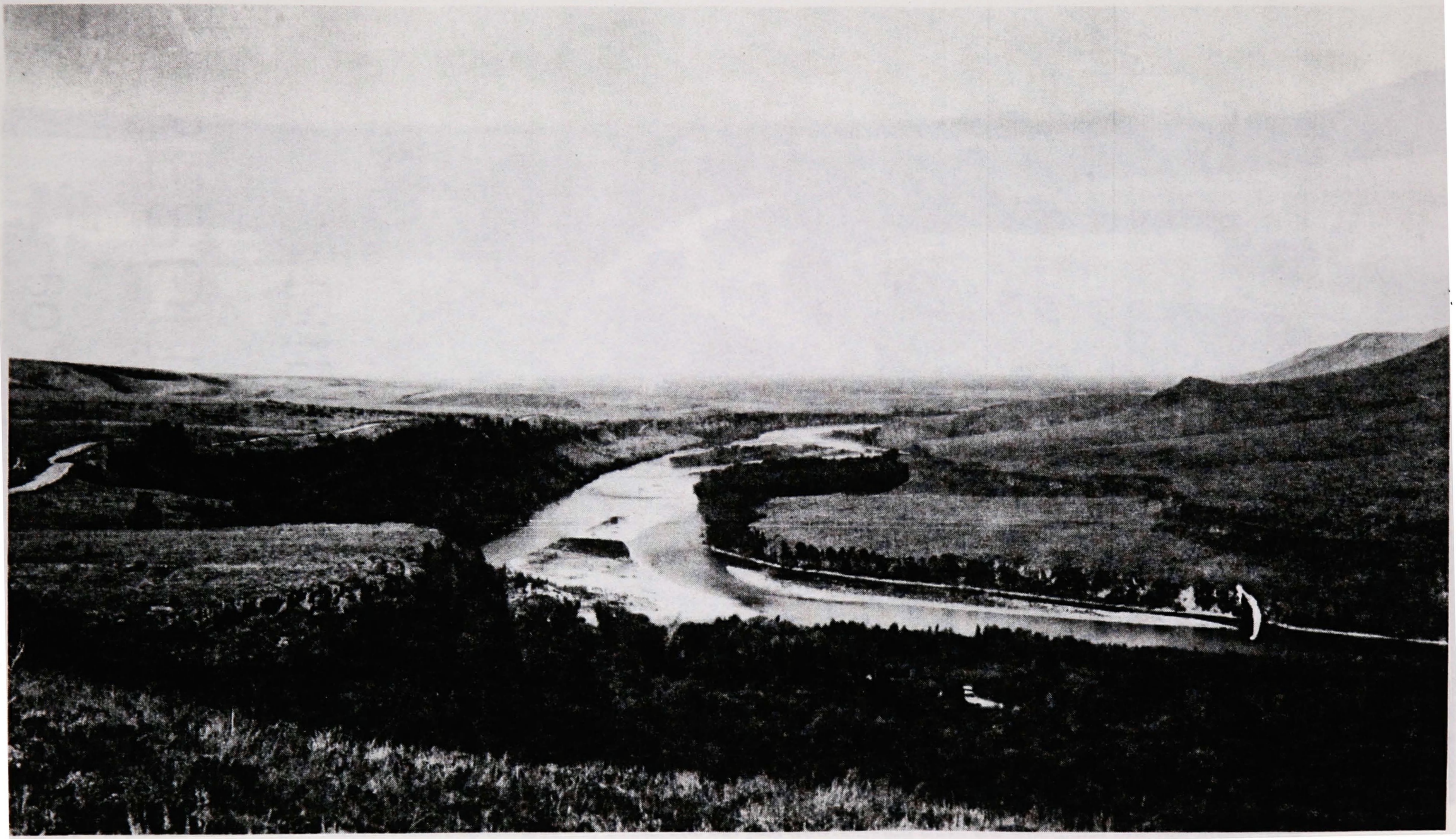


Figure 69. South Fork below Clark Hill, September 10, 1925. This is the downstream view of the bars shown in figures 64 to 68. The shrubby bar and the recently vegetated bar shown in figure 67 is in center. The large, flat steppe area fringed by cottonwoods is colluvial and alluvial. This flat may be a remnant of the 30-foot Pinedale glacial terrace. The narrow fringe of trees is on a terrace scarp. The steep slope just above the flat is basalt. Flow is 5950 cfs. (W. C. Alden #1605)

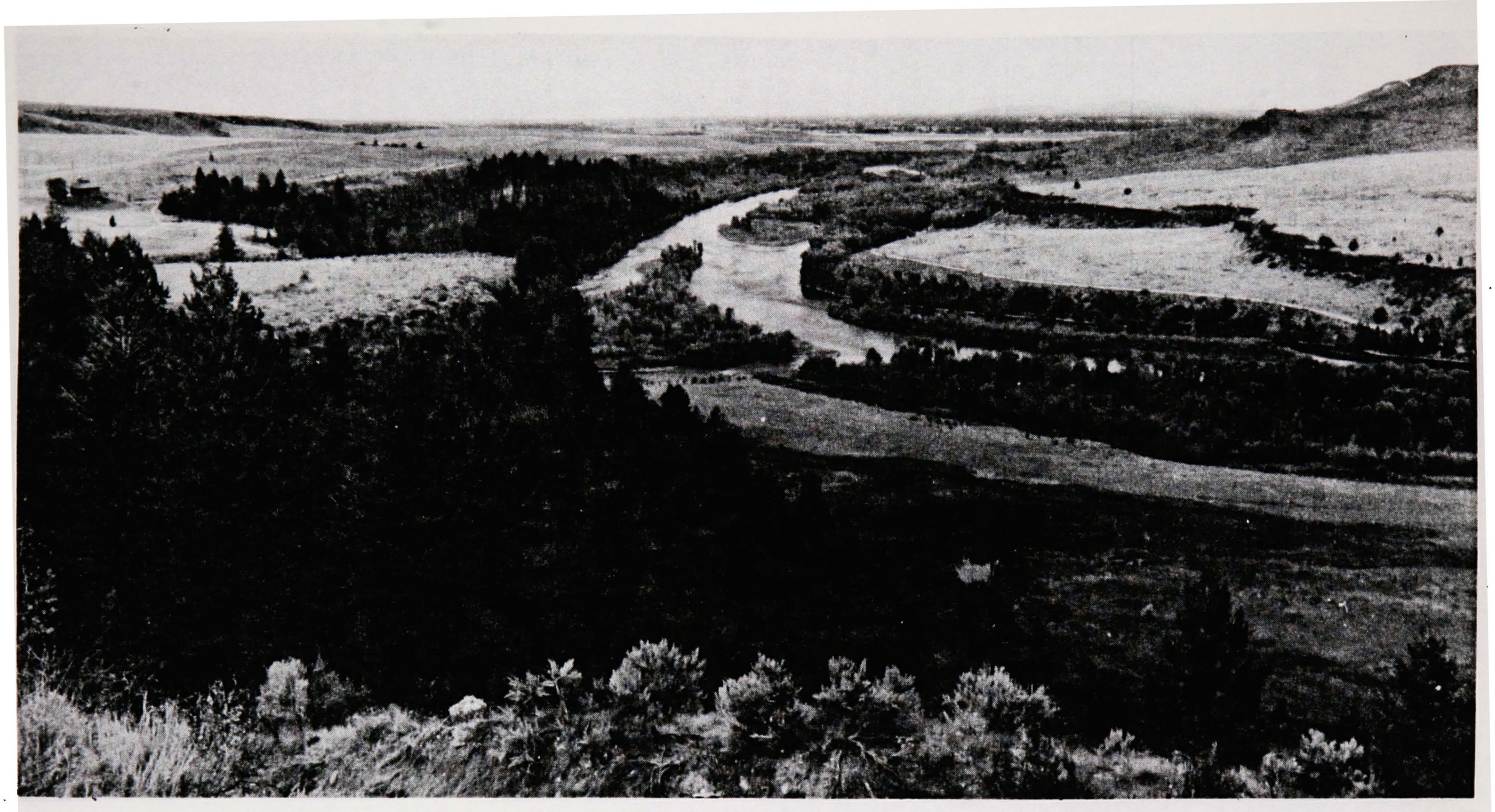


Figure 70. South Fork below Clark Hill, September 14, 1992. The bar just downstream from the triangular one has much reed canarygrass *(Phalaris arundinacea)*, which together with sandbar, willow, yellow willow, and young cottonwood, surrounds a small clump of older cottonwoods. The lighter vegetation on the flat (figure 69) is likely due to increased grass after a fire in 1991. Channel migration has been much less since 1925 than from 1911 to 1925. Flow is 5950 cfs. Note similar active channel width, but upper-channel margins were bare in earlier scene (figure 69).

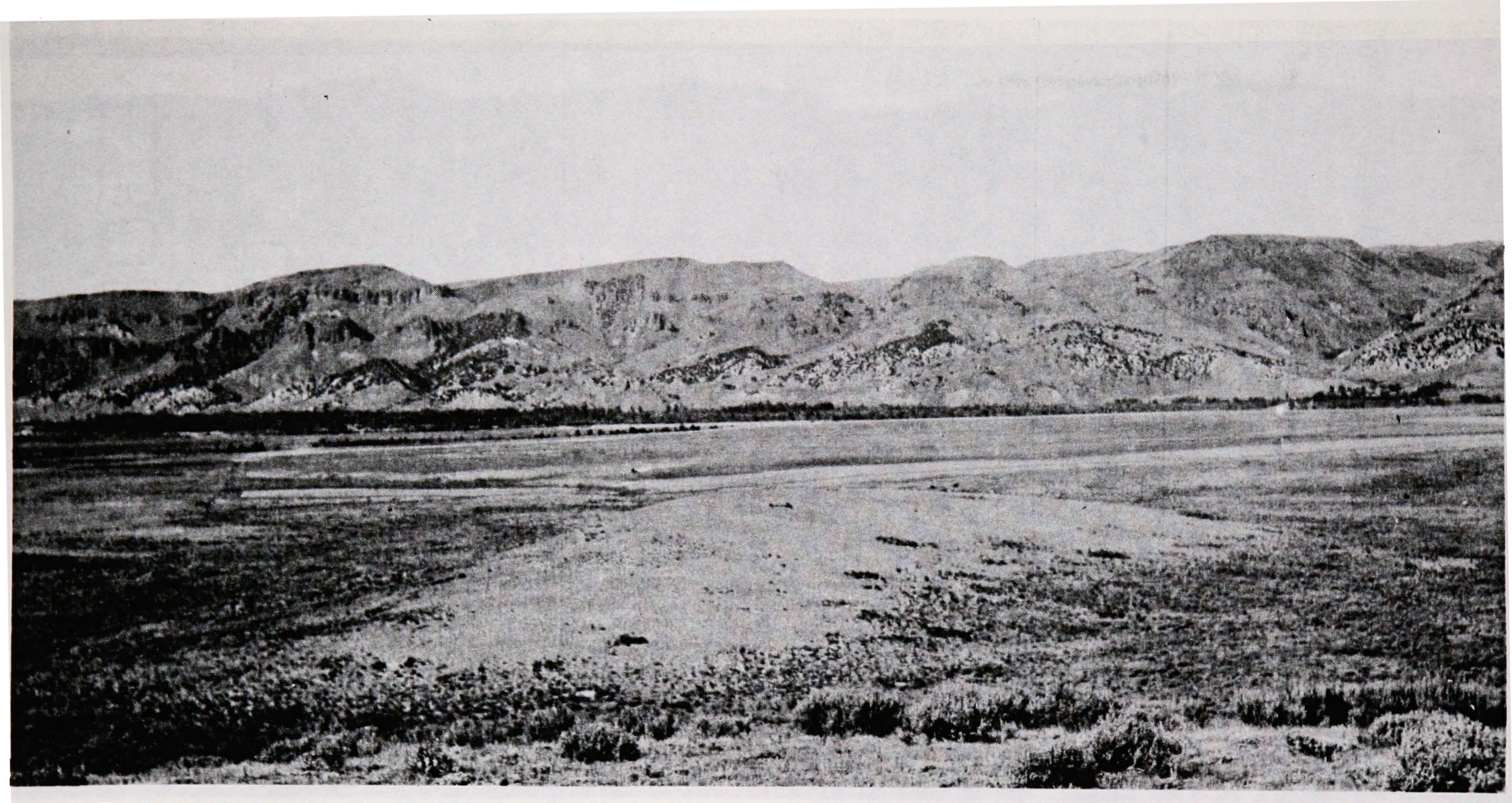


Figure 71. South Fork and environs from near Poplar, Idaho, circa 1908 to 1911. The riparian forest is about one mile away. The area in the bottom third is loess-covered, and alluvial terraces and the flood plain comprise the smooth flat beyond. The sparse hill in foreground is an extension of the ridge Heroy stood on; the sparse vegetation is likely due to thinner soil. The row of vegetation on the flat lines the Riley Ditch, built in 1899 to 1900. Dark vegetation on volcanic foothills in far distance is juniper. (W. B. Heroy #27)

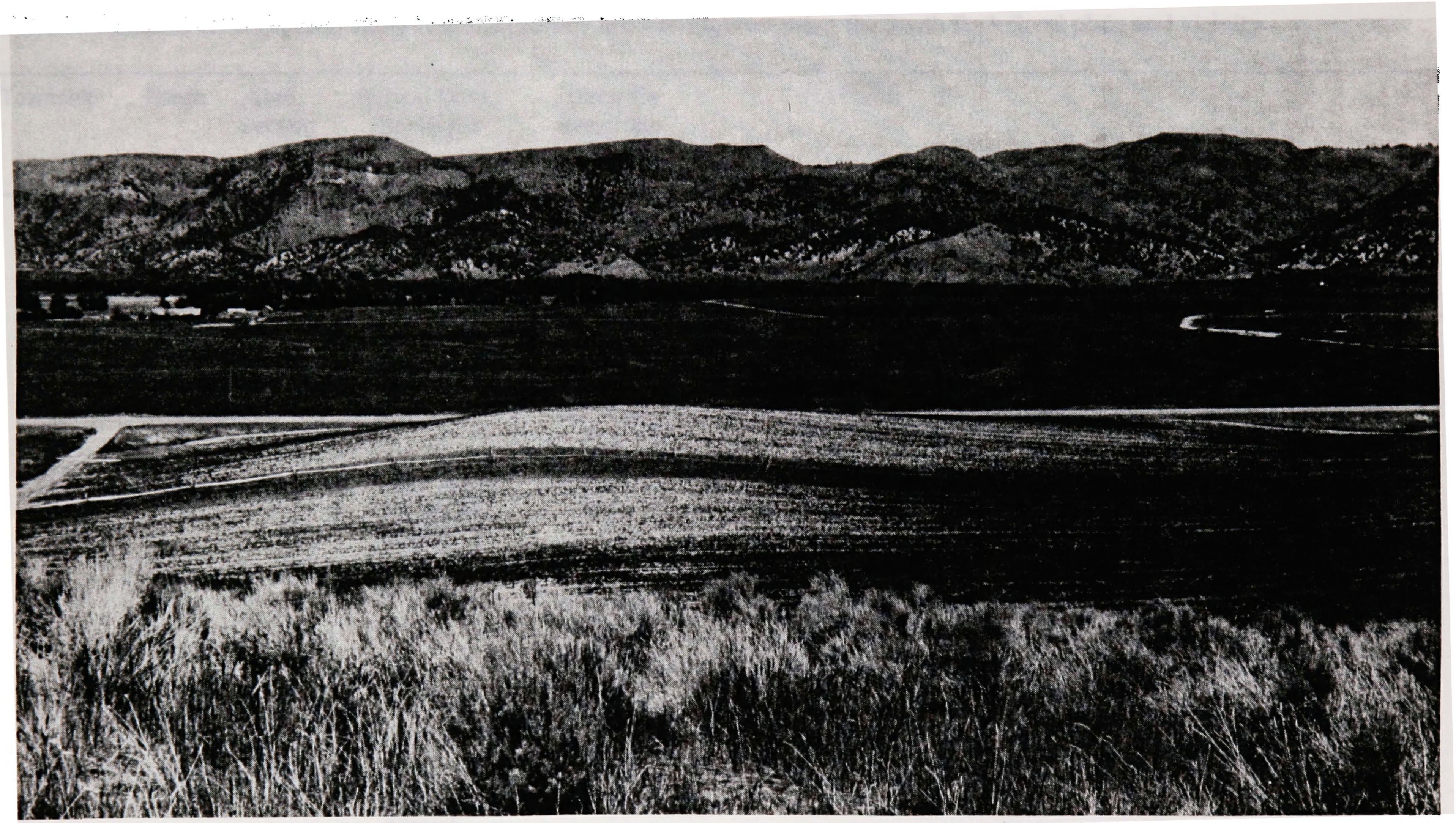


Figure 72. South Fork and environs from near Poplar, Idaho, June 18, 1992. More of the hill that Heroy stood on is included and is covered with bluebunch wheatgrass *(Agropyron spicatum)* and other grasses, as well as some sagebrush and rabbitbrush. Dead sweetclover *(Melilotus* spp.) adds a rougher appearance. Potatoes are in foreground, and small grains are on the flat. Mature cottonwoods line the Riley Ditch. Junipers have increased on distant foothills. Highway 26 crosses the middle of the scene. Heise hot springs areat the base of the prominent hill on the left.

Table 15. Remarks on vegetation along cadastral survey line corridors crossing the South Fork flood plain and vicinity.

Township	Range	Line, Section	Survey Date, Surveyor	Distance along line (chains)	Remarks
T1S	R45E	west, 8	Sept. 1900 Sonnenkalb	0 to 15 N. of SC	over precipitous land, descent through aspen and dense conifer growth
				15 to 35	foot of hill, and continues over benchland and through aspen timber
				63 to 72	crossing Snake River
				72 to 80	continue over benchland, through dense undergrowth
T1N	R44E	west, 35	Apr. 1898 Rhoads and Kimmel	45 N. of SC	road course
				51 to 57	crossing Snake River
				MC BT's	12" cottonwood, 6" birch
				57 to 58	through scattering timber and dense undergrowth
				58 to 76	meadow, house, ditch
T1N	R44E	west, 21	Apr. 1898 Rhoads and Kimmel	0 to 2 N. of SC	over rolling land, through dense undergrowth
				2 to 9	crossing Snake River
				MC BT's	5" cedar, 8" cedar, 11" cottonwood, 4" cottonwood

Table 15. Remarks on vegetation along cadastral survey line corridors crossing the South Fork flood plain and vicinity — continued

Township	Range	Line, Section	Survey Date, Surveyor	Distance along line (chains)	Remarks
T1N	R44E	west, 21	1898, cont.	9 to 11	dense undergrowth
				11 to 27	roads, fence, ditch
T1N	R44E	west, 18	Apr. 1898 Kimmel	37 N. of SC	foot of mountains
				43 to 45	severe undergrowth
				45 to 80	Snake River, section corner falls in river
T1N	R43E	west, 2	Oct. 1903 Sonnenkalb	11 S. of SC	wagon road
				13	Rainy Creek, 1 chn. wide, continue over level bottom, through dense high willow growth
				56	slough, 15 lks. wide
T1N	R43E	west, 2	Sept. 1945 Harris & Good	0 t 20 N. of SC	over level land through scattering timber and dense undergrowth
				24 to 32	crossing Snake River
				MC BT's	3" thornapple, 12" cottonwood
				32 to 49	scattering timber (cottonwood) and undergrowth

Table 15. Remarks on vegetation along cadastral survey line corridors crossing the South Fork flood plain and vicinity — continued

Township	Range	Line, Section	Survey Date, Surveyor	Distance along line (chains)	Remarks
T1N	R43E	west, 2	1945 cont.	1/4 C BT	8" cottonwood
				49 to 62	cultivated field
				62 to 65	dense undergrowth
				65	Rainy Creek, 60 lks. wide
				70	highway
T2N	R43E	west, 33	June 1893 Wilkins and Perkins	43 N. of SC	foot of bluff, entering S.E. end of Conant Valley, thence over level land
				43	irrigating ditch, 10 lks. wide
				46 to 60	crossing Snake River
				60 to 80	lava bluffs and talus
				General	Timber: aspens, cottonwoods and willows along river
T2N	R43E	south, 19	June 1893 Wilkins and Perkins	8 E. of SC	enter meadow at fence
				44	branch of Garden Creek
				52	slough, carries remainder of Garden Creek

Table 15. Remarks on vegetation along cadastral survey line corridors crossing the South Fork flood plain and vicinity — continued

Township	Range	Line, Section	Survey Date, Surveyor	Distance along line (chains)	Remarks
T2N	R43E	south, 19	June 1893, cont.	60	leave meadow, enter dense willow
				63	left bank of River, at mouth of overflow channel end of line at 80 chains is in channel
				MC BT's	7" cottonwood, 12" cottonwood; MC is cottonwood post
T2N	R43E	west, 17	June 1893 Wilkins and Perkins	7 N. of SC	brow of steep descent, about 350 ft. above river. enter aspen and scattering fir timber
				21 to 49	crossing Snake River
				MC BT's	48" juniper, 25" juniper
				35+	a low island, covered with cottonwood and willow, 2 chns. wide, 1/4 corner falls in river
				51	on slope above river
T3N	R43E	west, 32	Oct. 1919 Davis and Schaffner	0 to 6 N. of SC	over level land, through scattering timber and dense and undergrowth
				6 to 15	crossing Snake River
				1/4 C BT's	6" aspen, 7" aspen
				48	road

Table 15. Remarks on vegetation along cadastral survey line corridors crossing the South Fork flood plain and vicinity — continued

Township	Range	Line, Section	Survey Date, Surveyor	Distance along line (chains)	Remarks
T3N	R43E	west, 32	1919 cont.	52	foot of descent, thence over level marsh
				66 to 78	crossing Snake River
				MC BT's	20" cottonwood, 16" cottonwood, 6" aspen, 8" cottonwood
				SC BT's	20" cottonwood, 4" aspen, 15" cottonwood,
				66 to 78	crossing Snake River
				MC BT's	20" cottonwood, 16" cottonwood, 6" aspen, 8" cottonwood
				SC BT's	20" cottonwood, 4" aspen, 15" cottonwood,
				General	Timber: cottonwood, aspen, fir, pine. Undergrowth: willow and aspen
T3N	R42E	west, 12	July 1912 Anderson	0 to 18 N. of MC between S 13 and 14	crossing Snake River
				MC BT's	6" cottonwood
				18	trail
T3N	R42E	west, 10	July 1912 Anderson	25 to 30	enter heavy timber, land exceptionally hard to survey

Table 15. Remarks on vegetation along cadastral survey line corridors crossing the South Fork flood plain and vicinity —continued

Township	Range	Line, Section	Survey Date, Surveyor	Distance along line (chains)	Remarks
T3N	R42E	west, 10	July 1912, cont.	34 to 46	crossing Snake River
				MC BT's	8" aspen, 9" cottonwood
				General	Timber: aspen, cottonwood, fir; Undergrowth: same, dense, also sagebrush
T3N	R42E	south, 5	August 1912 Anderson	56 W. of SC to 78	crossing Snake River
				MC BT's	two 8" aspens, two 9" cottonwoods
				General	Timber: aspen fir, and cottonwood; Undergrowth: willow, buckbrush, and sagebrush
T3N	R41E	west, 15	Sept. 1910 Bates and Spofford	31 S. of SC	edge of rimrock, continue descending over rocky ground
				32	right bank of Snake River (line notes end here)
				MC BT's	two 8" willows
				General	Timber: scattering willow and cottonwood; Undergrowth: sage and buckbrush

Table 15. Remarks on vegetation along cadastral survey line corridors crossing the South Fork flood plain and vicinity — continued

Township	Range	Line, Section	Survey Date, Surveyor	Distance along line (chains)	Remarks
T3N	R41E	south, 5	Sept. 1910 Bates and Spofford	49 W. of SC	road
				50	right bank of Snake River (line notes end here)
				MC BT's	12" cottonwood, 14" juniper
				General	Timber: juniper, cottonwood, along bank of river Undergrowth: sagebrush; good bunchgrass

Explanation:

cedar is juniper (*Juniperus scopulorum*)

buckbrush is probably *Ceanothus velutinus*

sagebrush is *Artemisia tridentata* and *A. tripartita*

MC is meander corner

BT;s is bearing trees

SC is section corner, 1/4 C is quarter corner

i chain (chn.) = 66 feet = 20.117 meters

1 link (lnk.) = 7.92 inches = 20.117 centimeters

N = north, E = east, etc.

DISCUSSION

The various types of evidence related to South Fork vegetation have a common theme, which is there has been few gross, extensive changes in dominant species composition and physiognomy since white settlement. There are some less-obvious changes that are still important which include exotic species and herbivory. Although figures 58 to 61 may give an impression of extensive clearing of cottonwoods, there has been little clearing of cottonwoods in the primary study area as awhole.

So that the South Fork vegetation changes can be better understood, vegetation responses to various factors with examples from other rivers are presented, followed by actual changes on the South Fork.

Riparian vegetation response to changing factors - Plants growing on fluvial sites can increase or decrease with changing flow regimes, disturbance from animals (herbivory) or fire, and introduced or exotic plants. These factors can act in combination.

There are two general scenarios involved with changing flow regime and riparian vegetation response. The first is a change in channel-forming flows, where direct physical changes in channel form occur because of a change in frequency and magnitude of peak flows or floods. The second is where non-channel-forming (low) flows change in magnitude and duration during the growing season. Vegetation can increase or decrease, depending on the nature of change in these two factors.

Riparian vegetation often responds to channel adjustments due to changing flow regime, and these responses result in either reductions or increases in riparian vegetation cover and species composition. Flow regime can change due to climate changes or from human influence. Human influences can mimic natural climate changes.

A common situation is where channel-forming flows are inhibited, as in flood control. For example, riparian vegetation has increased on many rivers after flood control

(Williams and Wolman 1984). Between large, periodic floods, vegetation can become established on the higher-portions of the active channel (Lisle 1989). With flood control, established vegetation that would normally be eliminated by inundation or erosion survives for much longer periods. This encroaching vegetation can be native or exotic or a combination of the two.

Riparian vegetation responds to other changes in flow regime besides flood control, although it is difficult to completely isolate their respective effects. For example, the South Platte River in eastern Colorado has undergone dramatic changes due to flow regulation, which has mimicked a change from an arid to a humid climate. Since flow regulation, which includes transmountain diversions, an extensive cottonwood (*Populus deltoides*) forest has encroached on the formerly wide, intermittent channel (Crouch 1979; Nadler and Schumm 1981), and the oldest aged cottonwood trees (Sedgwick and Knopf 1989) are of similar vintage as the onset of South Platte water management.

A situation opposite to the previous one occurs when a naturally arid flow regime is exaggerated by diversions during low summer flows. Along some eastern-Sierran streams, cottonwood growth has decreased and mortality increased on streams with diversions compared to a nearby free-flowing stream (Stromberg and Patten 1992).

Channels also adjust to climatic or tectonic changes, the first affecting sediment- and water-flow regimes, which in turn affect channel morphology. Tectonic activity can change the slope, which causes mutual adjustments in other channel parameters. Many streams in the American Southwest have undergone drastic channel changes in the last century or more and the vegetation-change parallels them. (Bryan 1925; Leopold 1951b). The vegetation along the San Pedro River in southern Arizona changed considerably during a period of high rainfall and flooding after which the channel entrenched and then widened (Jackson et al. 1987; Hereford 1991). Vegetation changed from mostly herbaceous communities (cienegas) to a cottonwood- and shrub- dominated one. Land uses such as grazing and farming plus a large earthquake probably augmented the climatic changes (Hereford 1991).

Entrenchment does not always result in complete shifts in vegetation type, however. I have seen many streams in Utah with cottonwood forests perched up to 30 feet above the new flood plain, which also supports a cottonwood forest. But in these cases, the respective understory vegetation was very different, presumably due to differing rooting depths and drought tolerance of the various species. Shallow-rooted, drought intolerant species were absent on the high terraces.

Although seasonal timing of river stages is not very important in a physical sense (a flood will make changes in either spring or fall), seasonal timing is very important in vegetation establishment. Artificially-lower flows during and after the seed-shed period can allow encroachment that would otherwise not occur, and a different suite of species — native or exotic— may result. The effect is the same as with reduction in peak flows, but vegetation can encroach even further into the channel.

Herbivory, which includes browsing of woody species and grazing of herbaceous ones directly changes vegetation to some degree. There are many case studies in grazing, but a common thread seems to connect them. As in upland situations, the amount of change depends on timing and amount of herbivory (both seasonal and year-to-year) and the resistance of the plant species involved. Species composition of herbivores and plants also matter, because certain plants may be preferred over others, and the response of impacted species can vary depending on response of ungrazed, associated species. Also, because of the commonly wet conditions, soil compaction can be more prevalent on riparian sites than on uplands, especially if soil texture contain a range of size classes (Hillel 1980). Because of the many combinations of animal use patterns and plant communities and limited amount of studies, it is hard to generalize about vegetation response to grazing. However, some examples follow to allow some context for later discussion

A common situation is cattle grazing in willow-dominated communities. Willows can be browsed back to varying degrees depending on the animal use history, and the amount and time to recovery after grazing reduction depends on the willows' condition and amount of reduction. For example, severely hedged high elevation willows (mainly *Salix planifolia, S. pseudocordata,* and *S. monticola*) in poor condition recovered very slowly (if at all) after a shift to moderate grazing pressure, while willows in good condition remained so (Knopf and Cannon 1982). This study concluded that twelve years was not enough time for willows to recover after a long history of excessive grazing. In another study, a very sparse willow community (*Salix amygdaloides*) grazed by horses and cattle for decades and human tree cutting increased to a continuous-canopy forest at most 17 years after excluding livestock and tree cutting , and probably sooner (Rickard and Cushing 1982). However, recovery can be quicker in some cases (Platts and Wagstaff 1984).

Cattle use in cottonwood stands may be a factor in this species' regeneration success (Behan 1981). Crouch (1979b) noticed that nearly all seedlings were eaten by cattle on grazed portions of the South Platte River. However, in ungrazed areas along the Platte, there was essentially no seedling survival due to competing vegetation (Crouch 1979b). Sedgwick and Knopf (1989) monitored seedling on the Platte, and virtually all died of desiccation during summer. Cattle grazing and cottonwood survival is a complicated relationship, but considering Crouch's observations (1979), cattle do eat cottonwoods in at least some situations. However, Crouch (1979b), Sedgwick and Knopf (1989), and Bradley and Smith (1986) suggest or found that river dynamics are still very important in perpetuating cottonwood forests. Even if competing vegetation is removed, cottonwood seeds may still not survive. If the soil dries out before seedling roots reach a permanent water table, seedlings will die (Rood and Heinz-Milne 1989). Also, quotes 5 and 6 (page 178) show that heavy bison grazing and cottonwood forests were not mutually exclusive on Plains Rivers before settlement.

Beavers are another important herbivore, especially for woody vegetation (Allen 1980; Bown 1988). They occur naturally in many streams, and survive best in areas with woody and herbaceous vegetation and stable water levels (Collins 1979; Allen 1980). Fire was prevalent in the Rocky Mountain Region before settlement (Loope and Gruell

1973), but was probably much less frequent in riparian areas than the steppe and mid-montane zone (Gruell 1980a,b; Romme and Knight 1981). In addition to the historical data, fire appears detrimental to at least cottonwood forests, and perhaps other communities. Obviously, sprouting ability after a top-killing fire is a major determinant of vegetation response to fire. Conifer-dominated areas along valley bottoms probably burned less frequently than on adjacent uplands (Romme and Knight 1981), but were likely converted to early-successional communities after the rarer, stand-killing fires. Cottonwood forests decline with fire (Turner 1974; Akashi 1988), as it is a poor sprouter at advanced ages (personal observation). Young trees sprout more vigorously, but often grow on very wet sites with lower fuel loading, so fires were likely very rare here. However, based on personal experience of local fire managers, willow communities recover quickly and vigorously after fire, but this alone does not mean that fires were frequent in willow communities. The sprouting ability of willows may be an adaptation to damage by beaver and ice.

Exotic vegetation adds another layer of complexity, especially if it out-competes native vegetation that would otherwise become established; salt cedar or tamarisk (*Tamarix* spp.) invasion of many Southwest rivers is a notable example. Tamarisk has not only invaded flow-regulated systems but natural systems as well (Akashi 1988; Graf 1978; Nadler and Schuum 1981; personal observations). Invaded channels have adjusted to the sediment-trapping and bar-stabilizing effects of tamarisk by decreasing in width (Graf 1978). Width was not only narrower, but banks became more resistant to erosion. Interestingly, riparian vegetation is often credited with reducing floods, but on sandy southwestern rivers with tamarisk, flooding increased (Graf 1978). Overbank floods increased due to decreased channel capacity because the channel could not erode to as large a cross-section during flood passage as had occurred before tamarisk. (Graf 1978). Apparently, any increase in depth due to scour was not enough to make up for the constrained width, and depth increased faster than velocity This phenomenon obviously has flood control implications for many rivers constrained by levees.

Changes in South Fork vegetation - The limited changes in South Fork riparian vegetation parallels the slight change in channel form and process discussed in chapter 3. Considering the very slight changes in active channel width, mid-summer flows, and sediment composition, it is not too surprising that South Fork riparian vegetation has changed little in general appearance. The extensive clearing of the riparian forest in the Conant Valley area (figures 58 to 61) is atypical of much of the study area. Aerial photography shows some forest clearing in the Swan Valley area and possibly a greater percentage of riparian forests were cleared below Heise. Most of this clearing occurred before the 1940's and 1950's — the earliest aerial photography years. Clearing can still be inferred from aerial photography using fence- or property-line contrasts.

The most obvious change in South Fork riparian vegetation is the increase in woody-vegetation on formerly bare islands (figures 64 to 70). This increase is partly due to the flow history bracketing the early and late photographs. As discussed in chapter 3, there were some large floods (> 40,000 cfs) in 1895, 1903, 1909, 1917, 1918, and 1927, followed by a long hiatus until the mid-1940's. Even without flood control, no flow exceeded 40,000 cfs (a 10-year event) until 1986 (figure 11; p. 60). (The recurrence interval is based on probabilities for the record period, but high flow events are often clustered.) The obvious encroachment of woody vegetation, especially cottonwood, is not due to large changes in channel morphology. As discussed in chapter 3, morphology has changed little and only a few reaches decreased in width, which would allow encroachment. Overall, the 1987 active channel at about the mean annual flow (7000 cfs) is 4 percent wider compared to a similar flow in 1941. However, the fringes or margins of many bars are now dominated by three vegetation types: 1) a riparian shrub mixture dominated by *Cornus stolonifera* (red-osier dogwood), *Betula occidentalis* (water birch), *Elaeagnus commutata* (silverberry), *Salix lutea*,(yellow willow) and *Salix exigua* (sanbar willow); 2) *Salix exigua*; and 3) *Phalaris arundinacea*(reed canarygrass). The possible dynamics behind the increase in these types is discussed later.

Nearly all of the cottonwoods visible in the recent photos were present before the onset of flood control, but it is unlikely that the cottonwood forest would look like it does today if there was still a natural flow regime. The controlled high flows of the mid-1970's and mid-1980's (figure 11) would have likely eroded some old stands and created new bars, thus allowing young trees and shrubs to become established. However, only a portion of the riparian forest is destroyed during the very large floods as evidenced by the presence of mature cottonwoods in nearly every early photograph. For example, figure 62 shows remarkably little damage only 5 years after the Gros Ventre flood, which destroyed at least 3 bridges.

It is conceivable that a 30- to 40-year hiatus in large floods could have occurred naturally, but the present domination of mature riparian forests is probably unusual. However, the conditions during the late 1800's and early 1900's (figures 56, 58, 60, 64, 66, 67, and 69) may be unusually open because the large floods during this time moved flood plain features more often. With just a little imagination, one can picture transitional conditions between the early and late periods, and although not shown here, photography from the 1940's to 1960's confirms this, as well as tree-age data.

The rise and fall of riparian forest coverage reflect the dynamic nature of rivers — or more specifically — channel migration. Future work will cover this aspect in more detail. For now, based on the remarks of Russell from the 1830's (quote 3, page 177), the Hayden Survey (table 13, quotes 9 and 10, page 179), the cadastral survey notes (table 15), and the mature cottonwood trees shown in nearly every early photograph (figures 50, 52, 54, 58, 60, 62, 64, 66, 67, and 69), the South Fork has supported some semblance of a cottonwood forest for at least 250 years. Going back further, the pollen record for nearby Yellowstone National Park shows an almost continuous cottonwood presence for the last 15,000 years (Whitlock 1993).

The cottonwood forest is limited to a narrow strip for 8 river miles along the nearly straight, entrenched channel below Palisades dam. Considering these channel characteristics and experience on other dammed rivers, one may think that the channel degraded (downcut) since dam closure or was artificially modified, thereby reducing the cottonwood forest here. Evidence to the contrary is presented in chapters 2 and 3, and this confinement is visible in figures 50, 52 and 54. These two figures pre-date the dam-building era and therefore reenforce what shows in figures 40 and 43 and the findings based on them and other data presented in chapter 3. The remark from the Hayden Survey (quote 10, page 179) portrays a similar scene.

More subtle changes have occurred due to the dam-induced change in flow regime, exotic plants, and a shift in herbivory pattern. Most of these changes are inter-related and will be discussed together.

The perennial grass, *Phalaris arundinacea* (reed canarygrass), seems to be more common now than in the past, although it still covers a very small percentage of the flood plain. Today, this species occurs mainly on young (<20 years) alluvial bars and often forms dense, nearly pure stands. The young bar shown in figure 67 is analogous to the young bars of today, and dense stands of *P. arundinacea* do not show. *Phalaris* is strongly rhizomatous and can grow underwater. Because many riparian species such as *Populus angustifolia, (Narrowleaf cottonwood), Salix lutea* (yellow willow), *and Salix exigua* (sandbar willow) become established on new bars, the possible exclusion of these species because of *P. arundinacea* interference may reduce future structural and species diversity.

When looking just at the young bars, the dense, extensive stands of *Phalaris arundinacea* can give the impression of an aggressive weed. Angradi (1989) had this impression and considered *P. arundinacea* an exotic species and "uneradicatable" without a change in hydraulic regime. This species' presence before settlement (table 13) negates the exotic status, but the present flow regime probably has an influence on *Phalaris* abundance. The following is based on field observations and recent sequential aerial photography. Future work will explain this in more detail.

The flow depth during large floods and the resulting bar topography seems to be the key to the relative abundance of *Phalaris* and woody species such as *Populus angustifolia* and *Salix lutea*. On the recent young bars, *Phalaris* is most common on the lower parts of the bar such as the outer fringe and the shallow channels on the bars themselves. *Populus angustifolia* and *Salix lutea* occur on the slightly higher parts of the bar, or ridges. Once *Phalaris* becomes established from seed, it can spread rhizomatously to the lower areas that are still under water during the seed-shed period (early summer) of *Populus* and *Salix*. *P. angustifolia* and *S. lutea* are non-rhizomatous, and their seeds float, so they cannot colonize areas inundated during early summer. *Phalaris* seeds are shed in late summer, when the lower areas become exposed with lower river stages.

In braided streams, the height of bars formed during a flow competent enough to move sediment is very near the water surface at peak discharge (Leopold and Wolman 1957). Therefore, bars formed during very large floods have higher surfaces relative to the water surface at bankfull discharge than bars formed during smaller floods. Based on the spatial pattern of young *Salix* and *Populus*, these higher surfaces may be more conducive to *Populus* and *Salix* colonization. South Fork bars dominated by *P. arundinacea* are inundated with flows above ca 18,000 cfs, and become fully-exposed at flows below ca 6000 cfs. *Phalaris* is found with young *Salix* and *Populus*, but as the shrub- and tree- canopies grow and shade increases, *Phalaris* becomes less common. Perhaps it cannot survive in moderate shade.

The new bars formed since dam closure have very little area above the bankfull water surface. *Phalaris* may be more common on new bars formed since dam closure because of reasons stated above. *Salix exigua* has a similar establishment pattern as *Phalaris*, and can invade existing *Phalaris* stands by vegetative reproduction. Also, *S. exigua* is scarce to non-existent under mature forest canopies. Perhaps if *Salix exigua* was considered exotic, it would receive the attention *Phalaris* has. However, both of these species require attention, regardless of their native status, because if new bars form as they have since dam closure, these two species may increase at the expense of *Populus* species. They may also persist longer, because they would not be shaded out later by *Populus* forest canopies.

One other shrub, *Betula occidentalis,* appears more common today than in the early photographs. *Betula* typically occupies older bar fringes and old, shallow channels on the larger bars. It sheds seeds in late summer and fall, and like *Phalaris,* may tend to colonize lower areas at lower stages. However, *Betula*'s fine-scale spatial pattern is not as distinct as *Phalaris*', and more work is required to understand its dynamics. On a coarser scale, *Betula* is more common in the canyon and lower Swan Valley compared to the alluvial fan below Heise. Based on many visits, the former areas are cooler than the region below Heise. This temperature difference is likely due to cold air drainage from the adjacent mountains and adiabatic cooling with increasing elevation.

Riparian vegetation decreases bank erodibility (Smith 1976) and encourages overbank deposits (Graf 1988). With the increased vegetation, aggrading bars or accreting channel margins are probably more resistant to seasonal scour. *Phalaris* and *Salix exigua* often invade and dominate these sediment additions, and may even augment the additions by limiting scour during falling stages (see chapter 3). Also, the local decrease in velocity in the rougher, vegetated areas encourages settling of suspended sediment. These two species seldom dominate cut banks areas, but where they occur, the bank angle is similar to banks vegetated with the usual mixture of *Populus, Cornus stolonifera, Betula* , and various grasses and forbs. Typically, root mass is much reduced in the lower, exposed part of channel deposits. Eroding cut banks are undercut, either due to greater shear stress at deeper levels, greater erodibility due to fewer roots, or a combination of the two.

Although the native flora is largely intact, there are some exotic grasses and forbs present now (tables 13 and 14). These occur mainly on the older, drier parts of the flood plain which are dominated by mature and older forests. These areas pre-date Palisades dam, so the bars formed under natural water and sediment regimes. Also, the flows during the growing season are similar for the pre- and post-dam periods (figure 7; p. 56), so water availability has probably not changed significantly. Therefore, factors other than hydrology and geomorphology are probably more important to the vegetation on these older bars. The most important factor may be a change in herbivory pattern, while another is the availability of exotic plant seeds.

In his more elaborate description of the regions wildlife, Russell describes the following herbivores: marmot, porcupine, bighorn sheep, pronghorn antelope, mule deer, 3 rabbit species, buffalo, elk, and beaver (Haines 1955). Russell never mentions moose in his journal, but C. Merriam collected three of them in Teton Canyon (Hayden 1873). They are probably more common today and often browse riparian shrubs and cottonwoods, especially in winter (personal observation). Of these, bison and beaver are probably the most important to shaping South Fork vegetation before settlement.

Like many places in western North America, the bison has been replaced with domestic cattle, so understanding the bison's role in shaping South Fork vegetation is important in assessing the present effects of domestic cattle on today's vegetation. Paramount to this understanding is the respective diet and behavior of bison and cattle, the plant species composition during the presettlement and recent periods, and the effects of herbivory on these plants.

Compared to the North American plains region, the intermountain valleys had much fewer ungulate herbivores. Bison especially, were much less common west of the Rocky Mountains, and during recorded history, the western-end of their range was the upper Snake River Plain (Roe 1951; Van Vuren 1987). Bison remains are found further west in Idaho, Oregon, and Washington, but these are from an earlier time (Van Vuren 1987; Meahger 1973). Prehistoric evidence indicates bison extinction about 2500 years ago (Mack and Thompson 1982).

More specifically, many bison were seen in the South Fork valley during the 1830's (quote 1). Besides this quote, Russell mentions "buffaloe" several times throughout his journal (Haines 1955). The mountain bison (*Bison bison* form *athabascae*) was native to the South Fork area (Roe 1951; Meagher 1973; Van Vuren 1987). Very little is known about this now extinct form; the closest relatives are the plains bison/mountain bison hybrids in Yellowstone National Park. When the mountain bison arrived in the South Fork Valley is also unknown. Meagher (1973) estimates bison reached the Yellowstone

Plateau before the "most recent intermountain glaciation", which was less than 4000 years ago (see chapter 2). Bison likely migrated from the Yellowstone Plateau down the Henrys Fork valley to the upper Snake River Plain. Bison were also present in the Teton Basin and Jackson Hole, but grassland habitat is more continuous from the Snake River Plain to the South Fork valley than from these latter two places.

The timing of bison elimination from the South Fork is very important for assessing the bison's effect on the native plant communities. Even though the area was not settled until after Hayden Surveys, the vegetation would likely have changed from the pristine bison interaction period if bison were much reduced or eliminated several years before the Surveys. The timing of bison elimination was an important point in interpreting the shift from short-grass to mid-grass prairie on the Great Plains (Larson 1940), and there are similar interpretation problems for the South Fork situation.

Considering the evidence at hand, pinning down an accurate date for bison elimination is difficult. The Hayden Surveys during 1872 and 1877 do not mention bison, which is in contrast to Russell's remark about "thousands" in 1834 (quote 1, page 177). There are at least three possible reasons for this contrast in bison numbers: 1) bison were eliminated before Hayden's visit, 2) bison had migrated out of the valley by late summer, or were hidden in dense vegetation, 3) the Hayden Survey did not concentrate on wildlife, and the presence or absence of wildlife — especially common species — may have gone unnoticed. Of the the three reasons, the first deserves the most discussion, and the second two reasons will merely support the supposition that bison were present during the 1870's.

Events outside the isolated South Fork valley allow some insight into whether bison were present or not. The bison slaughter on the northern Great Plains reached its peak in the 1880's, but the trade in bison skins was well established since the trapping era in the 1830's and 1840's (Roe 1951). Railroads and the conscious shift to eliminating bison beginning in the late 1860's accelerated the bisons's demise from the Plains (Roe 1951). During the 1870's the closest railhead to the South Fork was about 200 miles away in

Ogden, Utah, so a large trade would have been difficult. However, there were relatively few bison in the intermountain valleys like the South Fork's as compared to the Plains, so the mountain herds were more vulnerable. F. Bradley (Hayden 1873) mentions Indian travel routes in the Jackson Hole area and near the then-established Fort Hall Indian reservation. Fort Hall was also a prominent trade center. Because of the bison's market value, Indians may have killed more bison than they normally would have for food (Roe 1951). Even before Indians had guns, on horseback they could kill 1000 bison in one day, which Russell witnessed on the Snake River plain (Haines 1955). The South Fork valley was nearly pristine during the 1870's, but there were still rudimentary roads and trails, and surrounding areas were rapidly being settled. The South Fork Valley bison may have been eliminated either in the Valley itself or on the upper Snake River Plain if they migrated there during winter. If bison were eliminated before the Hayden Survey's visits, it was probably not many years before. One of the last bison refuges was in nearby Yellowstone National Park.

The Hayden Surveys may have not noted bison in the South Fork because they had migrated out of the valley. Bison are extensive roamers, and during the exploration period, subsequent explorers noted bison in places where bison were not noted before and vice versa (Roe 1951). Bison may have been hidden in dense stands of riparian shrubs, if in fact these shrubs were present. This is less likely, because bison tend to avoid insect ridden or "buggy" areas (Meagher 1973, which these areas would have been. Yellowstone bison often move out of buggy places to higher elevations (Meahger 1973). Russell saw the vast herds of bison in early May (quote 1, page 177), Hayden Surveyors visited the South Fork area mostly in in mid-summer and a hasty pass-through in October enroute to Fort Hall (Hayden 1873; Hayden 1879). Whether there were in fact dense riparian shrubs at all is an important question, especially in context to cattle-grazing impacts along the present South Fork. This question is considered next.

Bison and domestic livestock have similar diets, both preferring graminoids to a similarly large degree (Meagher 1973; Van Vuren 1984). This similarity may only be valid in grasslands or shrub-steppe habitats, because cattle certainly eat riparian shrubs enough to change species composition and community structure. There are numerous fence-line contrasts throughout the west showing this effect, and the effect is well documented. Local areas are grazed heavily on the South Fork, and these places have reduced shrub components.

Bison and woody riparian vegetation apparently coexisted under natural conditions. Cottonwood was still present along Plains Rivers even with heavy bison use of nearby grasslands (quotes 5 and 6, page 178). Russell travelled 3 miles to an isolated willow stand in search of water and found "large numbers of Buffaloe" there (Haines 1955). Willow was apparently common enough along the South Fork to be a handy raft material when bison were definitely present (quote 2, page 177). The common reference to dense stands of willow and other shrubs during the early cadastral surveys (table 15) suggest that riparian shrub stands were robust and common since at least the late 1800's. If bison browsed-down riparian shrubs to the degree that cattle can over extensive areas, I doubt that the riparian shrubs would have been as they were — even if bison were eliminated by the mid-1860's.

The above interpretation of bison and riparian shrub coexistence is complicated by the early reference to abundant rose (*Rosa woodsii*) on or near the South Fork riparian zone (quotes 8 and 9, page 179). Hansen and others (1991) describe a *Rosa woodsii* community type for Montana, and consider it a disturbance-induced, seral community. Despite a wide wide range of disturbance on the South Fork due to cattle grazing, flooding, and fire, I found no dense stands of rose along the South Fork.

Rose may not have been as abundant in the late 1800' as in the impenetrable stands described by Hansen et al. (1991), but assuming that rose was in fact much more abundant during the late 1800's than today raises questions related to the palatability of rose to livestock and possible changes in site.

Nearby, along the lower Henrys Fork, rose is dominant enough in places to classify such stands as a *Rosa woodsii* community type (Hansen et al. 1991). Species that are considered highly palatable to cattle and wild ungulates such as *Amelanchier alnifolia* (serviceberry) and *Cornus stolonifera* (Hansen et al. 1991) are typically scarce. Also, the lower-Henrys Fork flood plain soils are much finer-textured than along the South Fork.

The present South Fork situation is much different than the lower Henrys Fork. If rose is at all common, so is *Cornus stolonifera* (red-osier dogwod), which tends to negate a strong connection between cattle grazing, rose increase, and *Cornus*decrease. *Cornus* typically dominates rose where they coexist, so increase in *Cornus* due to the protection of rose is an unlikely scenario. Where grazing is obviously heavy, *Cornus* is hedged back, as one would expect, but rose does not have noticeably higher coverage in these situations. Rose is also scarce where *Cornus* is browsed back to a minimal degree. Rose occurs in flood-prone areas, but it is scarce here as well. Likewise, the few burned areas do not have exceptionally high amounts of rose.

Based on my field observations, two factors lend insight into the rose paradox. One is that with all other factors equal, rose appears more common on finer-textured sites along the South Fork. Although the earlier-mentioned Henrys Fork sites may not be equal to these South Fork sites, the general commonality is apparent. Also, the flood plain soils deposited before about 1850 are much sandier (see terrace section in chapter 2) than afterward. During Hayden's visits in the 1870's, the flood plain was likely dominated by the sandier sites compared to today.

The other factor is the life span of rose stems, which arise from the rhizomatous rootstock. In the course of cottonwood aging, I needed to clip away impeding shrub stems, and even the largest live rose stems were only about 5 to 10 years old. The largest dead stems were often similarly sized. Although mature stems are probably not browsed due to thorns, new shoots may be eliminated by grazing and the stand slowly declines. Perhaps in places where rose is better adapted to the site, it is thick enough to preclude grazing in the stand's interior, thus allowing survival of new shoots.

From the foregoing, one may think that because *Cornus* was not mentioned or collected along the South Fork in 1872, bison had eliminated it and rose increased. This is a possibility, but Coulter collected *Cornus pubescens* in the Teton Basin, (Hayden 1873) where bison also occurred. *Cornus pubescens* is probably the same as *Cornus stolonifera;* Welsh and others (1987) renamed the western *Cornus stolonifera, Cornus sericea.* The latter epithets, *pubescens* and *sericea,* refer to fine hairs or fuzziness.

The beaver is the other important herbivore especially in regards to woody vegetation. Beaver were apparently numerous even during the trapping era (quote 4, page 178), and beaver-impounded side channels show in 1941 aerial photography. They are still common today. One possible difference is that small-stemmed cottonwoods, a preferred food source, is less common now and beavers may be cutting down the larger trees because of the relative lack of small cottonwoods as compared to the pre-dam period. Defining changes in beaver herbivory patterns needs further study.

The herbaceous component has probably undergone the greatest change since settlement through the invasion of exotic grasses. Interpreting changes in the grass flora is difficult due to the fragmentary data, but it is important in context to evaluating range condition. It will also allow some reconstruction of the native grass component under bison influence and test some hypotheses.

The early flora (table 13) indicate both rhizomatous and bunchgrass species were present. Russell noted bunchgrass on the foothills (quote 4, page 178) which was obviously bighorn sheep winter range. Bunchgrasses are still common on most of the steppe surrounding the riparian zone, and the early photographs suggest the same was true for the early-settlement period (figures 58, 64, 69, and 71).

Bunchgrasses tend to be less resistant to grazing pressure than the rhizomatous types of grass because the former depend more on seed for regeneration and have lower potential for vegetative regeneration than the rhizomatous or turf grasses (Mack and Thompson

1982). Bunchgrasses are often reduced under heavy cattle grazing, yet they appeared to flourish under during the bison period on the South Fork. It already seems that bison did not heavily browse the shrubs, and it is doubtful they ate trees or tree foliage. Bison had to eat something,. and the most likely forage were the rhizomatous grass species and less likely, the bunchgrasses. The low lying areas in Grand and Swan Valley may have supported productive stands of rhizomatous grasses, but these areas are either cultivated or under the reservoir today. However, the miry soils (quote 12, page 180) and the *Triticum* species (table 13) lend some support for this idea. The bison may have eaten bunchgrasses too, and the bunchgrass habit itself does not always mean low grazing resistance. Some bunchgrass species evolved with large grazing animals and survive well (Mack and Thompson 1982), and conversely, even the rhizomatous form of *Agropyron spicatum* was reduced by cattle grazing along with the usual bunched form (Daubenmire 1970). Perhaps the bunchgrasses in the upper Snake River region can tolerate some grazing pressure; experimentation may bear this out.

Although difficult to interpret, the high amounts of annuals and "weedy" species in the early flora (e. g., *Oxytheca, Chenopodium, Iva, Achillea,* table 13) suggest some form of disturbance. Coulter also collected many cryptogram species (not listed in table 13), in higher elevations, with *Byrum* the most important (Hayden 1873), but not in the Snake River Valley. *Byrum* species typically occur in undisturbed steppe communities (Daubenmire 1970). *Selaginella densa* is considered a disturbance species (Mack and Thompson 1982), and Coulter remarks that this "was common everywhere on the route" (Hayden 1873). If the *Byrum* species were truly scarce or absent in the Snake River Valley and the *Selaginella* was common, this would cohere well with the assumption that bison grazed the Snake River Valley up until the 1870's. I am not familiar enough with the steppe flora to compare present floristics in detail, but at the least, there is no shortage of annuals today, with *Polygonum engelmannii* being quite conspicuous recently. The introduced annual grass, *Bromus tectorum,* becomes much more common below the study area and on some south-facing slopes; this species tends to survive much better in drier, warmer climates (Mack and Thompson 1982).

The most certain and obvious change in vegetation is the addition of exotic grasses, most notably *Agrostis alba var. stolonifera* (redtop), *Poa pratensis* (Kentucky bluegrass), *Bromus inermis* (smooth brome), and *Dactylis glomerata* (orchard grass) (table 14). Except for the first, these species have invaded both moist uplands and many riparian areas. As mentioned in the results, the first two are likely to stay even if grazing is eliminated. Seed source rather than heavy grazing may be more of a factor in these grasses success. These same species are quite common along pack trails in Yellowstone National Park and the Teton Wilderness in Wyoming (personal observation). Although not perfectly pristine, these trails traverse places that were never grazed by livestock. Experiments as done by Caldwell and others (e.g., Eissenstat and Caldwell 1988)) should give more precise reasons for the success of these grasses in the Snake River basin.

However, many native grass species are still present (table 14). Because of the apparent interbreeding among the various wheat- and rye-grasses, attempts to further reconstruct the native grass component should at least consider the newer taxonomy for the Triticeae (Barkworth et al. 1983), and the works of Soreng (1990) and Hiesey and Nobs (1982) on *Poa* for the same reason. The latter work includes *Poa ampla* (*juncifolia*) collected near Heise.

Finally, the effect of fire seems minimal on the South Fork riparian zone. Although the lower montane forests and steppe show recent fires occurred during the late 1800's (Gruell 1980a, b;) (figures 52, 60, 64, 69, and 71). The primary sagebrush species is *Artemisia tridentata*, a non-sprouting species (Hironaka et al. 1983). Sagebrush was less dominant during the early years, indicating a more frequent fire regime (Vale 1975). Similarly, *Juniperus scopulorum* (rocky mountain juniper) was also less common on the steppe. A similar species, *J. occidentalis* invades the steppe in western Idaho with less frequent fire (Burkhardt and Tisdale 1976).

Conversely, juniper occupied the flood plain during the early-settlement period (table 15), suggesting that fires were less frequent on the riparian zone than on the steppe. Also, as discussed earlier, cottonwood forests decline with fire, and I found little evidence of fire on the flood plain. Fire suppression on the uplands has probably not affected the riparian forest, because the natural fire frequency was quite low. Based on cottonwood aging, there are several stands adjacent to steppe that originated during the mid-to late-1700's. One of these stands, originating about 1790, shows in figures 69 and 70; it is just downstream of the narrow fringe of cottonwoods. This type of information will be expanded on in future work, but apparently, stands more prone to fire survived and probably did not burn, for I rarely saw fire scars in the field.

SUMMARY

Riparian vegetation during the early-settlement period is similar to the recent period's, but there have been changes. The most important changes include an increase in mature cottonwoods (*Populus angustifolia, P. acuminata*) and invasion of exotic grass species. The shrub component has increased on bar fringes, but the species composition is probably the same for the two periods. The only exotic woody species are is Russian olive (*Elaeagnus angustifolia*), and apple (*Pyrus malus*). Russian olive is very scarce and restricted to the extreme downstream part of the study area starting near Kelly Island, but it becomes more common below this area. The few apple trees occur on or near a few homesteads. Reed canary grass (*Phalaris arundinacea*) may be more common today, but it was part of the presettlement flora, so it can be considered as native to the South Fork valley.

The recent increase of mature cottonwoods, as compared to the early-settlement period, is largely due to the flood history bracketing the two comparison periods. Encroachment of cottonwoods on the formerly active channel is not obvious, and flood control is not a direct cause of the increase in mature cottonwoods. The present extent of mature cottonwood can conceivably happen under natural flow regime, but it is unlikely because such a long period between large floods has a low probability under the present climate.

Reed canary grass is more common on young bars today compared to their early-settlement analogue. This increase is probably due to lower bar relief on bars formed during the relatively low magnitude floods since dam closure.

The increase in riparian shrubs and reed canary grass on bar fringes is likely related to a change in the natural flow regime resulting from flood control. Large flood peaks have not occurred since dam closure in 1956, and sediment that was more frequently mobilized during large floods is now vegetated with various riparian shrubs. The most common are sandbar willow (*Salix exigua*), yellow willow (*S. lutea*), red-osier dogwood (*Cornus stolonifera*), water birch (*Betula occidentalis*), and silverberry (*Elaeagnus commutata*).

Cattle grazing, especially where use is high and long, reduces riparian shrubs more than probably occurred during bison grazing. The exotic grasses thrive under cattle grazing, but also occur on areas not grazed by cattle for several decades. Cattle may have been a seed vector bringing in the exotic grasses, but at least two species appear "naturalized", or do not require man or domestic animals to maintain their populations. Kentucky bluegrass (*Poa pratensis*) and redtop (*Agrostis alba* var. *stolonifera*) are the most common of the exotic grasses. The most common exotic grasses are: intermediate wheatgrass (*Agropyron intermedium*), smooth brome (*Bromus inermis*), and orchard grass (*Dactylis glomerata*). Much scarcer exotic grasses are fowl bluegrass (*Poa palustris*), and crested wheat grass (*Agropyron cristatum*).

Fire suppression has affected the nearby upland vegetation, allowing an increase in sagebrush (*Artemisia tridentata*), rocky mountain juniper (*Juniperus scopulorum*), and maturation and establishment of Douglas-fir (*Pseudotsuga menziesii*). However, fire suppression has not had much asffect on the riparian zone, for species that indicate fire presence have not changed prominence over the analysis period.

CHAPTER 5

CONCLUSIONS AND REMARKS

River environments are naturally dynamic and can also change due to human influence. This study, using a range of time and spatial scales, put many of the observed changes into this perspective, mainly for understanding the dynamics themselves and allowing for predictions. The separation between human and natural influences is often a blurred one because our actions typically initiate, facilitate, or inhibit an existing natural process. The difference is usually a matter of degree.

Because the study's scope was broad, yet contains considerable detail, a complete set of conclusions following these levels would be rather long and tedious. For a more complete picture, see the chapter summaries. The following concluding narrative covers the main points and ties them together, for a variety of evidence often leads to a similar conclusion.

Like many other rivers, the South Fork Snake River had a changing sediment and water discharge regime since at least the early Pleistocene. The amount of sediment entering the stream and the ability of the stream to carry it was not always in balance, as evidenced by the extensive terraces that we can still see today. Most of the terraces have similar slopes and sediment composition. Through most of its known history, the channel carried much pebbles and cobbles as bed load. At least three terrace sets are paired and the treads are quite broad, indicating that the river was either graded for a significant period or migrated rapidly before a downcutting episode. Nearly all terraces are composed of cobbles and pebbles, as well as the most recent flood plain deposits. One exception to this pattern is a recent fill that was cut or abandoned about 150 years ago and is now a low terrace about one foot above the present flood plain. The river apparently carried much more sand for an unknown period beginning about 150 years ago. I do not know the reason behind the increased sand. This period approximates the end of the Little Ice Age, when many temperate glaciers ceased their advance. A study in the drainage basin showed that sediment yield is much higher from existing land after fire, especially with rain on glacial tills. Based on existing vegetation and photography from the late 1800's, fires may have been more frequent and extensive in the region. The increased glacial activity or fires may have increased the sediment load over what it was before, thus creating the sandy fill terrace, but more study is needed to gain a better understanding of this terrace's genesis.

The most obvious change to the South Fork during recent time is impoundment of Palisades Reservoir behind Palisades Dam. The Dam was closed in 1956. The reservoir traps nearly all the sediment above it, and reservoir management to date has eliminated the larger peak flows or floods higher than the 3 year event which occurred during the 46 years before dam closure. The bankfull discharge (1.5 year event) for the post-dam period is about 15% less than the pre-dam (1910 to 1956) period's.

Within the study area, tributaries entering below the Palisades Dam are small, thus sediment injection is like-wise small. Despite this and the severe sediment trapping above the dam, channel morphology has hardly changed 35 years after dam closure.

Based on many cross-section surveys at gaging stations, the channel bed has remained at the same level since dam closure. Evidence of scour and fill occurs at all stations except maybeone, where it is very slight and the channel is very stable. This most-stable station is 1.4 miles below the dam near Irwin, Idaho. The Irwin station showed no net lowering of its bed since dam closure, yet it clearly showed temporary aggradation during the dam construction period and rapid return and stabilization to the present level. Bed dynamics at the stations below the dam, except at Irwin, were similar to a station above the dam that served as a control. For those stations that had before- and after-dam records and a constant cross-section location, the hydraulic geometry changed slightly between the pre- and post-dam periods. The station furthest from the dam at Heise showed the most change, but it showed similar variability before dam closure. Nearly all changes in hydraulic geometry exponents were statistically significant, but the actual changes were very small from a practical point of view. More detailed analysis of roughness showed no practical changes in skin resistance, and repeat photography of the channel at low flow confirms this. Although suspended sediment was likely higher in the pre-dam, below-dam reaches, it was probably still low compared to many other natural rivers studied by others. The clear-water condition below the Palisades Dam had a similar friction factor as the presumably higher sediment-laden condition for the same place before the dam.

There has been some obvious changes in channel morphology due to the Palisades Reservoir and these show within the first half mile below the Dam. These changes include a coarsening of bed material as a result of finer pebbles and cobbles being scoured away and not replaced. The width also increased, but to an uncertain degree since dam closure. With bed coarsening, roughness likely increased and the slope likely decreased. This extreme-upper reach is becoming more stable.

Channel width is usually sensitive to changes in discharge or sediment regime. For a similar discharge, overall water surface area during 1987 was only 4 % higher than the same during 1941. Some or all of this change may have been due to the flow history bracketing the measurement periods. Width similarity between the pre- and post-dam periods is likely due to a similar bankfull discharge. Because width is so reponsive and easy to measure, it is a good indicator for monitoring channel change and any future work on the South Fork should start with it.

Although slope was not measured directly after dam closure, it has likely remained constant except for the previously-mentioned reach just below the dam . The lack of channel bed degradation at the gaging stations and a similar sinuosity measured during 1941 and 1956 indicate that if the channel is cutting down, it is too small to detect.

The largest change in river process is the elimination of the larger floods, especially those that exceed what was a 10-year event. This is partly the reason why the river has changed little in morphology since dam closure. Another reason is the inherent stability of the channel during moderate flows. With larger, more frequent peak flows, the morphology may change faster. Width and roughness will increase and slope will decrease. Starting just below the dam, these changes will progress in a downstream direction, continuing as it has in the reach just below the dam to an uncertain extent. Based on the morphology of an unregulated Snake River tributary below a lake, width and roughness changes on the south Fork will be slowly progress downstream. As with the tributary, the South Fork channel will likely degrade but the increasingly-high banks should allow more sediment recruitment for a given distance of lateral channel shift. Thus, over much of its length, the width will likely be maintained if bankfull discharge stays the same.

The vegetation most closely associated with the river has changed since dam closure or the presettlement period. These changes include an increase in mature cottonwoods and the invasion of exotic species.

The most obvious change since the early-settlement period is the increase in mature cottonwood trees. Most of these trees were established before dam closure, but the lack of large floods since the mid-1940's has probably allowed more forest to mature than would occur under a natural flow regime.

Before settlement, many bison grazed in the South Fork valleys, and early documentation indicates that dense riparian shrub stands were still present. Some areas are heavily grazed by cattle, and riparian shrubs are often much reduced in these places compared to less-grazed areas. The native flora is largely intact. The most important change in flora is the addition of non-native grass and forbs. The most common non-native species are Kentucky bluegrass, (*Poa pratensis*), redtop or bentgrass (*Agrostis alba* var. *stolonifera*) , smooth brome (*Bromus inermis*), and orchard grass (*Dactylis glomerata*). Canada thistle (*Cirsium arvensis*) is the most widespread non-native forb. Although livestock grazing can decrease shrubs and increase the amount of these non-native species, elimination of livestock grazing will probably not allow a return to pristine conditions. The first two grass species are persistent enough to have high coverages in areas that have not been grazed for decades. However, more work is needed to confirm this. Reed canary grass (*Phalaris arundinacea*), considered by some as non-native to the interior west, was part of the pre-settlement flora. The change in flora is mainly due to seed availability and vectors and the coincidence of the exotic species being adapted to the sites.

Most changes in the South Fork are small, especially if compared to other rivers after damming. The relatively small changes are mostly due to natural river characteristics and our own attempts at making the Snake River less dynamic. However, a less dynamic river may be detrimental to plants and animals that depend on disturbance. For example, based on observations on the South Fork and other studies, the cottonwood depends on disturbance that creates moist, bare mineral soil required for seed germination and survival. An important aspect in river dynamics is channel migration, and disturbance conducive to establishment of cottonwoods and ecologically similar species is associated with channel migration. The relation of flood frequency and magnitude to channel migration rates is an important question. If larger floods created higher channel migration rates, existing flood control may affect the long-term existence of disturbance-dependent plants such as cottonwood and willow.

This latter question is the primary one for the main study (mentioned in the preface) where cottonwood forest dynamics will be related to river dynamics. The present study forms an important basis for the main study, for if river processes or plant components change, the above relation is affected. This study uncovered many changes, but again, most were slight, especially compared to what has occurred on other dammed rivers. Flood control and sediment reduction have likely decreased channel dynamics. Yet, the physical aspects of today's river appear similar to those of the pre-dam river until about 150 years ago. The most important biological changes are the elimination of bison, introduction of domestic livestock — especially cattle— and the naturalization of exotic grasses.

As in many studies, there are deficiencies, and this one is no exception. This study's most important deficiency is related to its broad scope. Although the broad scope allows many cross-connections between different types of evidence, this type of confirmation is not as powerful as simple rejection of hypotheses. Any of the aspects I investigated could be studied in greater detail and tested more rigorously. What follows is what I think are the most important deficiencies and some suggestions for improvement.

As for the river's physical characteristics, bed load movement rate is the most uncertain. I do not know whether the bed still moves at the upper reaches represented by the Irwin station. If it has not moved since dam closure, this allows an alternative explanation to why the bed has not degraded here: Flows near the bankfull discharge may not be competent enough to move material. If this is true, my estimate for channel changes in the upper reaches are too optimistic; the channel will enlarge and roughen faster than I stated if larger floods occur. The mechanism behind the rapid change in bed elevation during dam construction is still a mystery. If increased sediment loads from dam construction are responsible, I would expect the bed to return to the level it had before construction if bed particles still move. Yet there is evidence of bed scour just below the dam at Sheep Creek, so particles do move. A more direct way to detect bed load movement is with painted tracer particles.

Although the present gaging station locations are on natural channel boundaries, they are not representative of the braided reaches. The discontinued Lyon and Dry Canyon gages are the most representative, and it is too bad their record periods did not include the post-Palisades Dam period. The Heise gage has a long history, and I looked at the hydraulic geometry and bed elevation changes since 1917. Although interesting, I did present this data because of the inconsistent cross section location and periodic changes in channel control (Anderson Dam) in the early years.

The problems in hydraulic geometry interpretation are fairly clear, but a stable river such as the South Fork is not a good place to begin and end inquiries relating scour and fill behavior with exponent values and their ratios. The precise curve fits were certainly an advantage, but the tiny amount of bed movement made interpretation much more difficult. The converse situation may also have difficult interpretation: On less stable rivers, sediment dynamics will be less equivocal, but the curve fitting will be more problematic. The log-linear model may not be appropriate for unstable channels, so its easier set of of exponents won't be available for interpretation. Judging by data on other studies, the more complex log-piecemeal model will probably fit the data better and still allow for interpretation. The log quadratic is easier to fit to data, but I think interpretation will be much harder with it.

The quadratic equations have near collinearity, and collinearity can confound interpretation because least squares algorithms are generally not robust to colinearity. More detailed studies comparing log-linear and log-quadratic models should correct for collinearity using orthogonal polynomials or re-scaling procedures.

The biological aspects of the study are based on much more fragmentary data as compared to the physical aspects. The weakest part is my interpretation of bison and cattle dynamics. This has strong implications for livestock grazing management, so short of a time machine, further field testing using the animals in this environment would be required for a better understanding of the relative impacts of cattle and bison herbivory.

I am curious about the native status of *Agrostis alba* var. *stolonifera*. This plant is widespread and occurs in many apparently undisturbed and remote places. It will be interesting to see if it is introduced or not. This plant has probably been in the region for many years: the 1922 version of Rydberg's flora for the Rocky Mountains includes it.

Finally, I often did not know whether I was looking too hard for changes, not hard enough, or even looking at the most important changes. Subjectivity enters the picture here, and I drew upon my familiarity with the region to help with this. Although I relied on many other studies as a guide, my experiences and biases are buried deeply in this study. One way around this is another investigator.

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Spaulding, Sonny. various dates. Informal conversations. Spaulding lives and ranches along the South Fork, near Table Rock. The Spaulding family began ranching here in 1898.

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APPENDIX A

STREAMFLOW MEASUREMENT DATA INDEX AND EXAMPLE NOTES

Table A-1. Index to published Snake River discharge data for the study area until 1960.

Water Year	Water Supply Paper Number	Water Year	Water Supply Paper Number
1903	100	1932	738
1904	135	1933	753
1905	178	1934	768
1906	214	1935	793
1907	252	1936	813
1908	252	1937	833
1909	272	1938	863
1910	292	1939	883
1911	312	1940	903
1912	332	1941	933
1913	362	1942	963
1914	393	1943	983
1915	413	1944	1013
1916	443	1945	1043
1917	463	1946	1063
1918	483	1947	1093
1919	513	1948	1123
1920	513	1949	1153
1921	533	1950	1183
1922	553	1951	1217
1923	573	1952	1247
1924	593	1953	1287
1925	613	1954	1347
1926	633	1955	1397
1927	653	1956	1447
1928	673	1957	1517
1929	693	1958	1567
1930	708	1959	1637
1931	723	1960	1717

Before 1905, the above have the general title: Progress in stream measurements for the calender year (190_), and although still USGS Water Supply Papers, are published as House Documents. After 1905, the above have the general title: Surface Water Supply of the United States. (year). Water Supply Paper (number). All published by US Government Printing Office, Washington D.C.

Table A-2. Example of discharge record.

Snake River near Heise, Idaho

Location.- Water-stage recorder, lat. 43°37', long. 111°40', in sec. 5, T. 3 N., R. 41 E., 3 miles upstream from Heise and 23 miles upstream from Henrys Fork. Altitude of gage, 5,015 feet (from river-profile map).

Drainage area.- 5,740 square miles.

Records available.- September 1910 to September 1942, except for winters of 1914-24.

Average discharge.- 32 years (1910-42), 6,682 second-feet (unadjusted).

Extremes.- Maximum discharge during year, 19,500 second-feet June 10 (gage height, 7.33 feet); minimum, 1,740 second-feet Feb. 18 (gage height, 1.69 feet).
1910-42: Maximum discharge, about 60,000 second-feet May 19, 1927, result of washing out of a landslide on Gros Ventre River (gage height, about 16.0 feet, present datum); minimum, 1,210 second-feet Jan. 22, 1935 (gage height, 1.15 feet).

Remarks.- Records excellent except those for period May 25 to June 15, which are good, and those for periods of ice effect, which are fair. Station is above all irrigation diversions from main river except Riley ditch (capacity about 30 second-feet), which diverts 1 mile above station. About 105,000 acres in Wyoming and Idaho irrigated by diversions from tributaries above station. Flow partly regulated by Jackson Lake (see p. 13).

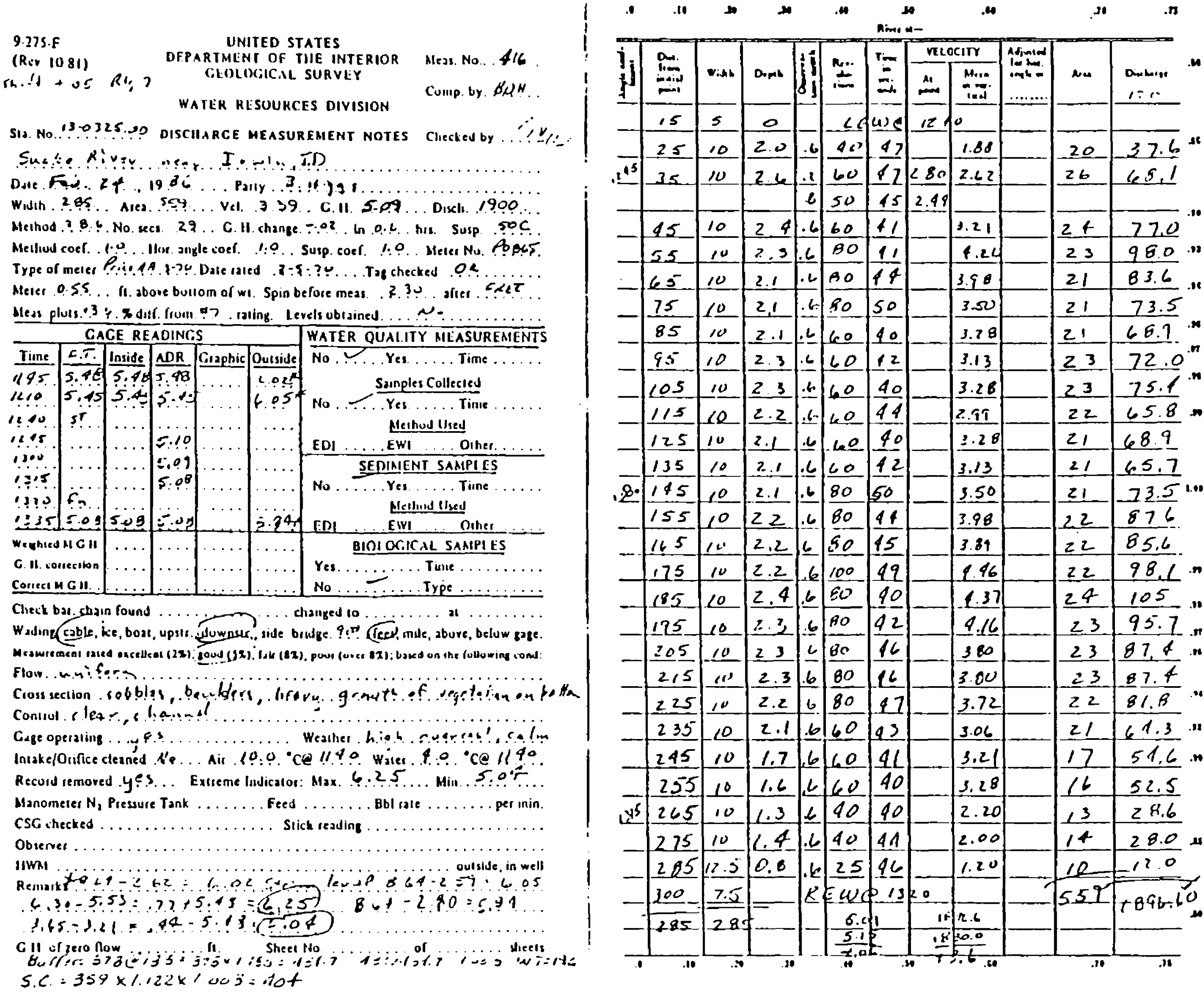
Discharge, in second-feet, water year October 1941 to September 1942

Day	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1	3,340	2,860	2,460	2,210	2,340	2,080	2,170	5,820	11,400	10,400	10,300	6,660
2	3,510	2,900	2,510	2,010	2,340	2,080	2,260	5,790	11,100	12,100	10,100	6,060
3	3,450	2,960	2,720	1,900	2,340	2,120	2,370	5,710	11,700	13,000	10,200	6,200
4	3,360	3,170	3,430	1,850	2,320	2,120	2,610	5,630	13,200	13,100	10,100	6,870
5	3,340	3,430	3,230	1,850	2,300	2,140	3,320	5,760	14,600	12,800	9,180	7,370
6	3,400	3,230	2,880	1,900	2,260	2,120	3,490	5,680	15,100	13,300	8,260	7,430
7	3,380	3,090	2,700	1,950	2,240	2,100	3,540	5,760	15,400	13,600	8,400	7,400
8	3,320	2,960	2,690	1,960	2,250	2,040	3,890	6,140	17,100	13,400	9,250	7,270
9	3,260	2,860	2,580	2,010	2,240	2,110	4,310	6,960	18,300	12,700	9,180	6,810
10	3,210	2,820	2,560	2,070	2,210	2,120	5,230	8,030	19,100	11,800	8,980	6,600
11	3,150	2,780	2,600	2,150	2,150	2,150	5,900	8,370	18,100	10,900	8,740	6,540
12	3,130	2,760	2,650	2,210	2,180	2,170	7,370	8,470	15,800	10,500	8,740	6,930
13	3,170	2,760	2,600	2,190	2,120	2,170	8,710	8,030	14,200	11,700	8,540	6,860
14	3,320	2,760	2,600	2,190	2,120	2,170	9,460	7,500	13,200	11,800	8,370	4,600
15	3,230	2,760	2,600	2,190	2,020	2,100	9,500	7,300	12,900	11,300	8,300	3,960
16	3,170	2,820	2,610	2,170	1,980	2,020	8,370	7,460	13,800	11,800	8,400	3,670
17	3,150	2,880	2,630	2,150	1,860	2,070	8,130	7,630	13,100	11,700	8,470	3,490
18	3,110	2,980	2,610	2,140	1,790	2,100	8,470	7,180	11,800	11,300	8,430	3,360
19	3,090	2,900	2,610	2,120	1,790	2,070	8,640	7,120	11,900	10,800	8,370	3,320
20	3,070	2,700	2,560	2,150	1,790	2,010	8,770	7,460	11,000	10,700	8,330	3,320
21	3,070	2,620	2,560	2,150	1,840	2,010	9,960	7,990	11,100	10,800	8,200	3,280
22	3,070	2,540	2,560	2,170	1,940	2,020	11,200	9,280	10,400	11,000	7,590	3,260
23	3,040	2,480	2,500	2,170	2,010	2,040	11,600	11,200	10,300	11,100	7,460	3,230
24	3,000	2,430	2,460	2,170	2,060	2,080	10,100	14,000	11,600	10,600	7,430	3,210
25	3,000	2,480	2,500	2,170	2,070	2,140	8,810	14,900	12,500	10,900	7,860	3,760
26	3,070	2,460	2,500	2,210	2,080	2.070	7,960	16,300	15,400	11,000	7,820	5,410
27	3,020	2,430	2,260	2,220	2,080	2,030	7,270	18,400	15,300	11,000	7,790	5,820
28	3,040	2,380	2,250	2,340	2,080	2,040	6,780	17,700	13,700	10,800	7,600	4,900
29	3,020	2,400	2,380	2,380	-	2,040	6,400	16,200	12,900	10,700	7,690	4,600
30	2,980	2,400	2,510	2,370	-	2,060	6,090	13,500	11,000	10,800	7,720	3,600
31	2,920	-	2,510	2,340	-	2,100	-	12,300	-	10,600	7,240	-

Month	Second-foot-days	Maximum	Minimum	Mean	Run-off in acre-feet
October	98,390	3,510	2,920	3,174	195,200
November	83,000	3,430	2,380	2,767	164,600
December	80,820	3,430	2,250	2,607	160,300
Calendar year 1941	1,880,900	14,000	1,770	5,153	3,731,000
January	66,060	2,380	1,850	2,131	131,000
February	58,790	2,340	1,790	2,100	116,600
March	64,690	2,170	2,010	2,087	128,300
April	202,460	11,600	2,170	6,749	401,600
May	288,470	18,400	5,630	9,305	572,200
June	407,800	19,100	10,300	13,590	808,900
July	358,000	13,600	10,400	11,550	710,100
August	262,940	10,300	7,240	8,482	521,500
September	155,370	7,430	3,210	5,179	308,200
Water year 1941-42	2,126,790	19,100	1,790	5,827	4,219,000

Note.- Stage-discharge relation affected by ice Jan. 1 to Feb. 2, Feb. 16, 17, Feb. 19 to Mar. 3.
Time basis: Mountain standard time prior to 2 a.m., Feb. 9, 1942; mountain war time thereafter. To convert war time to standard time, subtract 1 hour.

Table A-3. Example discharge measurement notes



9-275-F
(Rev 10 81)
Rh.11 + 05 Rt. 7

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

Meas. No. 416
Comp. by BAH
Checked by [illegible]

Sta. No. 13-0325.00 DISCHARGE MEASUREMENT NOTES

Snake River near Irwin, ID

Date Feb. 24, 1986 Party [illegible]

Width 285 Area 559 Vel. 3.39 G.H. 5.09 Disch. 1900

Method .2 .8 .6 No. secs. 29 G.H. change -.02 in 0.6 hrs. Susp. 50C

Method coef. 1.0 Hor. angle coef. 1.0 Susp. coef. 1.0 Meter No. [illegible]

Type of meter Price AA 3-74 Date rated 3-5-74 Tag checked OK

Meter 0.55 ft. above bottom of wt. Spin before meas. 2.30 after [illegible]

Meas. plots 3 % diff. from #7 rating. Levels obtained No

GAGE READINGS					
Time	C.T.	Inside	ADR	Graphic	Outside
1195	5.48	5.48	5.98		6.02
1210	5.45	5.4	5.13		6.05
1240	ST				
1245			5.10		
1300			5.09		
1315			5.08		
1330	Fn				
1335	5.09	5.09	5.09		5.94
Weighted M.G.H.					
G.H. correction					
Correct M.G.H.					

WATER QUALITY MEASUREMENTS
No ✓ Yes Time

Samples Collected
No ✓ Yes Time

Method Used
EDI EWI Other

SEDIMENT SAMPLES
No Yes Time

Method Used
EDI EWI Other

BIOLOGICAL SAMPLES
Yes Time
No ✓ Type

Check bar, chain found changed to at

Wading, [✓ cable], ice, boat, upstr., [✓ downstr.], side bridge 9.0 [✓ feet], mile, above, below gage.

Measurement rated excellent (2%), [✓ good (5%)], fair (8%), poor (over 8%); based on the following cond:

Flow uniform

Cross section cobbles, boulders, heavy growth of vegetation on bottom

Control clear, channel

Gage operating yes Weather high overcast, calm

Intake/Orifice cleaned No Air 10.0 °C @ 1140 Water 4.0 °C @ 1140

Record removed yes Extreme Indicator: Max. 6.25 Min. 5.04

Manometer N₂ Pressure Tank Feed Bbl rate per min.

CSG checked Stick reading

Observer

HWM outside, in well

Remarks 8.64 - 2.62 = 6.02 Set level 8.64 - 2.59 = 6.05
6.30 - 5.53 = .77 + 5.48 = 6.25 8.64 - 2.70 = 5.94
3.65 - 3.21 = .44 - 5.13 = 5.04

G.H. of zero flow ft. Sheet No of sheets

Buffer: 378 @ 135 = 375 × 1.153 = 431.7 431.7 / 431.7 1.003 WT=142
S.C. = 359 × 1.122 × 1.003 = 404

River at —

Angle coef.	Dist. from initial point	Width	Depth	Observation depth	Revolutions	Time in seconds	Velocity At point	Velocity Mean in vertical	Adjusted for hor. angle or	Area	Discharge
	15	5	0		LEW @ 1210						
	25	10	2.0	.6	40	47		1.88		20	37.6
1.45	35	10	2.6	.2	60	47	2.80	2.62		26	68.1
				.8	50	45	2.49				
	45	10	2.4	.6	60	41		3.21		24	77.0
	55	10	2.3	.6	80	41		4.26		23	98.0
	65	10	2.1	.6	80	44		3.98		21	83.6
	75	10	2.1	.6	80	50		3.50		21	73.5
	85	10	2.1	.6	60	40		3.28		21	68.9
	95	10	2.3	.6	60	42		3.13		23	72.0
	105	10	2.3	.6	60	40		3.28		23	75.4
	115	10	2.2	.6	60	44		2.99		22	65.8
	125	10	2.1	.6	60	40		3.28		21	68.9
	135	10	2.1	.6	60	42		3.13		21	65.7
.8	145	10	2.1	.6	80	50		3.50		21	73.5
	155	10	2.2	.6	80	44		3.98		22	87.6
	165	10	2.2	.6	80	45		3.89		22	85.6
	175	10	2.2	.6	100	49		4.46		22	98.1
	185	10	2.4	.6	80	40		4.37		24	105
	195	10	2.3	.6	80	42		4.16		23	95.7
	205	10	2.3	.6	80	46		3.80		23	87.4
	215	10	2.3	.6	80	46		3.80		23	87.4
	225	10	2.2	.6	80	47		3.72		22	81.8
	235	10	2.1	.6	60	43		3.06		21	64.3
	245	10	1.7	.6	60	41		3.21		17	54.6
	255	10	1.6	.6	60	40		3.28		16	52.5
1.45	265	10	1.3	.6	40	40		2.20		13	28.6
	275	10	1.4	.6	40	44		2.00		14	28.0
	285	12.5	0.8	.6	25	46		1.20		10	12.0
	300	7.5		REW @ 1320						559	1896.10
	285	285			6.01 5.15 .86		1F R.6 1820.0 75.6				

Table A-4. Example discharge measurement summary sheet.

9-207
(Rev. 1-65)

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY (WATER RESOURCES DIVISION)

Station No. 13-0225.00

Discharge measurements of SNAKE RIVER NEAR ALPINE WYOMING during the year ending Sept. 30, 1983

No.	Date	Made by—	Width	Area	Mean velocity	Gage height	Discharge	Rating 3		Method	Number meas. sections	Gage height change	Time	Meas. rated	AT °C	WT °C	REMARKS
								Shift adj.	Percent diff.								
			Feet	Sq ft	Fps	Feet	Cfs	Feet				Feet	Hr				
299	Aug 12	N. Jacobson	227	734	3.40	3.67	2490	+.08	+0.1	.6 .2.8	27	.00	1.0	E	27.3 1312	17.0 1312	
300	Oct 7	N. Jacobson	226	423	2.58	2.90	1610	+.17	.00	.6 .2.8	28	.00	1.0	G	16.4 1320	9.8 1320	
301	Nov 17	S. Landon (N) N. Jacobson (m)	224	610	2.54	2.92	1550	+.09	+0.3	.6 .2.8	27	.00	1.0	G	2.5 1430	5.0 1430	
302	Dec 16	S. Landon (m) M. Campbell (N)	215	606	2.93	3.10	1770	+.11	+0.3	.6 .2.8	26	.00	5/6	G	0.0 1428	3.0 1428	
	Jan 7	R. Erickson M. Campbell				3.14	Visit										
	Feb 10	S. Landon N. Jacobson				4.98	QW Visit										No measurement made because of ice jam
303	Mar 17	N. Jacobson (m) S. Landon (N)	230	828	3.33	3.74	2760	+.17	.00	.6 .2.8	30	.00	1.0	G	5.2 1155	4.6 1155	
304	April 16	S. Landon (m) N. Jacobson (N)	234	1030	4.44	4.70	4570	+.15	+0.2	.6 .2.8	29	+.01	1.1	G	6.0 1515	5.8 1515	
305	June 10	N. Jacobson	242	1770	7.44	7.81	13,200	.00	-2.0	.2.8	28	-.01	1.2	E	13.0 0950	7.0 0950	
306	Aug 18	N. Jacobson	237	1240	5.09	5.50	6,320	+.12	+0.08	.6 2.8	27	.00	1.1	G	25.3 1632	16.3 1632	
307	Oct. 20	N. Jacobson M. Campbell	230	836	3.38	3.84	2830	+.11	+0.01	.6 .2.8	27	.00	1.0	G	2.2 1840	5.0 1840	

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APPENDIX B

MISCELLANEOUS CURVE FITTING DATA

Table B-1. Regression results for predicting annual instantaneous peak discharge (IP) from highest annual mean daily discharge (MP).

```
DEP VAR:        IP      N:   41    MULTIPLE R: 1.000    SQUARED MULTIPLE R:  .999
ADJUSTED SQUARED MULTIPLE R:   .999      STANDARD ERROR OF ESTIMATE:      244.198

 VARIABLE     COEFFICIENT     STD ERROR     STD COEF TOLERANCE      T    P(2 TAIL)

CONSTANT          326.695       128.442        0.000 1.0000000    2.544    0.015
      MP            1.004         0.005        1.000 1.0000000  197.968    0.000

                              ANALYSIS OF VARIANCE

   SOURCE    SUM-OF-SQUARES    DF  MEAN-SQUARE      F-RATIO        P

 REGRESSION     .233708E+10     1  .233708E+10    39191.406       0.000
   RESIDUAL    2325668.124     39    59632.516

WARNING: CASE     4 HAS UNDUE INFLUENCE (LEVERAGE =         .348)  ok
WARNING: CASE    39 IS AN OUTLIER (STUDENTIZED RESIDUAL =        3.043) ok

DURBIN-WATSON D STATISTIC     1.429
FIRST ORDER AUTOCORRELATION    .258
```

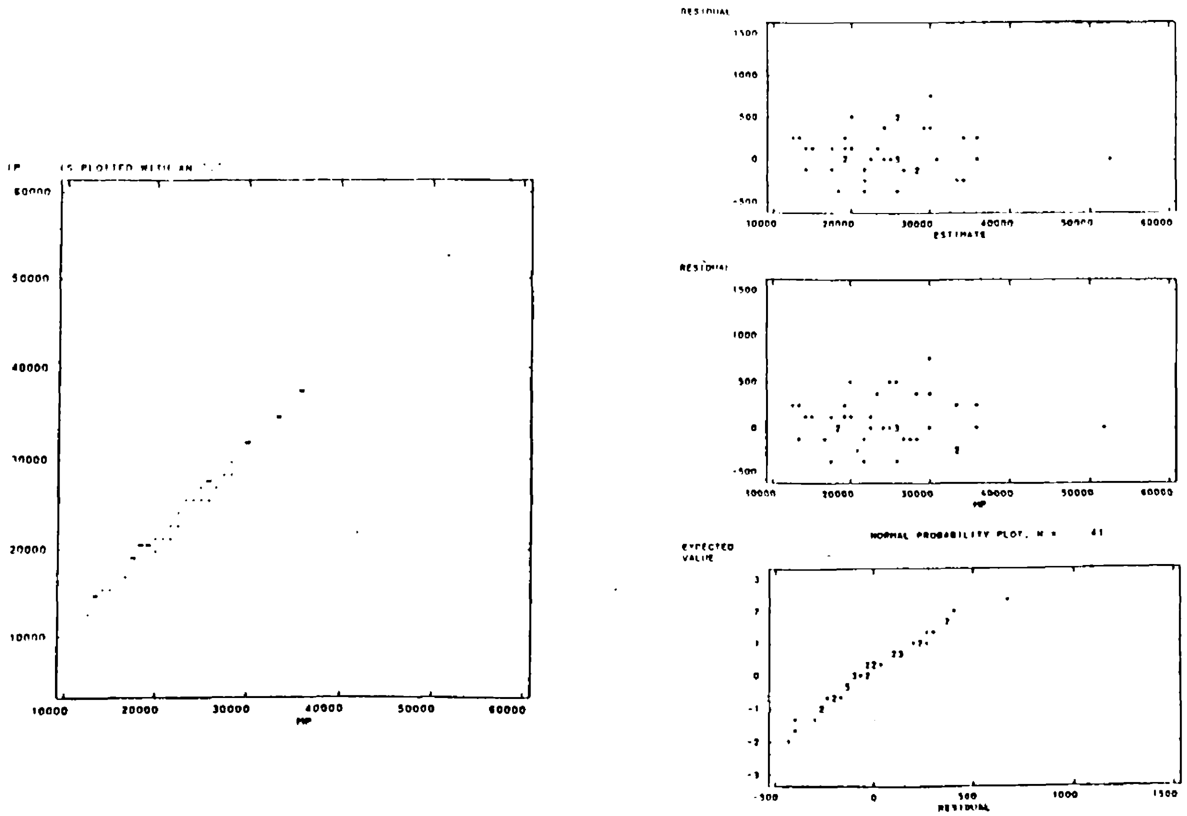


Figure B1. Scatter plots of IP with MP, Residual with Predicted IP and MP, and normal probability plot of residuals.

Table B-2. Regression results for predicting mean daily flow at Heise gage (HMDF1) from mean daily flow at Irwin gage (IMDF1). Original data had high serial correlation (r = .806). This is the lagged fit.

```
DEP VAR:    HMDF1       N:  365    MULTIPLE R:   .996    SQUARED MULTIPLE R:   .993
ADJUSTED SQUARED MULTIPLE R:   .993      STANDARD ERROR OF ESTIMATE:     142.899027

 VARIABLE      COEFFICIENT       STD ERROR      STD COEF TOLERANCE      T     P(2 TAIL)

CONSTANT          48.767469       10.707659      0.000000 1.0000000  4.55445   0.00001
   IMDF1           1.034075        0.004661      0.996333 1.0000000  .22E+03   0.00000

                                  ANALYSIS OF VARIANCE

   SOURCE    SUM-OF-SQUARES    DF   MEAN-SQUARE      F-RATIO         P

 REGRESSION    .100506E+10      1   .100506E+10  .492190E+05     0.000000
   RESIDUAL    .741251E+07    363   .204201E+05

DURBIN-WATSON D STATISTIC      2.066
```

~~FIRST~~ ORDER AUTOCORRELATION -.034

2nd

CONSTANT = 48.767/(1-.806) = 251.379

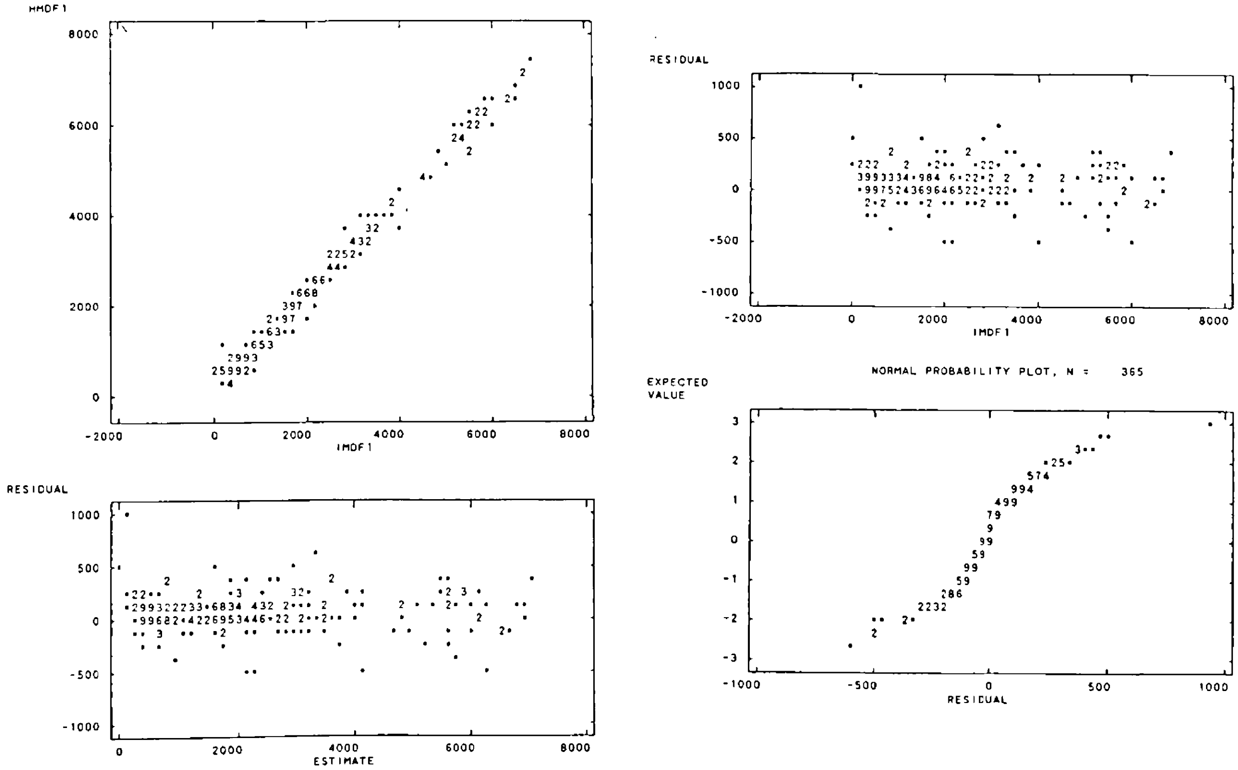


Figure B-2. Scatter plots of HMDF1 and IMDF1, Residual with Predicted HMDF1 and HMDF1, and normal probability plot of residuals

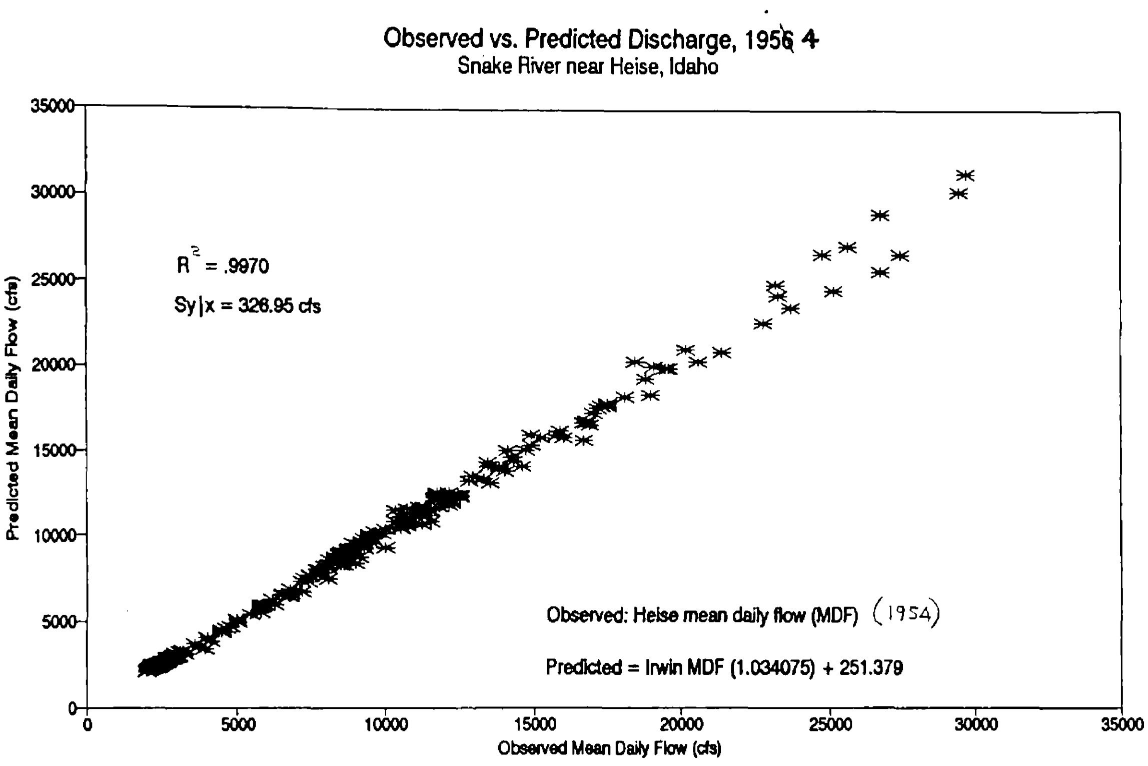


Figure B-3. Flood control effect model validation. Actual mean daily flow at Heise versus predicted flow at Heise for water year 1954. Sy|x is standard error of the estimate, MDF is mean daily flow.

Table B-3. Slope coefficients and ANOVA table for the velocity (V) versus discharge (Q) for higher discharges at the Alpine gage. The dummy variable (G) is for pre-dam or post-dam periods.

```
DEP VAR:          V       N:    33    MULTIPLE R:   .960    SQUARED MULTIPLE R:   .921
                                     -1
ESTIMATES OF EFFECTS  B = (X'X)   X'Y

                           V

  CONSTANT           4.958610047

         Q           0.000191620

         G         1-0.366501176

         G         1
         Q           0.000022581


                                ANALYSIS OF VARIANCE

   SOURCE    SUM-OF-SQUARES    DF  MEAN-SQUARE      F-RATIO          P

         Q       7.178548676    1  7.178548676 .154852E+03 0.000000000
         G       0.082558806    1  0.082558806 1.780918641 0.192420814
        G*
         Q       0.099686845    1  0.099686845 2.150396423 0.153293872

     ERROR       1.344365380   29  0.046357427

DURBIN-WATSON D STATISTIC     2.051
FIRST ORDER AUTOCORRELATION   -.027
```

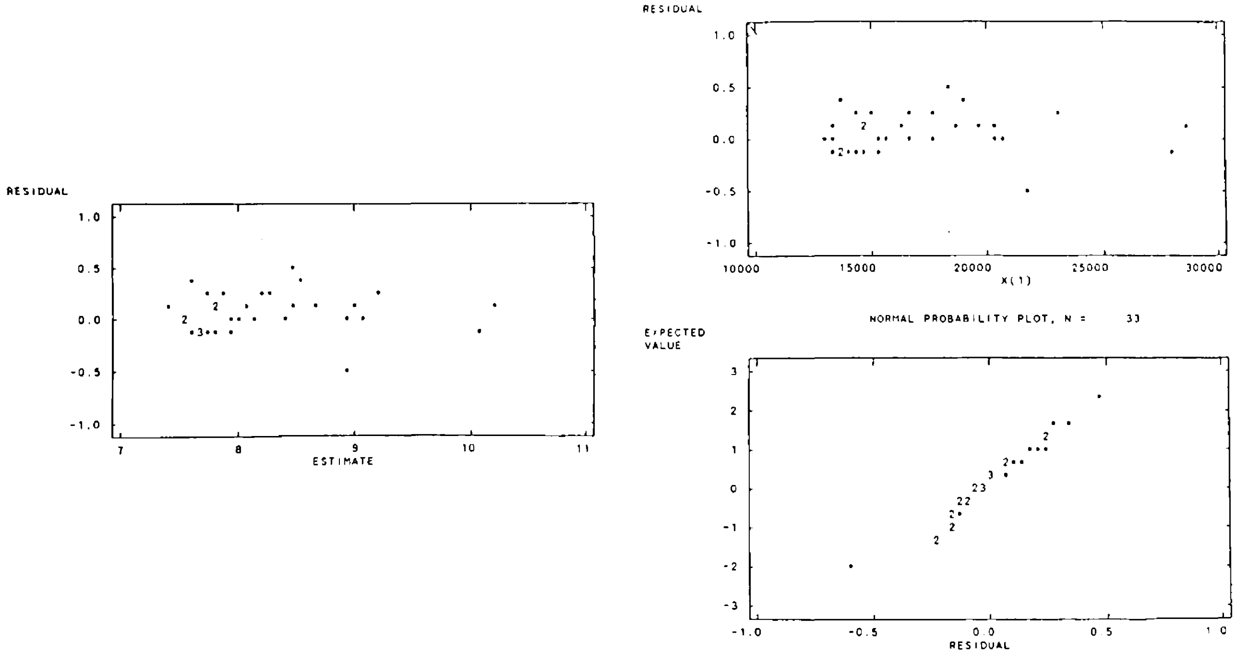


Figure B-4. Scatter plots of Residuals with Estimate (V), Residuals with discharge (X1), and normal probability plot of residuals for the Alpine gage data.

Table B-4. Slope coefficients and ANOVA table for the velocity (V) versus discharge (Q) for higher discharges at the Irwin gage. The dummy variable (G) is for pre-dam or post-dam periods.

```
DEP VAR:          V      N:   42    MULTIPLE R:   .988    SQUARED MULTIPLE R:   .977
                                                -1
ESTIMATES OF EFFECTS   B = (X'X)   X'Y

                             V

  CONSTANT            4.954901790

        Q             0.000136623

        G           1 0.170984083

        Q
        G           1-0.000009215


                                ANALYSIS OF VARIANCE

   SOURCE   SUM-OF-SQUARES     DF   MEAN-SQUARE      F-RATIO        P

       Q        8.428086581     1   8.428086581 .915760E+03 0.000000000
       G        0.034803009     1   0.034803009 3.781544974 0.059249730
      Q*
       G        0.038341173     1   0.038341173 4.165986707 0.048233336

   ERROR        0.349728574    38   0.009203384

DURBIN-WATSON D STATISTIC    1.493
FIRST ORDER AUTOCORRELATION   .243
```

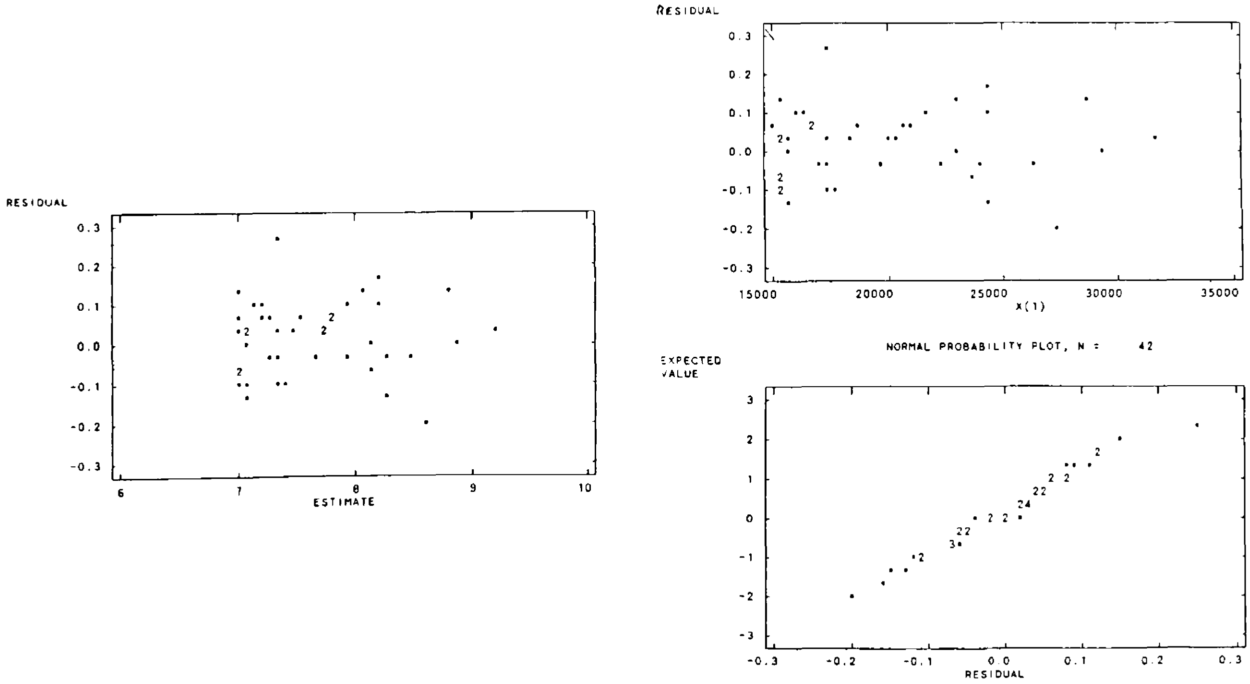


Figure B-5. Scatter plots of Residuals with Estimate (V), Residuals with discharge (X1), and normal probability plot of residuals for the Irwin gage data.

Table B-5. Slope coefficients and ANOVA table for the velocity (V1) versus discharge (Q1) for higher discharges at the Heise gage. The dummy variable (G) is for pre-dam or post-dam periods. Original data had high serial correlation (r = .602). This is lagged fit.

```
DEP VAR:        V1      N:    50    MULTIPLE R:   .977    SQUARED MULTIPLE R:   .955
                                  -1
ESTIMATES OF EFFECTS    B = (X'X)   X'Y

                          V1

  CONSTANT             1.569153475      CONSTANT ≈ 1.5691/(1-.602) = 3.942

        Q1             0.000144011

         G           1-0.023942717

        Q1
         G           1-0.000008296


                               ANALYSIS OF VARIANCE

   SOURCE    SUM-OF-SQUARES    DF   MEAN-SQUARE       F-RATIO         P

       Q1       .120379E+02     1   .120379E+02  .899376E+03  0.000000000
        G       0.003095059     1   0.003095059  0.231238788  0.632886192
      Q1*
        G       0.039950559     1   0.039950559  2.984795325  0.090759160

    ERROR       0.615695729    46   0.013384690
```

DURBIN-WATSON D STATISTIC 2.286

2nd ~~FIRST~~ ORDER AUTOCORRELATION -.156

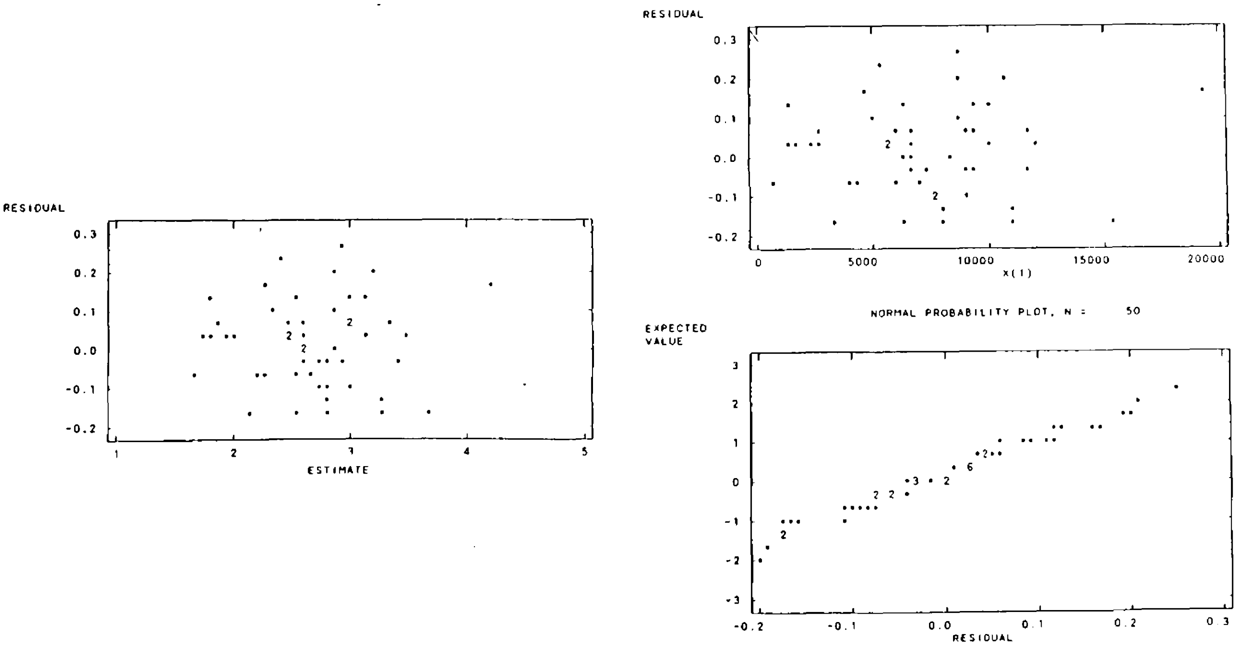


Figure B-6. Scatter plots of Residuals with Estimate (V1), Residuals with discharge (X1), and normal probability plot of residuals for the Heise gage data.

Explanation of comparing two straight line models using a single regression equation.

The compared models are: $V = \text{constant} + b1Q + b2\ G + b3(G^{*}Q)$ which is complete model, and
$V = \text{constant} + b1(Q)$, the reduced model

Using the Alpine data as an example, the separate line models can be obtained as follows:

$V_{\text{pre-dam}} = (\text{constant} + b2) + (b1+b3)$ and $V_{\text{post-dam}} = (\text{constant} - b2) + (b1 - b3)$ and they are:

$$V_{\text{pre-dam}} = (4.9586 + -.3665) + (.0001916+.0000226) = 4.5921 + .0002142(Q)$$

$$V_{\text{post-dam}} = (4.9586 - -.3665) + (.0001916+.0000226) = 5.3251 + .0001690(Q)$$

The tests involve the assumption of equal variances regarding the separate line regressions (should not reject variances are equal hypothesis) and the test for coincidence.

1) Test for equal variance of the two separate models*: (variance = mean square for error)

larger variance / smaller variance, using the F test statistic.

2) Test for coincidence of the two lines, using the single model with dummy variables and the F test statistic:

$$\frac{(\text{sum of squares complete model - sum of squares reduced model})/2}{\text{mean square error of complete model}} = F$$

Table B-6. Results of testing for coincidence of two lines using the single model approach.

Alpine.	**Irwin**	**Heise**
Equal variances tests	Equal variances test	Equal variances test
.0535644/.0117639 = 4.553	.0099884/.0086324 = 1.1571	.0415401/.0243697 = 1.7045
$P(F_{24,5} \geq 4.553)$ $.05 < p <. .10$	$P(F_{16,22} \geq 1.1571)$ $p > .25$	$P(F_{4,43} \geq 1.7045)$ $.10 < p < .25$
Coincidence tests		
$\frac{(7.3608 - 7.1786)/2}{.0463574} = 1.965$	$\frac{(8.5012 - 8.4280)/2}{.00920} = 3.974$	$\frac{(12.0810 - 12.0379)/2}{.01338} = 1.608$
$P(F_{2,29} \geq 1.965)$ $.10 < p < .25$	$P(F_{2,38} \geq 3.974)$ $.025 < p < .05$	$P(F_{2,46} \geq 1.608)$ $.10 < p < .25$

---

* Complete information for separate models are not shown.

Table B-7. Example of hydraulic geometry regression, using the velocity-to-discharge relation at the Irwin gage, 1957 to 1990. LV = log velocity; LQ = log discharge.

```
DEP VAR:      LV      N:  347    MULTIPLE R:  .994    SQUARED MULTIPLE R:  .988
ADJUSTED SQUARED MULTIPLE R:  .988     STANDARD ERROR OF ESTIMATE:  0.016601307

 VARIABLE     COEFFICIENT     STD ERROR      STD COEF TOLERANCE     T    P(2 TAIL)

CONSTANT     -0.695631894  0.007915562  0.000000000 1.0000000 -.88E+02  0.00000
     LQ       0.366674647  0.002146433  0.994140885 1.0000000  .17E+03  0.00000


                            ANALYSIS OF VARIANCE

  SOURCE    SUM-OF-SQUARES     DF   MEAN-SQUARE      F-RATIO        P

 REGRESSION    8.042881810      1   8.042881810  .291828E+05 0.000000000
   RESIDUAL    0.095083175    345   0.000275603
                                   (4-d)
DURBIN-WATSON D STATISTIC     1.230  2.77
FIRST ORDER AUTOCORRELATION    .385
```

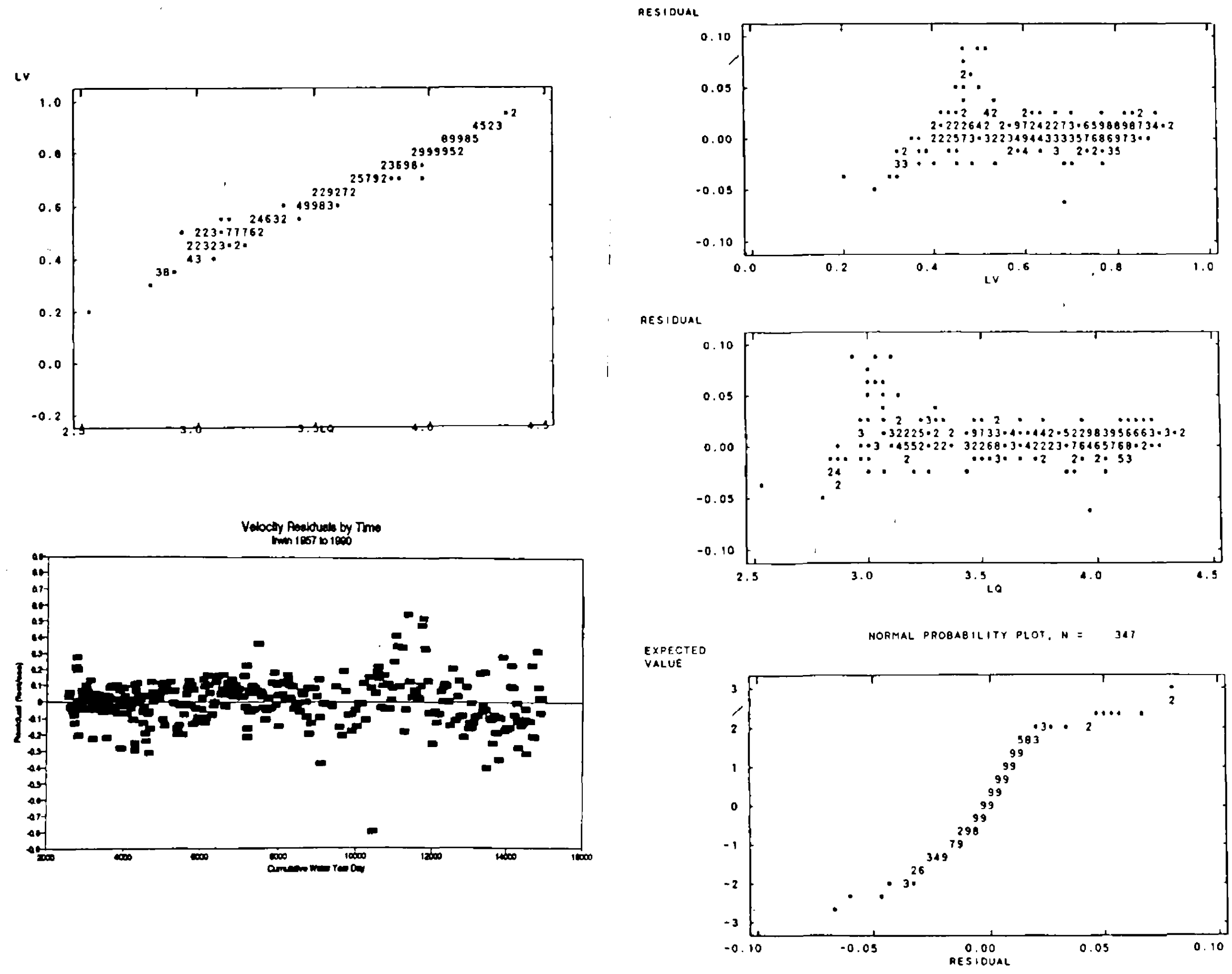


Figure B-7. Scatter plots of LV and LQ, Residuals against LV and LQ, and normal probability plot of residuals, and time series of residuals. Note fan-shaped variance at low flow.

Table B-8. Regression Slope coefficients, ANOVA table, and correlation matrix for the regressing of velocity on discharge and reservoir water elevation. LV is log velocity, LQ is log discharge, and LEL is log elevation in feet above sea level. Note how the slope for LEL is statistically insignificant and negative. If there was an effect, it should be positive. Correlation matrix on original variables shows low dependence of discharge (Q) on elevation (EL), yet the slope for LEL is still not important. Hydraulic head shows little effect on velocity for a fixed discharge.

```
DEP VAR:        LV      N:  137    MULTIPLE R:  .998    SQUARED MULTIPLE R:  .995
ADJUSTED SQUARED MULTIPLE R:   .995     STANDARD ERROR OF ESTIMATE:       0.01032

 VARIABLE     COEFFICIENT     STD ERROR      STD COEF TOLERANCE      T     P(2 TAIL)

CONSTANT          2.22923       1.80317       0.00000 1.0000000  1.23629  0.21852
      LQ          0.36951       0.00232       1.00119  .8783909  .16E+03  0.00000
     LEL         -0.78339       0.48198      -0.01021  .8783909 -1.62535  0.10644

                            ANALYSIS OF VARIANCE

  SOURCE    SUM-OF-SQUARES    DF   MEAN-SQUARE      F-RATIO        P

 REGRESSION        3.05821     2        1.52910 14356.61984     0.00000
   RESIDUAL        0.01427   134        0.00011

 DURBIN-WATSON D STATISTIC     1.122
 FIRST ORDER AUTOCORRELATION    .432
```

Correlation Matrix (Pearson product moment)

	V	Q	EL
V	1.000		
Q	0.976	1.000	
EL	0.347	0.364	1.000

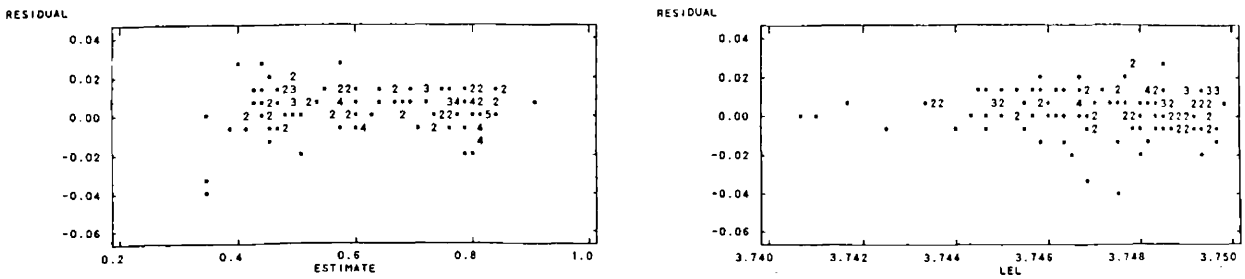


Figure B-8. Scatter plots of residuals against Estimate (LV) and LEL.

APPENDIX C

SEDIMENT SIZE AND MOVEMENT DATA

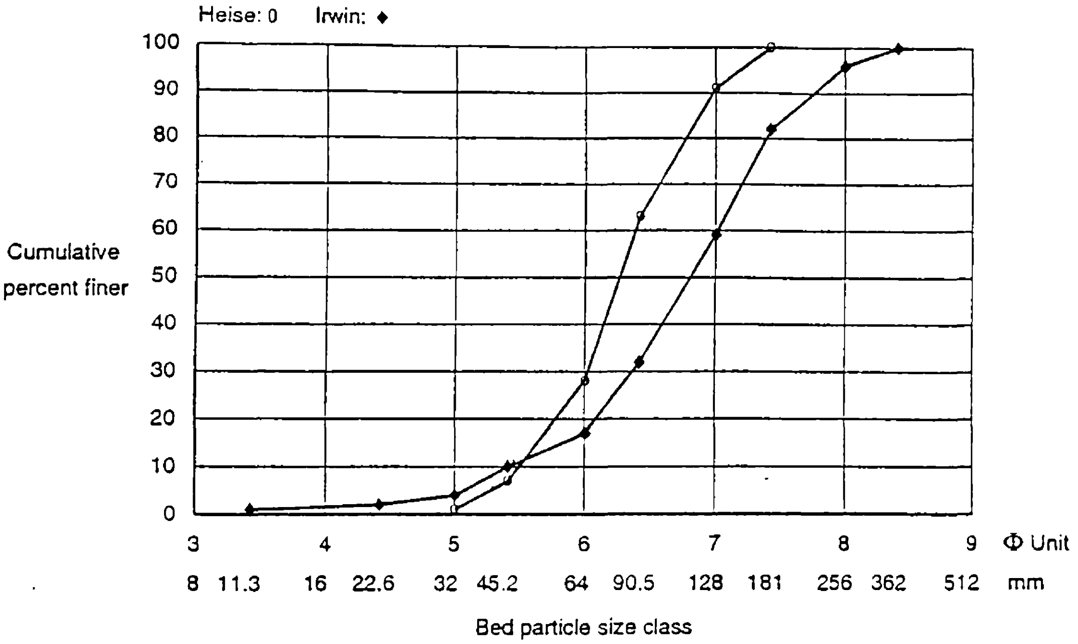


Figure C-1. Particle size distribution for channel locales at gaging stations.

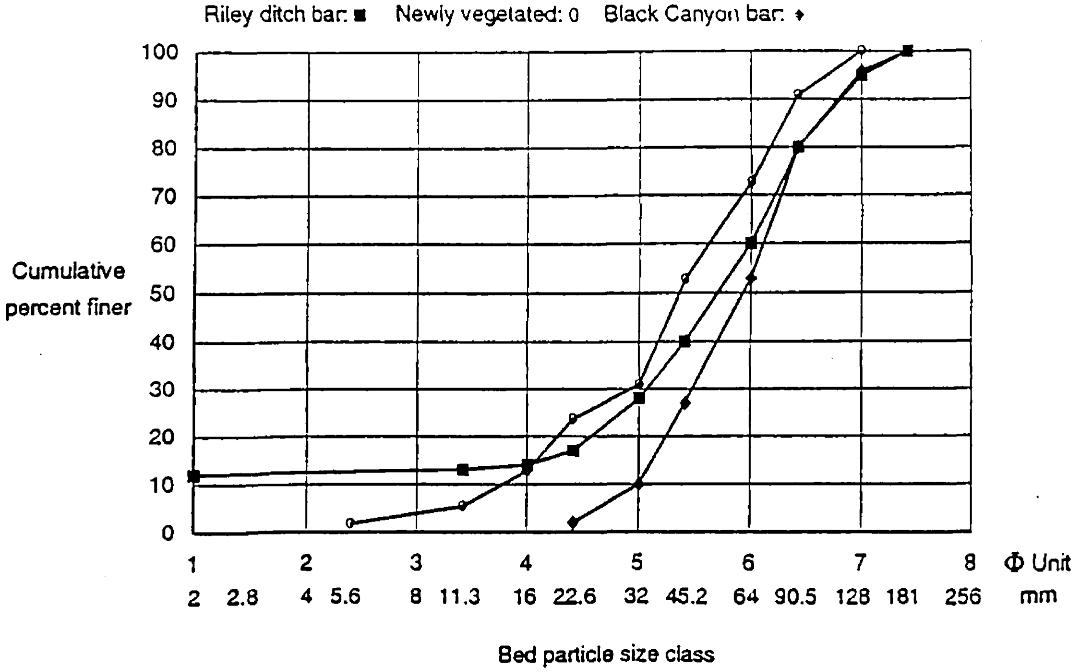


Figure C-2. Particle size distribution for flood plain locales.

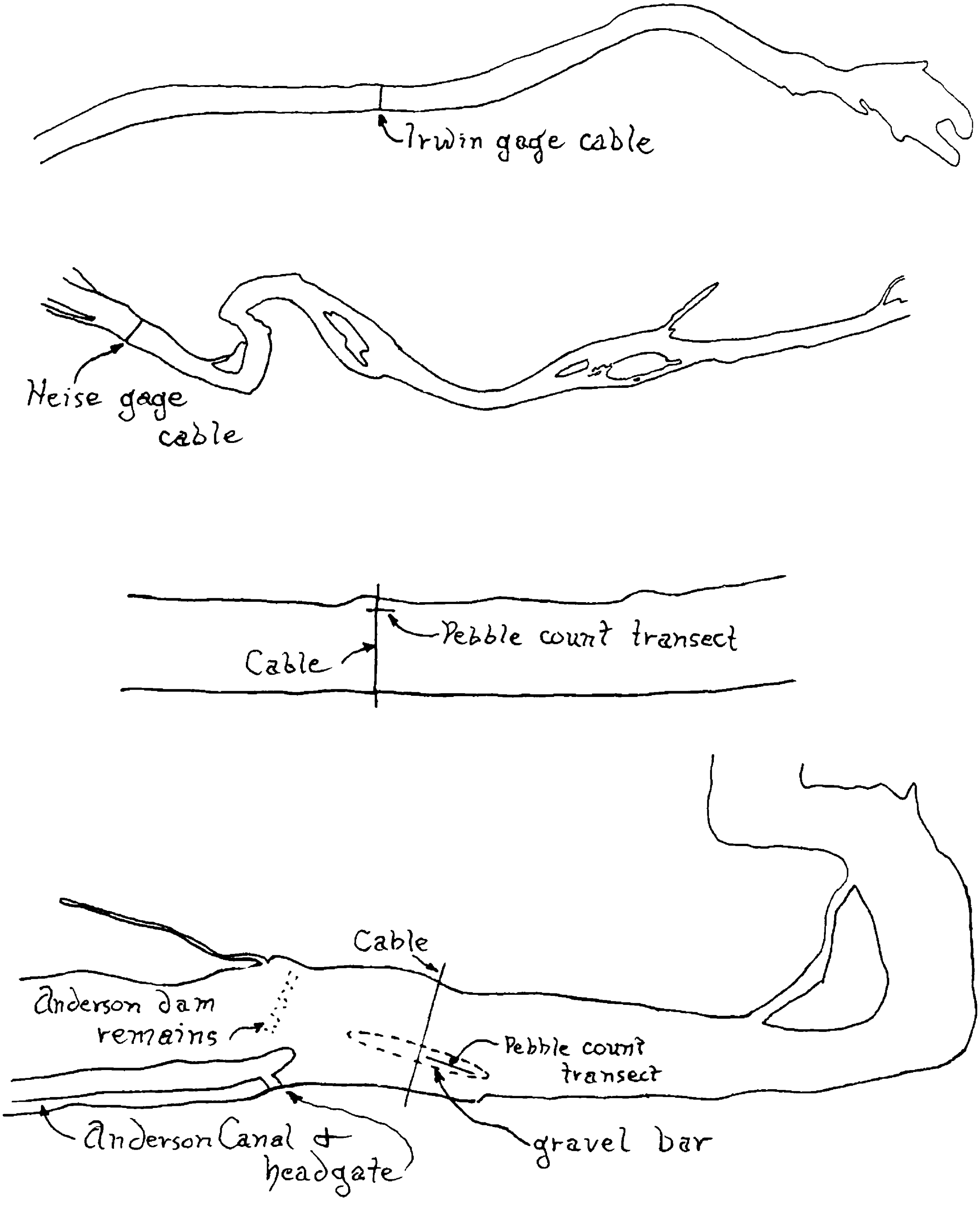
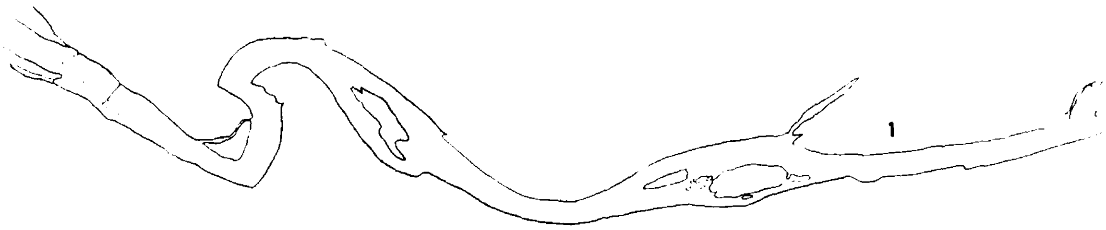


Figure C-3. Pebble count locations for channel locales at Irwin and Heise gaging stations.



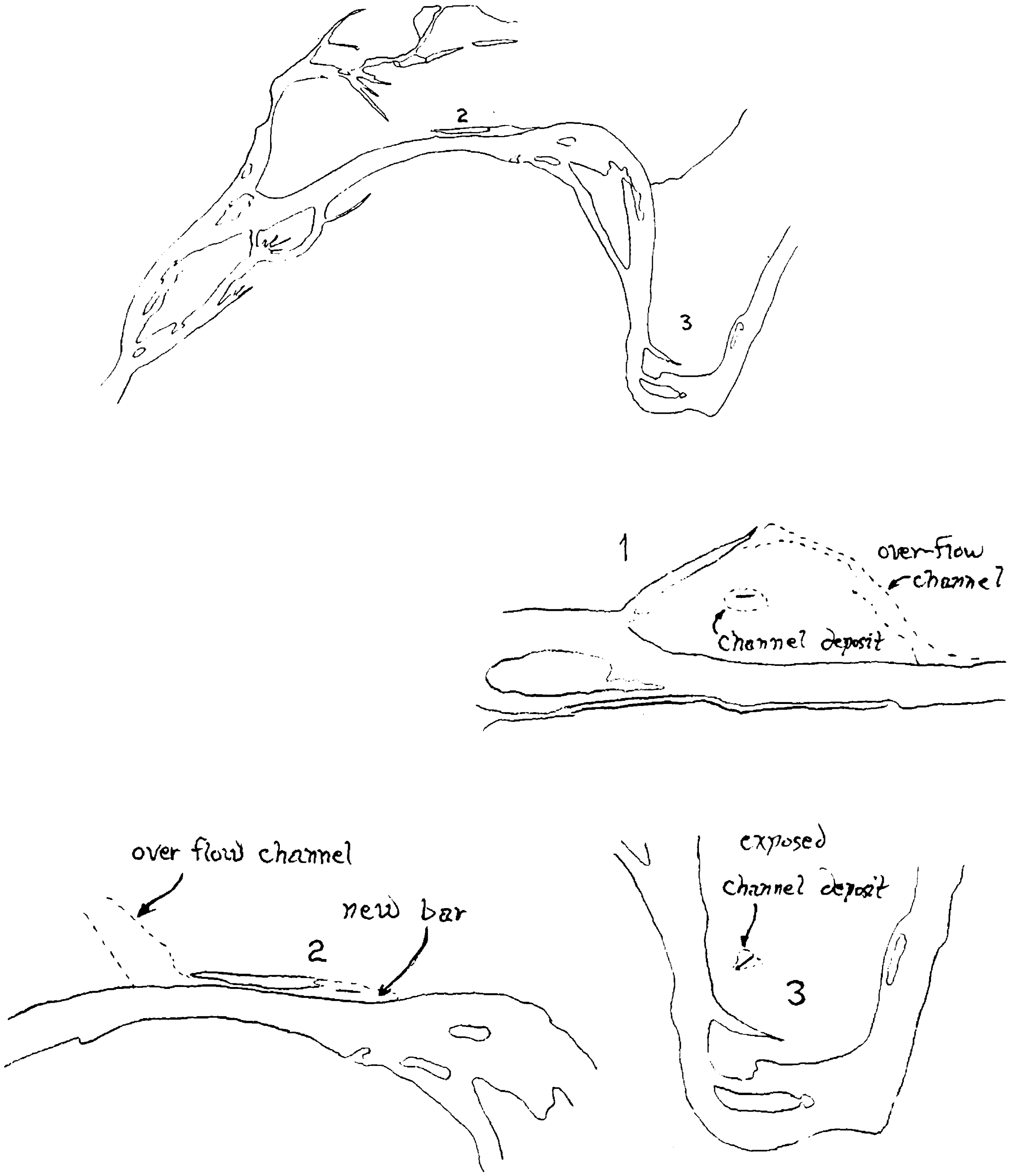
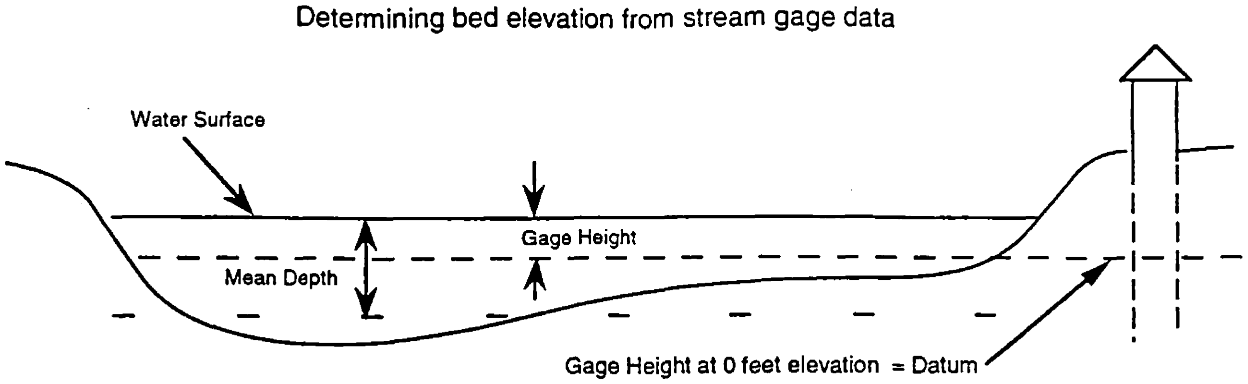
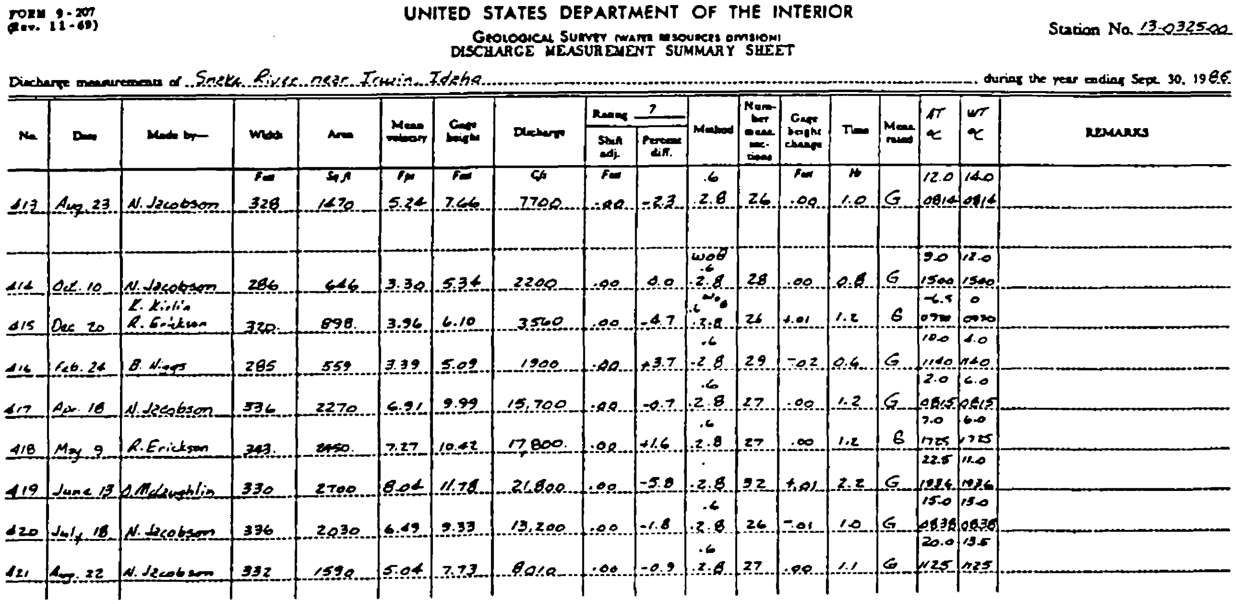


Figure C-4. Pebble count locations for flood plain locales at Riley ditch bar (1), newly vegetated bar (2), and Black Canyon Bar (3).


Determining bed elevation from stream gage data

$$\frac{\text{Area}}{\text{Width}} = \text{Mean Depth} \qquad \text{Datum} + \text{Gage Height} - \text{Mean Depth} = \text{Mean Bed Elevation}$$


FORM 9-207
(Rev. 11-69)

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY (WATER RESOURCES DIVISION)
DISCHARGE MEASUREMENT SUMMARY SHEET

Station No. 13-0325-00

Discharge measurements of Snake River near Twin Idaho during the year ending Sept. 30, 1986

No.	Date	Made by—	Width	Area	Mean velocity	Gage height	Discharge	Rating 7		Method	Number meas. sections	Gage height change	Time	Meas. rated	AT °C	WT °C	REMARKS
								Shift adj.	Percent diff.								
			Feet	Sq ft	Fps	Feet	Cfs	Feet				Feet	Hr				
413	Aug. 23	N. Jacobson	328	1470	5.24	7.66	7700	.00	-2.3	.6 .2.8	26	.00	1.0	G	12.0 0814	14.0 0814	
414	Oct. 10	N. Jacobson	286	646	3.30	5.34	2200	.00	0.0	woB .6 .2.8	28	.00	0.8	G	9.0 1500	12.0 1500	
415	Dec 20	L. Kirlin R. Erickson	320.	898.	3.96	6.10	3560	.00	-4.7	.6 .2.8	26	+.01	1.2	G	-6.5 0930	0 0930	
416	Feb. 24	B. Higgs	285	559	3.39	5.09	1900	.00	+3.7	.6 .2.8	29	-.02	0.6	G	10.0 1140	4.0 1140	
417	Apr. 18	N. Jacobson	336	2270	6.91	9.99	15,700	.00	-0.7	.6 .2.8	27	.00	1.2	G	2.0 0815	6.0 0815	
418	May 9	R. Erickson	343.	2450.	7.27	10.42	17,800.	.00	+1.6	.6 .2.8	27	.00	1.2	G	7.0 1725	6.0 1725	
419	June 13	D. McLaughlin	330	2700	8.04	11.78	21,800	.00	-5.8	. .2.8	32	+.01	2.2	G	22.5 1936	11.0 1936	
420	July 18	N. Jacobson	336	2030	6.49	9.33	13,200	.00	-1.8	.6 .2.8	26	-.01	1.0	G	15.0 0838	13.0 0838	
421	Aug. 22	N. Jacobson	332	1590	5.04	7.73	8010	.00	-0.9	.6 .2.8	27	.00	1.1	G	20.0 1125	13.5 1125	

YEAR	DAY	WIDTH	AREA	VEL	GH	CFS	DEPTH	DATUM	BED ELEV
1986	10	286	646	3.3	5.34	2200	2.258741	5353	5356.081
	81	320	898	3.96	6.1	3560	2.80625	5353	5356.294
	147	285	559	3.39	5.09	1900	1.961404	5353	5356.129
	200	336	2270	6.91	9.99	15700	6.755952	5353	5356.234
	221	343	2450	7.27	10.42	17800	7.142857	5353	5356.277
	256	330	2700	8.04	11.78	21800	8.181818	5353	5356.598
	291	336	2030	6.49	9.33	13200	6.041667	5353	5356.288
1986	326	332	1590	5.04	7.73	8010	4.789157	5353	5355.941

Figure C-5. Calculation of mean bed elevation.

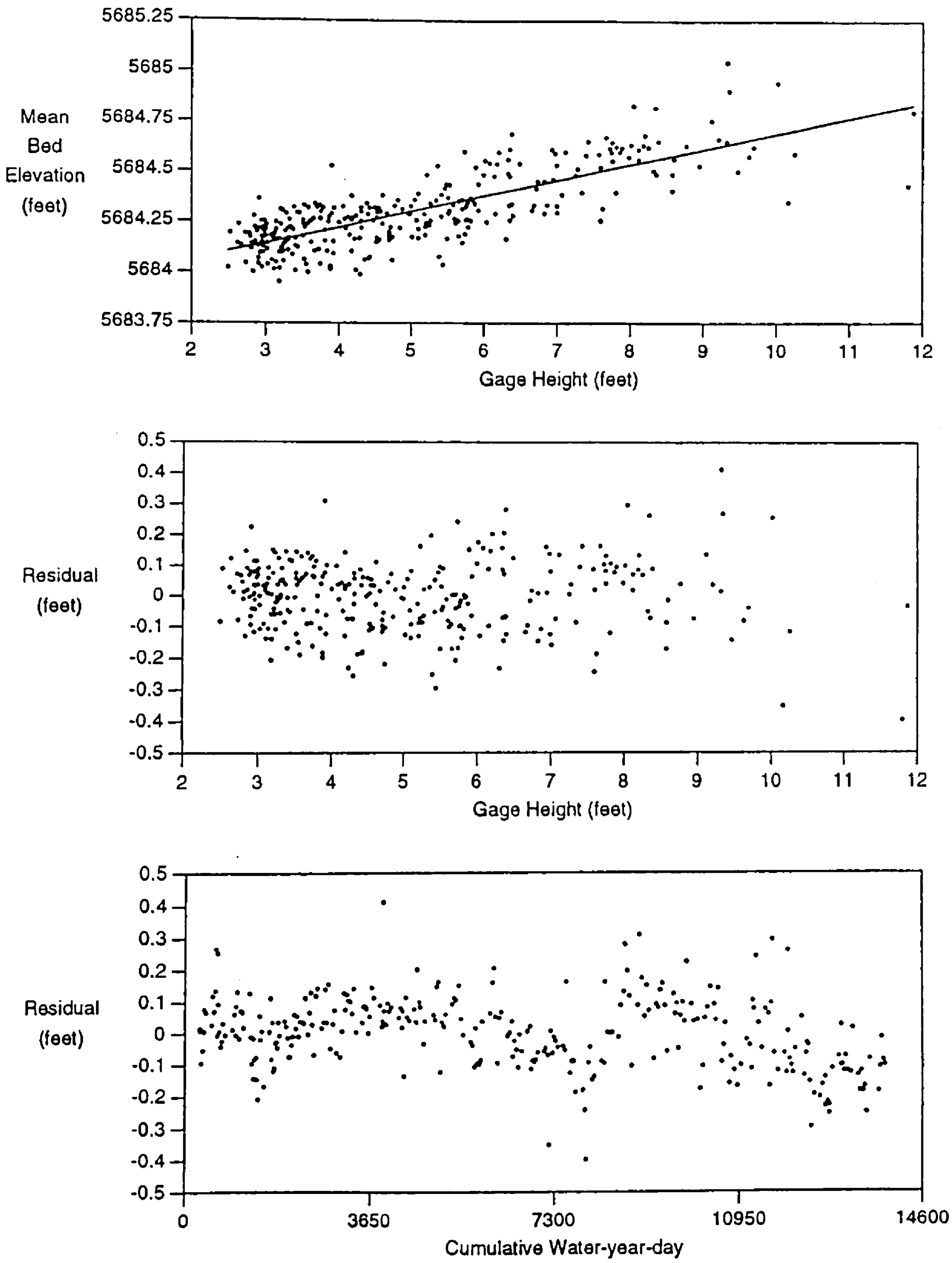


Figure C-6. Regression and residual plots for mean bed elevation on gage height, Alpine gage The more scatter, the more likely bed movement has occurred.

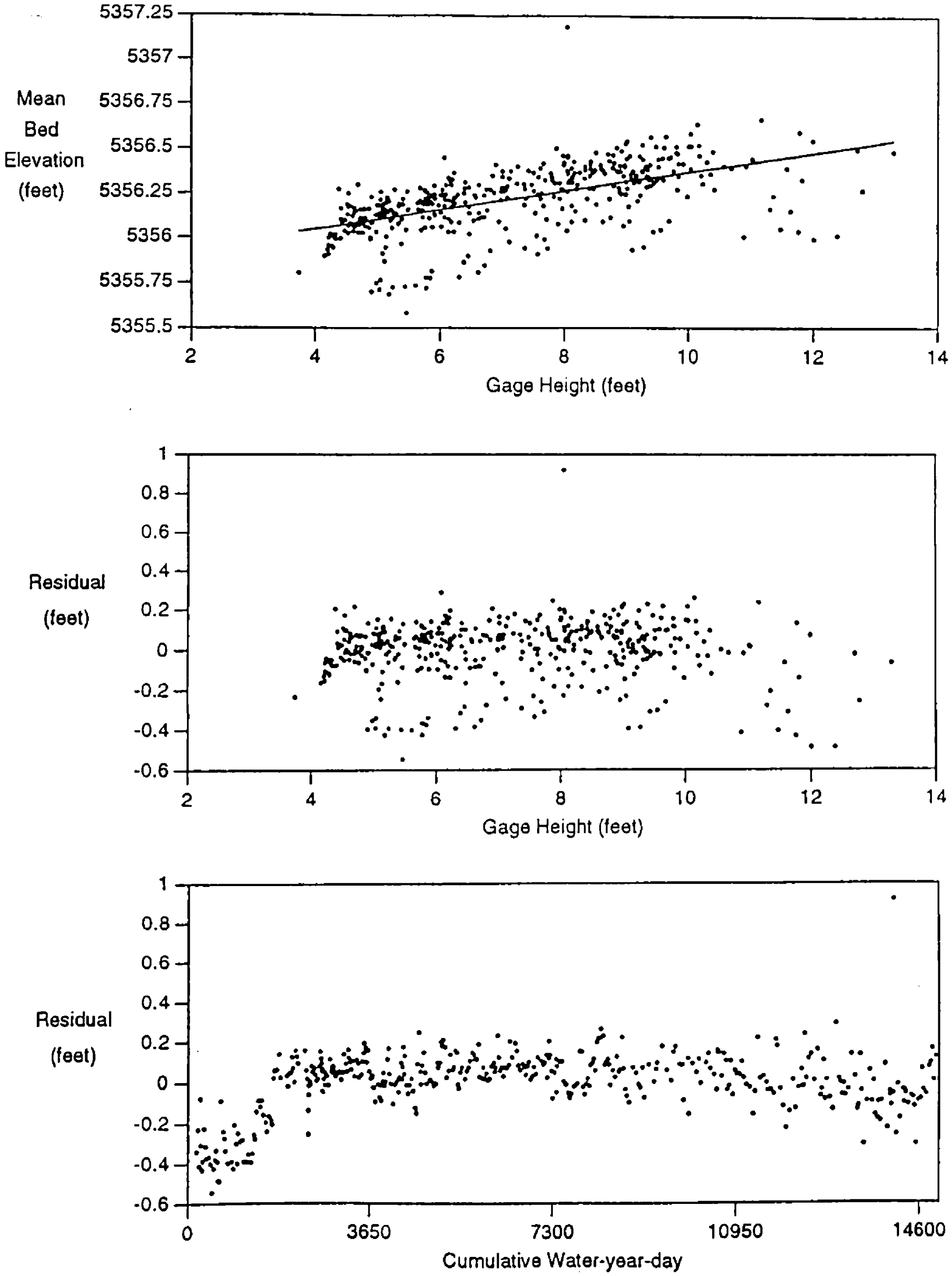


Figure C-7. Regression and residual plots for mean bed elevation on gage height, Irwin gage. The more scatter, the more likely bed movement has occurred.

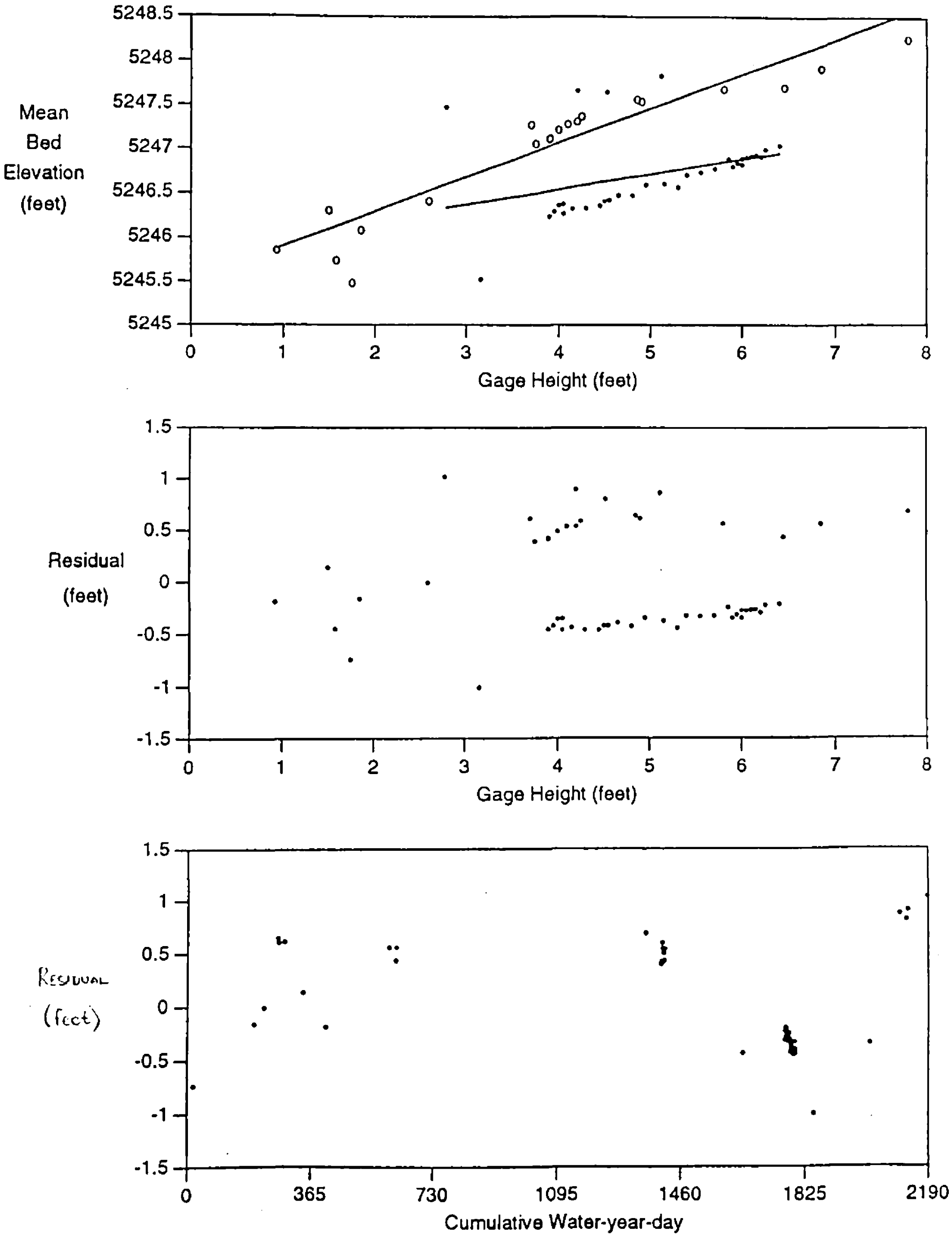


Figure C-8. Regression and residual plots for mean bed elevation on gage height, Lyon gage. The more scatter, the more likely bed movement has occurred.

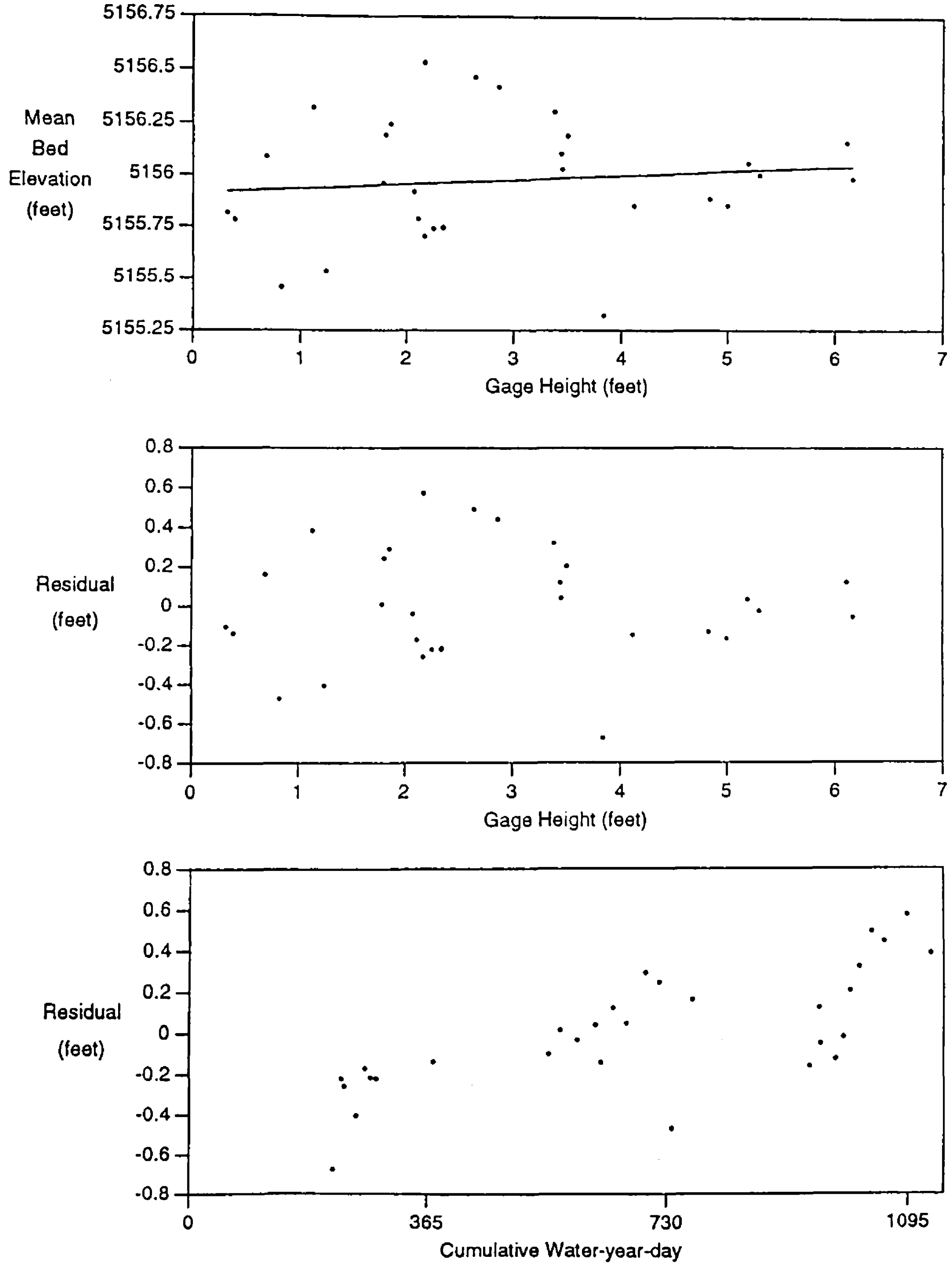


Figure C-9. Regression and residual plots for mean bed elevation on gage height, Dry Canyon gage. The more scatter, the more likely bed movement has occurred.

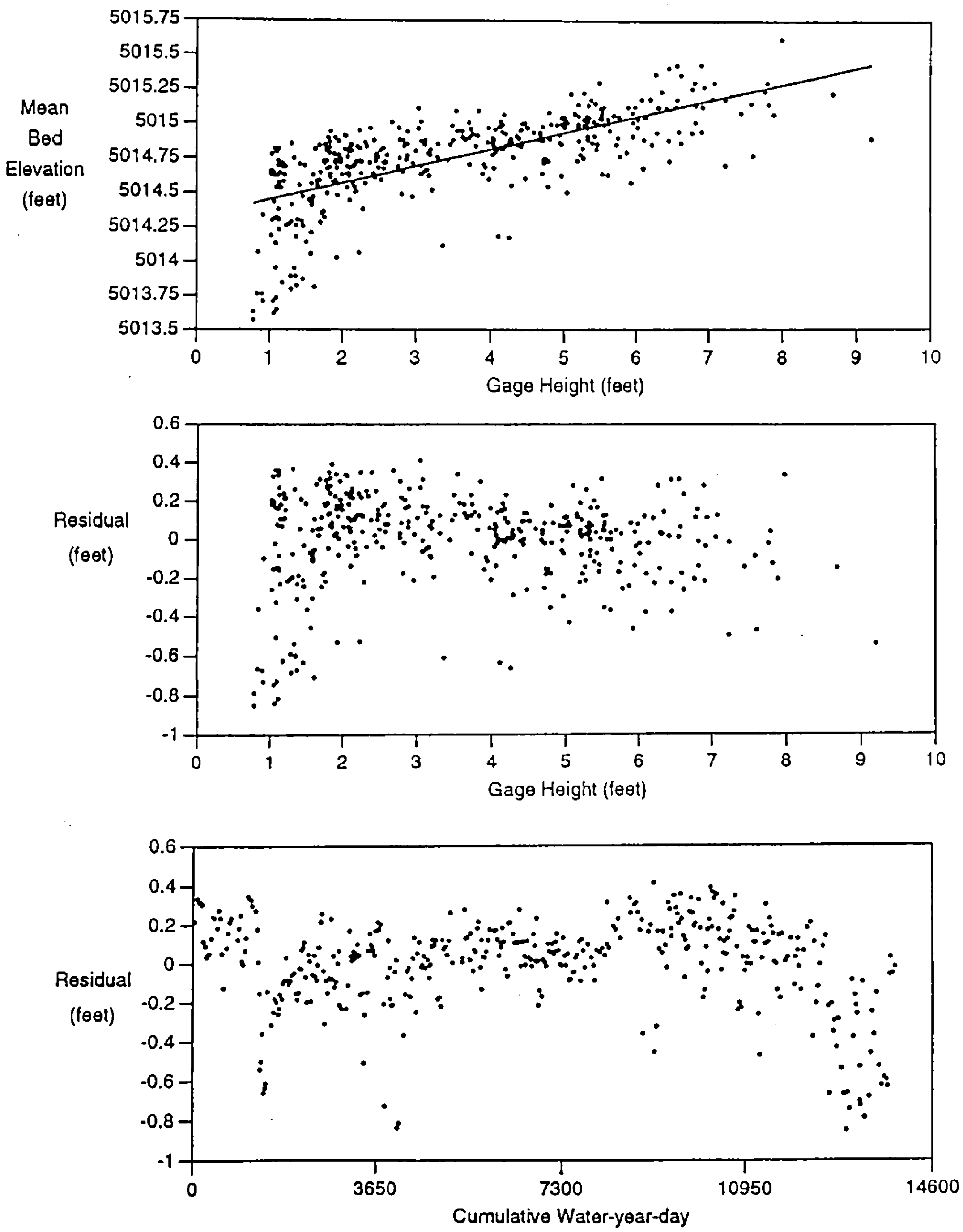


Figure C-10. Regression and residual plots for mean bed elevation on gage height, Heise gage. The more scatter, the more likely bed movement has occurred.

APPENDIX D

SCIENTIFIC AND COMMON NAMES
FOR THE
SOUTH FORK SNAKE RIVER RIPARIAN FLORA

Trees

Abies lasiocarpa	subalpine fir
Juniperus scopulorum	Rocky Mountain juniper
Picea pungens	blue spruce
Pinus contorta var. *latifolia*	lodgepole pine
Populus acuminata	lanceleaf cottonwood
Populus angustifolia	narrowleaf cottonwood
Psuedotsuga menziesii	Douglas-fir
Pyrus malus	apple

Shrubs

Acer glabrum	Rocky Mountain maple
Acer grandidentatum	bigtooth maple
Alnus incana	mountain alder
Amelanchier alnifolia	serviceberry
Artemisia tridentata	big sagebrush
Berberis repens	Oregon grape
Betula occidentalis	water birch
Chrysothamnus viscidiflorus	green rabbitbrush
Clematis ligusticifolia	western virgin's bower
Cornus stolonifera	red-osier dogwood
Crataegus douglasii	hawthorn
Elaeagnus angustifolia	Russian olive
Elaeagnus commutata	silverberry
Lonicera involucrata	bearberry honeysuckle
Pontentilla fruiticosa	shrubby cinquefoil
Prunus virginiana	chokecherry
Ribes lacustre	prickly current
Ribes aureum	golden current
Rhus trilobata	skunkbush
Rosa woodsii var. *ultramontana*	Wood's rose

Appendix D. —continued

Shrubs, continued:

Salix bebbiana	Bebb willow
Salix exigua ssp. *melanopsis*	sandbar willow
Salix geyeriana	Geyer willow
Salix lasiandra	whiplash willow
Salix lutea	yellow willow
Symphoricarpos albus	common snowberry
Symphoricarpos occidentalis	western snowberry

Forbs

Achillea millefolium	common yarrow
Actaea rubra	baneberry
Anemone cylindrica	thimbleweed
Anemone multifida var. *multifida*	cliff anenome
Angelica arguta	sharptooth angelica
Anthemis cotula	stinking mayweed
Arabis holboellii var. *collinsii*	Holboell's rockcress
Antennaria microphylla	rosy pearly-everlasting
Arenaria laterifolia	bluntleaf sandwort
Arnica longifolia	seep-spring arnica
Artemisia dracunculus	tarragon
Artemisia ludoviciana	praire sage
Asclepias speciosa	showy milkweed
Astragalus canadensis	Canada milkvetch
Astragalus tenellus	pulse milkvetch
Campanula rotundifolia	scotch bellflower
Carduus nutans	musk thistle
Castilleja miniata var. *miniata*	scarlet paintbrush
Castilleja pilosa var. *longispica*	white paintbrush (Dorn)
Cirsium arvensis	Canada thistle
Convolvulus arvensis	small bindweed
Corallorhiza wisteriana	Wister coral-root
Chrysopsis (Heterotheca) villosa	golden-aster
Euphorbia esula	leafy spurge
Equisetum laevigatum	smooth scouring rush

Appendix D. — continued

Forbs, continued:

Erigeron glabellus var. *glabellus*	smooth daisy
Erigeron speciosa var. *macranthus*	showy fleabane
Eriogonum heracleoides var. *heracleoides*	Wyeth buckwheat
Fragaria virginiana var. *glauca*	bluelf strawberry
Galium triflorum	sweet-scented beadstraw
Gentiana affinis	pleated gentian
Geranium richardsonii	white geranium
Geum macrophyllum	large-leaved avens
Gilia aggregata var. *aggregata*	scarlet gilia
Glycyrrhiza lepidota	licorice root
Grindelia squarossa var. *serrulata*	gumweed
Habenaria hyperborea	green bog-orchid
Heracleum lanatum	cow parsnip
Hippuris vulgaris	common mare's-tail
Lupinus argenteus	silvery lupine
Lychnis alba	white campion
Lysimachia ciliata	fringed loosestrife
Medicago sativa	alfalfa
Melilotus alba	white sweet-clover
Melilotus officinalis	yellow sweet-clover
Mentha arvensis	field mint
Myosotis scorpioides	common forget-me-not
Penstemon angustifolius var. *caudatus*	long-leaf beardtongue (Dorn)
Potentilla glandulosa	sticky cinquefoil
Potentilla gracilis	slender cinquefoil
Prunella vulgaris var. *lanceolata*	self-heal
Pyrola asarifolia var. *asarifolia*	pink pyrola
Rudbeckia occidentalis	coneflower
Rumex crispa	curly dock
Sedum lanceolatum var. *lanceolatum* ??	lance-leaved stonecrop
Senecio indecorus	mountain butterweed
Senecio hydrophilus	alkali-marsh butterweed
Sium suave	water parsnip
Silene menziesii var. *viscosa*	Menzies' silene
Smilacina stellata	starry solomon-plume

Appendix D. — continued

Forbs, continued:

Solanum dulcamara	bittersweet nightshade
Solidago canadensis	Canada goldenrod
Solidago occidentalis	western goldenrod
Sonchus ugilinosus	marsh sow-thistle
Sisyrinchium angustifolium	blue star
Taraxacum officinale	common dandelion
Thalictrum sp.	meadowrue
Tragopogon dubius	yellow salsify
Trifolium dubium	suckling clover
Typha latifolia	common cattail
Urtica dioica	stinging nettles
Verbascum thaspus	common mullein
Veronica anagallis-aquatica	water speedwell
Vicia americana var. *truncata*	American vetch
Viola canadensis	Canada violet
Xanthium strumarium	cockle-bur

Graminoids

Agropyron cristatum	crested wheatgrass
Agropyron smithii	western wheatgrass
Agropyron spicatum	bluebunch wheatgrass
Agrostis alba var. *stolonifera*	redtop
Bromus anomalus	nodding brome
Bromus inermis	smooth brome
Carex nebraskensis	Nebraska sedge
Carex rostrata	beaked sedge
Dactylis glomerata	orchard grass
Eleocharis palustris	common spike-rush
Elymus canadensis	nodding wildrye
Elymus cinereus	Great Basin wildrye
Elymus virginicus	terrell-grass
Festuca idahoensis	Idaho fescue
Glyceria grandis	American mannagrass
Hierochloe oderata	sweetgrass

Appendix D. — continued

Graminoids, continued:

Hordeum depressum	meadow barley
Hordeum jubatum	foxtail barley
Juncus longistylis	long-styled rush
Muhlenbergia asperifolia	alkali muhly
Oryzopsis hymenoides	Indian ricegrass
Phalaris arundinacea	reed canarygrass
Phleum pratensis	common timothy
Poa nervosa	Wheeler's bluegrass
Poa palustris	fowl bluegrass
Poa pratensis	Kentucky bluegrass
Scirpus americanus	three-square bulrush
Scirpus validus	softstem bulrush
Stipa comata var. *intermedia*	needle-and-thread

"(Dorn)" after common name means the species was keyed in Vascular Plants of Wyoming (Dorn 1988) All other names from Hitchcock and Cronquist (1973)