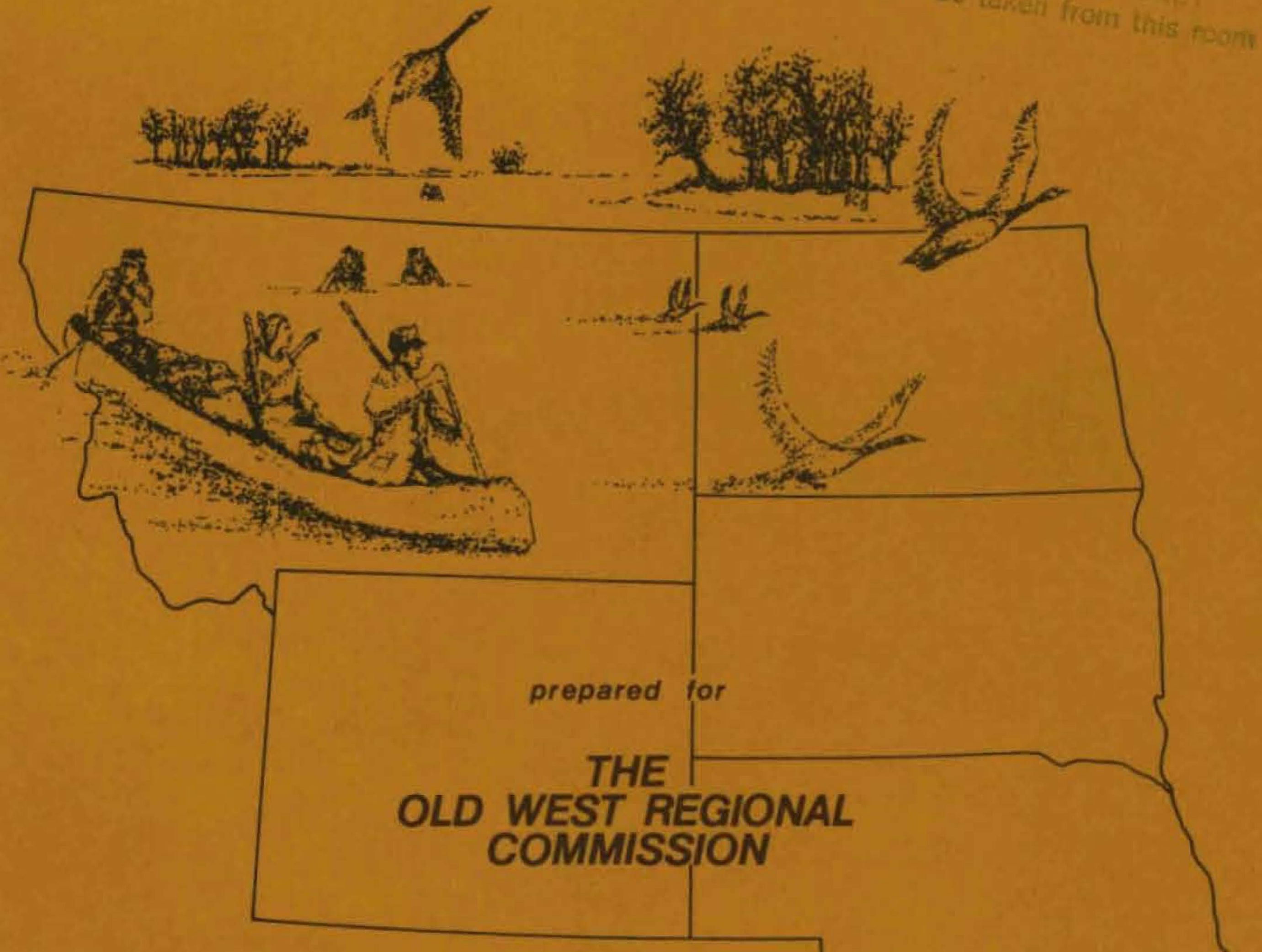
The effect of altered streamflow on the hydrology and geomorphology of the Yellowstone River Basin, Montana

YELLOWSTONE IMPACT STUDY

TECHNICAL REPORT NO. 2



prepared for

THE
OLD WEST REGIONAL
COMMISSION

by

DNRC WATER RESOURCES DIVISION — JULY 1977

MONTANA DEPARTMENT OF NATURAL RESOURCES & CONSERVATION

YELLOWSTONE IMPACT STUDY Hydrology and Geomorphology 2

The effect of altered streamflow on the hydrology and geomorphology of the Yellowstone River Basin, Montana

by
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TECHNICAL REPORT NO. 2

YELLOWSTONE IMPACT STUDY

conducted by the

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The Old West Regional Commission is a Federal-State partnership designed to solve regional economic problems and stimulate orderly economic growth in the states of Montana, Nebraska, North Dakota, South Dakota and Wyoming. Established in 1972 under the Public Works and Economic Development Act of 1965, it is one of seven identical commissions throughout the country engaged in formulating and carrying out coordinated action plans for regional economic development.

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FOREWORD

The Old West Regional Commission wishes to express its appreciation for this report to the Montana Department of Natural Resources and Conservation, and more specifically to those Department staff members who participated directly in the project and in preparation of various reports, to Dr. Kenneth A. Blackburn of the Commission staff who coordinated the project, and to the subcontractors who also participated. The Yellowstone Impact Study was one of the first major projects funded by the Commission that was directed at investigating the potential environmental impacts relating to energy development. The Commission is pleased to have been a part of this important research.

George D. McCarthy
Federal Cochairman

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Abbreviations used in this report

af	acre-feet
af/y	acre-feet per year
b/d	barrels per day
cfs	cubic feet per second
cfs/m^2	cubic feet per second per square mile
cm	centimeters
DNRC	Department of Natural Resources and Conservation
EIS	Environmental Impact Statement
ft	feet
ha	hectares
hm^3	cubic hectometers
hm^3/y	cubic hectometers per year
in	inches
km	kilometers
km^2	square kilometers
m	meters
m^3/sec	cubic meters per second
$m^3/sec/km^2$	cubic meters per second per square kilometer
MEAC	Montana Energy Advisory Council
mi	miles
mm	millimeters
mmaf/y	million acre-feet per year
mmt/y	million tons per year
mw	megawatts
Q	discharge
$Q_{1.5}$	high flow occurring, on the average, every 1.5 years
Q_B	bankfull discharge
RM	river mile
RKM	river kilometer
t/d	tons per day
t/yr	tons per year
$t/mi^2/yr$	tons per square mile per year
USDI	United States Department of Interior
USGS	United States Geological Survey
yr	year

Preface

THE RIVER

The Yellowstone River Basin of southeastern Montana, northern Wyoming, and western North Dakota encompasses approximately 180,000 km^2 (71,000 square miles), 92,200 (35,600) of them in Montana. Montana's portion of the basin comprises 24 percent of the state's land; where the river crosses the border into North Dakota, it carries about 8.8 million acre-feet of water per year, 21 percent of the state's average annual outflow. The mainstem of the Yellowstone rises in northwestern Wyoming and flows generally northeast to its confluence with the Missouri River just east of the Montana-North Dakota border; the river flows through Montana for about 550 of its 680 miles. The major tributaries, the Boulder, Stillwater, Clarks Fork, Bighorn, Tongue, and Powder rivers, all flow in a northerly direction as shown in figure 1. The western part of the basin is part of the middle Rocky Mountains physiographic province; the eastern section is located in the northern Great Plains (Rocky Mountain Association of Geologists 1972).

THE CONFLICT

Historically, agriculture has been Montana's most important industry. In 1975, over 40 percent of the primary employment in Montana was provided by agriculture (Montana Department of Community Affairs 1976). In 1973, a good year for agriculture, the earnings of labor and proprietors involved in agricultural production in the fourteen counties that approximate the Yellowstone Basin were over $141 million, as opposed to $13 million for mining and $55 million for manufacturing. Cash receipts for Montana's agricultural products more than doubled from 1968 to 1973. Since that year, receipts have declined because of unfavorable market conditions; some improvement may be in sight, however. In 1970, over 75 percent of the Yellowstone Basin's land was in agricultural use (State Conservation Needs Committee 1970). Irrigated agriculture is the basin's largest water use, consuming annually about 1.5 million acre-feet (af) of water (Montana DNRC 1977).

There is another industry in the Yellowstone Basin which, though it consumes little water now, may require more in the future, and that is the coal development industry. In 1971, the North Central Power Study (North Central Power Study Coordinating Committee 1971) identified 42 potential power plant sites in the five-state (Montana, North and South Dakota, Wyoming, and Colorado) northern Great Plains region, 21 of them in Montana. These plants, all to be fired by northern Great Plains coal, would generate 200,000 megawatts (mw) of electricity, consume 3.4 million acre-feet per year (mmaf/y) of water, and result in a large population increase. Administrative, economic, legal, and technological considerations have kept most of these conversion facilities, identified in the North Central Power Study as necessary for 1980, on the drawing board or in the courtroom. There is now no chance of their being completed by that date or even soon after, which will delay and diminish the economic benefits some basin residents had expected as a result of coal development. On the other hand, contracts have been signed for the mining of large amounts of Montana coal, and applications have been approved not only for new and expanded coal mines but also for Colstrip Units 3 and 4, twin 700-mw, coal-fired, electric generating plants.

In 1975, over 22 million tons of coal were mined in the state, up from 14 million in 1974, 11 million in 1973, and 1 million in 1969. By 1980, even if no new contracts are entered, Montana's annual coal production will exceed 40 million tons. Coal reserves, estimated at over 50 billion economically strippable tons (Montana Energy Advisory Council 1976), pose no serious constraint to the levels of development projected by this study, which range from 186.7 to 462.8 million tons stripped in the basin annually by the year 2000. Strip mining itself involves little use of water. How important the energy industry becomes as a water user in the basin will depend on: 1) how much of the coal mined in Montana is exported, and by what means, and 2) by what process and to what end product the remainder is converted within the state. If conversion follows the patterns projected in this study, the energy industry will use from 48,350 to 326,740 af of water annually by the year 2000.

A third consumptive use of water, municipal use, is also bound to increase as the basin population increases in response to increased employment opportunities in agriculture and the energy industry.

Can the Yellowstone River satisfy all of these demands for her water? Perhaps in the mainstem. But the tributary basins, especially the Bighorn, Tongue, and Powder, have much smaller flows, and it is in those basins that much of the increased agricultural and industrial water demand is expected.

Some impacts could occur even in the mainstem. What would happen to water quality after massive depletions? How would a change in water quality affect existing and future agricultural,industrial, and municipal users? What would happen to fish, furbearers, and migratory waterfowl that are dependent on a certain level of instream flow? Would the river be as attractive a place for recreation after dewatering?

One of the first manifestations of Montana's growing concern for water in the Yellowstone Basin and elsewhere in the state was the passage of significant legislation. The Water Use Act of 1973, which, among other things, mandates the adjudication of all existing water rights and makes possible the reservation of water for future beneficial use, was followed by the Water Moratorium Act of 1974, which delayed action on major applications for Yellowstone Basin water for three years. The moratorium, by any standard a bold action, was prompted by a steadily increasing rush of applications and filings for water (mostly for industrial use) which, in two tributary basins to the Yellowstone, exceeded supply. The DNRC's intention during the moratorium was to study the basin's water and related land resources, as well as existing and future need for the basin's water, so that

YELLOWSTONE RIVER BASIN

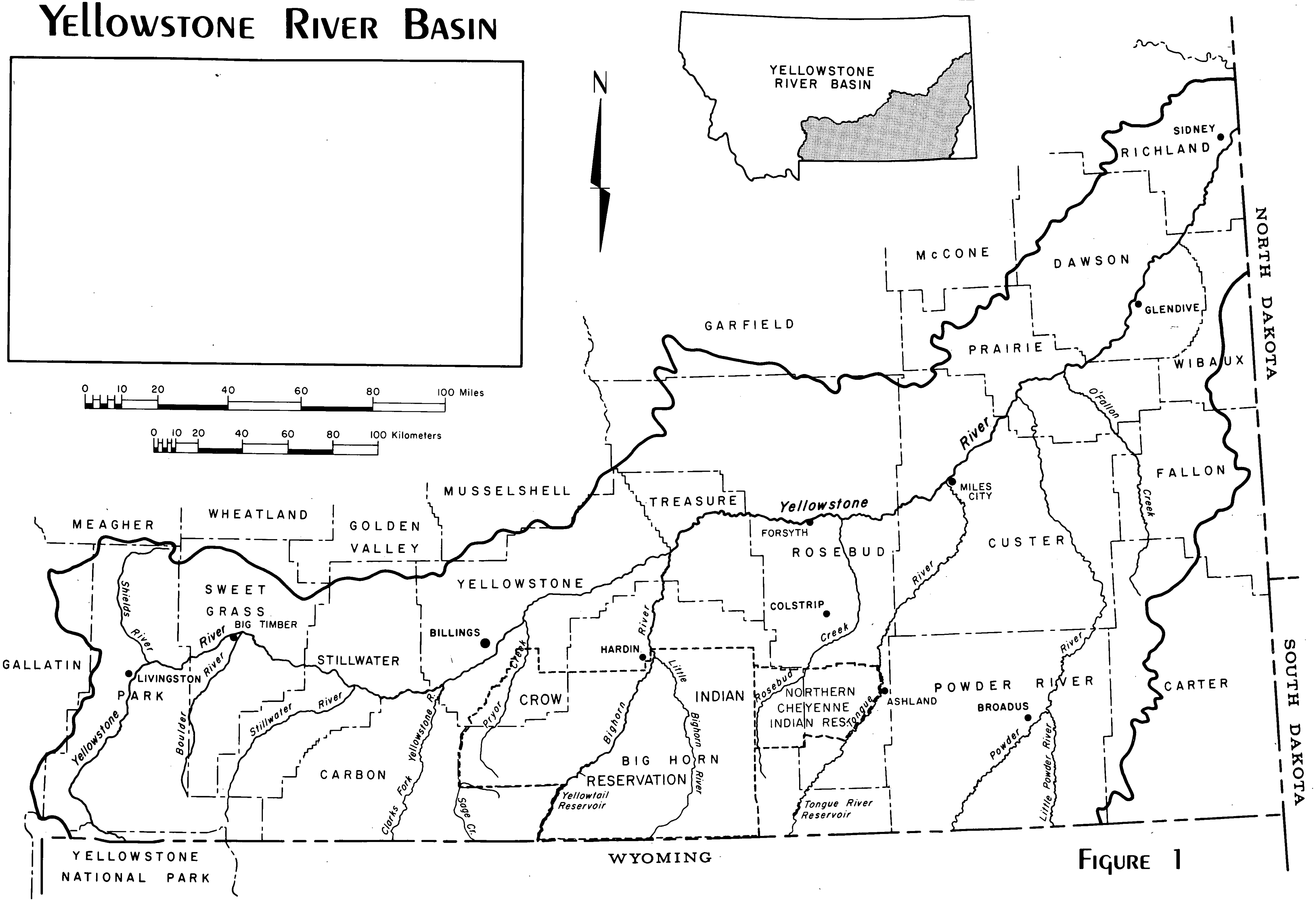


FIGURE 1

the state would be able to proceed wisely with the allocation of that water. The study which resulted in this series of reports was one of the fruits of that intention. Several other Yellowstone water studies were undertaken during the moratorium at the state and federal levels. Early in 1977, the 45th Montana Legislature extended the moratorium to allow more time to consider reservations of water for future use in the basin.

THE STUDY

The Yellowstone Impact Study, conducted by the Water Resources Division of the Montana Department of Natural Resources and Conservation and financed by the Old West Regional Commission, was designed to evaluate the potential physical, biological, and water use impacts of water withdrawals and water development on the middle and lower reaches of the Yellowstone River Basin in Montana. The study's plan of operation was to project three possible levels of future agricultural, industrial, and municipal development in the Yellowstone Basin and the streamflow depletions associated with that development. Impacts on river morphology and water quality were then assessed, and, finally, the impacts of altered streamflow, morphology, and water quality on such factors as migratory birds, furbearers, recreation, and existing water users were analyzed.

The study began in the fall of 1974. By its conclusion in December of 1976, the information generated by the study had already been used for a number of moratorium-related projects--the EIS on reservations of water in the Yellowstone Basin, for example (Montana DNRC 1976). The study resulted in a final report summarizing all aspects of the study and in eleven specialized technical reports:

Report No. 1	Future Development Projections and Hydrologic Modeling in the Yellowstone River Basin, Montana.
Report No. 2	The Effect of Altered Streamflow on the Hydrology and Geomorphology of the Yellowstone River Basin, Montana.
Report No. 3	The Effect of Altered Streamflow on the Water Quality of the Yellowstone River Basin, Montana.
Report No. 4	The Adequacy of Montana's Regulatory Framework for Water Quality Control
Report No. 5	Aquatic Invertebrates of the Yellowstone River Basin, Montana.
Report No. 6	The Effect of Altered Streamflow on Furbearing Mammals of the Yellowstone River Basin, Montana.
Report No. 7	The Effect of Altered Streamflow on Migratory Birds of the Yellowstone River Basin, Montana.

Report No. 8	The Effect of Altered Streamflow on Fish of the Yellowstone and Tongue Rivers, Montana.
Report No. 9	The Effect of Altered Streamflow on Existing Municipal and Agricultural Users of the Yellowstone River Basin, Montana.
Report No. 10	The Effect of Altered Streamflow on Water-Based Recreation in the Yellowstone River Basin, Montana.
Report No. 11	The Economics of Altered Streamflow in the Yellowstone River Basin, Montana.

ACKNOWLEDGMENTS

Parts I and II of this report were written by different authors at different times and for different purposes. They are included under one cover here primarily because of similarity in subject matter. Statements made in either of the parts should be taken as the statements of the author(s) of that part only. There are minor discrepancies in analytical methods between the two parts, and some repetition, which the editor thought it best to let remain. Part I of this report was prepared in 1975, using the most appropriate methods available at that time, so that its conclusions could be used by the authors of the other reports in this series.

This report was reviewed by and guidance received from John C. Orth, Director of the Montana Department of Natural Resources and Conservation; Orrin Ferris, Administrator of the DNRC's Water Resources Division; and Carole Massman, of the DNRC's Special Staff.

Assistance with Part I of this report came from a variety of sources, including the U.S. Geological Survey. The Helena office of that agency provided data for use in the flow duration curves included here. Bill Emmett and Bob Meade, with the USGS in Denver, reviewed and commented on a draft of Part I. Ned Andrews, also with the Denver office, provided field assistance in addition to reviewing the draft report. Connie Bergum, a technician with the Montana DNRC, assisted in data collection and reduction. The "Geologic History and Stratigraphy" section of Part I was compiled by Mark Weber, co-author of Part II of this report, and by Tony Van der Poel. The study of the geologic character of the Bighorn River before and after the closure of Yellowtail Dam (pages 32 to 37) was researched and written by Peter Martin of the Montana Department of Fish and Game as part of his inquiry into the effects of altered streamflow on furbearing mammals in the Yellowstone River Basin; the rest of that study is described in Report No. 6 in this series. His conclusions are his own and not necessarily those of Roy Koch, primary author of Part I.

With regard to Part II of the report, special thanks are due to Thomas Bäteridge, Mike Coughlan, Tony Van der Poel, and Gary Parry, all from the University of Montana Geology Department, for their persistent effort in field mapping and data analysis.

DNRC personnel providing assistance were Peggy Todd and Ronald J. Schleyer, who performed editing tasks, and Janet Cawlfield, Kris MacIntyre, Lynda Howell, typists. Graphics were coordinated and performed by Gary Wolf, with the assistance of Gordon Taylor. The cover was designed and executed by D. C. Howard.

Part 1

Channel form and processes

by

Roy Koch

Introduction

The Yellowstone River provides habitat for both terrestrial and aquatic organisms, including furbearing mammals, migratory birds, raptors, fish, and aquatic insects. Changes in the present flow regime or physical channel alterations would alter the physical environment of the river and directly affect those species inhabiting it. The magnitude and direction of such changes are the subjects of this investigation.

Physical river characteristics to be considered include flow regime, sediment transport, channel pattern, channel slope, bed and bank material, and geologic history. These are complexly interrelated, and even the identification of independent and dependent variables is difficult. As a result, rivers are only now being physically and mathematically modeled, and with difficulty. Since even these models are unlikely to provide the information required for this study, an approach combining what quantitative tools exist with the abundance of qualitative observations and information documenting river processes and changes would seem to be the most helpful. The following report combines information on the geology, hydrology, sediment transport, and other geomorphic characteristics of the Yellowstone and its major tributaries to provide estimates of the impacts of projected water use on the morphology of the stream channels.

The major emphasis of this investigation was limited to the Yellowstone River from Billings, Montana, to the confluence of the Yellowstone with the Missouri River near the Montana-North Dakota border. The major tributaries in this reach, the Bighorn, Tongue, and Powder rivers, were also considered, though not in such detail.

Geologic history and stratigraphy

The lower Yellowstone River Basin is mostly underlain by soft, flat-lying rock of Tertiary age, in particular, the Fort Union Formation. This formation varies in thickness from 125 to 1500 feet (40 to 460 m) and is composed of alternating beds of sandstone, shale, lignite, and red clinker.

As shown in figure 2, there are two major structural features in the study area--the Cedar Creek anticline and the Porcupine Dome. The Cedar Creek Anticline is a northwest-southeast trending feature whose axis runs from Glendive to Baker. The northern tip crosses the Yellowstone mainstem near Glendive. Three lithologies are exposed as a result of the folding: the Hell Creek Sandstone, the Fox Hills Sandstone, and the Pierre Shale--all of Upper Cretaceous age. The Porcupine Dome, located north of Forsyth, has a center composed of Colorado Shale of Middle Cretaceous age. The exposed strata then progresses through the Eagle Sandstone, Clagett Shale, Judith River Sandstone, Bearpaw Shale, and Hell Creek Sandstone--all of the Upper Cretaceous--and the Fort Union of the Tertiary. Only the Hell Creek Sandstone and Bearpaw Shale underlie the Yellowstone River.

Today, the Rocky Mountains are the eroded cores of rock masses that were pushed upward about 70 million years ago, partially buried in their own, water-worn detritus, and then reexposed by the action of water and ice during a period of excavation which has lasted to the present. A series of planar landforms is preserved in the Yellowstone drainage basin, the relics of ancient landscapes which achieved temporary stability during this latest cycle of erosion which began when the ancestral Rockies were partially buried in debris.

Some of the larger mountain ranges in the Yellowstone watershed, the Beartooths, the Crazys, the Bighorns, and the Owl Creeks, are composed of crystalline rocks at the cores and flanked with Paleozoic and Mesozoic rocks which have commonly been tilted and broken by the mountain-building process. The Bighorn, Tongue, and Powder river basins, constituting a significant part of the lowlands of the Yellowstone drainage, are surfaced by relatively soft sands, shales, and coal beds deposited when the whole region lay close to sea level in late Cretaceous and early Tertiary time, some 60 to 70 million years ago. Many of these rock units contain volcanic detritus of the then-newborn mountains surrounding them and to their west.

Fossil evidence suggests that the early Tertiary relief of the region was low compared with that of the present. A change in the character of the sediments in the Great Plains suggests that later, about 40 million years ago, in Eocene or Oligocene time, an increasingly arid climate developed, interpreted by Mackin (1937) as resulting from a broad, regional uplift of the Rocky Mountains that established strong eastward gradients for mountain streams and caused widespread aggradation. Alden (1932) contends that, during an Oligocene-Miocene interval, a gravelly surface known as the Cypress Plain existed in southern Canada, northern Montana, and possibly the Yellowstone Basin. Still later, during the Pliocene period (11 to 3 million years ago), gravels spread outward from the mountainous regions to form nearly planar landforms that may have resembled the modern landscapes in the arid valleys of the Southwest. It is the eroded remnants of these arid Tertiary landscapes that now form the highest benches in the Yellowstone Basin, along the mountain fronts and the river.

These Pliocene gravels probably represent the last stage of prolonged, regional aggradation before the onset of the fluctuating climate of the Pleistocene that allowed temperate periods to alternate with periods of glacial advance in both the northern mountains and the plains (Richmond 1965, Lemke et al. 1965). During the last three million years, the dominant geomorphic activity has been basin excavation, that removed thousands of feet of sediment and, in the process, lowered the Bighorn River onto the Bighorn and Owl Creek mountains so that its present course cuts directly through the crystalline rocks. At intervals, the valleys of mountain streams were aggraded with outwash from alpine glaciers, only to be reincised when stream loads were reduced in relation to discharge following deglaciation. The remnants of this process may be seen as a series of terraces in the valleys of most of the streams that experienced glaciation in their headwaters (Thom et al. 1935, Alden 1932, Mackin 1937, Ritter 1967, and Moss and Bonini 1961). Not all the stream terraces in any valley are paired. In many instances, the higher landforms on the plains bordering the mountain fronts are capped by the gravels of streams that now flow several miles from their earlier courses. This topographic inversion is felt to be the result of (1) the greater erodability of the soft tertiary bedrock than of the permeable stream gravels of their former beds, and (2) the process of stream capture, which suddenly filled low-gradient streams of the plains with the sediment loads of higher-gradient mountain watercourses (Mackin 1937, Ritter 1967).

Although several authors have written on the geomorphic history of physiographic subdivisions of the Yellowstone Basin, to date no one has produced a comprehensive treatment. W. C. Alden, who is included in the bibliographies of almost every writer concerned with the geomorphology of eastern Montana, made the first attempt to correlate and date the major features of the area on a broad scale. Though requiring some major revisions on the strength of more recent investigations, his original heirarchy of the geomorphic surfaces still serves as a standard for comparison.

Many of Alden's concepts of geomorphology accomodated those of W. M. Davis, whose theoretical stages of landscape evolution postulated peneplains as the representation of old age. At the time that Alden wrote, Eliot Blackwelder (1915) and Arthur Bevan (1925) had published papers that described two planar erosion surfaces in the heights of the Wind River and Absaroka ranges at approximately 9,000 to 12,000 foot elevation. Correlating these with other high-level surfaces in the Rocky Mountains, they named these the summit and subsummit peneplains. Drawing on the work of Willis (1902) and Collier and Thom (1918), Alden used the name Cypress Plain for a prominent erosion surface preserved in northcentral Montana, southern Alberta, and Saskatchewan. This surface is capped with gravels dated Oligocene by the presence of fossils that include crocodiles, horses, rhinoceroses, and titanotheres. Although lacking any local fossil material for dating, Alden tentatively correlated several anomalously high stream gravel deposits in the Yellowstone Basin to this landform. One area where these inferredly Cypress-age gravels are preserved in on the top of Pine Ridge, between the Bighorn and Yellowstone rivers east of Billings, where the Upper-Cretaceous Lance Sandstone forms

Yellowstone River Basin

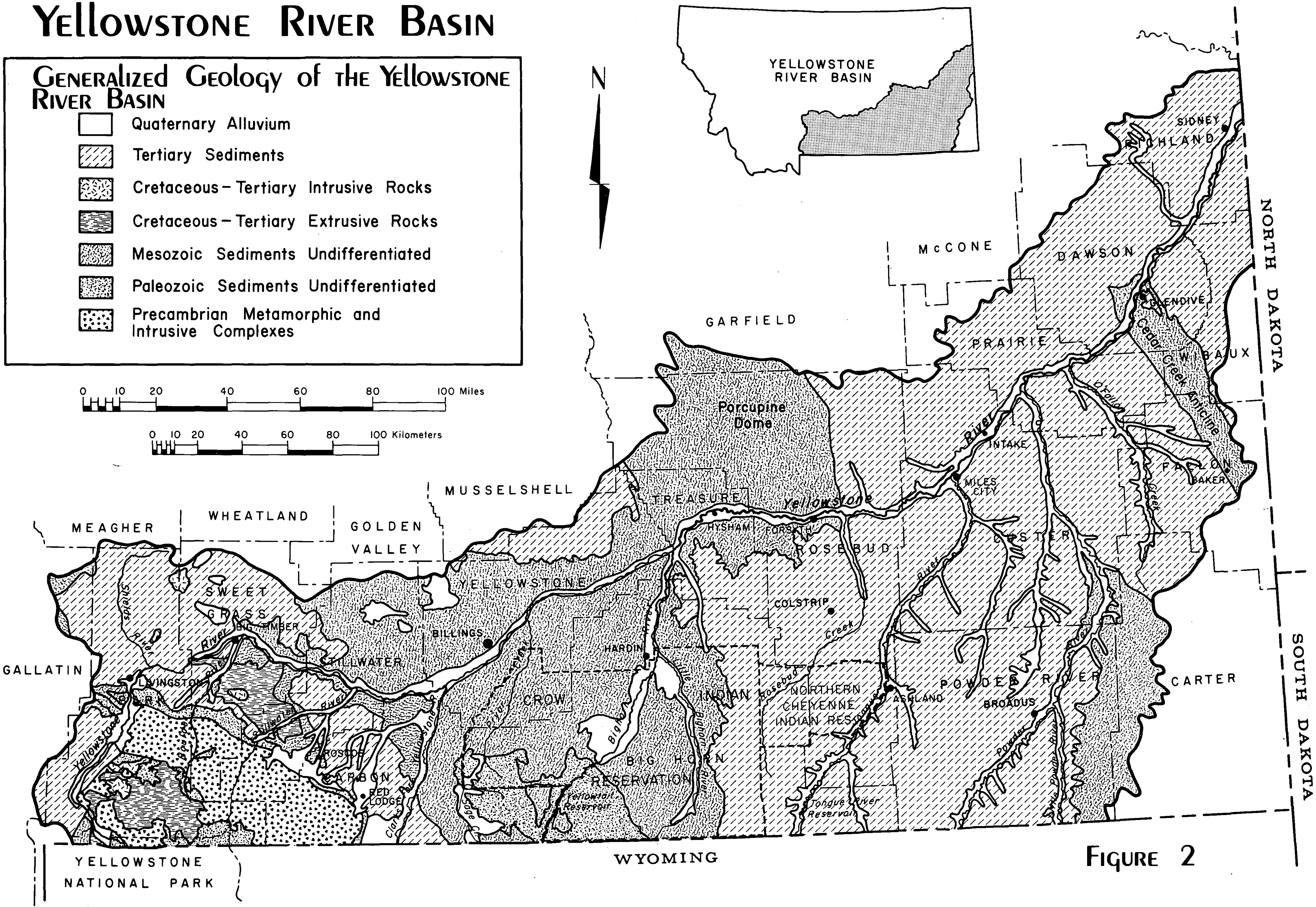


Figure 2

steep escarpments 1,100 feet above the rivers. Alden attempted to correlate the gravels on Pine Ridge with the supposed subsummit peneplain in the Beartooths on the basis of reconstructed stream gradients, but this hypothesis requires either excessively high gradients in the upper reaches or subsequent differential uplift of the mountains and basins, the validity of which has not been established. Alden did establish, however, that the Pine Ridge gravels are reasonably old and that they were deposited by high-energy streams since the deposits include cobbles up to 8 inches in diameter.

On the basis of physiographic position, Alden considered the Tatman Mountain gravels in the Bighorn Basin in Wyoming to be of similar age. Also in the Bighorn Basin, Northern Wyoming's Polecat Bench was correlated with the Cypress Plain surface north of the Pryor Mountains on the basis of a reconstructed drainage profile. Thom et al. (1935), in collaboration with Alden, speculated that the eastward-sloping, truncated surface of the Rosebud and Wolf mountains may have been formed as a part of this surface though not serving as a site of deposition.

Following the development of the Cypress Plain, Alden inferred that differential uplift initiated a cycle of erosion which resulted in 700 to 1,500 feet (200 to 450 m) of dissection of the land surface on the plains and 2,000 to 3,000 feet (600 to 900 m) of dissection in the mountains. Below the level of the Cypress Plain, gravel-capped surfaces or benches were interpreted to represent successive cycles of aggradation that interrupted the regional pattern of degradation. The uppermost and oldest of these gravel benches was correlated with the Flaxville gravel in northeast Montana named by Collier and Thom (1918). Alden designated this relic surface the No. 1 Bench. The deposits of this bench have been found to contain fossils of Miocene and Pliocene fauna including three-toed horses, horned gophers, rabbits, rhinoceroses, oreodonts, camels, and saber-toothed tigers. In addition, Collier and Thom found what may be the tooth of a Pleistocene camel, leaving the deposit's age assignment open to interpretation. Below the No. 1 Bench, Alden recognized the No. 2 and No. 3 benches of supposed early and late Pleistocene age, separated from one another by a vertical interval of from 100 to 200 feet (30 to 60 m). These landforms, while truncating consolidated rocks of both the Mesozoic and Tertiary, are not strictly erosional feastures since all are capped with veneers of gravel of varying degrees of consolidation which locally reach a thickness greater than 100 feet (30 m). Alden's chronology for the erosion surfaces in the northern Great Plains is summarized in table 1.

TABLE 1. Assumed chronology of erosion surfaces in the northern Great Plains.

Cypress Plain	--- Oligocene-Miocene (?)
Flaxville Plain or No. 1 Bench	--- Pliocene (? possibly Pleistocene)
No. 2 Bench	--- Early Pleistocene (probably pre-Kansan or Kansan)
No. 3 Bench	--- Late Pleistocene (Possibly Illinoian)

SOURCE: Modified from Alden (1932)
NOTE: Modifying information derived from subsequent work in parentheses

The No. 1 Bench of Alden is well represented in the Yellowstone drainage; prominent examples are found bordering Rock Creek on the southwest flank of the Crazy Mountains, adjacent to the Boulder River near Big Timber, along the Beartooth Mountain front near Red Lodge and Roscoe, along the northeast flanks of the Pryor and Bighorn Mountains (particularly along the Bighorn River) and on several interfluvial ridges south of the Yellowstone River near Hysham and Forsyth. Further east, remnants of the No. 1 Bench cap an extensive area north of Glendive and south of the furthest extent of the Keewatin glacial drift which mantles the same surface north of the Missouri River.

The No. 2 and No. 3 benches are represented along most of the glaciated mountain streams as two sets of terraces, not always differentiable, though usually separated by 100 to 200 feet (30 to 60 m) of elevation. These distinct, important landforms are often several miles wide along the Yellowstone mainstem and constitute some of the most productive agricultural land in the area. Alden, as well as many other investigators, noted the relationships of many of these terraces to moraines in the mountain canyons. Although the evidence for Pre-Wisconsin advances of the mountain glaciers in this area had not been conclusively demonstrated at the time, Alden concluded that the second set of terraces along the Yelowstone River was capped with gravels deposited when the Kansan advance of Keewatin ice obstructed the drainage. In addition, he speculated that it was this glacial advance which diverted the Yellowstone and Missouri southward from their former drainage into Hudson Bay. The third set of terraces was thereby inferred to be correlative with the Illinoian advance, leaving the modern valley bottom fill as a product of the Wisconsin.

Rejecting the concept of peneplanation, Mackin (1937) suggested that pedimentation and its requisite lateral corrasion were the formative process for features such as the higher level gravel deposits of the Bighorn Basin. Mackin also inferred that cryoplanation or altiplanation were significant forces in the evolution of the highest erosion surfaces in the mountains and concluded that the summit surface was more likely of Pleistocene origin than mid-Tertiary. Mackin stressed the importance of graded streams and of stream capture in the evolution of many of the region's watersheds as well as the role that variations in climate and discharge have had upon the downcutting capacity of the streams.

More recently, work on the Cody and Powell terraces of the Shoshone River by Moss and Bonini (1961) has shown that not all of Mackin's interpretations of the formative processes of stream terraces were correct. Using geophysical methods, they showed that the bedrock beneath the terraces was not thoroughly planed by the lateral cutting action of the stream before gravel was laid on top, as the most simplistic interpretation of Mackin's explanation might lead one to believe. The Cody and Powell terraces must therefore be considered alluvial terraces rather than rock-cut terraces. A significant part of the value of their work appears to lie in illustrating the value of geophysical techniques, particularly seismic refraction, in geomorphic studies.

Ritter (1967) described the distribution and composition of terraces of several streams near and including Rock Creek. Using analytical techniques and a rationale similar to that of Mackin, he demonstrated the importance stream capture and preferential erosion of the soft bedrock in the evolution of the mountain-front landscape. Ritter also concluded that the mountain-front streams now drain in a more northerly course than they did during the deposition of the highest benches, equivalent to Alden's No. 1 Bench.

In his discussion of the age of the landforms in the Bighorn Basin, Mackin (1937) took issue with the techniques used by Alden (1932) in correlating the age of landforms on the basis of physiographic position, particularly their heights above watercourses. In reference to the gravels on Tatman Mountain, the highest planar surface in the basin proper, he disagreed with Alden's correlation with the Cypress Plain because the plain's lower elevation required it to be younger than the Tatman Mountain subsummit erosion surface considered Pliocene by Bevan (1925) and Blackwelder (1915). He further criticized the age assignment of Oligocene for the surface of the Cypress Plain, noting that Oligocene gravels might well have been beveled at a later date. More recently, Rohrer and Leopold (1963) demonstrated that the uppermost of the Tatman Mountain gravels contain a Pleistocene or upper Pliocene palynological suite.

Only the northeastern reaches of the Yellowstone River in Montana were directly affected by continental ice during the Pleistocene, when at least one lobe extended southward to the location of the town of Intake. Alden (1932) and Howard (1960) describe the flooding of the Yellowstone Valley by glacial Lake Glendive to a distance of at least 15 miles south of the modern town of Glendive during an early Wisconsin advance.

Geomorphology of the Yellowstone River channel and tributaries

The present-day alluvial channel of the Yellowstone River is the result of the river's history and of man's impact on the river and watershed. A profile of the lower Yellowstone River from Billings to Sidney is shown in figure 3. No abrupt changes in slope can be noted, indicating that there is no overloading of the mainstem by sediment of the tributaries. There is, however, some outcropping of bedrock in the channel bed and banks at several points in the reach from Miles City to Fallon. This reach of the river, apparently stable with the slope imposed by bedrock, is incised into the lacustrine deposits of the ancestral Glacial Lake Glendive. This reach may dictate the slope of the river above and below.

CHANNEL FORM

YELLOWSTONE MAINSTEM

The general character of the Yellowstone is the same today as it was when Captain William Clark traveled the river in the summer of 1806; that is, those reaches of the river that were braided with wooded islands still show that character, and those reaches where there were no islands and only a few gravel bars still show that character. The form of the Yellowstone River varies throughout its length, seemingly in relation to the river valley. The valley is variable in width, ranging from less than a mile where rock terraces confine the valley, such as near Billings and Forsyth, to nearly four miles where the alluvial valleys of several smaller drainages intersect the mainstem, such as the Mission Valley below Hysham. In general, when the river flows along a valley wall, it will continue to follow the wall until the valley changes direction. The river then continues along the previous course until it meets the opposite valley wall, and the circumstances are repeated. It is along the reaches where the river is not directed by a valley wall that it is free to develop and change its form.

In order to characterize the river, five reaches (figure 4) which represent five forms seen along the river have been selected:

1. Huntley to Pompey's Pillar, 19.9 mi (32.0 km)
2. Mouth of Bighorn to mouth of Froze-to-Death Creek, 24.9 mi (40.1 km)
3. Near Hathaway to above Miles City, 19.2 mi (30.9 km)
4. Buffalo Rapids to below Terry, 18.4 mi (29.6 km)
5. Intake to Savage, 17.0 mi (27.4 km)

In order to adequately describe these reaches, the description of such factors as channel length, channel slope, bed material, sinuosity, the ratio of the channel length to down-valley distance, type of lateral activity, and bankfull discharge (assumed to be the discharge with channel-forming properties) is required.

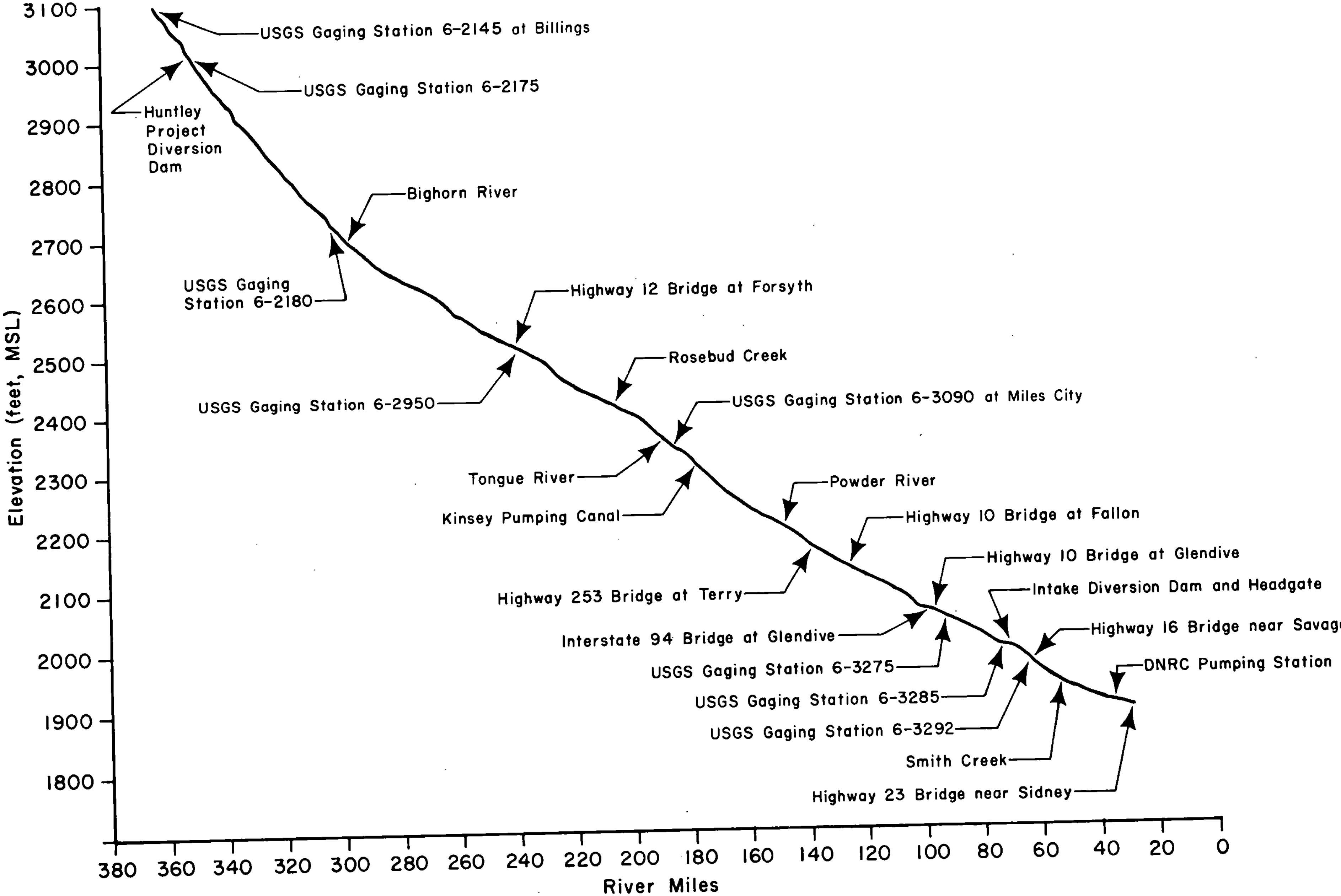


Figure 3. Profile of the Yellowstone River Mainstem between Billings and Sidney.

Yellowstone River Basin

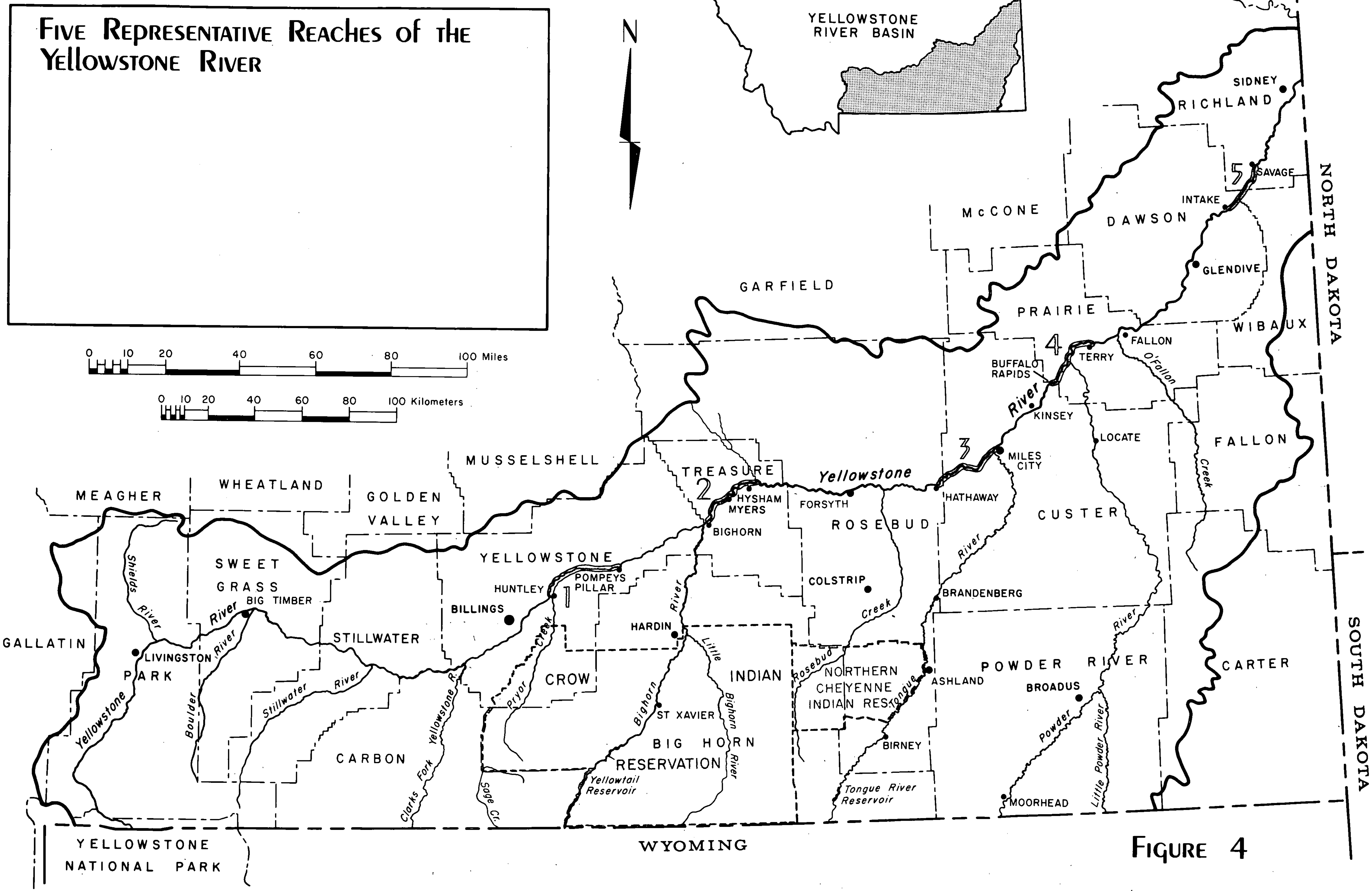


Figure 4

A few of the terms to be employed in the following discussion should be explained. A classification of river form and process presented by Kellerhals et al. (1975) involves the identification of the following:

1) flood plain, alluvial terraces, and the valley floor
2) relation between the river channel and its valley, and
3) the channel description

The last two of these characteristics are the most important for the present analysis.

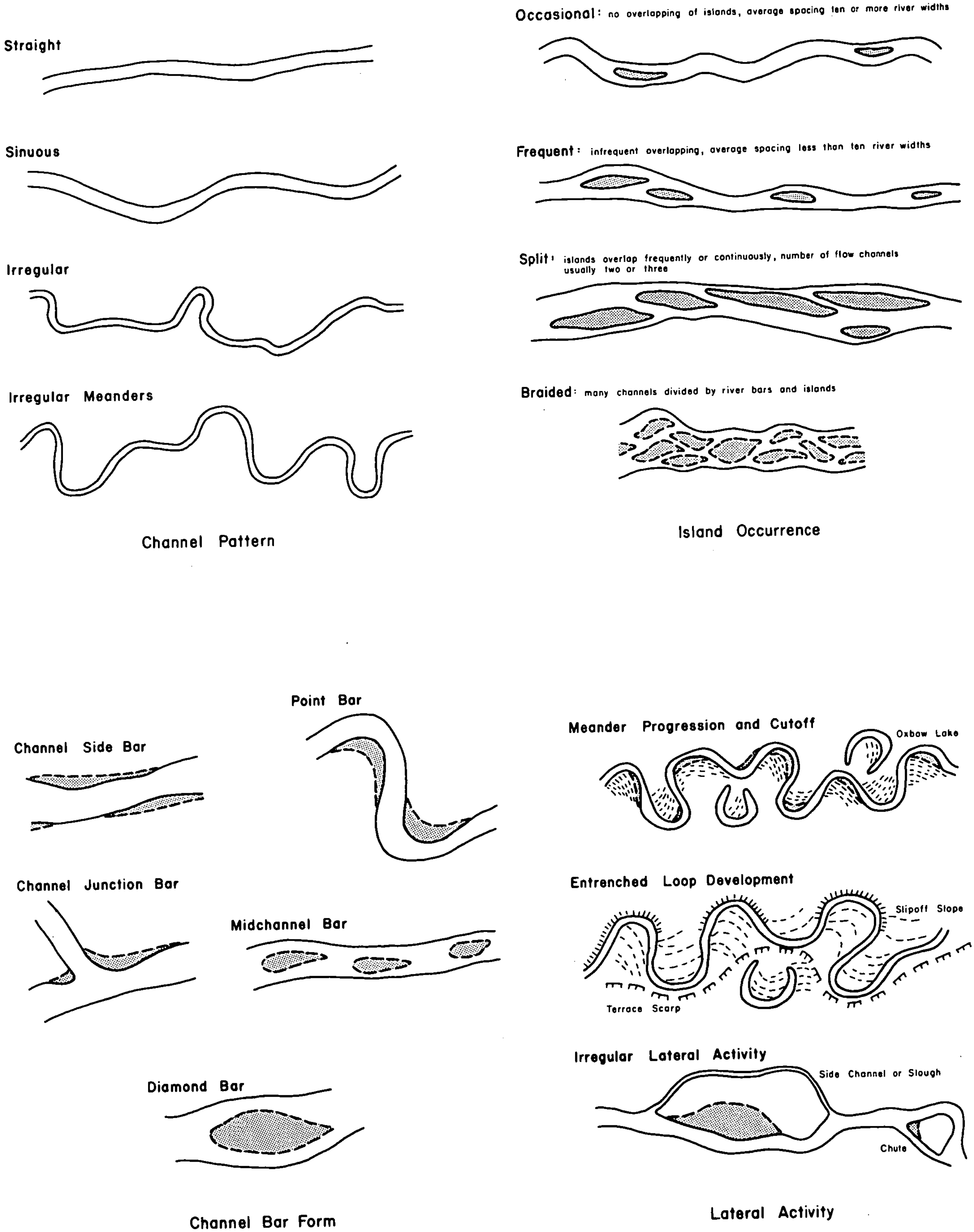
The relation of the river to its valley implies an analysis of the relation of the channel to the valley floor and to the valley walls, i.e., Is the river aggrading or degrading? Are the walls influencing channel pattern by confining the river?

The description of the channel is most important in this study and involves the classification of channel pattern, islands, channel bars, and lateral channel activity. Each of these characteristics, illustrated in figure 5, can help to identify the forces presently at work in the river. Three channel patterns occur in the Yellowstone: sinuous, irregular, and irregular meanders; the river tends more toward a braided than a meandering stream. Islands, stable features at the same elevation as the valley floor, are important to the river ecosystem. Channel bars can be either stable or ephemeral features depending on bed material. In the Yellowstone, the midchannel bars typical of large, gravel-bed channels are prevalent, as are alternating or lateral bars occurring at the bends in the sinuous reaches of the river. These bars can remain in position for many years with transport of bedload occurring over the bar (Kellerhals et al. 1975). Finally, lateral channel activity can indicate the stability and character of the river. Irregular activity, in which the main channel occasionally changes course, is common in active gravel-bed streams such as the Yellowstone.

A summary of the major geomorphic characteristics of the five study reaches in the lower Yellowstone and of its three major tributaries is presented in table 2. A short description of each reach follows.

Reach 1

The section of the river from Huntley (river mile 349, river kilometer 561) to Pompey's Pillar (river mile 329, river kilometer 529) appears to be characteristic of the middle Yellowstone River (figure 6). In this reach, the river follows the north valley wall for most of the distance, deviating only for four miles directly below Huntley. The channel pattern is sinuous where controlled by the valley wall and irregular where uncontrolled. Sinuousity averages 1.14 through the reach. Islands occur frequently. Several types of channel bars occur, indicating active bed material transport. Junction bars, some small, occur at the confluence of each small creek, formed by the deposition of the creeks' sediment load. Side bars, the counterpart of point bars in a meandering channel, also occur. Midchannel bars occur infrequently, and a few diamond bars, large midchannel bars, are apparent. That lateral activity in the reach is classified as irregular due to the prevalence of chutes, side



SOURCE: Adopted from Kellerhals et al. 1976.

Figure 5. Characteristic forms of the Yellowstone River Channel.

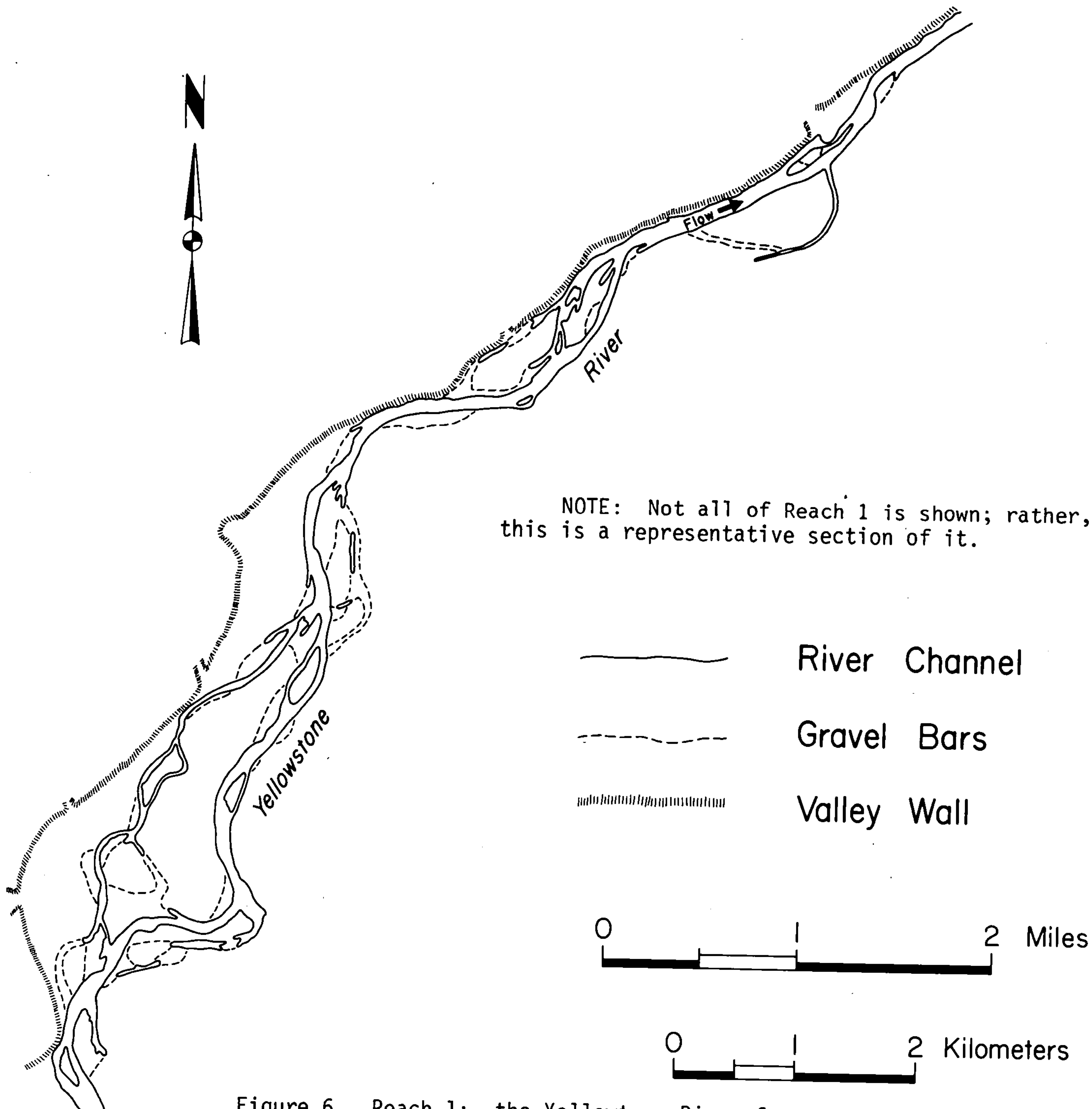


Figure 6. Reach 1: the Yellowtone River from Huntley to Pompey's Pillar.

TABLE 2. Geomorphic characteristics of the middle and lower Yellowstone River Basin and major tributaries.

River Reach	Reach Length	Average Slope	Average Sinuosity	Bed Material d_{50} (mm)	Bankfull Discharge[a] (cfs)
1	19.9	0.0014	1.14	21	34,500
2	24.9	0.00058	1.36	38	45,000[b]
3	19.2	0.00067	1.24	19	47,000
4	18.4	0.00058	1.27	18.5	51,000[b]
5	17.0	0.00046	1.17	22	52,000[b]
Bighorn River at Bighorn		0.0013	NA[c]	NA[c]	12,700
Tongue River at Miles City[d]		0.0019	1.7	1.9	3,080
Powder River near Locate[d]		0.0011	1.2	3.6	6,800

CONVERSIONS: 1 mm = .0394 in
1 cfs = .0283 m^3/sec

[a]Estimated as the 1.5-year flood

[b]Estimated based on drainage area

[c]Not available

[d]Schumm (1969)

channels, and backwater areas is typical of active gravel-bed rivers and indicates shifts in the position of the main channel (Kellerhals et al. 1975).

Reach 2

This reach extends from the confluence of the Bighorn and Yellowstone rivers (river mile 296, river kilometer 476) downstream to the confluence of Froze-to-Death Creek and the Yellowstone (river mile 270, river kilometer 434) (figure 7). The valley line in this reach is irregular, changing in direction from east to north and back to east and in width from 1.2 mi (1.9 km) to 4 mi (6.4 km). The channel pattern varies from sinuous to irregular meandering where the channel is mobile, but no real pattern is evident. The average sinuosity of this reach is 1.36. Islands are frequent, overlapping head and tail ends in some instances. Point, midchannel, and diamond bars occur, indicating an active channel bed. The irregularity of lateral channel activity where the channel is not controlled by the valley walls would also indicate an active channel bed.

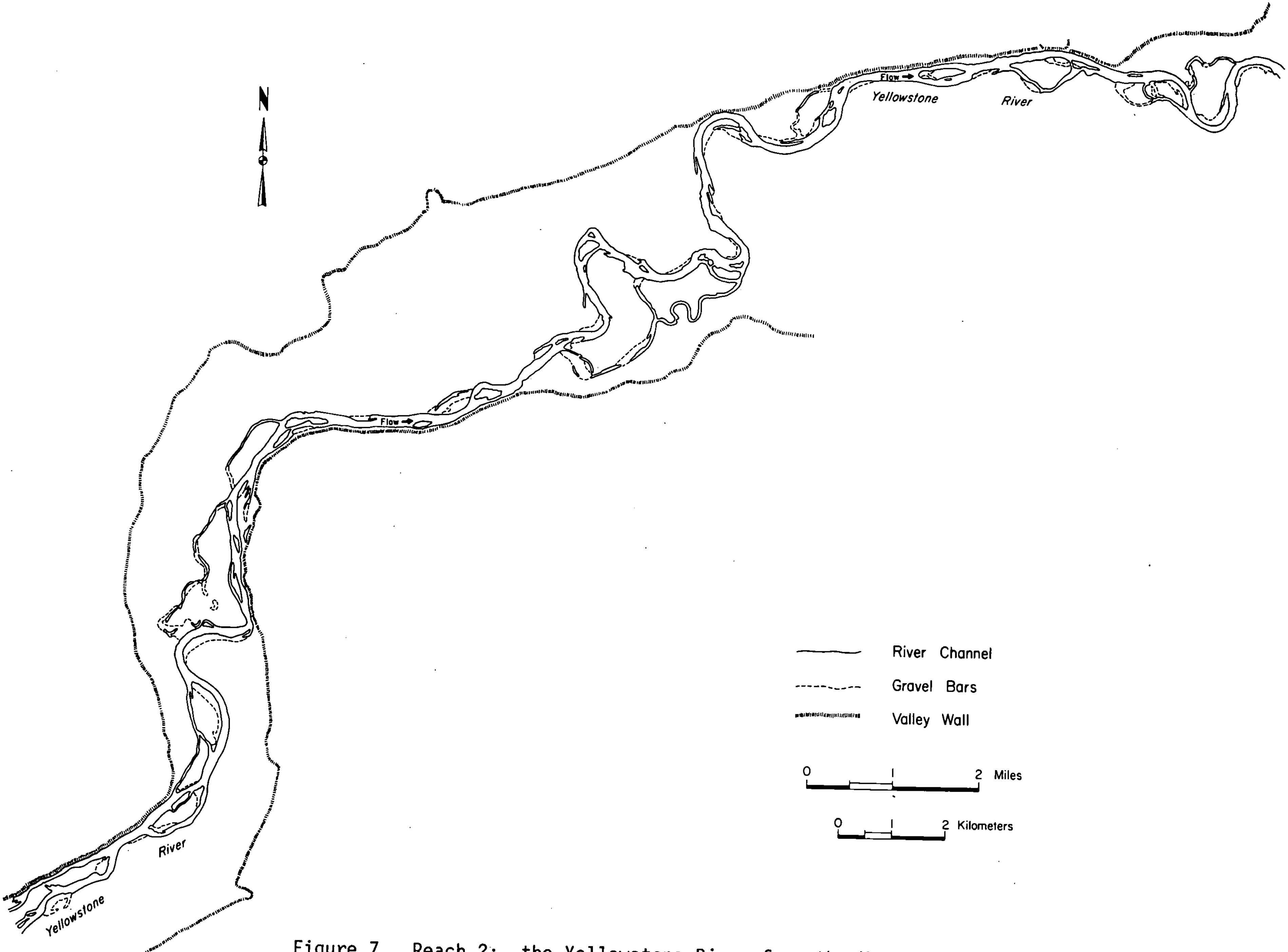


Figure 7. Reach 2: the Yellowstone River from the Mouth of the Bighorn River to the Mouth of Froze-to-Death Creek.

Reach 3

Along this reach, from near Hathaway (river mile 187.6, river kilometer 301.8) to above Miles City (river mile 168.4, river kilometer 271.0) the river exhibits a character much different from that seen along the rest of the river (figure 8). In this reach, the valley is relatively narrow and irregular in direction, exhibiting a slightly meandering character. The river itself is more regularly meandering in sections of this reach than throughout the rest of the river; where the valley wall is controlling the direction, the channel pattern is sinuous to straight. The sinuosity averages 1.24. Islands are less frequent, with lateral bars occurring along the sinuous section and point bars in the meandering sections. Midchannel bars are present but mostly in the straight-to-sinuous section of the reach. Lateral channel activity is much more regular in the meandering parts of this reach, exhibiting some meander progression, enlarging, and cutoffs. There is some irregular lateral channel activity in the sinuous section of the reach.

Reach 4

This reach (figure 9), which extends from Buffalo Rapids (river mile 150.5, river kilometer 242.2) to below Terry (river mile 132.3, river kilometer 212.9), is representative of the river from below Miles City to below Fallon. In this reach, the river is incised into the flood plain, probably lacustrine deposits of Glacial Lake Glendive as discussed on page 17 . In addition to the incised nature of the channel, bedrock outcroppings are prevalent in both the sides and bottom of the channel, as exemplified by Buffalo Rapids and Wolf Rapids, both named by Captain Clark during his journey through the reach. It seems likely that the slope in this reach is determined by the obvious bedrock constraint. The channel pattern varies from sinuous to meandering. There are few islands. Midchannel bars exist, as do alternating and point bars. Probably due to the influence of the bedrock, there is no apparent lateral channel activity, nor is there any indication of past activity through flood plain scars or abandoned channels.

Reach 5

This reach, from Intake Diversion Dam (river mile 71.1, river kilometer 114.4) to Savage (river mile 54.1, river kilometer 87.0) is representative of the lower section of the river from below Glendive to the mouth (figure 10). For most of the length of this reach, the river is on the east side of the valley; it is in contact with the valley wall in several locations. The channel pattern varies from sinuous to irregular, depending on proximity to the valley wall. There are many islands, overlapping frequently along their entire length. Midchannel and diamond bars occur frequently. Lateral channel activity is irregular, indicating instability of the main channel, a classic characteristic in active gravel-bed channels, evidenced here by the presence of numerous chutes and backwater areas.

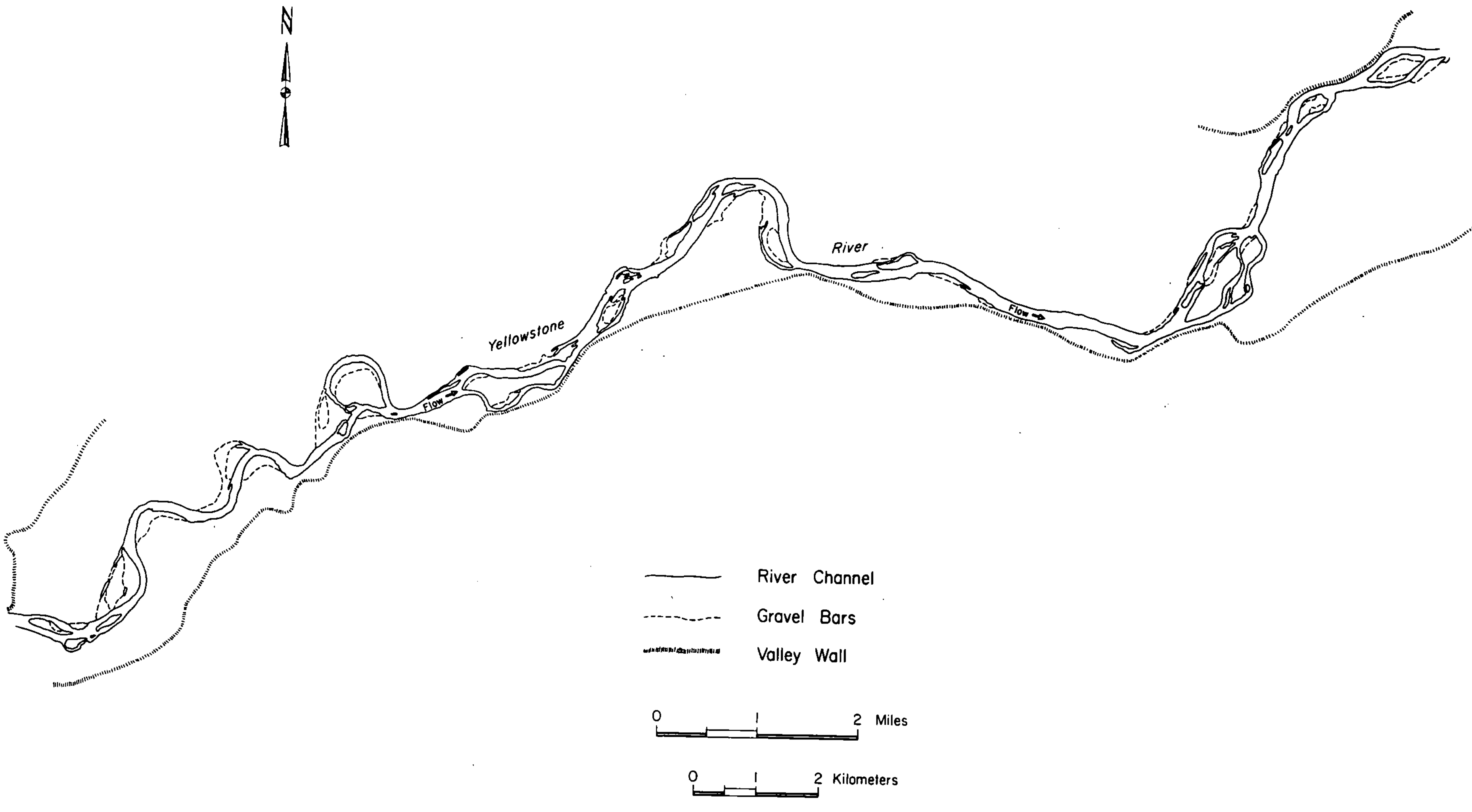


Figure 8. Reach 3: the Yellowstone River from near Hathaway to above Miles City.

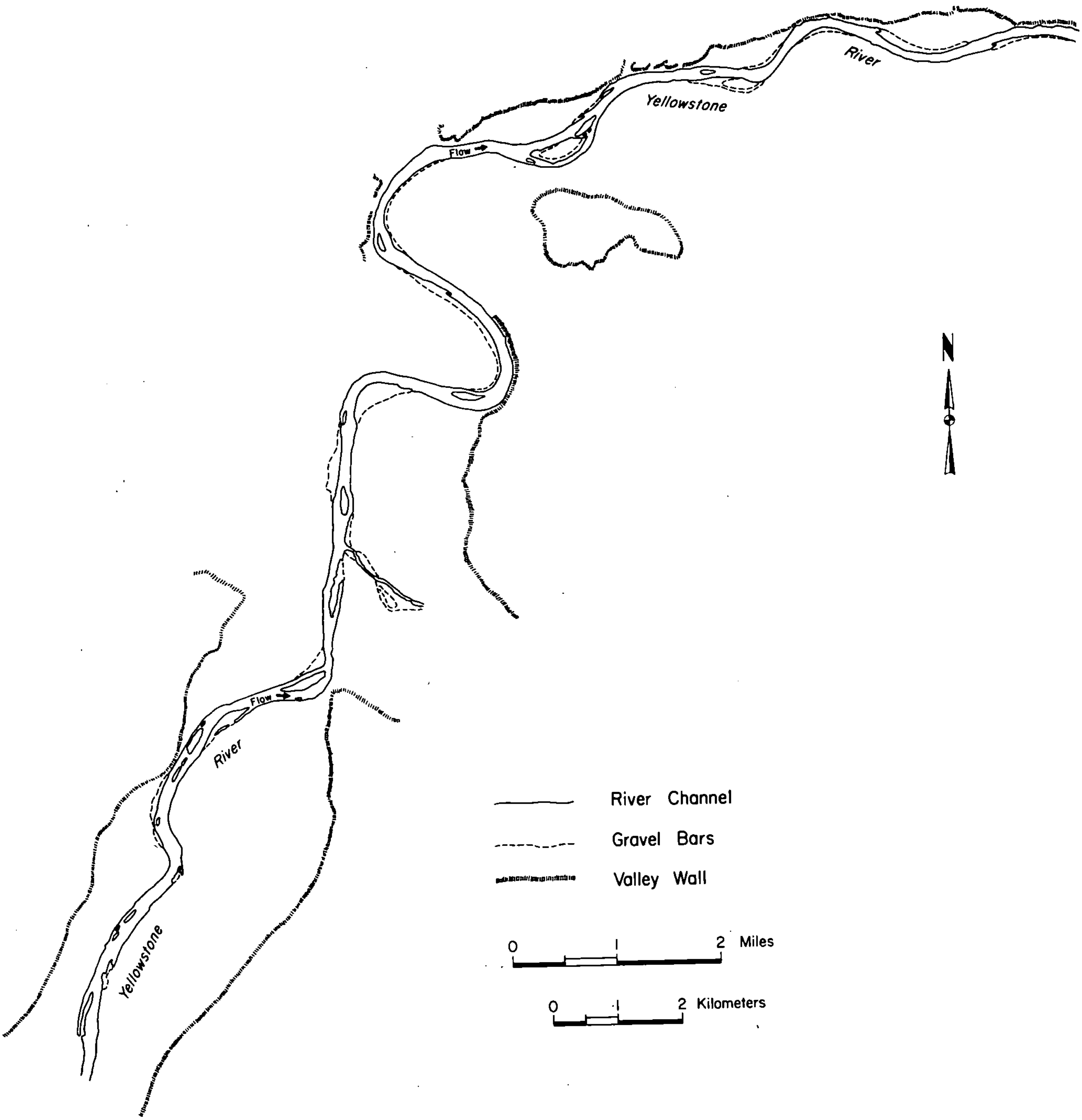


Figure 9. Reach 4: the Yellowstone River from above the Mouth of the Powder River to below Terry.

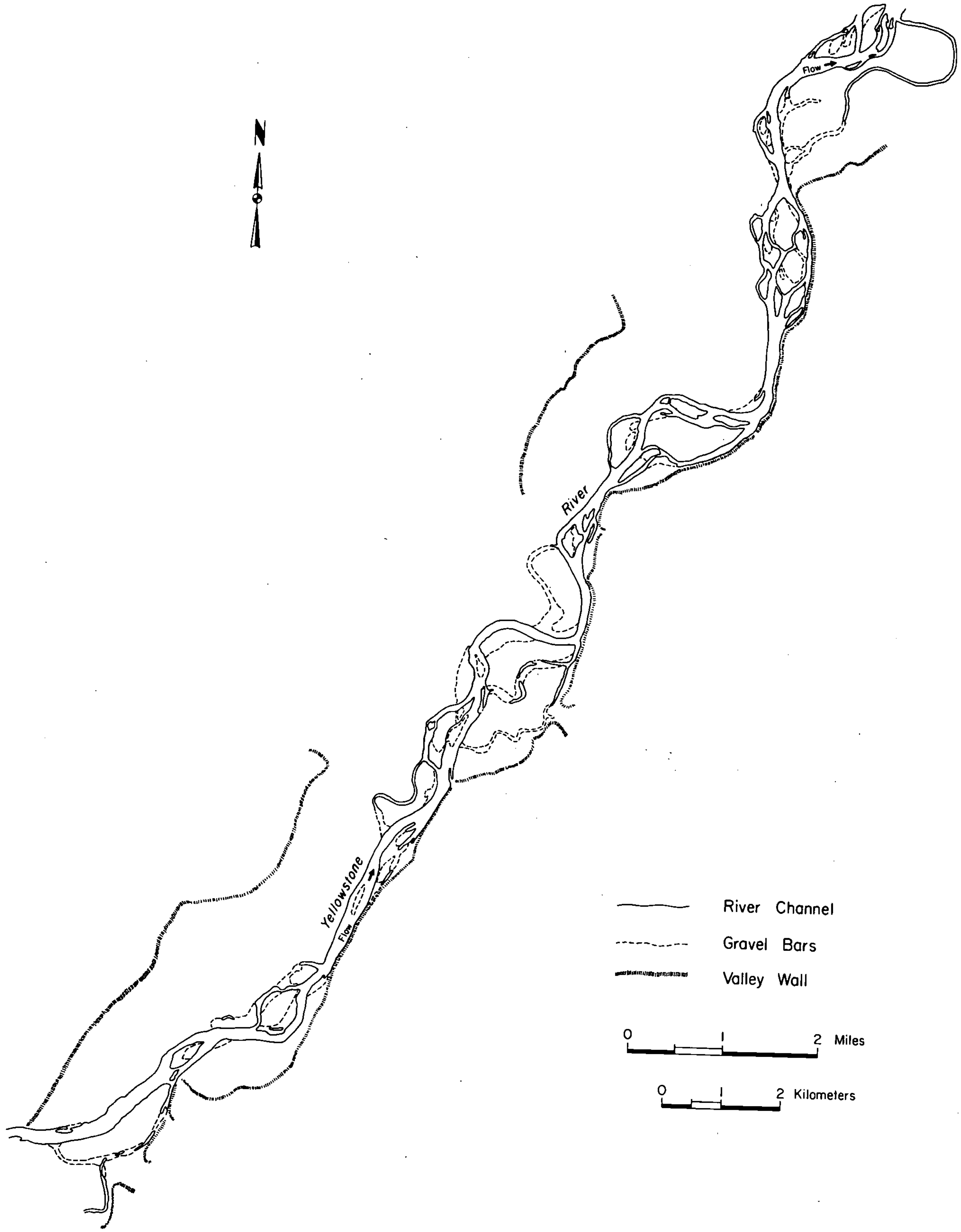


Figure 10. Reach 5: the Yellowstone River from Intake Diversion Dam to Savage.

TRIBUTARIES

The geomorphic character of the major tributaries, including the Bighorn, Tongue, and Powder rivers, is also of interest.

Bighorn River

An important factor affecting streams or rivers is the construction of reservoirs. These reservoirs trap sediments, releasing clear water downstream which has the potential to degrade the river channel (Simons 1972). Sediment moving through a river system is an important variable affecting slope and sinuosity (Schumm 1972). Besides resulting in the elimination of side channels, backwater area, sloughs, and islands, reservoir construction also eliminates peak flows which are instrumental in moving sediments and in the formation of new islands.

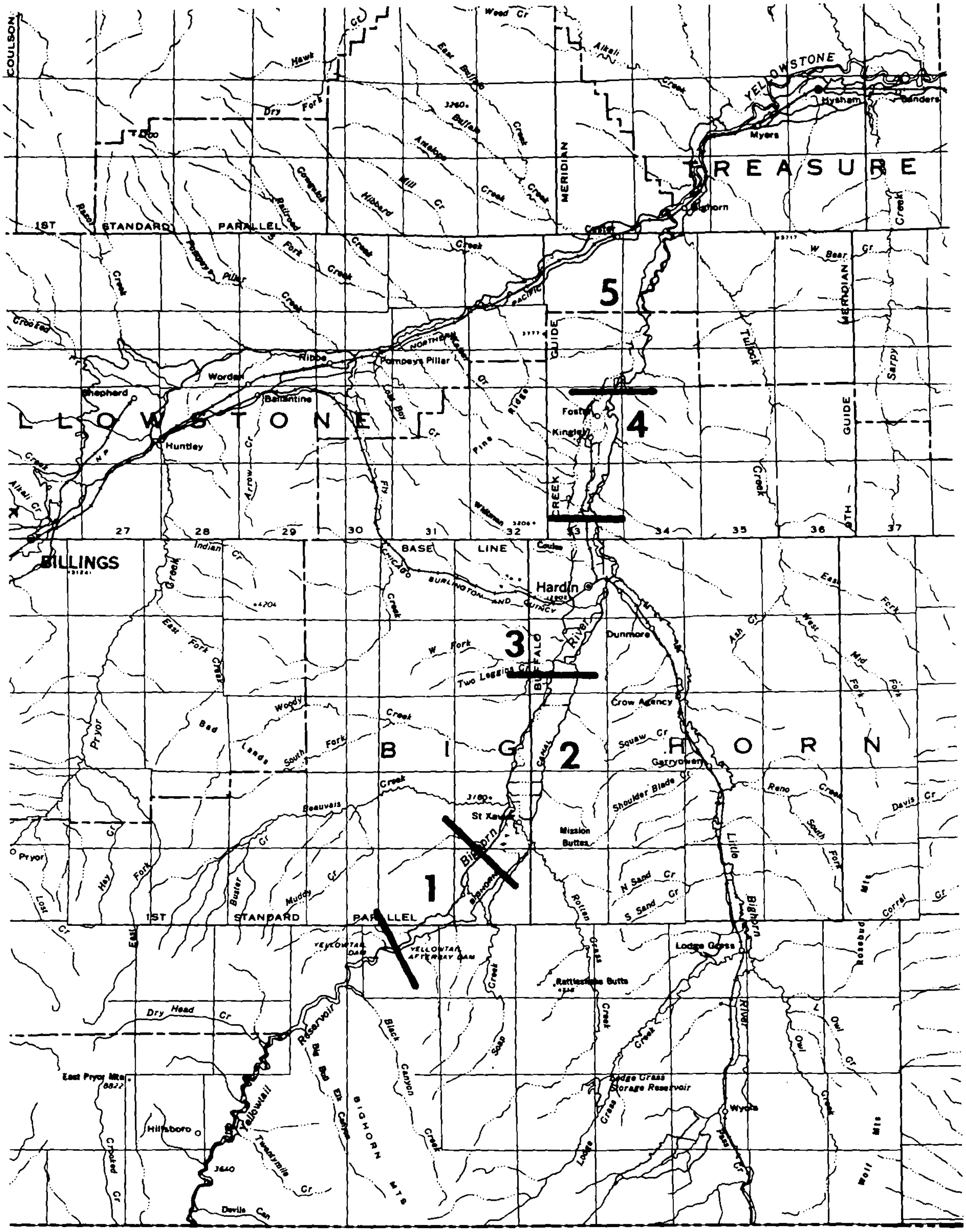
Many changes have taken place in the physical structure of the Bighorn River since 1939. Several dams have been constructed, two in Wyoming and one (Yellowtail Dam) in Montana. As part of his study of the effect of altered streamflow on furbearing mammals in the Yellowstone River Basin (see Report No. 6 in this series), Peter Martin conducted an extensive analysis of the Bighorn River in order to determine changes in channel morphology since the closure of Yellowtail Dam in 1965; the following discussion of Bighorn River geomorphology was written by him. Photographs taken in 1939 for that portion of the river in Bighorn County below the afterbay dam (approximately 71 mi) and in 1950 for the mouth section (approximately 14 mi) were compared to photographs taken in 1974. Overlays of these photographs depicted vegetated islands, gravel bars, agricultural development, and riparian vegetation on the river bottom from Yellowtail Afterbay Dam to the Yellowstone River. Vegetated islands were defined as any vegetated land form separated from the main valley floor by water or gravel bars. Gravel bars were classified as "island" (separated from the valley floor by water) or "lateral" (adjacent to the valley floor). The areas of these physical features were measured with a digitized planimeter at the Civil Engineering and Engineering Mechanics Department of Montana State University, Bozeman.

For ease in interpreting data, the river was divided into five sections (figure 11):

1) Yellowtail afterbay dam to just above the mouth of Hay Creek,
2) Above Hay Creek to just above Two Leggins diversion dam,
3) Above Two Leggins diversion dam to just below the mouth of dry Creek
4) Below Dry Creek to above the mouth of Pocket Creek, and
5) Above Pocket Creek to mouth

The general statistical results of this investigation are given in table 3. Changes in island and gravel bar numbers and areas are given in table 4. Islands and gravel bars, divided into size (area) categories, are shown in tabular and graphical form in appendix B.

The river maintained its length and total riparian area. A 37.6-percent gain of 3,329 acres (1,347.4 ha) of bank riparian area was recorded. A corresponding loss in river area was noticed, as tabulated in table 5.



Base Map from USGS

Figure 11. Bighorn River sections delineated for interpretation of aerial photographs.

TABLE 3. Changes in the Bighorn River channel after construction of Yellowtail Dam

Section	Before Construction[a]	After Construction[b]	Change	Percentage
LENGTH OF MAIN CHANNEL IN MILES				
1	12.27	12.17	-0.10	-0.8
2	19.55	19.82	+0.27	+1.4
3	20.05	20.30	+0.25	+1.2
4	19.48	18.91	-0.57	-2.9
5	13.63	14.77	+1.14	+8.4
TOTAL	84.95	85.97	+1.02	+1.2
TOTAL RIPARIAN AREA IN ACRES (EXCLUDES FARM LAND AND OTHER DEVELOPMENT)				
1	2,894.27	3,197.41	+303.14	+10.5
2	5,433.19	5,516.61	+83.42	+1.5
3	5,846.29	5,486.22	-360.07	-6.2
4	4,474.50	4,458.89	-15.61	-0.3
5	3,546.69	3,470.42	-76.27	-2.2
TOTAL	22,194.94	22,129.55	-65.39	-0.3
TOTAL BANK RIPARIAN AREA IN ACRES				
1	1,552.04	2,232.25	+680.21	+43.8
2	2,543.53	3,528.83	+985.30	+38.7
3	1,910.02	2,761.91	+851.89	+44.6
4	1,255.15	1,981.81	+726.66	+57.9
5	1,590.59	1,675.96	+85.37	+5.4
TOTAL	8,851.33	12,180.76	+3,329.43	+37.6
TOTAL RIVER AREA IN ACRES (INCLUDES WATER, ISLANDS, AND GRAVEL BARS)				
1	1,342.23	985.16	-357.07	-26.6
2	2,889.66	1,987.78	-901.88	-31.2
3	3,936.27	2,724.31	-1,211.96	-30.8
4	3,219.35	2,477.08	-742.27	-23.1
5	1,956.10	1,794.46	-161.64	-8.3
TOTAL	13,343.61	9,948.79	-3,394.82	-25.4
TOTAL VEGETATED ISLAND AND GRAVEL BAR AREA IN ACRES				
1	759.56	409.97	-349.59	-46.0
2	1,921.15	979.29	-941.86	-49.0
3	2,765.53	1,646.43	-1,119.10	-40.5
4	2,090.37	1,465.63	-624.74	-29.9
5	1,022.22	1,056.23	+34.01	+3.3
TOTAL	8,558.83	5,557.55	-3,001.28	-35.1
TOTAL WATER AREA IN ACRES				
1	582.67	575.19	-7.48	-1.3
2	968.51	1,008.49	+39.98	+4.1
3	1,170.74	1,077.88	-92.86	-7.9
4	1,128.98	1,011.45	-117.53	-10.4
5	933.88	738.23	-195.65	-21.0
TOTAL	4,784.78	4,411.24	-373.54	-7.8

CONVERSIONS: 1 mi = 1.61 km
1 acre = .405 ha

[a]Aerial photos of sections 1-4 were taken in 1939, of section 5, in 1950.

[b]Aerial photos taken in 1974

TABLE 4. Number, average area, and total area of vegetated islands, island gravel bars, and lateral gravel bars on the Bighorn River before and after construction of Yellowtail Dam.

Section	Before Construction[a]			After Construction[b]			Area Change	
	Number	Average Area (acres)	Total Area (acres)	Number	Average Area (acres)	Total (acres)	Total (acres)	Percentages
VEGETATED ISLANDS								
1	54	8.5	459.2	42	8.5	355.2	-104.0	22.6
2	85	15.2	1293.7	84	9.8	823.4	-470.3	36.4
3	115	18.7	2155.2	56	25.8	1446.7	-708.5	32.9
4	90	17.4	1567.3	66	20.1	1323.2	-244.1	15.6
5	70	12.6	884.1	39	24.2	942.0	+ 57.9	6.6
TOTAL	414	15.4	6359.6	287	17.0	4890.6	-1469.0	23.1
ISLAND GRAVEL BARS								
1	79	2.8	219.4	42	0.7	30.1	-189.3	86.3
2	131	3.9	507.9	75	1.3	94.6	-413.3	81.4
3	183	3.0	548.3	77	1.5	118.6	-429.7	78.4
4	113	3.8	432.5	61	1.7	102.8	-329.7	76.2
5	113	0.9	106.0	46	1.5	66.6	- 39.4	37.2
TOTAL	619	2.9	1814.2	301	1.4	412.8	-1401.4	77.2
LATERAL GRAVEL BARS								
1	26	3.1	81.0	20	1.2	24.6	- 56.4	69.6
2	40	3.0	119.6	23	2.7	61.3	- 58.3	48.7
3	16	3.9	62.0	28	2.9	81.1	+ 19.1	30.8
4	21	4.3	90.5	22	1.8	39.6	- 50.9	56.2
5	19	1.7	32.1	18	2.7	47.7	+ 15.6	48.6
TOTAL	122	3.2	385.2	111	2.3	254.2	-131.0	34.0

CONVERSIONS: 1 acre = .405 ha
NOTE: Both average and total areas have been rounded to the nearest 0.1 acre.

[a]Aerial photos of sections 1-4 were taken in 1939, of section 5, in 1950.
[b]Aerial photos taken in 1974.

TABLE 5. Loss in Bighorn River Area following construction of Yellowtail Dam.

	Acreage Loss	Percentage Loss
Vegetated Islands	1,469	23.1
Island Gravel Bars	1,401	77.2
Lateral Gravel Bars	131	34.0
Water Area	374	7.8
TOTAL RIVER AREA[a]	3,374	25.4

CONVERSIONS: 1 acre = .405 ha

[a]Does not add due to rounding

The 7.8-percent water area reduction shown in table 5 is significant because the 2710-cfs flow at the river's mouth on September 30, 1974, the day the photographs were taken, was 730 cfs higher than the 1980-cfs flow on August 20, 1939 (Hadfield 1975). The histograms in appendix B show that the loss in numbers of vegetated islands was highest in the 5.01-to-10.00-acre (2-to-4-ha)category, with substantial losses in all categories except in the 3.01-to-5.00-acre (1.2-to-2-ha) and over-100 acre (40-ha) ranges. Island gravel bar numbers decreased dramatically (619 to 301 overall) in all categories. The larger bars suffered the highest losses; the percentage of bars less than 2.00 acres (0.8 ha) increased from 80 to 90 percent of the total. The large lateral gravel bars were also reduced in number. The reduction in numbers of vegetated islands, island gravel bars, and lateral gravel bars was accompanied by a reduction in the average size of gravel bars and an increase in the average size of vegetated islands. This can be explained by the combining of small islands and gravel bars into larger islands as degradation lowered the channel and water level. Stable flows allowed vegetation invasion of gravel bars, further reducing gravel bar areas.

In section 1, immediately downstream from Yellowtail Dam, the number of vegetated islands decreased from 54 to 42. The area of the islands decreased 22.6 percent from 459 to 355 acres (186 to 144 ha). Bank riparian area increased 43.8 percent as former islands and gravel bars were eliminated. The area of island gravel bars decreased 86.3 percent, as 189 acres (77 ha) of island gravel bars were lost. Fifty-six acres (23 ha) of lateral gravel bars were lost (69.6 percent of the 81 acres present in 1939). The total river area, which includes island, gravel bar, and water surface area, decreased from 1342 to 985 acres (543 to 399 ha), a loss of 27 percent. The makeup of vegetated islands (figures B-1 and B-4 of appendix B) in section 1 reveals the overall loss in numbers in the 1.01-to-2.00-acre (0.4-to-0.8-ha), 5.01-to-10.00-acre (2.0-to-4.0-ha) and 10.01-to-20.00-acre (4-to-:8 ha) categories. All of the medium and large island gravel bars (those over 2 acres) except one were lost. Lateral gravel bars followed the same pattern; only two of the 18 bars over two acres remained in 1974.

The other four river sections had similar changes. Section 3 had the greatest loss of riparian area (360 acres or 146 ha--6.2 percent). Section 4 gained the highest percentage of bank riparian area (57.9 percent), while section 2 gained the most acreage (985 acres, or 399 ha). Section 2 lost the highest percentage of river area (31.2), but section 3 lost the most acreage (1,212 acres, or 491 ha). Section 5, the furthest from the dam and theoretically the area least affected, demonstrated small changes in all categories except water area where it registered a 21.0 percent loss. Island gravel bar losses seemed to be most directly related to distance from the dam, in that section 1 had the highest loss at 86.3 percent and each successive section had a lower loss down to 37.2 percent in section 5. Lateral gravel bars actually increased in section 3 (31 percent), perhaps influenced by the sediment inflow from the Little Bighorn system, and section 5 (49 percent), possibly because of sediments moved from upstream sections.

Tongue River

The Tongue River in Montana is controlled by Tongue River Reservoir. Below the reservoir, the river flows for about 10 mi (16 km) through a steep-walled, sinuous canyon just wide enough for formation of a narrow flood plain. Below this canyon, the valley widens and meanders across a much wider flood plain to its confluence with the Yellowstone River at Miles City. The form of the Tongue River below the canyon is irregularly meandering with most of the lateral channel activity confined to meander formation and cutoff. Channel bars and islands are few, occurring only occasionally below where a bend is eroding a valley wall of gravel. Bovee (1975) describes the bed of the Tongue River as being completely armored from below the dam to near the town of Birney. From Birney to near the Brandenburg Bridge, the bed is armored in spots. Below Brandenburg, the bed appears to be in equilibrium, more characteristic of an alluvial stream. Bulk samples of bed material were collected at several points along the river, dried, and sieved. The data are presented in table 6.

TABLE 6. Bed material of the Tongue and Powder rivers, Montana

Station	d_{50}(mm)	d_{90}(mm)
TONGUE RIVER		
near Miles City	1.9	14
at SH Ranch	43.5	57
below Brandenburg Bridge	1.7	11
at Ashland	21.5	40
POWDER RIVER		
near Locate	3.6	42
at Moorhead	8.6	58

CONVERSIONS: 1 mm = .0394 in
NOTE: This table is based on bulk samples of surface bed material.

Powder River

The Powder River has been characterized since its settlement as "a mile wide and an inch deep, too thick to drink, and too thin to plow" because of its shallow, heavily sediment-charged waters. In general, the Powder flows through a relatively wide valley for most of its length. However, for approximately 25 mi (40 km) from its confluence with the Yellowstone upstream, it is incised from 20 to 50 ft (6 to 15 m) into the flood plain, probably as a result of a change in base level when Glacial Lake Glendive disappeared. Throughout its length, the river is either sinuous or irregularly meandering. Lateral activity is irregular with a few cutoffs in the more meandering reaches. There are many midchannel bars; many are ephemeral, occurring only at high flows, and many appear at low flows in the main channel as a result of the shifting bed. Islands are not prevalent in the Powder River. Data on bed material size of the Powder are presented in table 6.

COMPARISON WITH OTHER RIVERS

Based upon the discussion of channel form presented above, a comparison between the existing characteristics of the river and those of other rivers in the country would be enlightening in that such a comparison would point up any anomalous characteristics of the river. Leopold and Wolman (1957) have presented a channel-form relationship based on slope and bankfull discharge as shown in figure 12. Based on many data representing wide ranges of flow, drainage areas, and bed materials, this relationship was constructed using the criteria that channels with a sinuosity greater than 1.5 are meandering; those with sinuosity less than 1.5 are braided or straight. As can be seen from figure 12, the majority of the stations on the mainstem of the Yellowstone plot above the mean line, indicating that they occur in braided channels. For Reach 4, however, bedrock in the channel bank and bed and the incised channel preclude development of characteristic irregular lateral channel activity with the shifting main channel. Also of interest is the proximity of several of the points to the mean line, particularly in the Powder River Basin. This could indicate that, with a change in either bankfull discharge or channel slope, a change in channel form would result, subject to any local constraints such as in reach 4.

CHANNEL PROCESSES

The most significant characteristic of the Yellowstone River is its split channel due to the presence of many gravel bars and islands. The processes by which these bars and islands evolved are discussed below.

The formation process of a midchannel bar has not been finally established; however, several factors in the process have been identified (Leopold et al. 1964). It appears that, for a channel with coarse bed material, midchannel bars can be formed by the selective deposition of the coarser fraction of the bed load. This process implies several conditions necessary for braiding:

	Station	Bankfull Discharge[a] (cfs)	Slope
1	Yellowstone River at Livingston	18,200	.0024
2	Yellowstone River at Billings	34,500	.0014
3	Yellowstone River at Myers	45,000	.00058
4	Yellowstone River at Miles City	47,000	.00067
5	Yellowstone River at Terry	51,000	.00058
6	Yellowstone River at Intake	52,000	.00046
7	Yellowstone River near Sidney	52,000	.00025
8	Bighorn River at St. Xavier	11,800	.0020
9	Bighorn River at Bighorn	12,700	.0016
10	Tongue River at Miles City	3,080	.0019
11	Powder River at Moorhead	5,400	.0014
12	Powder River near Locate	6,800	.0011

[a] estimated by the 1.5-year-frequency flood

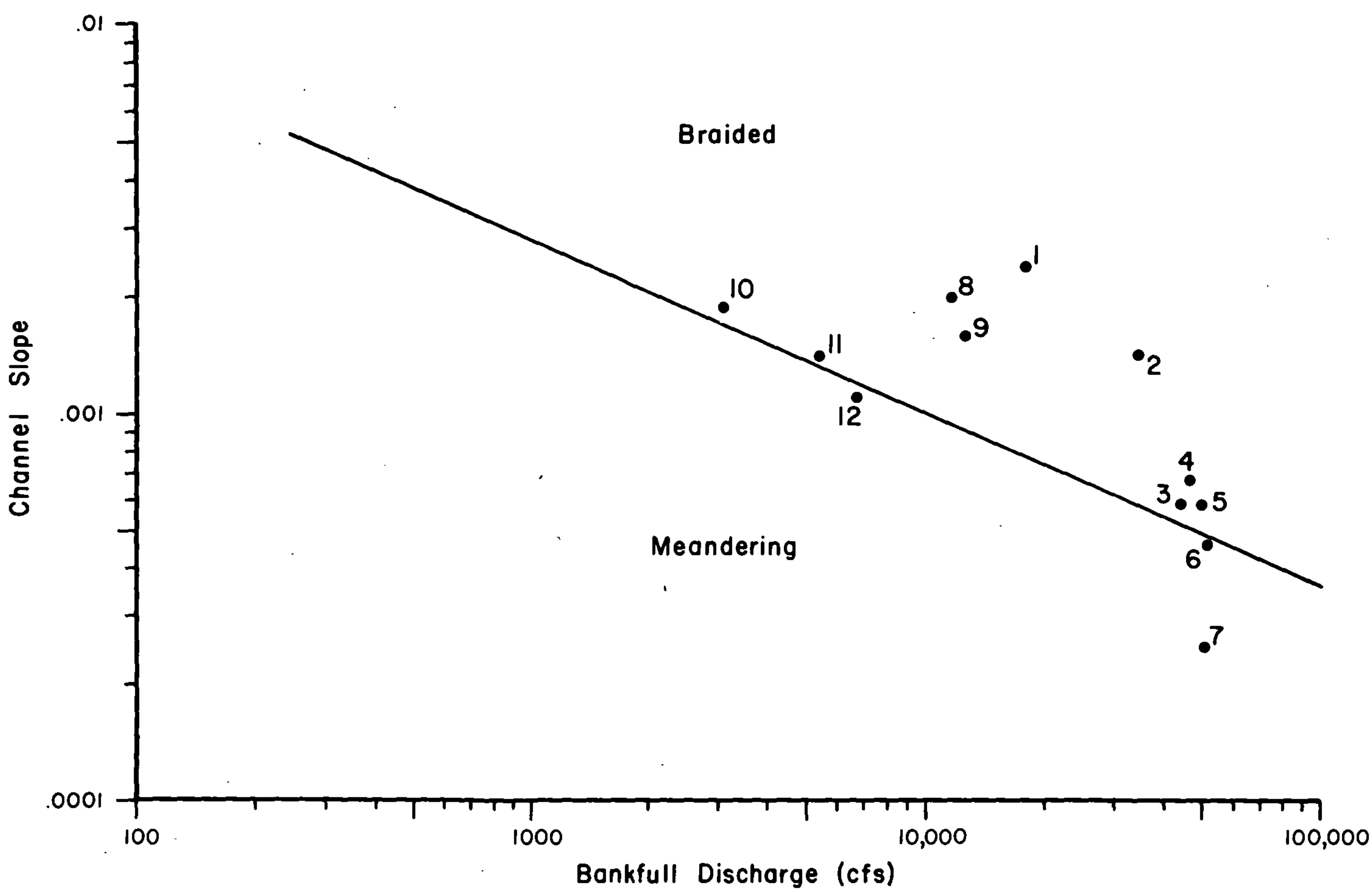


Figure 12. Relationship of rivers in the Yellowstone Basin to the general relation for channel form presented by Leopold and Wolman (1957).

1) Sediment transport, in particular of the bed material, is required, since bar formation is a depositional process. Heterogeneity of bed material contributes to the deposition of the coarse fraction of the bed material to begin the process, and once deposited, greater velocity is required to reestablish motion. The initial deposition then serves as a nucleus for further building.

2) Erodible channel banks are also necessary so that hydraulic capacity lost through formation of the bar will be provided by erosion of the banks.

3) Finally, rapid stage fluctuation has been shown to contribute to the formation of channel bars through added bank erosion and fluctuating transport capacity.

The change in channel morphology accompanying these processes tends to increase the bedload transport capacity in the reach and provide equilibrium (Simons et al. 1975).

In addition to formation of midchannel bars as described above, there are instances of midchannel bar formation by cutoff of a point bar in the more sinuous reaches, such as reaches 3 and 4. In this situation, the main flow of the river short-circuits the meander bend during high flow, eroding a path across the point bar. If the cut produced is deep enough, a perennial channel results, turning the point bar into a midchannel bar.

Many midchannel bars progress toward the formation of a stable island, requiring that vegetation become established on the bar. From field observation, it appears that deposition of sand on the leeward side of the island is required for establishing vegetation. When this has occurred, a period of several years without flows high enough to wash away the vegetation is necessary. Vegetation aids in island building by increasing flow resistance, causing deposition of fine material on the island. The growth of the island is tailward: the material composing the island grades from coarse at the head of the island to fine at the tail because flow velocity decreases through the vegetation and progressively finer particles are allowed to settle. This process often continues until the elevation of the island reaches the elevation of the flood plain.

The hydraulic characteristics of a split channel are also different from a single channel. In general, a split-channel reach is characterized by a steeper slope. Flow resistance is higher also, and therefore, velocities are generally less through a split channel than a single channel. In addition, the depths in a split section are generally less and the total width of the water surface greater.

Based on this analysis of the important channel processes in the system, the governing hydrologic processes can be identified. It is obvious that the annual high flows are a necessary part of the channel-forming process. These flows trigger bed movement, new channel cutting, erosion, and cutoffs, and it is movement of the bed and bank material and subsequent deposition which forms the michannel bars or cutoffs and subsequently the islands. It is these flows also that are capable of covering the already established bars with finer material in order to establish an island.

The high flows can occur from two sources: (1) the annual snowmelt cycle and (2) the less-predictable ice jam and break. The first of these high-flow producers is typified by a relatively gradual rise in the late spring and a sustained period of high flows. Velocity varies gradually with no sudden changes. The ice jam and break phenomenon, on the other hand, is a sudden local process characterized by rapid fluctuations in stage, velocity, and sediment transport regime. Because this is a local process, the effects are also normally local, consisting of (1) possible bed scour as water is sluiced under the ice jam and (2) some erosion scars in vegetated areas caused by rafting of large pieces of ice into channel banks and islands. Although this process may prevent or interrupt the establishing of vegetation locally, it is not likely to have a great impact on channel morphology. The spring runoff event affects the entire system and, in addition to high discharges, has the long duration necessary for the initation and continuation of such geomorphic processes as the inundation of backwater areas, retarding encroachment of vegetation.

The effects of the spring runoff in the formation and maintenance of channel pattern cannot be overemphasized. These high flows provide the dominant discharge--that flow which, through a combination of magnitude and frequency of occurrence, has the greatest impact on channel form. This discharge is identified by some to be the bankfull discharge (1.5-year recurrence) and by others to be the mean annual flood (2-year recurrence). As shown in the section on sediment transport (figures 32 and 33), flows of this magnitude move the greatest amount of material.

In addition to sediment transport capability, high spring flows also contribute to the channel form through flooding of abandoned channels, thereby keeping backwater areas open and preventing the encroachment of vegetation. Without the high discharges associated with the spring runoff, the building of midchannel bars through sediment deposition or cutoff of point bars would be diminished, and the backwater areas would eventually be filled by vegetation and sediment, thus becoming part of the flood plain.

In addition to the natural channel processes at work in the Yellowstone River Basin, man has had an impact, if only a small one, on the geomorphic character of the river. This impact has mostly been in the form of artificial alteration of the river and riparian areas and in alteration of controlling processes by development of the watershed. Riprapping, closing of side channels, and clearing of bank vegetation have been the major alterations of the river itself, with riprap far outweighing the other two. The effect of riprapping is, in many cases, to stabilize the bank and stop ongoing erosion. Bank clearing, on the other hand, promotes bank erosion by loss of the root system which aids in binding soil material together. Riprap is common along the river where railroads, highways, bridges, pumping plants, and any other structures approach the river bank.

Changes in watershed processes through changing land use and development have also occurred. In particular, increased agriculture (both farming and grazing) and timber cutting have probably increased sediment and water volumes delivered to the river, thereby slightly offsetting the impact of past water development. Data on these uses are not readily available, but the impact has probably been small.

Channel processes can be radically altered by impoundment of rivers. The effects of construction of Yellowtail Dam on the Bighorn River is discussed above, on pages 32 to 37 ; resultant geomorphic changes in the river are summarized in tables 3, 4 and 5.

Hydrology

Because river processes are a function of a basin's yield of water and sediment, this study included a review of the climate, streamflow characteristics, and hydraulic geometry of the Yellowstone Basin.

CLIMATE

Elevations in the basin range from over 12,000 feet (3660 m) in the Absaroka, Beartooth, Wind River, and Bighorn ranges to less than 2000 feet (610 m) at the confluence of the Yellowstone and Missouri rivers. This elevation difference results in great climatic variations from the alpine areas of the high mountains to the semiarid plains of the eastern part of the basin. In the plans areas, precipitation averages less than 15 inches (38 cm) per year and consists mainly of rainfall occurring from April through September with the greatest amounts falling in May, June, and July. In the mountainous areas, most precipitation occurs as snow during the late winter and spring months and can average up to 80 inches (200 cm) per year. Average annual precipitation for the area is shown in figure 13. Large annual deviations from these averages are common throughout the basin, particularly in the plains. As a result of these variations, large fluctuations in streamflow, particularly in the eastern prairie streams, have occurred. Potential evaporation averages approximately 30 inches(760 cm) during the growing season of May through September in the plains.

STREAMFLOW CHARACTERISTICS

Table 7 presents some of the streamflow characteristics for the mainstem Yellowstone River and its major tributaries. Table 7 shows that, as is most often the case, unit runoff decreases downstream along the mainstem. Further, it can be seen that the contribution of the tributary basins decreases downstream, reflecting the physiographic and concomitant climatic changes of the tributary basins. There are mountain areas which contribute large amounts of runoff in the upper Bighorn River watershed while there are almost no mountains in the Powder River watershed. A comparison over the period of record indicates that no great variation exists in flood peaks in the lower basin; that is, no catastrophic floods have occurred in the period of record along the mainstem. According to Stevens et al. (1975), if the ratio of the peak flood to the mean annual flood is small (less than 3), the river is likely to be in equilibrium. If the ratio is large (greater than 10), it is likely that the river will exhibit nonequilibrium form. It appears, then, that the streams of the lower Yellowstone River Basin are in equilibrium.

Flow duration curves have been developed by the U.S. Geological Survey (USGS) using mean daily flows for all the stations in the lower Yellowstone River Basin with sufficient length of record. Selected percentiles for the stations are shown in table 8. In addition, flood frequency curves were developed for the same stations using a procedure described by Beard (1962)

TABLE 7. Streamflow Characteristics in the Yellowstone River Basin.

Station	Period of Record	Mean Annual Discharge (cfs)	Unit Runoff (cfs/mi^2)	Bankfull Discharge[a] (cfs)	Maximum Flood of Record (cfs)	Ratio of Maximum Flood to mean Annual Flood
Yellowtone River at Corwin Springs	68	3,119	1.19	15,000	32,000	1.88
Yellowstone River at Livingston	49	3,757	1.06	18,200	36,300	1.77
Yellowstone River at Billings	46	6,913	0.59	34,500	69,500	1.76
Bighorn River at Bighorn	29	3,903	0.17	12,200	26,200	1.75
Tongue River at Miles City	31	427	0.08	3,080	13,300	3.24
Yellowstone River at Miles City	47	11,420	0.24	47,000	96,300	1.82
Powder River near Locate	36	616	0.05	6,800	31,000	3.23
Yellowstone River near Sidney	62	13,070	0.19	52,000	159,000	2.48

CONVERSIONS: 1 cfs = .0283 m^3/sec
1 cfs/m^2 = .0109 $m^3/sec/km^2$

[a]Bankfull discharge estimated by the 1.5-year frequency flood.

and the Water Resources Council (1967). This procedure consists of fitting a Log Pearson Type III to the annual peak flow series. This distribution is represented by the relation

$$\log Q = m + ks$$

where = Q = instantaneous annual peak discharge
m = the mean of the logs of the discharges
s = the standard deviation of the logs
k = a factor dependent on the skew coefficient and recurrent interval

As suggested by Beard (1962), a skew coefficient of 0.0 was applied in all cases. The results of this analysis are shown in table 9.

Yellowstone River Basin

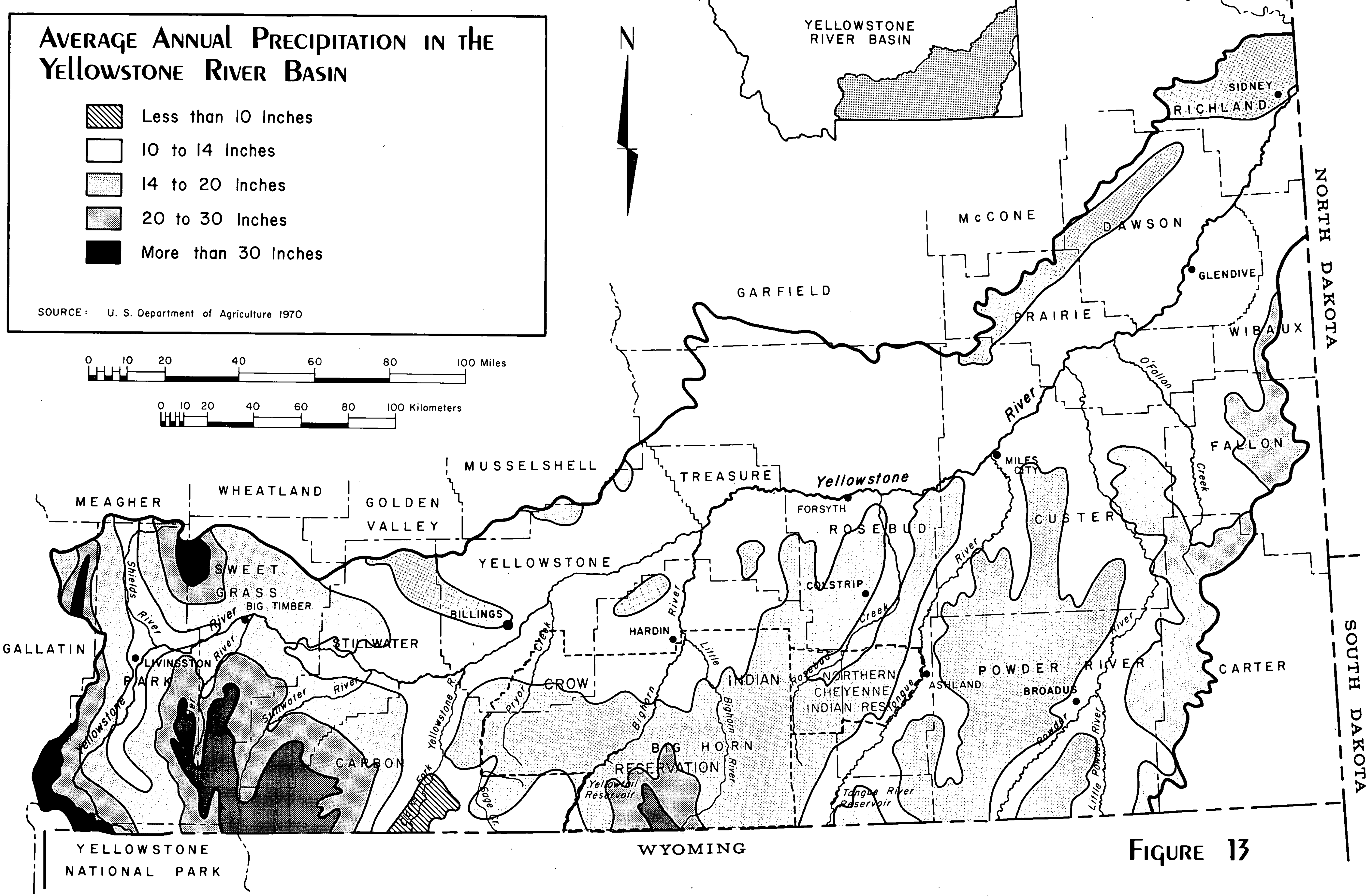


Figure 13

TABLE 8. Data from flow duration curves for the Lower Yellowstone River Basin (cfs)

Station	Percentage of Time Flow is Equalled or Exceeded						
	1	10	20	50	80	90	99
YELLOWSTONE RIVER at Corwin Springs	17,250	8,500	4,700	1,400	880	780	530
near Livingston	20,500	9,800	5,100	1,900	1,300	1,100	860
at Billings	40,000	17,000	8,800	3,700	2,500	2,100	1,350
at Miles City	56,000	26,000	14,500	7,200	4,700	3,700	2,100
near Sidney	65,000	28,000	17,000	8,000	5,000	3,900	1,600
BIGHORN RIVER near St. Xavier	17,000	6,200	4,600	2,700	1,750	1,400	540
at Bighorn	18,000	6,900	5,200	3,400	2,100	1,400	790
LITTLE BIGHORN RIVER at Pass Creek	1,220	440	240	130	96	78	42
at Hardin	1,950	680	340	160	105	70	9.2
TONGUE RIVER at the state line	3,500	1,200	650	260	200	160	2.5
below Tongue River Dam	3,000	1,000	560	250	150	110	31
at Miles City	3,150	1,000	550	220	110	54	0
POWDER RIVER at Moorhead	3,300	1,100	550	210	84	41	1.8
near Locate	6,000	1,400	760	220	70	28	1.4
LITTLE POWDER RIVER near Broadus	5,300	550	240	56	19	12	0

CONVERSIONS: 1 cfs = .0283 m^3/sec

In addition to mean flows, flow duration, and flood frequencies, the seasonal variation of streamflow in the basin is also of interest. Figure 14 shows the average monthly flows for the Yellowstone River at several stations along the mainstem. These distributions show that the peak flow occurs in June and decreases rapidly in July and August. The effect of the physiographic and climatic differences in the basin can also be seen in this figure. For instance, the data for the stations at Miles City and Sidney show an early peak in the month of March not present in the upstream-from-Billings data. This early increase in flow is the result of the early melting of snow on the prairie located mostly in the eastern part of the basin.

TABLE 9. Flood frequencies for the Lower Yellowstone River Basin (cfs)

Station	Recurrence Interval in Years							
	1.01	1.11	1.25	1.5	2	5	10	25
YELLOWSTONE RIVER at Corwin Springs	8,600	11,700	13,143	15,000	16,943	21,842	24,500	28,000
at Livingston	11,000	14,600	16,400	18,200	20,400	25,300	28,500	32,000
at Billings	19,500	26,800	30,600	34,500	39,400	50,900	58,000	65,000
at Miles City	26,500	36,000	41,300	47,000	53,100	68,300	78,000	90,000
at Sidney	22,000	35,500	43,200	52,000	63,400	93,100	113,700	140,800
TONGUE RIVER at state line	1,370	2,200	2,670	3,200	3,890	5,670	6,800	8,400
at dam	450	920	1,250	1,620	2,200	3,870	5,200	7,100
at Miles City	880	1,750	2,360	3,080	4,100	7,140	9,500	13,000
POWDER RIVER at Arvada	514	1,120	1,513	6,000	8,490	5,153	7,100	9,900
at Moorhead	1,730	3,250	4,220	5,400	7,060	11,800	15,400	20,200
at Broadus	319	562	714	900	1,126	1,779	2,258	2,912
at Locate	1,560	3,550	4,980	6,800	9,590	18,500	26,000	37,500
BIGHORN RIVER at Bighorn	5,350	8,430	10,200	12,200	14,700	21,200	25,700	31,500
at St. Xavier	4,000	7,300	9,300	11,800	15,000	24,200	31,500	41,000
at Hardin	567	1,040	1,340	1,700	2,190	3,570	4,600	6,000
LITTLE BIGHORN RIVER at Pass Creek	390	668	835	1,030	1,290	2,000	2,500	3,200

CONVERSIONS: 1cfs = .02832 m^3/sec

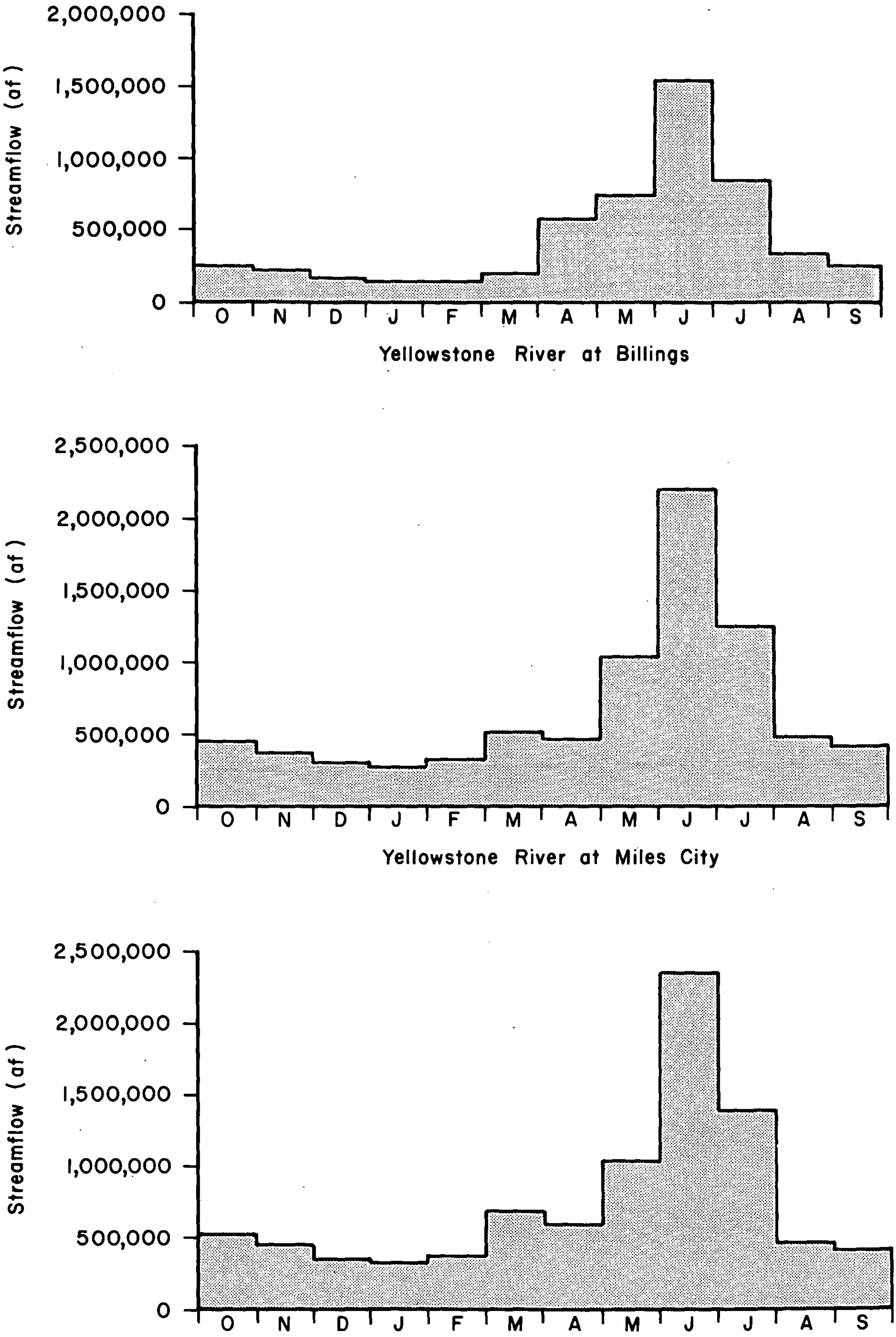


Figure 14. Mean monthly flows of the Yellowstone River mainstem at three stations.

EFFECTS OF EXISTING WATER DEVELOPMENT AND USE

Historically, water use in the basin has been mostly for irrigation with some municipal, industrial, and other agricultural uses. Since irrigation has been by far the major water use, depletion has been mostly during the growing season from April through October (table 10). Not all of the water diverted for irrigation is consumed. A portion returns to the stream. The annual distribution of return flow is shown in table 10. Industrial uses tend to be relatively constant throughout the year; municipal uses increase in summer.

TABLE 10. Monthly distribution of irrigation water withdrawals and return flow.

Month	Percentage of Yearly Irrigation Water Use	Percentage of Return Flow[a]
O	1	8
N	0	5
D	0	4
J	0	3
F	0	2
M	0	3
A	1	4
M	13	11
J	17	14
J	32	18
A	25	18
S	11	10

[a]USDI 1963

Accompanying an increase in water use over time has been a steady development of structural facilities in the basin in an attempt to temper the annual fluctuation in streamflow and provide a more stable water supply. For the most part, structural development in the form of on-stream storage facilities has been confined to the Bighorn River Basin, where three reservoirs--Buffalo Bill on the Shoshone River, Boysen on the Wind River, and Bighorn (Yellowtail) on the Bighorn River--almost completely regulate the streamflow; about 86 percent of the drainage area in the Bighorn Basin is above Yellowtail Dam. Other regulation includes the Tongue River Reservoir on the Tongue River and Cooney Reservoir in the Clarks Fork Basin. The total area of the Yellowstone River Basin controlled by reservoirs is approximately 31 percent; the average annual flow from this area is approximately 31 percent of the average for the basin. In addition to impoundments, diversion structures for irrigation are located along the river, the largest at Intake where a canal with a capacity of approximately 1200 cfs (34 m^3/sec) diverts water for irrigation on the west side of the valley. This diversion, like several others in the Yellowstone Basin, has a diversion dam just below the headgate to provide the necessary elevation for diversion even during low flows.

Present water use patterns and development structures have little effect on streamflows in the winter months because water use during that period is restricted to municipal and industrial uses and because the water supply is slightly augmented by irrigation return flows. During the April-to-October irrigation season, however, an estimated 1.5 million af is consumed for irrigation (Montana DNRC 1977). The portion of that total diverted during June has only a minor impact on that month's high flows; less than 10 percent of the total monthly discharge is diverted, and a significantly smaller percentage of daily or instantaneous peak flows. It is apparent that past water use has had a small impact on the flood discharges in the basin. The greatest impact has occurred in the late summer when low river flows are coupled with high demand for irrigation water.

Regulation by storage reservoirs has also affected peak flows. Although the reservoirs do not generally change the mean annual flow greatly, their main function is to decrease the annual variation in flows by storing peak discharges for release during periods of low flow. This scheme has been in operation in the Bighorn River Subbasin, and the floods of recent years have been reduced accordingly. Yellowtail Dam has been operating only since 1965, and the impact of its regulation has probably not yet been felt on the Yellowstone mainstem.

HYDRAULIC GEOMETRY

Leopold and Maddock (1953) presented a method for quantitatively describing the cross-section geometry and hydraulic characteristics of river systems which has been successfully applied and expanded upon by others (Stall and Fok 1968, Stall and Yang 1970, Emmett 1972 and 1975). The premise of the method is that certain physical streamflow characteristics, e.g. top width (W), average depth (D), and average velocity (V), are related to discharge (Q) by the relations

$$W = aQ^b \qquad (1)$$
$$D = cQ^f \qquad (2)$$
$$V = kQ^m \qquad (3)$$

where a, b, c, f, k, and m are statistically determined constants. Combining equations (1) and (2) provides a relationship between cross-sectional area (a) and flow:

$$A = (a \cdot c)\ Q^{b+f} \qquad (4)$$

Each of these equations produces a straight line when plotted on log-log paper. The validity of any relation presented using this format is easily tested by applying the relation

$$W \cdot D \cdot V = Q \qquad (5)$$

Substituting equations (1), (2), and (3) into (5) gives

$$a \cdot c \cdot k = 1 \qquad (6)$$

$$\text{if} \quad b+f+m = 1 \qquad (7)$$

which are necessary for the validity of the theory.

Equations (1), (2), and (3), called hydraulic geometry by Leopold and Maddock, can be applied either at-a-station (at a particular point along a stream) or in the downstream direction. Downstream (constant-frequency) hydraulic geometry is accomplished by applying the relationships at several points along a stream system for a constant frequency of discharge. For example, at several points where adequate streamflow data are available in a watershed, W, D, and V are plotted against that Q which is equalled or exceeded 10 percent of the time at each point. In order to establish the constant-frequency hydraulic geometry, then, continuous streamflow data are necessary at each of the downstream locations.

An analysis of hydraulic geometry in the middle and lower Yellowstone River Basin was undertaken. Since the only points in the basin where the necessary cross-sectional and flow data were available were the USGS and DNRC gaging stations, the analysis was based on these stations.

AT-A-STATION HYDRAULIC GEOMETRY

At-a-station hydraulic geometry relationships were calculated by simple linear regression for all stations shown in figure 15. A sample graph of the relationships for a single station is shown in figure 16. The b, f, and m exponents in equations (1), (2) and (3) represent the slope of the relations on a log-log plot and, therefore, show the rates of increase of W, D, and V, respectively, with Q. A flat curve shows a small rate of increase; a steep curve indicates a sharp increase. Even though the coefficients have little physical meaning, they are necessary to reconstruct the equation and are therefore presented along with the exponents in table 11. As can be seen in that table, there are considerable variations in the b, f, and m values. Table 12 compares the coefficients and exponents obtained for the Yellowstone River Basin with data derived for other areas of the country.

CONSTANT-FREQUENCY HYDRAULIC GEOMETRY

An increase of streamflow in the downstream direction is assumed in most parts of the country; however, this is not always true in Montana. In many streams, particularly in the Yellowstone's major tributary basins, depletion for irrigation and natural causes give a stable or, at times, decreasing flow in the downstream direction. For the flows (such as bankfull discharge) most often used in a constant-frequency analysis this is not the case, however. An analysis of the hydraulic geometry based on the 1.5-year flood, which is claimed by many researchers (Leopold et al. 1964, Emmett 1975) to be the frequency of the bankfull flow, was conducted for the lower Yellowstone River Basin. The constant-frequency hydraulic geometry for the lower Yellowstone Basin is shown in figures 17 and 18.

TABLE 11. Coefficients and exponents for at-a-station hydraulic geometry, Yellowstone River Basin

Station[a]	$W=aQ^b$		$D=cQ^f$		$V=kQ^m$	
	a	b	c	f	k	m
1	100.4	.105	.23	.36	.043	.53
2	105.3	.12	.15	.39	.06	.50
3	161.4	.075	.97	.25	.01	.66
4	9.98	.18	.15	.6	.71	.19
5	43.95	.18	.75	.25	.03	.56
6	41.3	.07	.05	.61	.47	.32
7	21.3	.22	.18	.39	.56	.28
8	3.02	.53	.23	.38	.7	.09
9	133.01	.07	.50	.30	.03	.54
10	3.08	.33	.56	.28	.58	.38
11	5.7	.37	.25	.33	.71	.29
12	99.3	.05	.08	.50	.10	.49
13	37.3	.16	.17	.41	.16	.44
14	4.9	.36	.69	.20	.29	.44
15	61.9	.12	.03	.60	.49	.28
16	5.1	.33	.25	.46	.79	.21
17	100.4	.11	.23	.36	.04	.53
18	51.7	.13	.15	.43	.12	.44
19	139.8	.02	.07	.50	.10	.48
20	4.8	.50	.35	.25	.58	.26
21	41.7	.18	.09	.50	.25	.33
22	159.7	.14	.10	.43	.06	.43
23	7.06	.35	.19	.42	.76	.21
24	20.1	.25	.11	.45	.45	.30
25	38.0	.12	.28	.33	.09	.54
26	13.2	.39	.12	.38	.27	.35
27	9.7	.33	.16	.39	.63	.26
28	4.6	.44	.32	.33	.64	.22
29	9.8	.33	.16	.39	.63	.26
30	18.9	.38	.12	.40	.32	.32
31	192.	.12	.21	.39	.03	.49

[a]See figure 15

Map Number	Station Number	Station Name
1	06191500	Yellowstone River at Corwin Springs
2	06192500	Yellowstone River near Livingston
3	06214500	Yellowstone River at Billings
4	06217750	Fly Creek at Pompey's Pillar
5	06287000	Bighorn River near St. Xavier
6	06290500	Little Bighorn River below Pass Creek near Wyola
7	06294000	Little Bighorn River near Hardin
8	06294690	Tullock Creek near Bighorn
9	06294700	Bighorn River at Bighorn
10	06294940	Sarpy Creek near Hysham
11	06294995	Armells Creek near Forsyth
12	06306300	Tongue River at State line near Decker
13	06307500	Tongue River at Tongue River Dam
14	06307600	Hanging Woman Creek near Birney
15[a]	42C02000	Tongue River below Birney
16	06307740	Otter Creek at Ashland
17	06307800	Tongue River near Ashland
18	06307830	Tongue River below Brandenburg Bridge near Ashland
19[a]	42C07000	Tongue River at SH Ranch
20	06308400	Pumpkin Creek near Miles City
21	06308500	Tongue River at Miles City
22	06309000	Yellowstone River at Miles City
23	06309075	Sunday Creek near Miles City
24	06317000	Powder River at Arvada, Wyoming
25	06324000	Clear Creek at Arvada, Wyoming
26	06324500	Powder River at Moorhead
27	06324970	Little Powder River above Dry Creek near Weston, Wyo.
28	06325500	Little Powder River near Broadus
29	06326300	Mizpah Creek near Mizpah
30	06326500	Powder River near Locate
31	06329500	Yellowstone River near Sidney

[a] DNRC stations

Yellowstone River Basin

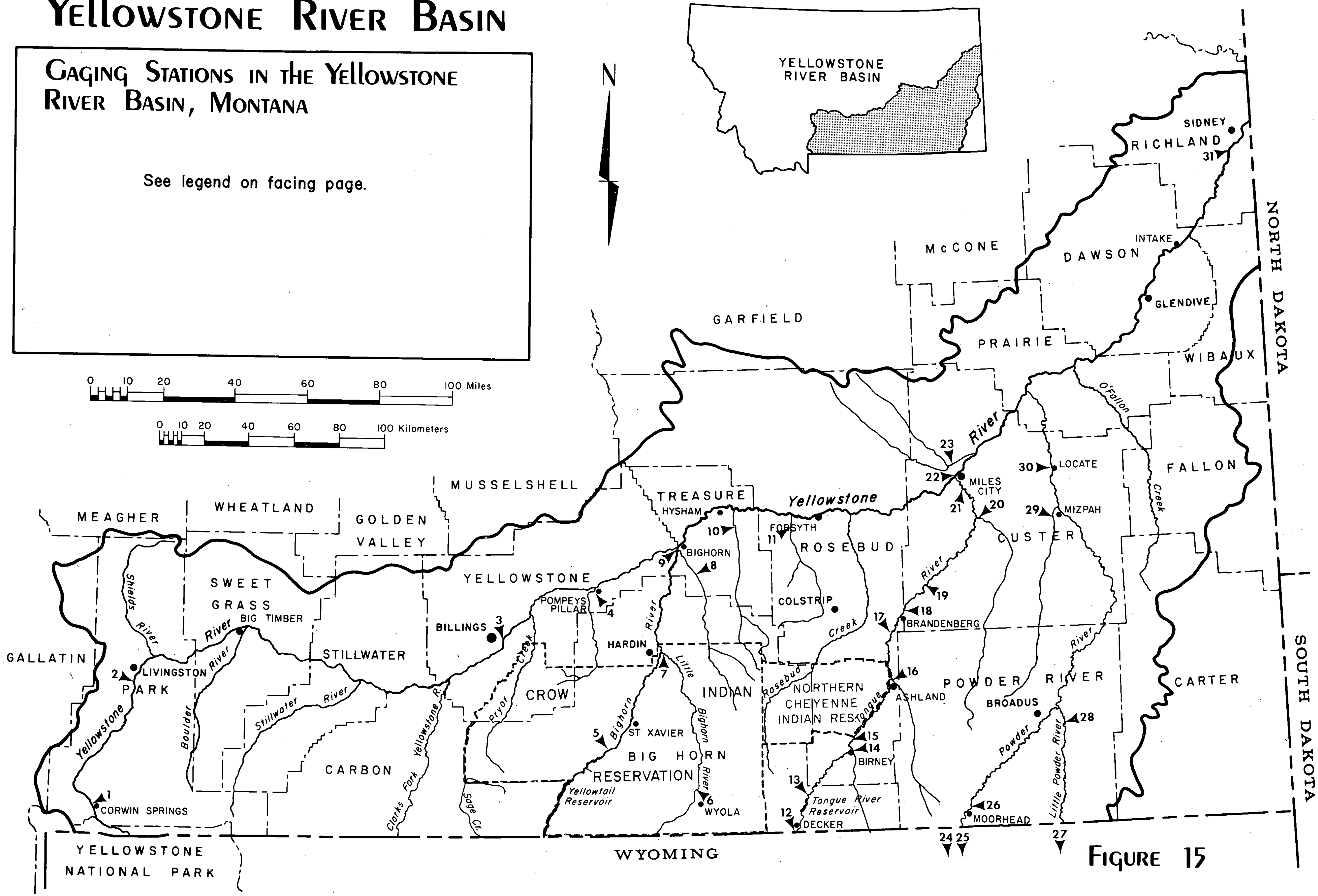


Figure 15

ELLOWSTONE RIVER BASIN

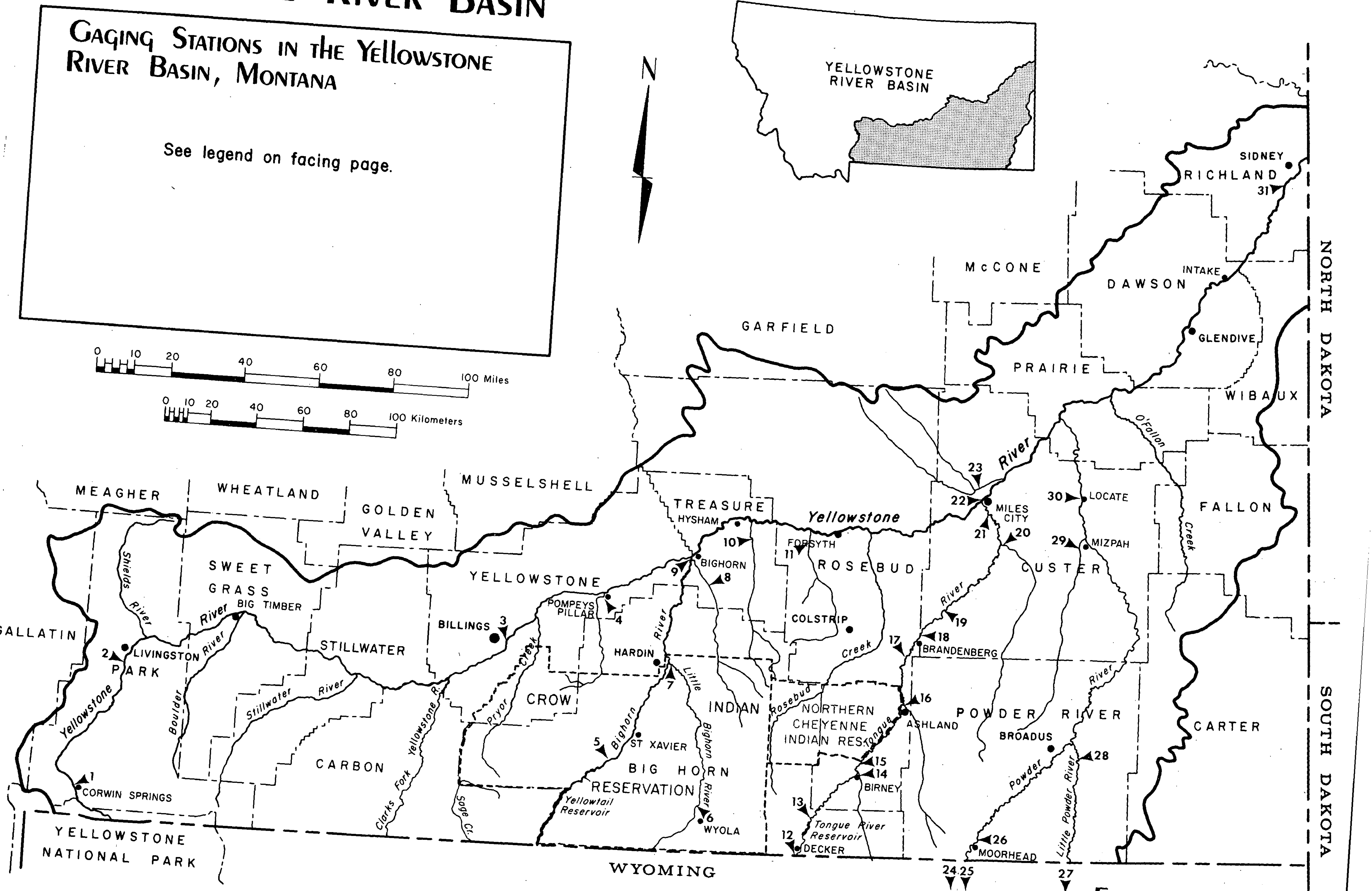


FIGURE 15

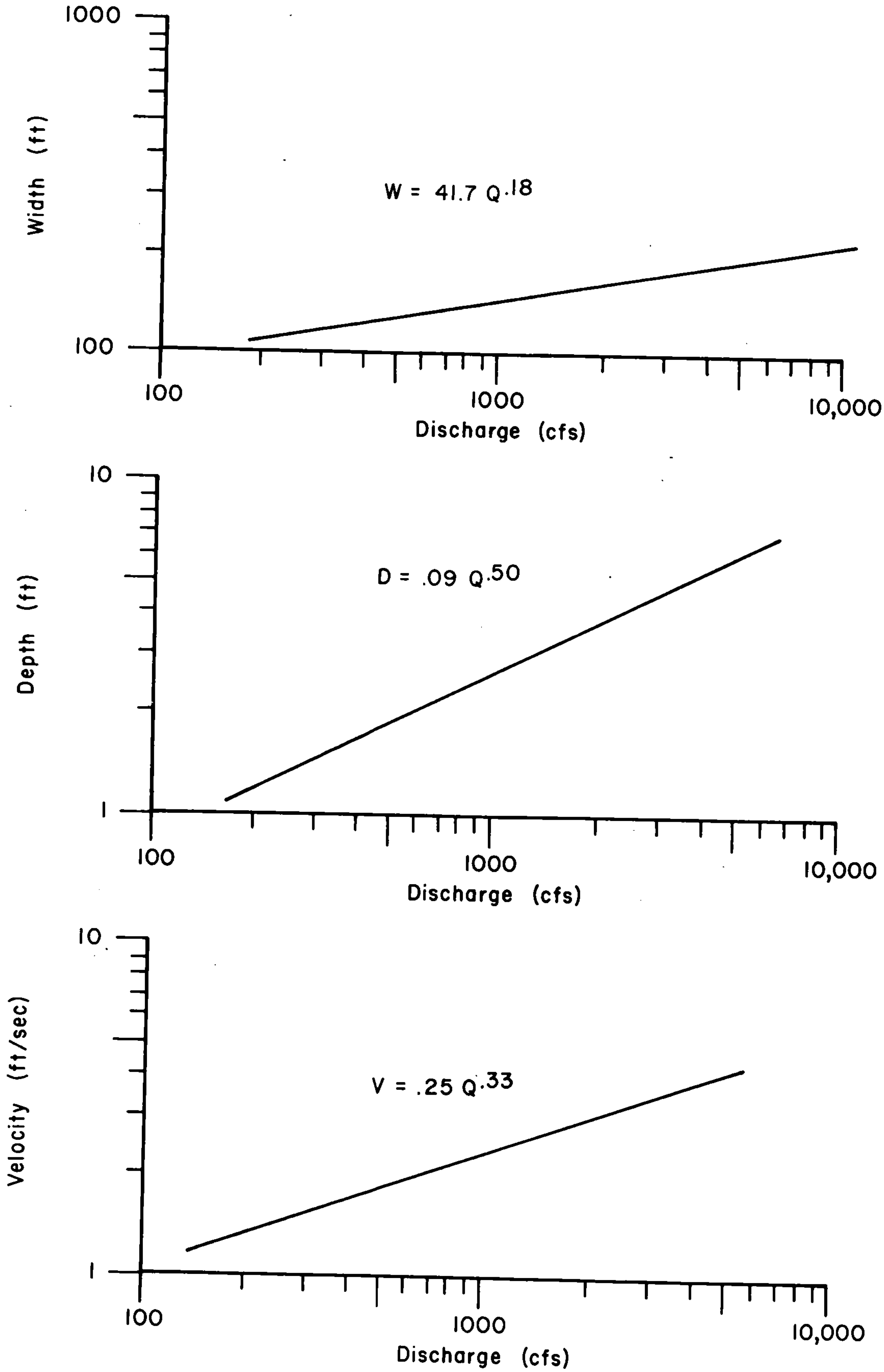


Figure 16. At-a-station hydraulic geometry for the Tongue River at Miles City.

TABLE 12. Comparison of at-a-station hydraulic geometry exponents for the Yellowstone Basin with other published values

River Basin	Average At-a-Station Exponents		
	b	f	m
Bighorn River Basin	.21	.39	.36
Tongue River Basin	.20	.42	.39
Powder River Basin	.32	.38	.32
Mainstem Yellowstone River	.11	.36	.52
Average for Midwestern United States[a]	.26	.40	.34
Ephemeral Streams in the semiarid United States[b]	.29	.36	.34
Average of 158 gaging stations in the U.S.[b]	.12	.45	.43
Some Alaska Streams[c]	.19	.39	.42
Upper Salmon River[d]	.14	.40	.46

[a]Leopold and Maddock (1953)

[b]Leopold et al. (1964)

[c]Emmett (1972)

[d]Emmett (1975)

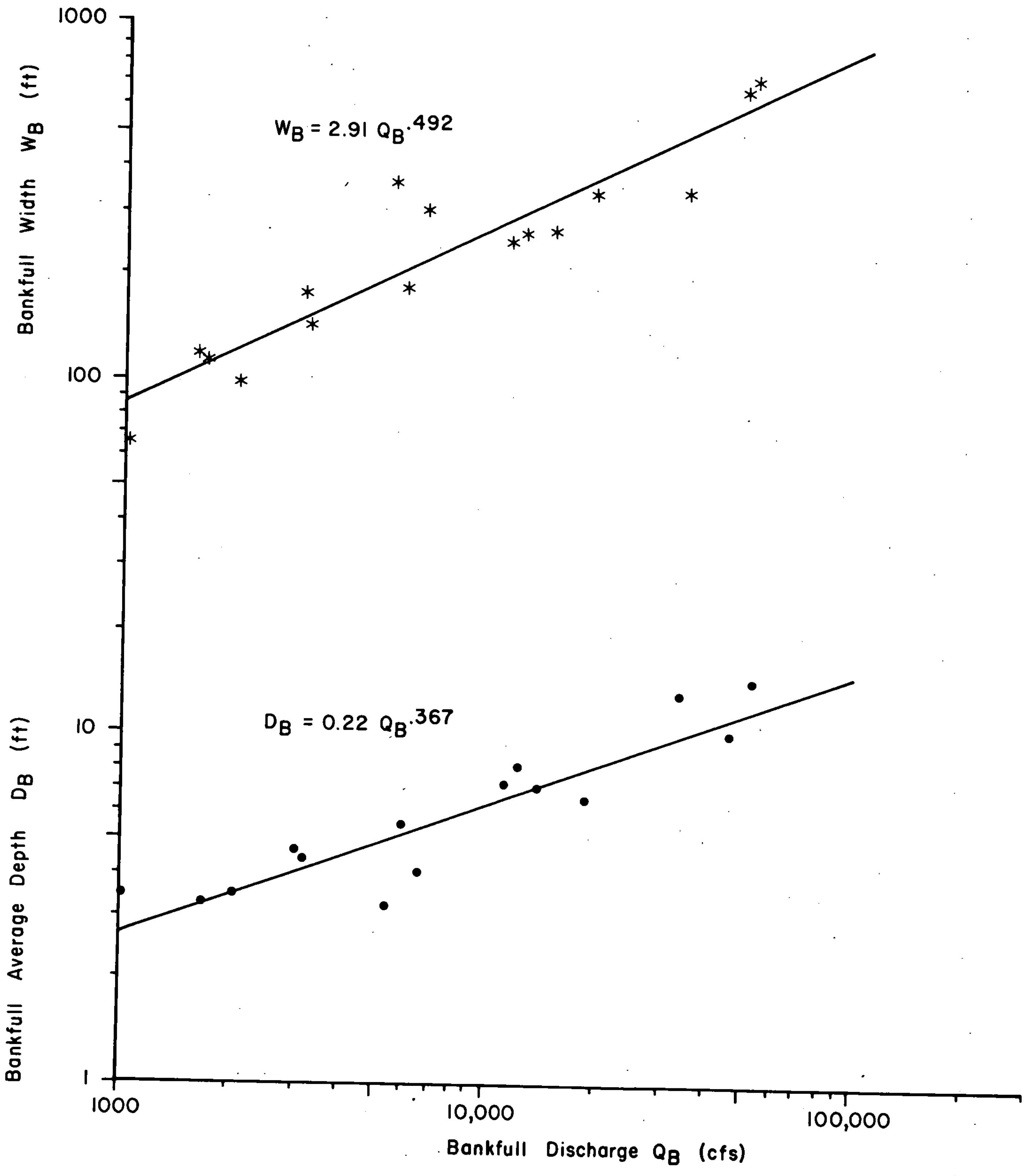


Figure 17. Lower Yellowstone River Basin constant-frequency hydraulic geometry: W_B and D_B

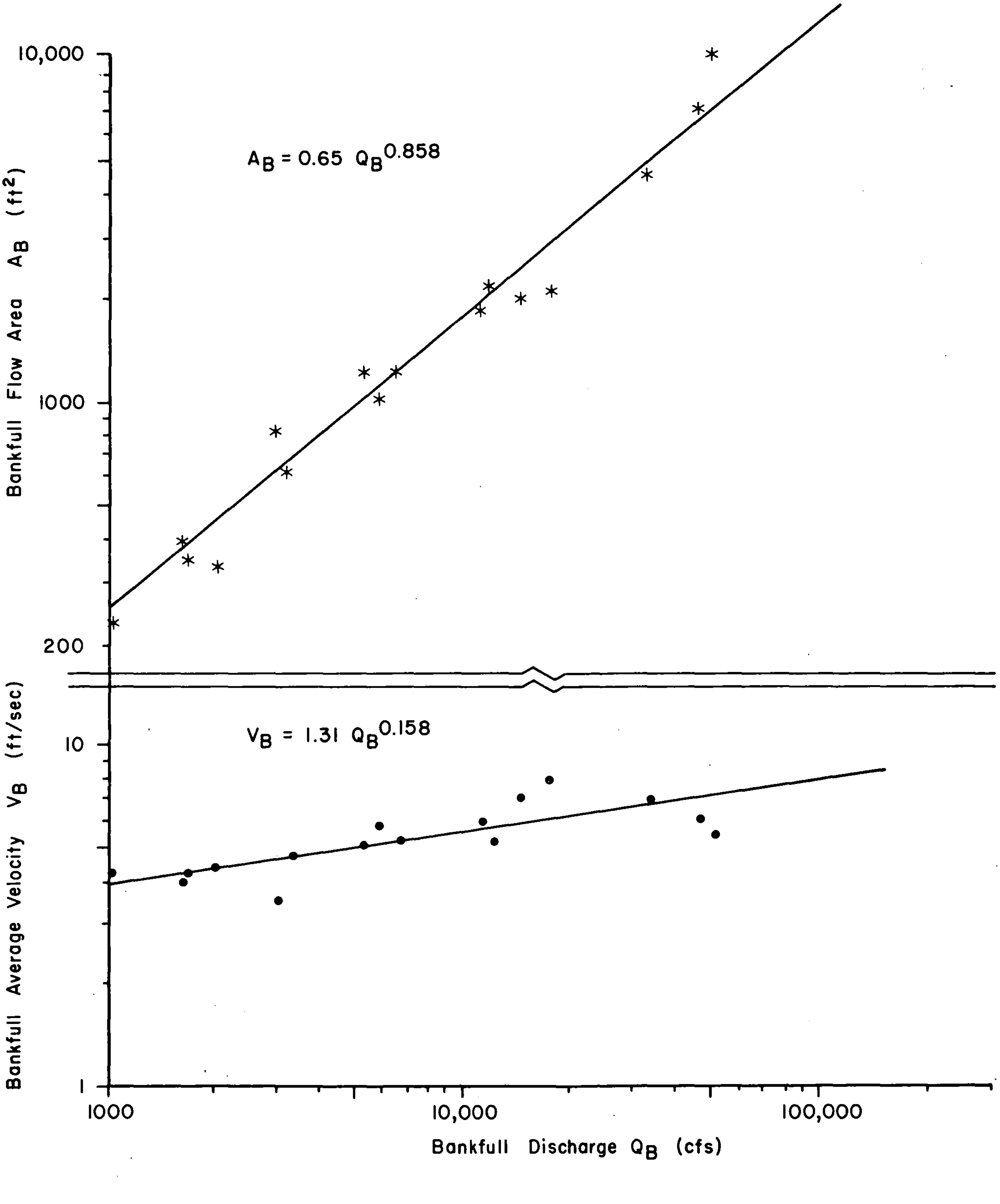


Figure 18. Lower Yellowstone River Basin constant-frequency hydraulic geometry: A_B and V_B

DIMENSIONLESS HYDRAULIC GEOMETRY

An outgrowth of the constant-frequency analysis is the dimensionless rating curves given by these equations (where B denotes bankfull):

$$\frac{W}{W_B} = \left(\frac{Q}{Q_B}\right)^b \qquad (8)$$

$$\frac{D}{D_B} = \left(\frac{Q}{Q_B}\right)^f \qquad (9)$$

$$\frac{V}{V_B} = \left(\frac{Q}{Q_B}\right)^m \qquad (10)$$

$$\frac{A}{A_B} = \left(\frac{Q}{Q_B}\right)^{b+f} \qquad (11)$$

When flow duration and flood frequencies are attached to these curves, the result is useful in estimating channel characteristics or flow rates. The rating curves developed for the mainstem Yellowstone River, Bighorn River, Tongue River, and Powder River basins are presented in figures 19 through 22. Each of these rating curves may be used to estimate channel characteristics for a similar stretch of channel. Because USGS gaging station data were used, the curves should be used only for relatively straight stretches above relatively stable flow controls. Flow rates determined from these relations can be assumed constant through a reach of river, providing there is no significant inflow or diversion in the reach.

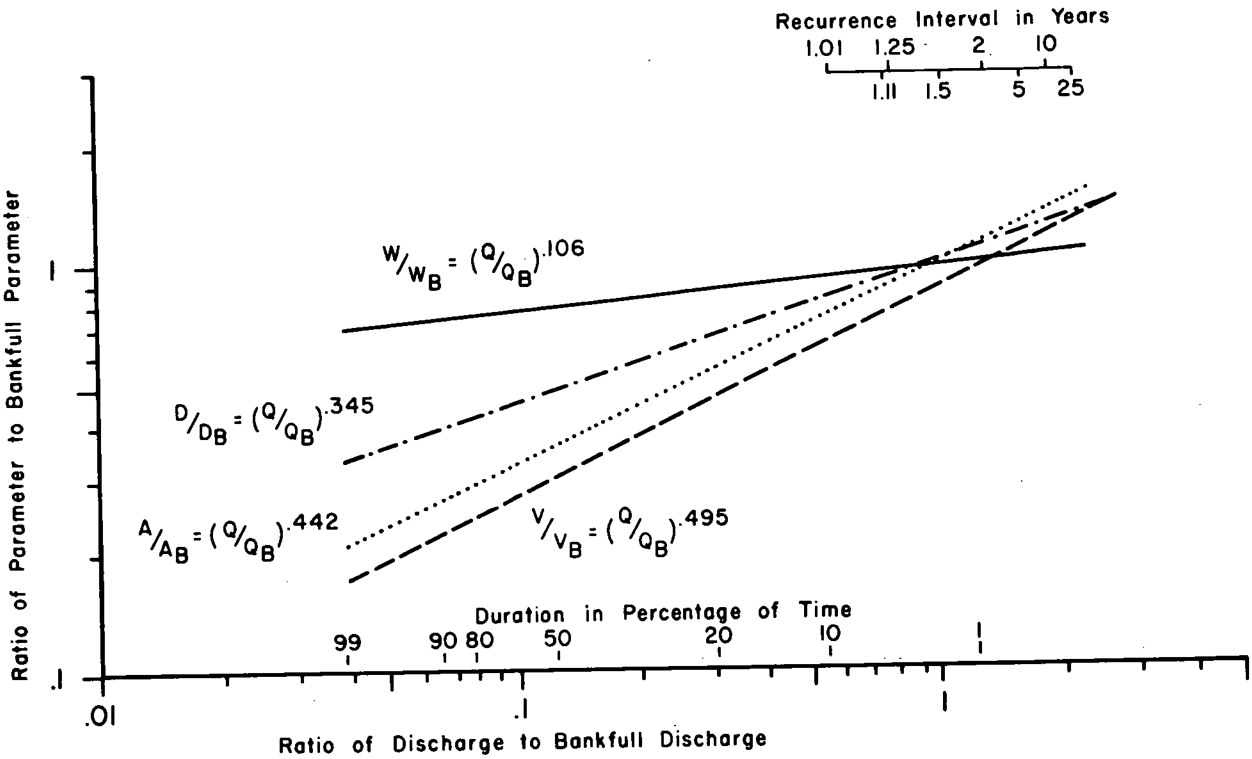


Figure 19. Dimensionless rating curve of the Yellowstone mainstem.

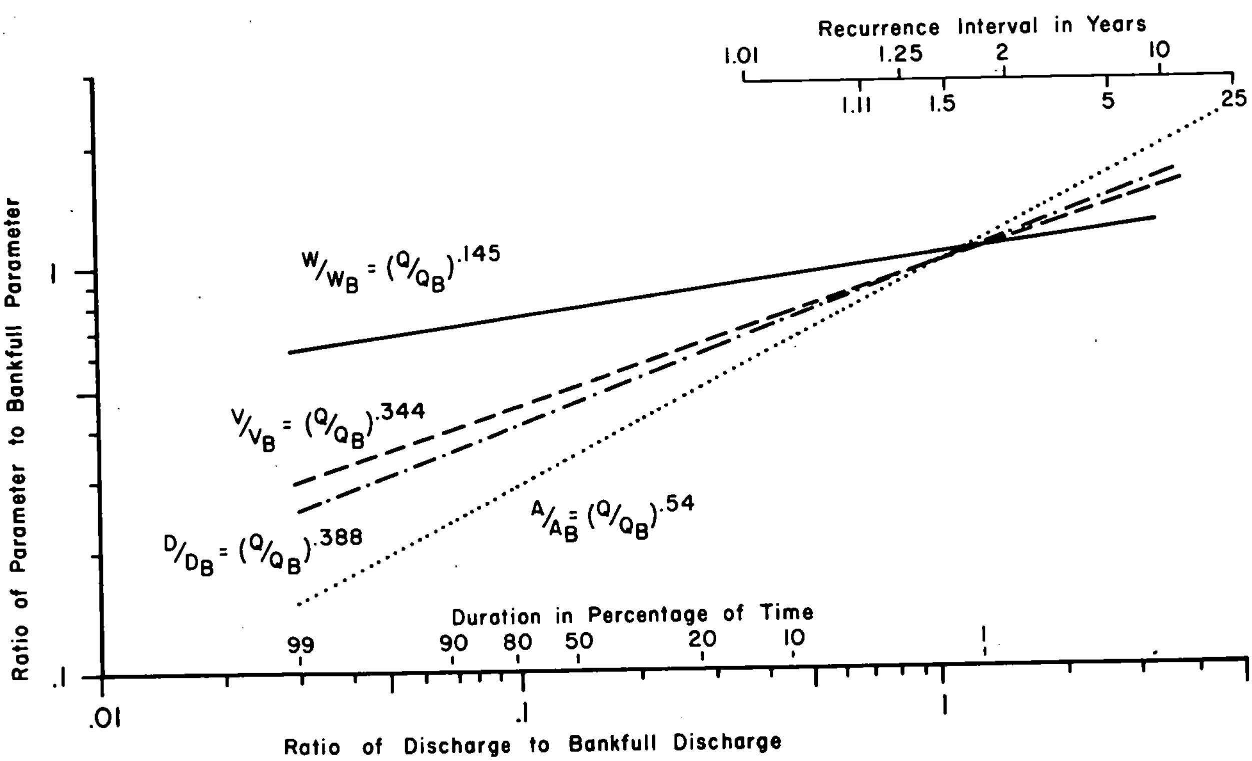


Figure 20. Dimensionless rating curve of the Bighorn River.

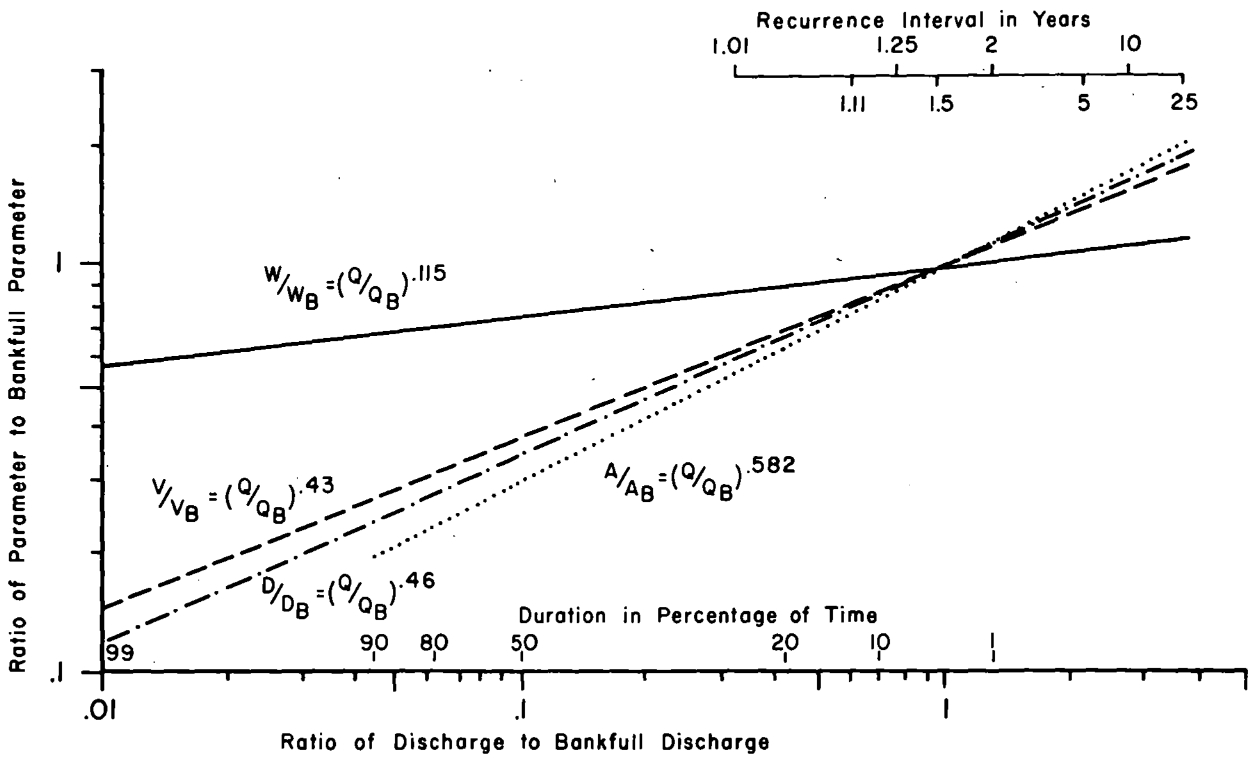


Figure 21. Dimensionless rating curve of the Tongue River.

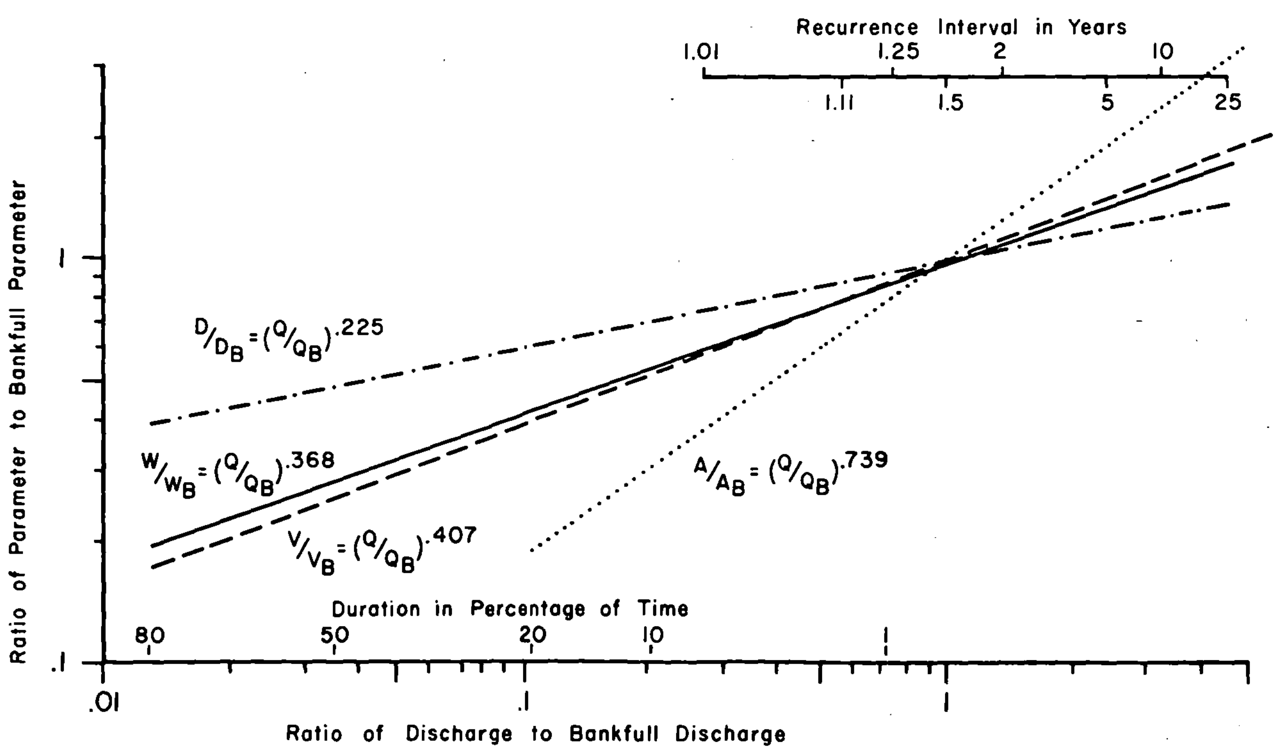


Figure 22. Dimensionless rating curve of the Powder River.

Bed material and sediment transport

BED MATERIAL

The results of pebble counts of bed material taken on midchannel bars within the portion of the river studied are presented in figure 23. Based on the size classification given in table 13, the great majority of the surface bed material is in the gravel size range. Bulk samples of the top one foot (.31 m) of the bed material were also taken; the results of a sieve analysis of these samples are presented in figure 24. It can be seen that the percentage of sand in the bulk samples is considerably larger than in the surface samples, a common situation in most gravel-bed rivers because the sand on the surface of the bed is winnowed out, leaving an armoring layer. In addition to the lack of sand on the surface of the bed, the gravel particles are interlocked as shown in figure 25. This interlocking would tend to make movement of the bed even more difficult, since this interlocking would first have to be disrupted.

TABLE 13. Sediment Size Classification

Size	Classification
64mm and larger	cobbles
2mm to 64mm	gravel
0.062mm to 2mm	sand
0.004mm to 0.062mm	silt
.00024mm to 0.004mm	clay

In the lower reaches of the river, near and downstream from Sidney, the bed material changes from gravel to predominantly sand. An analysis of data on bed material at the Sidney station collected regularly by the USGS shows that, except during the highest discharges, the bed material has a mean diameter of near 0.250 mm. Therefore, this section of river is more typical of a sand-bed river than of the gravel bed observed in the upper reaches.

SEDIMENT TRANSPORT

The transport of sediment in a river is the process by which the system maintains an equilibrium among the material delivered to the channel via the watershed, the makeup and form of the bed, and the discharge of water. Sediment may be transported either in suspension (where the turbulent forces of the flow are sufficient to counteract the gravitational forces on the particle) or as bedload (where the particles are moved by rolling, sliding, and bouncing along the bed of the channel). Bedload has the greater influence on channel form and characteristics. Unfortunately, less is known about bedload in terms of mechanics of motion and relationships to other hydraulic parameters.

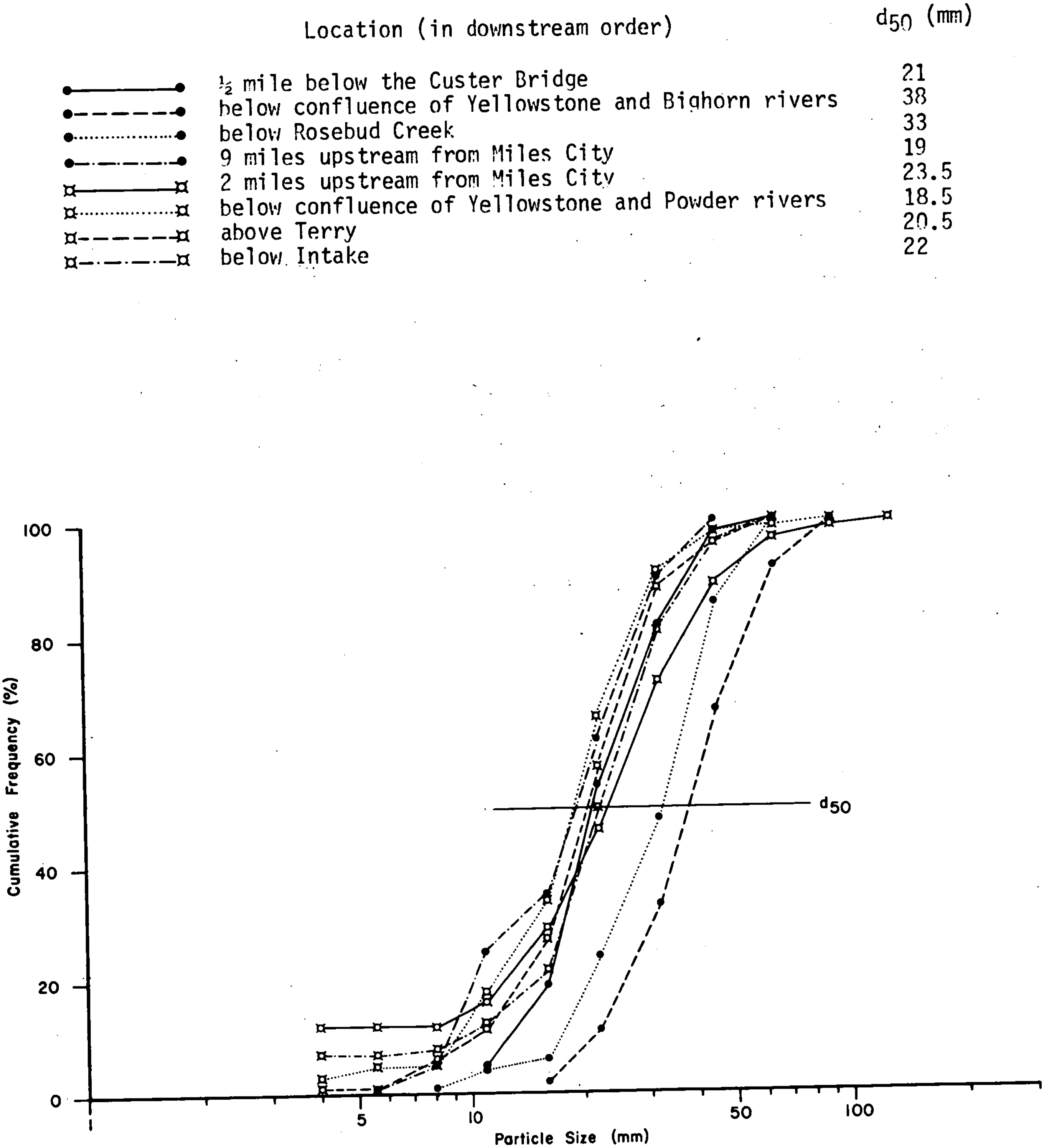


Figure 23. Grain size distribution from surface pebble counts on the lower Yellowstone River.

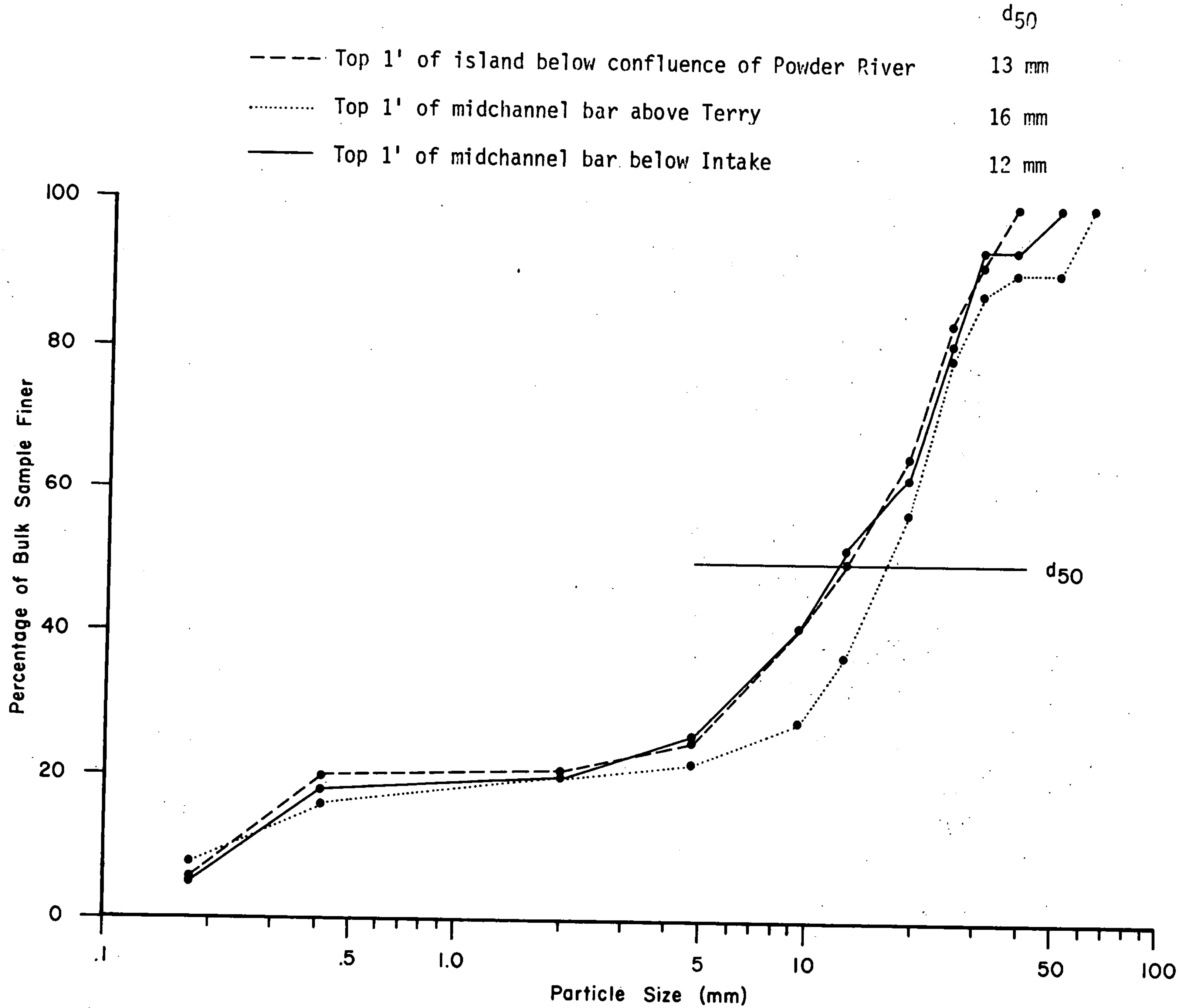


Figure 24. Bed material bulk samples.

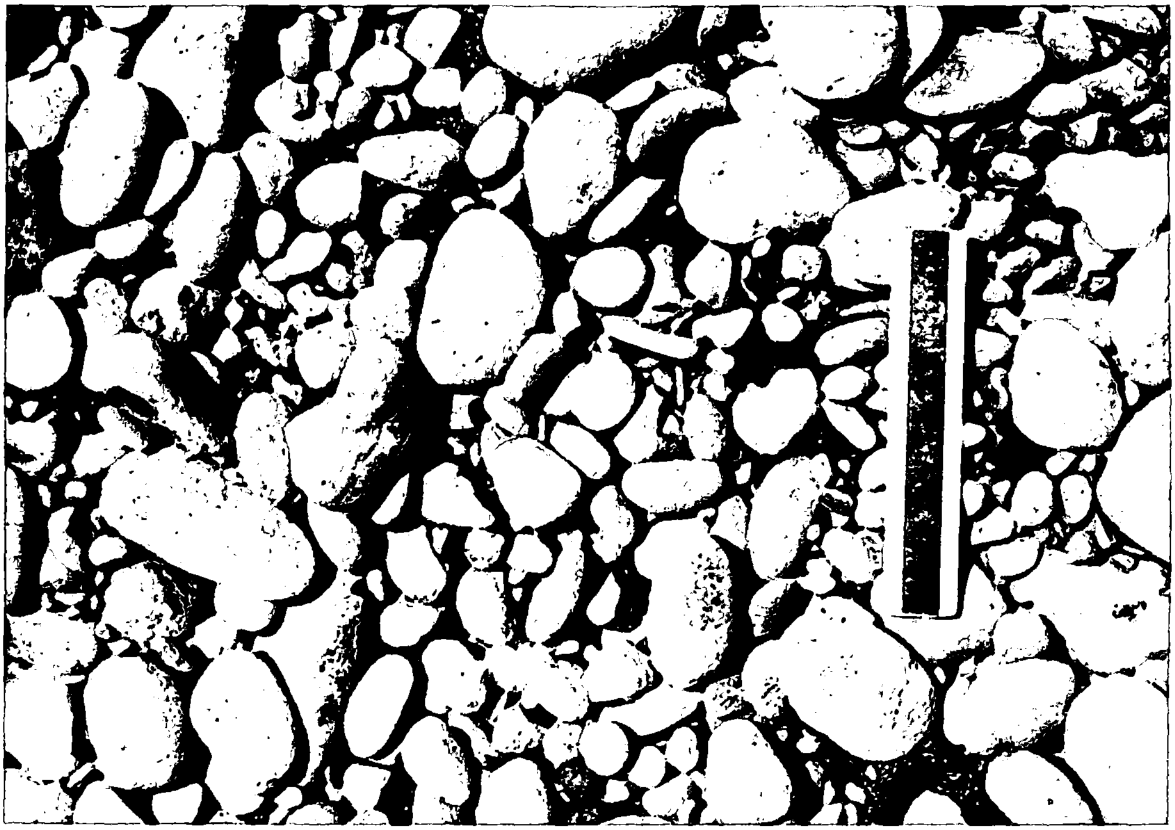


Figure 25. Typical bed material for the Yellowstone River above Sidney.

SUSPENDED SEDIMENT

Data on suspended sediment have been collected at several stations in the watershed; however, a continuous record has been collected in Montana only at those stations presented in table 14. Figures 26 and 27 are the rating curves of suspended sediment vs. discharge for the major sediment-producing areas in the basin. Suspended sediment is made up of sand, silt, and clay material. The latter two, classed as fine material, are a product of the watershed and have little influence on the channel form or sediment transport. These fine materials serve to slightly increase the velocity and density of the fluid, thus decreasing particle fall velocity and, therefore, increasing the transport of coarser sediment, particularly sand. Therefore, large increases in fine material will lead to increases in transport of the coarser fraction. The portion of sand transported as suspended load is related to discharge in figure 28 for the Sidney station.

Development of onstream storage reservoirs in the basin has altered suspended sediment transport. The long period of record for the Bighorn River at Bighorn (26 years) allows the investigation of this alteration. Figure 29

TABLE 14. Suspended sediment data for the Yellowstone River Basin

Station	Period of Record[a] (years)	Sampling Frequency	Average Flow[a] (acre-feet)	Average Suspended Load (T/yr)	Unit Sediment Production ($T/mi^2/yr$)
Bighorn River at Bighorn	26	daily	2,752,000	5,123,585	224
Little Bighorn River near Hardin	6	daily	327,000	396,273	306
Tongue River below Brandenburg Bridge	1	daily	641,000	267,828	66
Tongue River at Miles City	5	daily	258,000	568,000	105
Yellowstone River at Miles City	3	daily	8,920,000	16,580,000	344
Powder River at Moorhead	1	daily	489,000	5,763,551	713
Powder River near Locate	4	daily	392,000	6,032,000	468
Yellowstone River near Sidney	37	daily	9,194,000	25,051,000	260

CONVERSIONS: 1 cfs = .028 cms
1 ton (short) = .91 metric ton
1 $T/mi^2/yr$ = .35 metric $tons/km^2/yr$

[a]Only those years of record were included in this table for which sediment records were available. For that reason, the periods of record are not as long as they would have been for these stations if only flow records had been sought, and the "average flow" column reads differently than it would have if all years of flow record had been included.

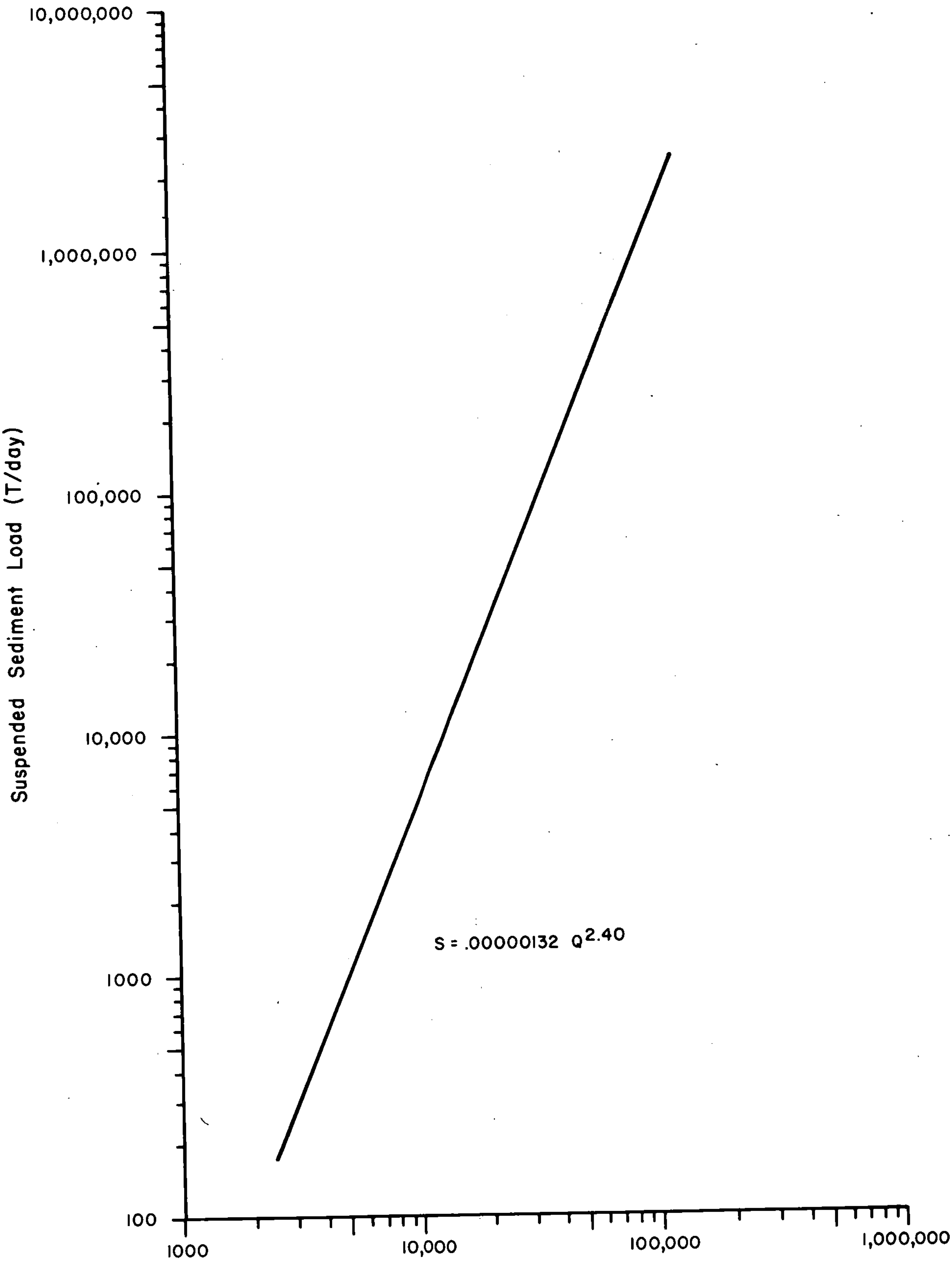


Figure 26. Suspended sediment load vs. discharge: Yellowstone River near Sidney.

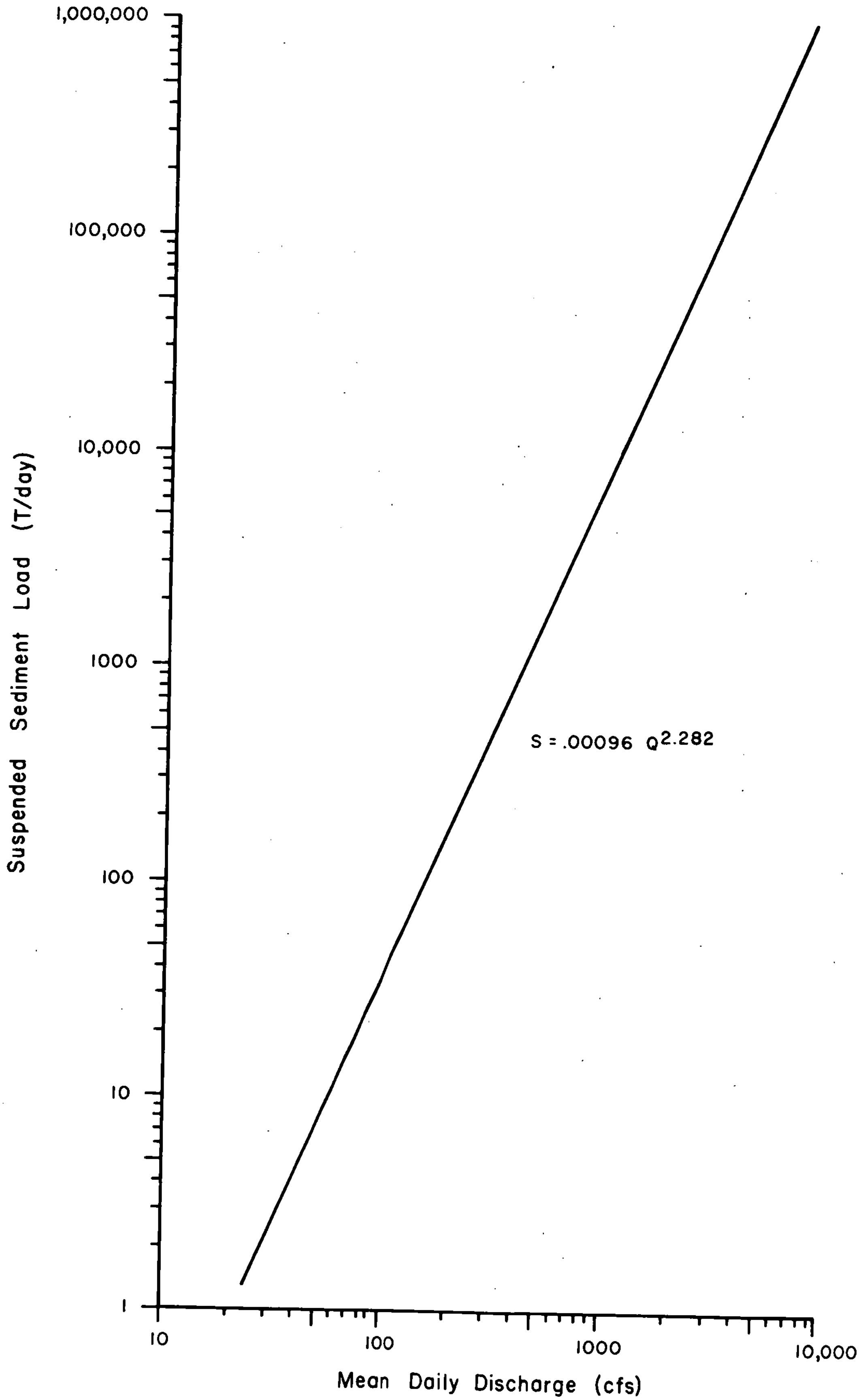


Figure 27. Suspended sediment load vs. discharge: Powder River near Locate.

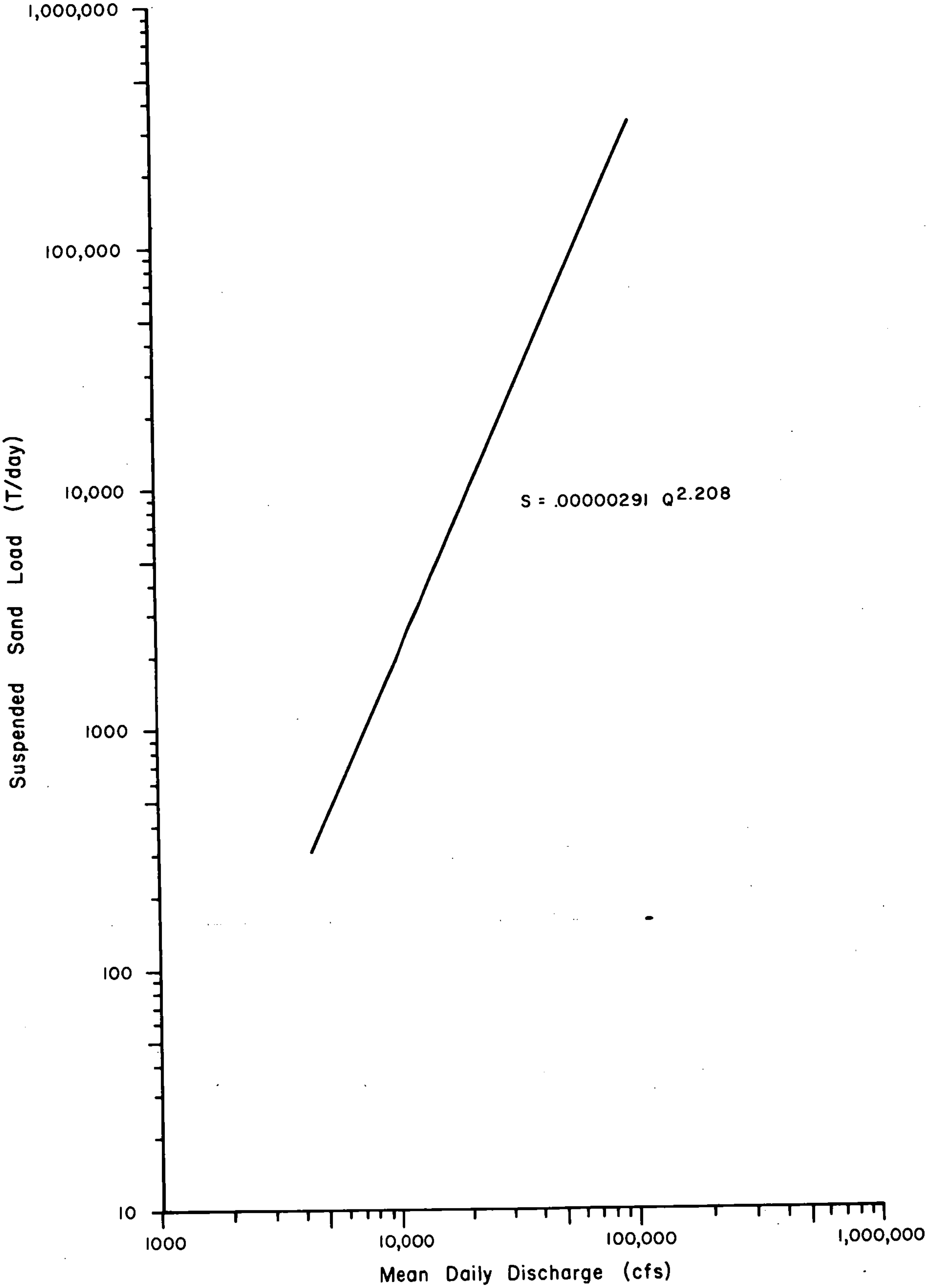


Figure 28. Suspended sand load vs. discharge: Yellowstone River near Sidney.

shows the relationship over time of the total annual streamflow to the total suspended sediment discharge. Although the closure of Boysen Dam seems to have had little impact on the sediment yield of the basin, the completion of Yellowtail Dam has affected the sediment yield significantly. From 1948 to 1965, the average runoff was 2,712,000 af (3340 hm^3), and the average annual suspended sediment production, 7,252,604 tons (6,579,562 metric tons). During the 6 years that data were collected after Yellowtail construction, the average annual runoff was 2,857,000 af (3520 hm^3), similar to that of the previous period, but the sediment in transport averaged only 1,515,990 tons (1,375,306 metric tons) annually. This change in sediment transport due to trapping most of the incoming sediment in the reservoir is also demonstrated in figure 30, where successive suspended sediment rating curves for the Bighorn station are shown. As can be seen in figure 30, the sediment production before and after the closure of Boysen did not differ significantly. After the closure of Yellowtail Dam, however, the relation was markedly altered, indicating the loss of incoming sediment. In addition to the shifting in the curve, the correlation between the sediment load and discharge decreased greatly, indicating a decreased dependence of sediment discharge on streamflow.

A corresponding change in sediment transport on the mainstem of the Yellowstone River, as reflected by records at the Sidney station, is not yet apparent. A long record of daily suspended sediment data exists at the Sidney station. Comparison of suspended sediment rating curves from periods before and after the closure of Yellowtail Dam reveals no trend to a change in slope, indicating that sediment previously in storage in the bed and banks along the mainstem is being removed to accommodate the decreased sediment inflows of the Bighorn River; prior to the closure of Yellowtail Dam, the Bighorn River contributed from 27 to 38 percent of the sediment measured at Sidney, but since the closure, the Bighorn River has produced only from 5 to 8 percent. At some future time, when a new equilibrium is reached along the mainstem, a shift in the sediment rating curve at Sidney is likely.

BEDLOAD

As stated previously, little is known about the mechanics of bedload transport, and no satisfactory method has yet been established that allows prediction of this phenomenon with any degree of confidence. In fact, complete agreement has not yet been reached on a technique for measuring bedload, although the Helley-Smith sampler is now being used by individuals in the USGS with apparently good results. The mechanics of bedload movement have been described by Simons et al. (1975) as being sudden and erratic with the particles sliding and rolling along the bed; periods of motion are followed by periods of rest. The motion is variable across the channel and with time. Based on this description, Simons et al. state that the statistical analysis of a large number of samples is required in order to estimate the bedload movement in a river. This character of bedload has also been documented by Emmett (1976) for large, gravel-bed rivers where wide variability in bedload transport under the same hydraulic conditions has been observed.

Even though bedload is not easily estimated, and in many cases is 10 percent or less of the total sediment load, bedload transport is the process which has the greatest impact on morphology of the river. Several

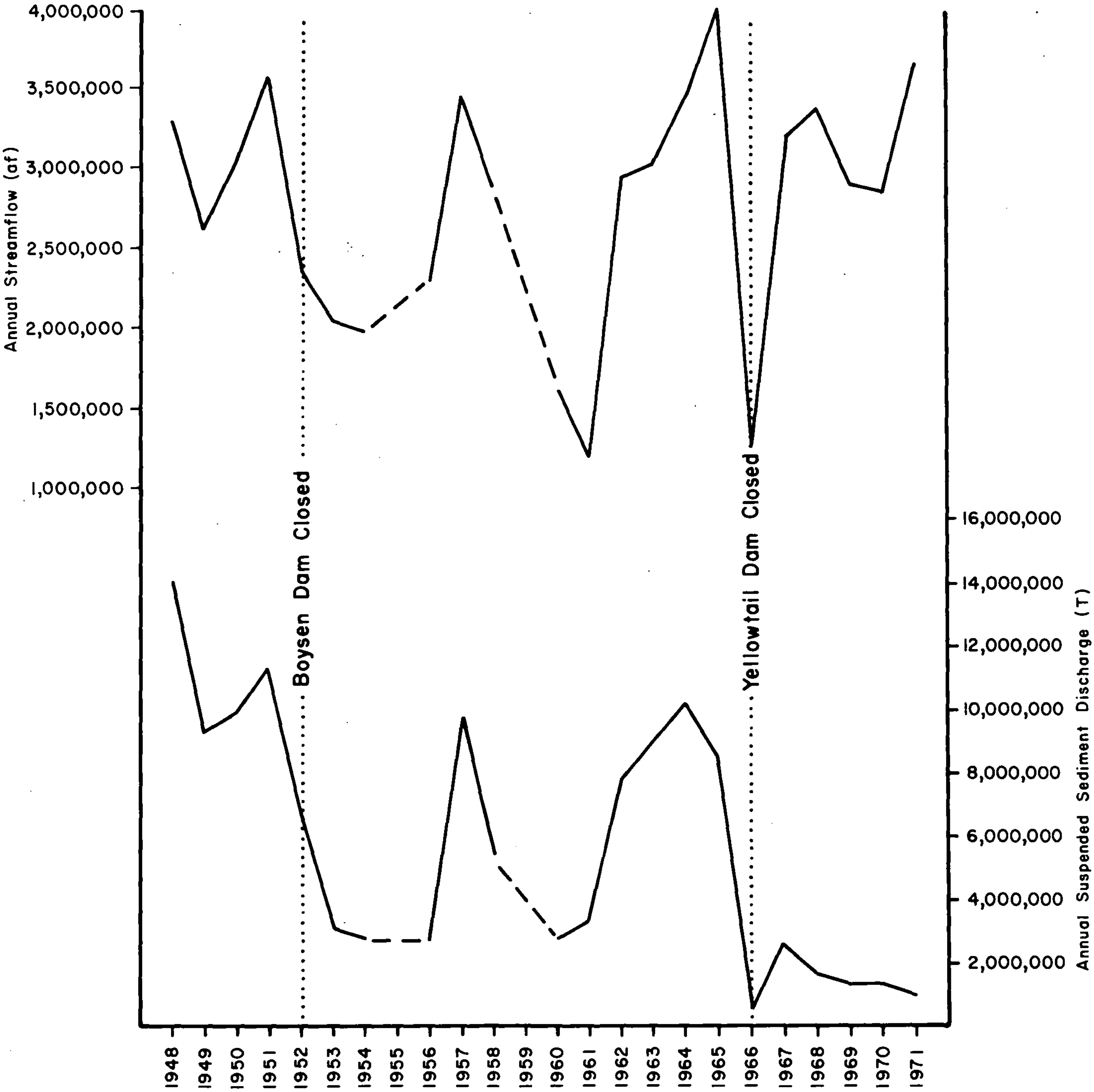


Figure 29. Streamflow and suspended sediment discharges for the Bighorn River at Bighorn.

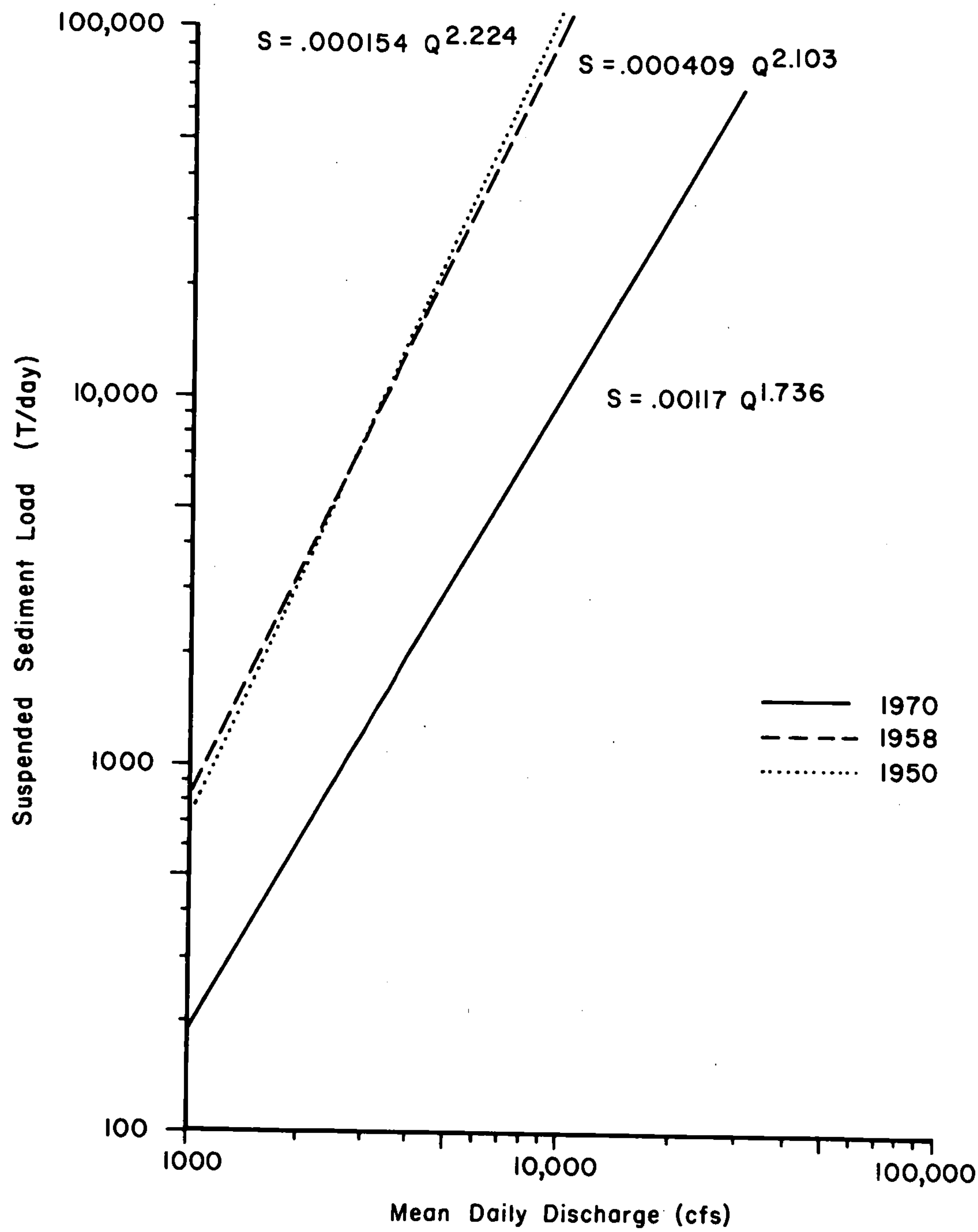


Figure 30. Suspended sediment rating curves for the Bighorn River at Bighorn: 1950, 1958, and 1970.

investigators (Lane and Borland 1954, Schumm 1971) have attempted to estimate bedload from such factors as suspended sediment concentration, bed and bank material, channel geometry, and channel stability. Based on these criteria, the bedload of the Yellowstone could be estimated to be less than 10 percent of the total sediment load.

In hopes of more accurately establishing the relationship of streamflow to bedload, samples were taken at several points along the mainstem of the Yellowstone River using a Helley-Smith sampler with a 3-inch-square orifice and a bag with 0.25-mm mesh. The adequacy of the sampling was, however, subject to both the annual variability of streamflow and technical problems. The streamflows during the 1976 spring runoff period were considerably less than would be desirable for such sampling; the peak flows and corresponding flow frequency are given in table 15. In addition, the loss of a sampler prior to the peak flow resulted in the loss of valuable data. Nonethless, some samples were collected (table 16). Much of the bed material was not moved due to the low peak flows, and sand made up the bulk of the samples. The wide variability of the samples can be seen in the data for the Sidney station, where the bedload shows little relation to discharge. The situation in the Yellowstone River in 1976 was much the same as that encountered by Emmett (1976) on the Snake and Clearwater rivers in Idaho during a low spring runoff event. Only sand and small gravels were in motion on the bed due to the incompetence of the flows to move the larger fraction of the material.

TABLE 15. Maximum flows for the lower Yellowstone River Basin in 1976.

Gaging Station	Maximum Discharge[a] for 1976 (cfs)	Flood Recurrence Interval (year)
Sidney	46,600	1.3
Miles City	45,300	1.4
Billings	39,200	2.0

CONVERSIONS: 1 cfs = .02832 m^3/sec

[a]Maximum mean daily discharge

TABLE 16. Bedload data collected in 1976: Yellowstone River Basin at Sidney

Date	Discharge (cfs)	Bedload Discharge (T/day)	Mean Particle Size (mm)
6/21/76	29,000	216	0.62
6/01/76	27,300	426	0.30
7/31/76	25,000	287	0.27

CONVERSIONS: 1 cfs = .0283 m^3/sec
1 T/day (short) = .907 T/day (metric)
1 mm = .0394 in

Because the sampling data covered such a small range of the particle sizes represented in the bed due to the small peak runoff, it was necessary to estimate the relationship of streamflow to bedload from information available in the literature and from existing data on bed material distribution along the river. Initially, an estimate of that portion of the bed in motion at a given discharge is enlightening because the flows at which the entire bed should be in motion can be estimated. Leopold et al. (1964) presented a relationship between shear stress and particle size. This relationship, which has been shown by Emmett (1976) to be reasonably accurate when applied to bedload data, is based on laboratory and field data. Using these data, figure 31 was developed for the Miles City station, chosen because of the availability of hydraulic data necessary for the analysis. The results must be considered site specific, or at least applicable only to those points in the basin that have geometric and bed material characteristics similar to the station being used. Also shown on figure 31 is the percentage of the bed material in motion at a given discharge and the frequency of occurrence of that discharge. These data indicate that a flood with a recurrence interval of once in two years is necessary to initiate movement of the entire bed. However, because some sections of the channel are deeper than the mean depth, particles larger than those indicated on figure 31 could actually be transported.

According to an analysis presented by Vanoni (1971), several equations can be applied to estimate bedload transport based on data used in development of the relation, particularly sediment size and gradation. In selecting a formula to use in estimating bedload, the character of the bed, the major criterion separating the many different formulas available, must be considered. Also, because the results obtained will still be only an estimate lacking supporting data, a simple equation which has been proven in situations similar to those found along the Yellowstone would be the best choice. Given these criteria, the equation of Schoklitsch (Graf 1972, Vanoni 1971), which was developed using both graded and ungraded sediments up to 5 mm in size, was chosen for the river above Savage. This equation has been successfully applied to two large gravel-bed rivers in Europe. In this reach of the Yellowstone, as discussed previously, the bed material is also gravel. In the river above and below Sidney, a simple rating curve of sand discharge vs. water discharge, previously presented as figure 28 will be used.

The form of the Schoklitsch equation, which incorporates the concept of a critical shear necessary to initiate motion, is given below:

$$q_b = \sum p_i \frac{25.03}{\sqrt{d_{si}}} S^{3/2} (q - q_{ci})$$

$$q_{ci} = 0.0638 \frac{d_{si}}{S^{4/3}}$$

where: q is the water discharge per foot of channel width
q_{ci} is the critical value of discharge for initiating movement
q_b is the sediment transport rate
S is the slope of the stream
d_{si} is the mean diameter of the particle
p_i is the fraction of bed material with mean size d_{si}

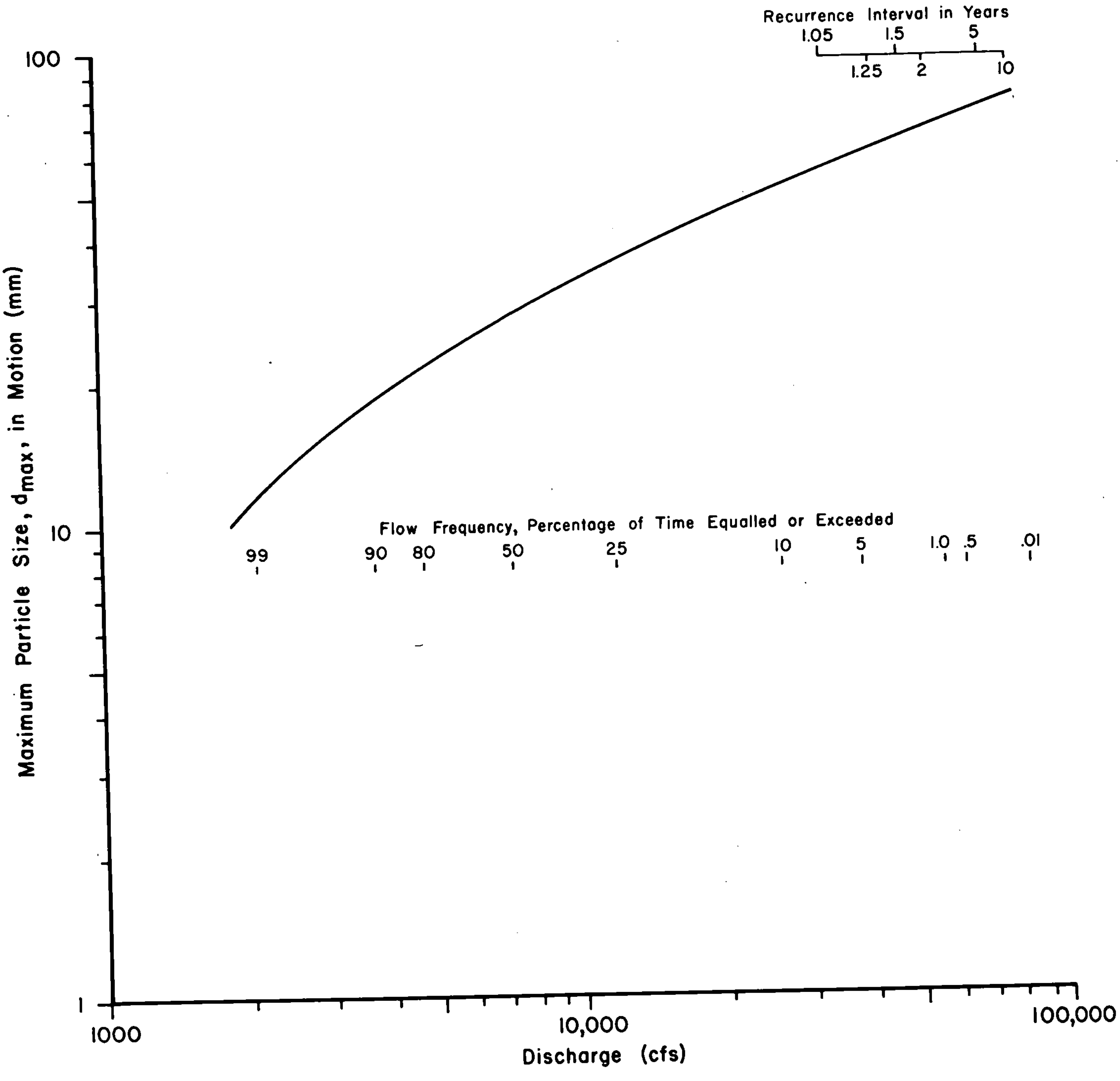


Figure 31. Estimated relationship between discharge and particle size moved for the Yellowstone River at Miles City.

Using discharges and channel geometry at the Miles City station and bed material information for a midchannel bar approximately nine miles above Miles City in a reach similar to the station, figure 32 was developed by applying the Schoklitsch formula. This curve, although hypothetical, shows the rapid decrease in competence to carry bed material with a decrease in discharge, indicating the presence of a point at which the bed is essentially still, with only sand in motion over the larger bed material. However, it should be remembered, as pointed out by Maddock (1976), that the particle size of the bed does not necessarily indicate the particle sizes of the sediment being transported.

Although the rating curve of sediment transport vs. discharge is informative, it does not describe frequency of occurrence of a given discharge nor the importance of a given discharge over the long term. Therefore, figures 33 and 34 were developed for the Yellowstone River at Miles City and at Sidney, respectively. These figures indicate that the flood with the frequency of occurrence of 1.5 years is the most effective discharge in bed sediment transport in the Yellowstone Basin. The other available applicable formulas for modeling sediment transport would have given similar results, since all employ approximately the same form.

Figure 33 is based on the flow duration curve for the USGS gaging station at Miles City and the hypothetical bedload rating curve presenting in figure 32. Figure 34 is based on the flow duration curve and the suspended sand load collected at the USGS gaging station near Sidney.

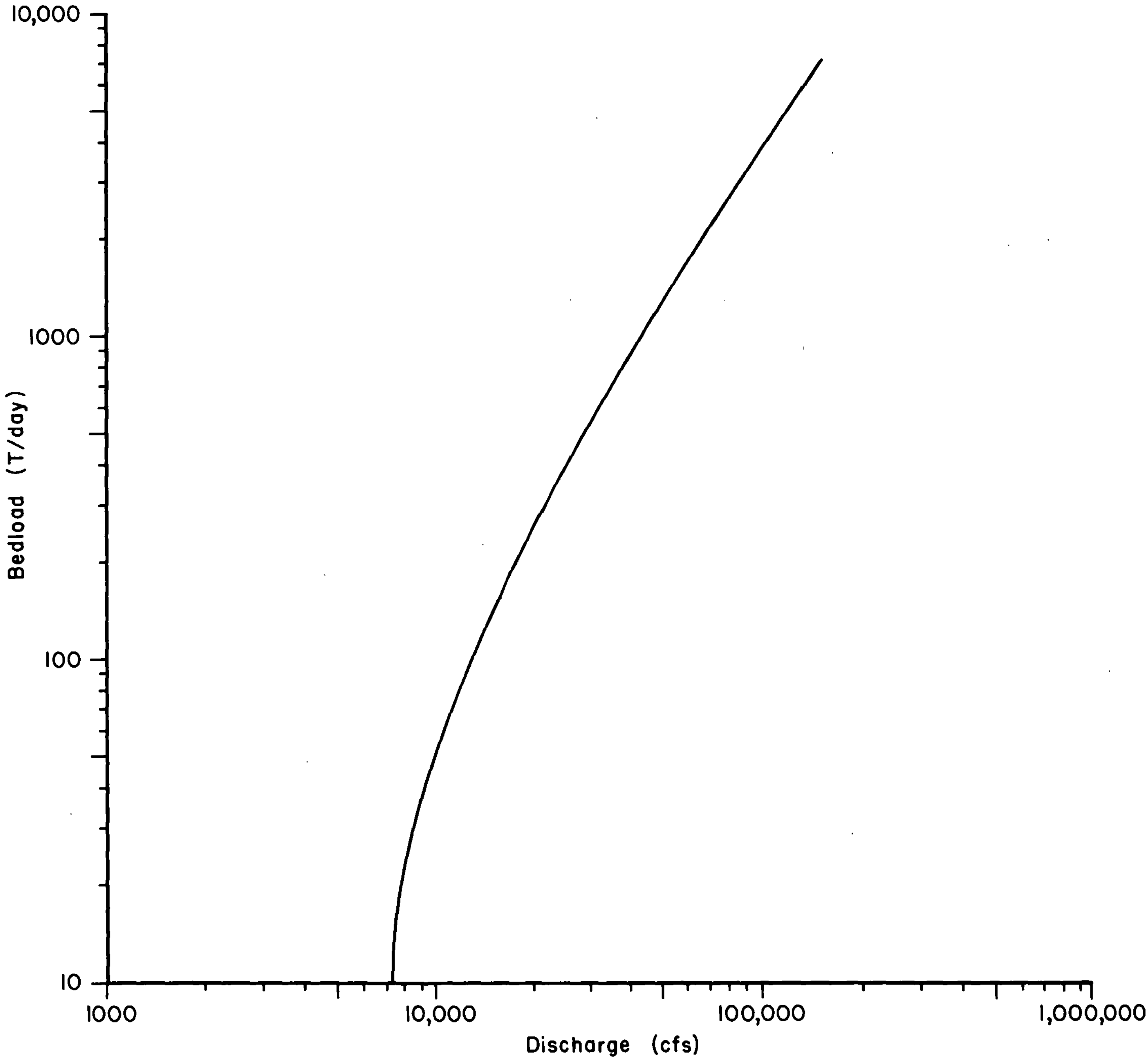


Figure 32. Schoklitsch bedload curve: Yellowstone River at Miles City.

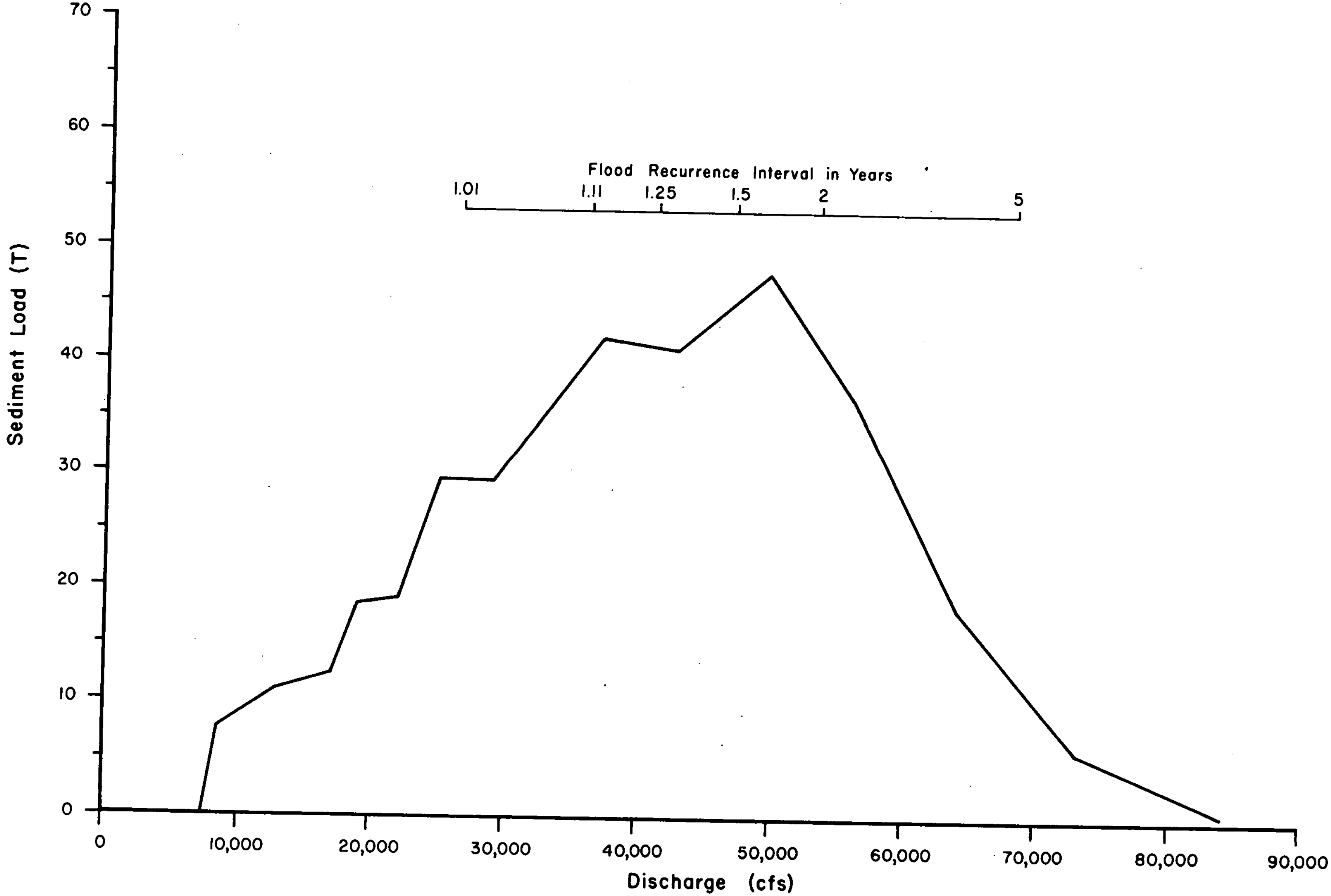


Figure 33. Sediment duration curve showing most effective discharge: Yellowstone River at Miles City.

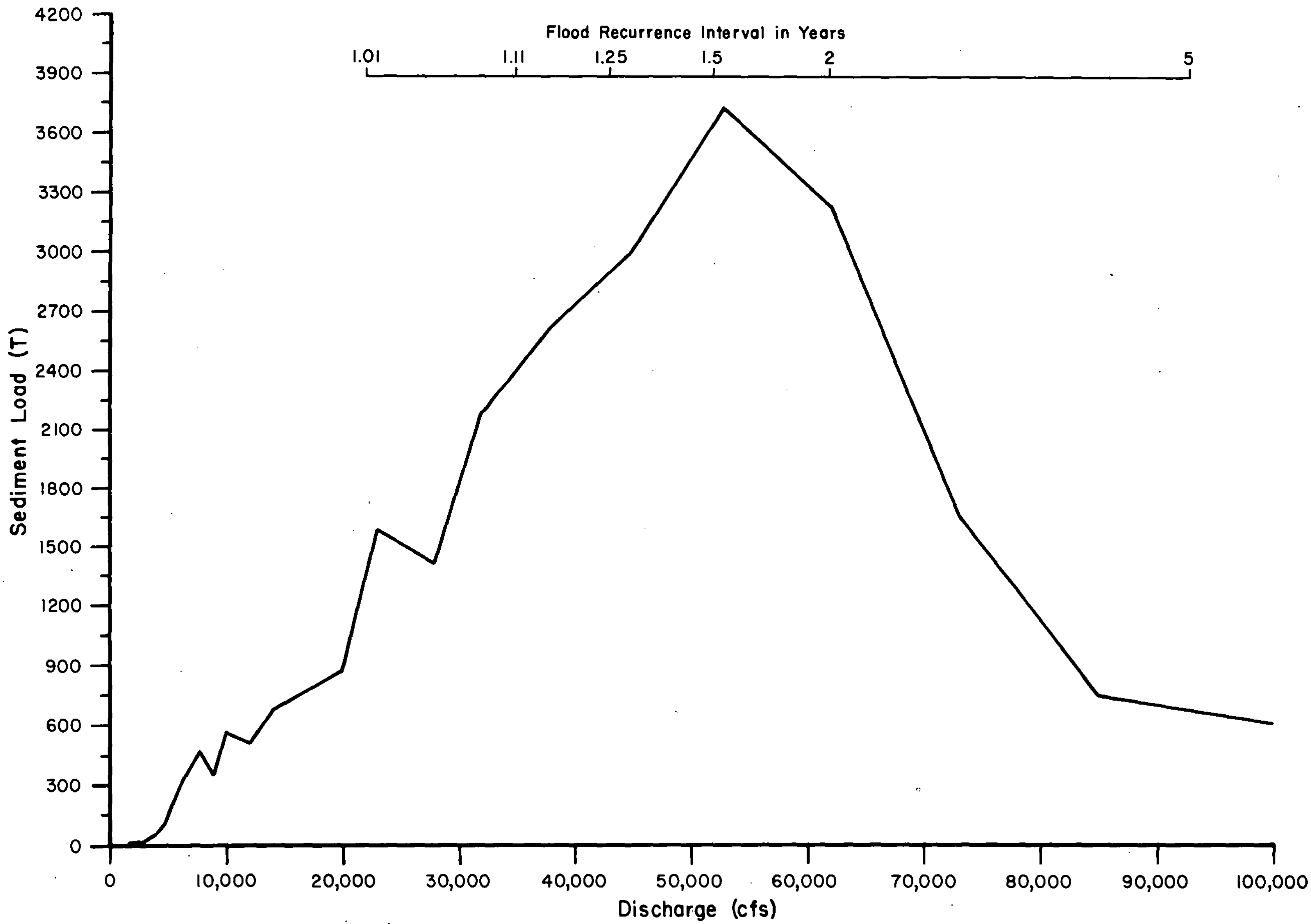


Figure 34. Sediment duration curve showing most effective discharge: Yellowstone River at Sidney.

Impacts of water withdrawals

PROJECTIONS OF FUTURE USE

In order to adequately and uniformly assess the potential effects of water withdrawals on the many aspects of the present study, it was necessary to make projections of specific levels of future withdrawals. The methodology by which this was done is explained in Report No. 1 in this series, in which also the three projected levels of development, low, intermediate, and high, are explained in more detail. Summarized in appendix A, these three future levels of development were formulated for energy, irrigation, and municipal water use. Annual water depletions associated with the future levels of development were included in the projections. These projected depletions, and the types of development projected, provide a basis for determining the level of impact that would occur if these levels of development were carried through.

IMPACT OF WATER DEVELOPMENT ON CHANNEL FORM AND PROCESSES

Development of water in the Yellowstone River Basin could take many forms, and the geomorphic impact would depend on the type of development. In general, as it pertains to geomorphic impact, development could be of two types; onstream storage or diversion. Diversions can be further divided into pumps, headgates, and headgates with a low diversion dam. The general impacts of each of these types of development will be discussed, with particular reference to their probable impact on the Yellowstone River.

IMPACTS OF ONSTREAM STORAGE

The geomorphic impacts of onstream storage reservoirs, which have been well documented (Leopold et al. 1964), result from decreasing the dominant discharge and sediment supply. Directly below a dam, the channel tends to be degraded and/or widened until an equilibrium is reached between channel erosion and stream energy. On the Yellowstone, this equilibrium would probably take the form of armoring of the bed for some distance below the dam. A change in channel form would also be likely due to decreases in discharge and sediment. Figure 12 on page 39 illustrates that decreasing discharge stimulates change toward a meandering channel. A similar change results from decreasing sediment load. Further downstream from a dam, there would be a possibility of aggradation along the mainstem at and below tributaries if mainstem flows were decreased below the level competent to carry the sediment load provided by the tributary streams. Considering the mainstem of the Yellowstone, this aggradation could occur below the mouth of the Powder River, given the large sediment load introduced by the Powder. In addition to aggradation on the mainstem, aggradation could also occur along the lower reaches of the tributaries as a result of the change in base level.

IMPACTS OF DIVERSION

Changes in channel form and sediment transport due to pumping or diversion are not easily assessed because the impact on the system would not be as great. In general, diversion decreases water discharge while the sediment discharge is either not affected, as through pumping, or is decreased only slightly. Decreases in sediment would seldom be equivalent to decreases in streamflow. For direct diversion and pumping developments, a change in channel form from braided to meandering could result if depletions were of great enough magnitude. For a diversion with a small dam, effects similar but much less pronounced than those noted below onstream storage projects would be noted until the area behind the dam filled with sediment. Sediment would then again be introduced to the channel and a slight reverse effect might be expected.

Based on the geomorphic analysis of the five reaches of the Yellowstone identified on pages 19 to 31 and on water use projected in appendix A, reaches 2 and 5 are the ones which could be affected most severely by water withdrawal. As stated previously, Reach 2 is representative of the Yellowstone River from the mouth of the Bighorn River to Forsyth, exhibiting considerable braiding in character; Reach 5 is representative of the river from Glendive to the mouth with much the same character. Impacts can be expected in these reaches due to a combination of the present form exhibited in these reaches and the projected decrease of discharge in them. Reach 1 should not be affected since there is little increased depletion expected above the Bighorn River. Reach 3, with less braiding and fewer islands than other reaches, should retain essentially the same meandering form currently being exhibited. Reach 4 exhibits control of the channel form by bedrock and its incised nature.

In order to adequately assess the impact of the proposed development schemes on the two sections of the river thought to be most likely to change, estimates of the change in flow regime as a result of this development are required. In considering channel morphology, changes in flow in the upper range would be of the greatest interest. Table 17 estimates the impact of development at Miles City and Sidney for the three possible levels of agricultural and industrial development. In general, development impacts are greater on middle and lower range flows than on high ranges; the major impact on flooding would come from new reservoirs in the basin.

These data indicate relatively small changes (on the order of 5 percent) in the dominant discharge, assumed to be bankfull stage. Referring to figure 12 on page 39, it can be seen that changes of this magnitude would result in no significant plotting position for the points in question, and, therefore, changes in channel form would not be expected.

Because stage largely determines the areas inundated during high flows, the relative impacts of these depletions on stage should be assessed. Based on the high level of development for the Middle Yellowstone and the existing stage-discharge relationship, a decrease in stage of approximately 0.2 ft (.06 m) can be expected at Miles City as this discharge is decreased through increased depletions. At Sidney a decrease of 0.4 ft (.12 m) can be expected, based on the depletions of the high development level in the Lower Yellowstone and the existing stage-discharge relationship. Smaller decreases in stage can be expected for lower levels of development. Corresponding to this stage decrease, presented in table 18 are estimates of changes in width, depth, and velocity associated with the decreases in bankfull discharge presented in table 17. These changes are based on the channel geometry relationships at those stations. Changes for lower development levels would be smaller.

TABLE 17. Projected Percentages of Streamflow Depletions in the Yellowstone River

Flow Category	Discharge (cfs)	Depletions (%)		
		High Level of Development	Intermediate Level of Development	Low Level of Development
AT MILES CITY				
Five-year flood	68,000	5.2	3.7	3.2
Mean annual flood	54,000	6.5	4.6	4.1
1.5-year flood	47,000	7.5	5.3	4.7
Mean annual flow	11,420	21.9	15.8	10.5
AT SIDNEY				
Five-year flood	92,000	4.0	3.3	1.9
Mean annual flood	64,000	5.8	4.7	2.7
1.5-year flood	52,000	7.1	5.8	3.3
Mean annual flow	13,070	36.0	29.1	19.1

NOTE: The methodology by which these depletions were projected and the details of the projections are given in Report No. 1 of this series and in appendix A.

Finally, changes in the size of sediment and rate and volume of sediment transport can be estimated from the projected effects of depletions on the existing flow regime. The ability of the Yellowstone River to carry fine sediments is likely to remain unchanged by flow depletions. The competence of the river to carry coarse material will decrease only slightly at bankfull discharge. Using the Miles City station as an example, the change in bankfull discharge associated with the high level of development would amount

TABLE 18. Changes in width, depth, and velocity at bankfull discharge ($Q_{1.5}$) due to decreased flows projected for two Yellowstone River stations at the high development level.

Station	Present $Q_{1.5}$ (cfs)	Percentage Change in $Q_{1.5}$	Percentage Change at $Q_{1.5}$ in: Width	Depth	Velocity
Yellowstone River at Miles City	47,000	-7.5	-0.8	-3.0	-3.0
Yellowstone River near Sidney	52,000	-7.1	-0.8	-2.7	-3.4

to a decrease in maximum particle size moved from 64 to 62 mm, approximately. The change in bedload transport rates is more substantial due to the exponential relation between discharge and sediment transport. At bankfull discharge, the transport of coarse material would be decreased by 10 percent due to the depletion resulting from the high level of development. By changing the flow duration curve, the depletions would decrease the capacity of the river to transport sediment over the entire range of flows experienced; in other words, streamflow depletions would reduce the area under the curve shown in figures 33 and 34. These estimated losses in sediment transport capacity, based on the change in area under the curves, are given in table 19.

TABLE 19. Projected losses in bed material transport capacity for two stations on the Yellowstone River (%)

	High Level of Development	Intermediate Level of Development	Low Level of Development
Yellowstone River near Miles City	28	21	17
Yellowstone River near Sidney	26	21	12

These losses in volume of sediment transported over the long term could have two results. First, as the volume of bed material transported is decreased, the channel forms and patterns dependent on this process must change accordingly. The state of the art does not now permit a quantitative estimate of this impact. It can be said that, first, there is likely to be some long-term decrease in island-forming. Second, since the capacity of the river to transport sediment will be decreased, it is possible that the river will not be capable of transporting the sediments delivered by the tributary basins, leading to aggradation in reaches directly below the confluences. The likelihood of these impacts is, however, not great when several facts are considered. First, the long-term influence of Yellowtail Dam will be to decrease sediment loads in the mainstem, tending to counteract decreases in discharge and prevent overloading problems. Second, it does not appear that any of the tributary streams produce a great deal of coarse material, the common cause of aggradation in channels. Finally, no onstream storage was considered for the mainstem in the study area, implying that large variations in streamflow are still likely even under the high development projection, since canals and pumps are not effective in appreciably affecting peak runoff events. Therefore, the annual scour of any fine material which has settled in pool and backwater areas should continue.

In addition to the mainstem, impacts would result on the major tributaries as a result of increased development. In general, the Bighorn and Tongue river basins, due to their high degrees of regulation and development, are unlikely to be further affected. The Powder River, however, has been subject only to minor individual development in the past, so that a large dam such as the one proposed at Moorhead would significantly affect this river. A dam and associated reservoir near the site of the one proposed for Moorhead would trap 98 to 99 percent of all incoming sediment (Borland 1971). Due to the highly erodable nature of the bed and banks of the river below the reservoir site, it is likely that a great deal of bed and bank erosion would occur along the entire river course, threatening existing diversion and pumping sites.

Finally, it should be noted that any attempt to decrease the impact of diversions during the low-flow period through on-site storage would further decrease peak discharges, thereby increasing the impact on the channel-forming processes.

Summary and conclusions

The Yellowstone River is under pressure from both agriculture and industry as water requirements in eastern Montana increase. The impact of water development, in particular of a decrease in discharge, on the morphology and sediment transport of the river is the subject of this report. These changes, which could affect the aquatic and terrestrial ecosystems, would result from changing the flow regime of the river.

Presently the Yellowstone River exhibits the same form found by Captain Clark in 1806--not that the river has not changed, since change is the character of much of the Yellowstone, but the braided quality of the stream has been maintained. It is this braided character, the most important geomorphic feature of the river, which creates the ecosystem that yields the diversity and abundance of wildlife found along the river. The river sections above Forsyth (RM 238, RKM 383) and below Glendive (RM 96, RKM 154) best exhibit braided form and would be most susceptible to change with depletions of flow.

In the past, water use has increased slowly along the Yellowstone, the major demand being for irrigation. The impact on the bankfull discharge as a result of this type of development has been small. The sediment characteristics in the basin have been recently altered through the construction of Yellowtail Dam, which has decreased the sediment load of the Bighorn River as much as 80 percent.

The levels of depletions considered in this report were small for the bankfull discharge; the relative impact was less for larger flows and greater for lesser flows. The changes in stage resulting from these changes in discharge would also be small, as would changes in width, depth, and velocity. The impact of changes in flow regime on sediment transport would be marked when the effect of this modification on total volume is considered.

Based on the analysis of channel morphology and sediment transport in the lower Yellowstone River Basin, the following specific conclusions can be drawn:

1) The estimated depletion levels will decrease the bankfull discharge for the mainstem Yellowstone River from about 7.5 percent at a high level of development to between 3 and 5 percent at the low level of development. High flows will be decreased by lesser percentages and lower flows by greater percentages.

2) The decrease in river stage caused by projected depletions would be less than 0.2 ft for Miles City and 0.4 ft for Sidney at bankfull conditions.

3) The impact of depletions on width, depth, and velocity would be between 1 and 3 percent at bankfull discharge.

4) The impact of depletions on the transport of bed material is larger than would be expected given the small changes in hydraulic variables. Decreasing the discharge at all frequencies leads to maximum losses of sediment transport of 28 percent at Miles City and 26 percent at Sidney at a high level of development, which could result in a decrease in channel activity, although aggradation in the main channel is unlikely.

5) The impact of the depletions on channel form are a direct result of changes in streamflow and in the concomitant sediment transport. The loss of bed-material transport would decrease channel activity and tend toward a smaller channel with less midchannel bar formation. Quantification of this is not possible.

In general, the impacts of the estimated depletion on the important elements of channel form cannot be quantitatively assessed. A look at history may shed some light on the change to be expected, however. The estimated future depletion, though increased over historical depletion, is of the same order of magnitude, and it appears that historical depletion has not appreciably altered the channel form of the Yellowstone since Captain Clark first described it in 1806. It is likely, then, that future depletion, if confined to diversion and pumping rather than onstream storage, will have a similarly small impact.

Part 11

Vigil Network establishment in southeastern Montana

by

Robert Curry
Mark Weber

Introduction

PURPOSE

Due to the paucity of detailed data on the form and behavior of small perennial and ephemeral streams in the northern Great Plains, there is no reliable data base from which to analyze the geomorphic and hydrologic impacts resulting from existing uses of the land to forecast the extent and nature of the potential impacts resulting from proposed coal-related and agricultural development in many of the watersheds of southeastern Montana. The first objective of this research was to establish quantitative and qualitative biophysical baseline data on the form and behavior of the streams of the Montana portion of the Fort Union Basin. To do so, a network of 22 Vigil monitoring sites was established during the summer of 1975. These Vigil monitoring sites, located on many of the nonglaciated, headwater tributaries to the Yellowstone River, are permanent, bench-marked, and recoverable.

SCOPE

An effort was made to include a broad sampling of stream channel type and size, geomorphic setting, and prevailing land use in the sites selected for inclusion in the Vigil Network. Of the sites surveyed, five are located in first-order watersheds (Horton 1945), five in second-order watersheds, five in third-order watersheds, and seven in fourth-order watersheds (see figure 35). Information collected for each site includes surveyed channel cross-sections, maps, transects of site vegetation, and photographs.

STUDY AREA

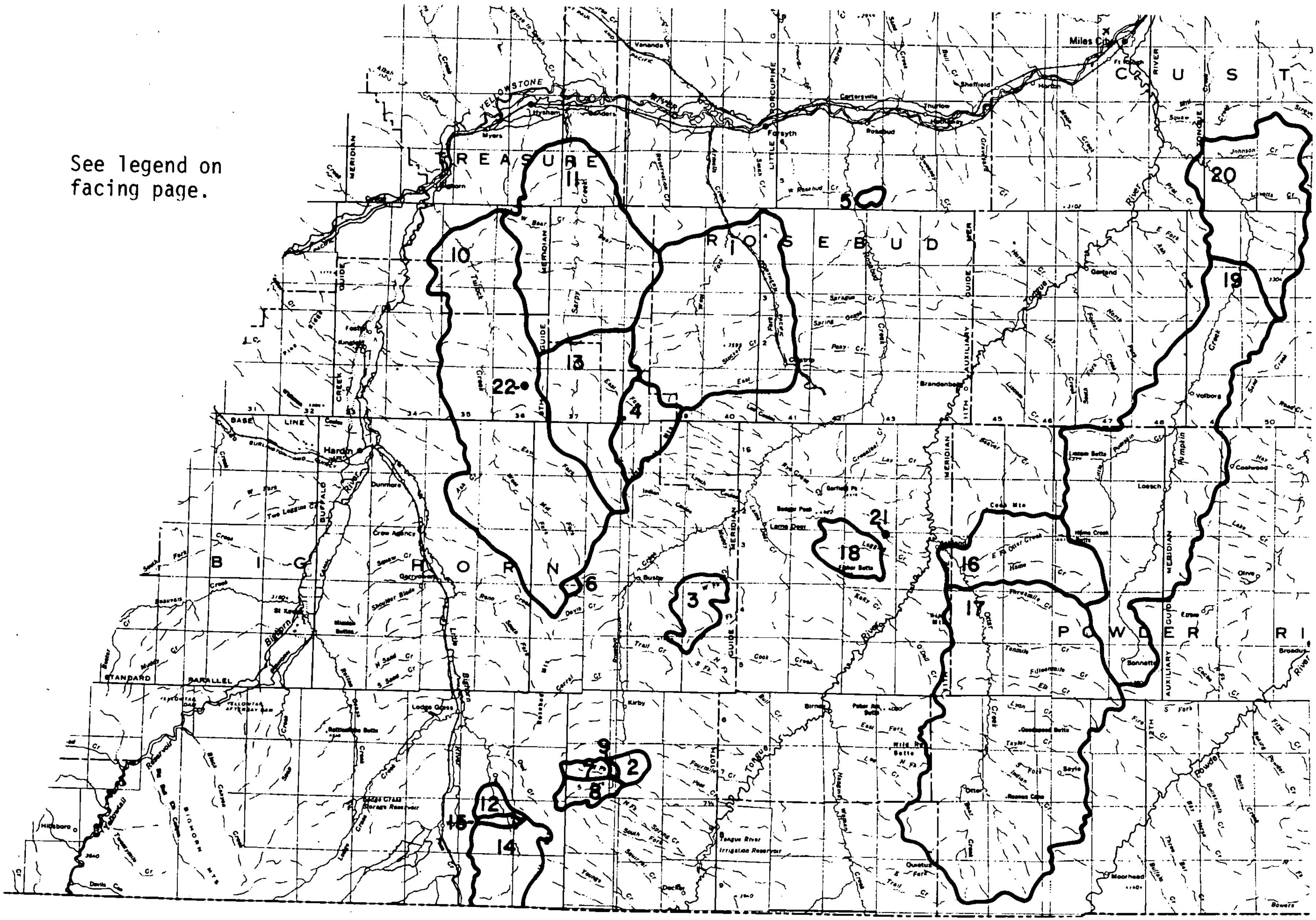
Twenty-two detailed Vigil Network stations were established on tributaries of the Yellowstone River (figure 35).

The relationship of the established Vigil sites to the generalized bedrock geology of the region is illustrated in figure 36. Because the perennial stream valleys of the region are floored by varying thicknesses of alluvium, stream channels through these valleys possess potentially mobile beds and banks. The ephemeral channels surveyed in this study, surrounded by much smaller volumes of alluvium, are more constrained by the local bedrock.

Site No. MY-	Vigil Site Location	Stream Order	Drainage Basin Area (km^2)
21	Tributary to Hollowood Creek[a]	1	2
22	Tributary to Padlock Creek[a]	1	2
6	West Fork Tullock Creek	1	4.5
5	Vance Creek[a]	1	15
7	North Fork Rosebud	1	21
8	South Fork Rosebud	2	47
9	Rosebud at Michael Ranch	2	69
18	Logging Creek	2	74.5
3	West Fork Muddy Creek	2	91
2	Rosebud Creek at Helvey Ranch	2	95
4	East Fork Sarpy Creek	3	136.5
14	Upper Owl Creek	3	170
15	Mid Owl Creek	3	181
12	Lower Owl Creek	3	221
13	Sarpy Creek at Colstrip Bridge	3	524.5
1	Armells Creek	4	807
10	Lower Tullock Creek	4	1163
11	Lower Sarpy Creek	4	1165.5
19	Upper Pumpkin Creek	4	1308.5
17	Upper Otter Creek	4	1516.5
20	Lower Pumpkin Creek	4	1798.5
16	Lower Otter Creek	4	1816.5

[a] Ephemeral stream

See legend on facing page.

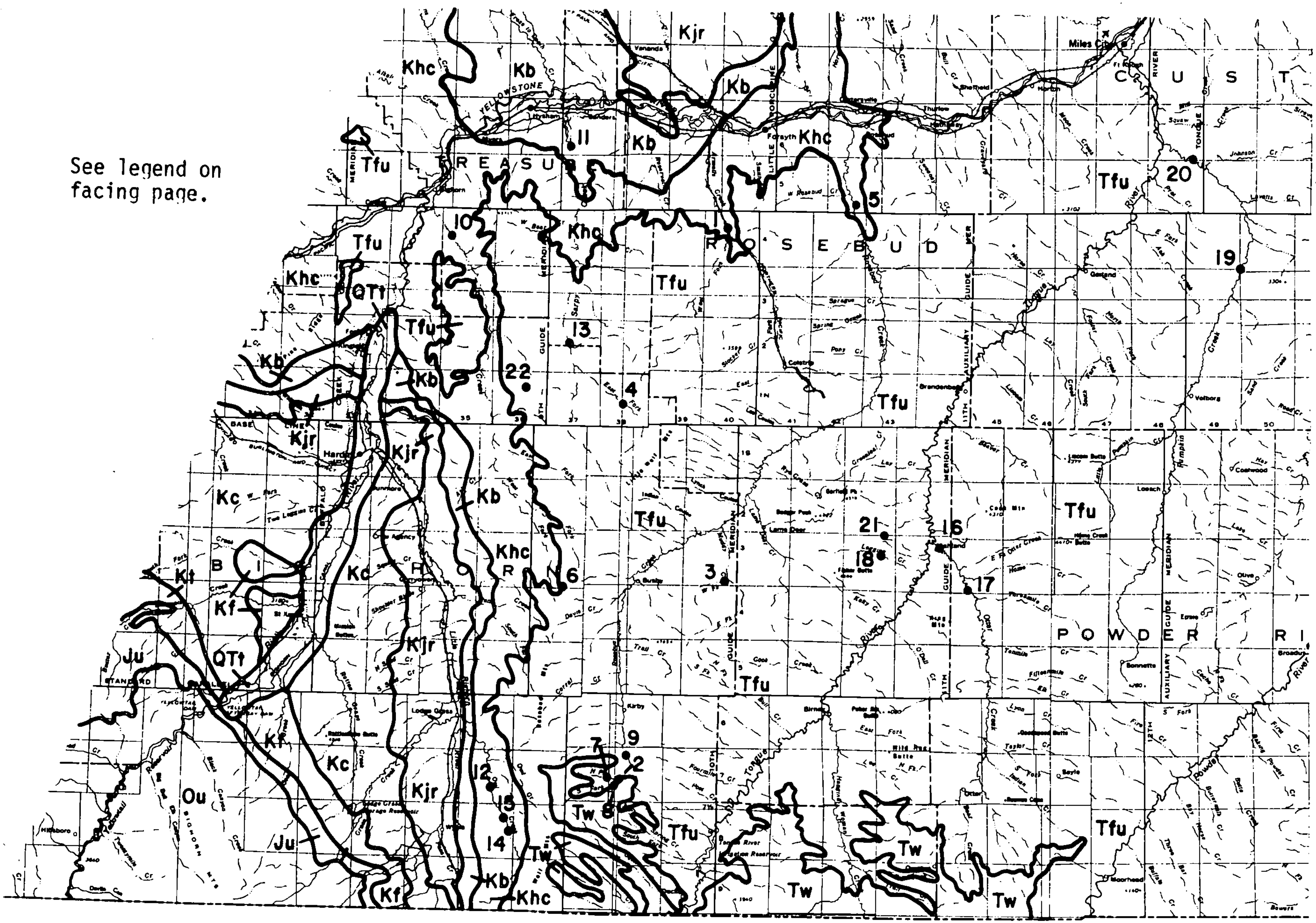


Base Map from USGS

Figure 35. Vigil network stations in southeastern Montana and the approximate boundaries of the watersheds monitored.

QTt	Terrace Deposits	Quaternary
Tw	Wasatch Formation	Tertiary
Tfu	Fort Union Formation	
Khc	Hell Creek Formation	Cretaceous
Kb	Bearpaw Shale	
Kjr	Judith River Formation	
Kc	Colorado Shale	
Kf	Frontier Formation	
Kt	Thermopolis Shale	
Ju	Jurassic, Undifferentiated	Jurassic
Ou	Older Undifferentiated	Prejurassic

See legend on facing page.



Base Map from USGS

Figure 36. Generalized bedrock geology of southeastern Montana.

Methods

BASIC CONCEPTS

Although river and stream channels constitute only a small percentage of the total landscape, their significance is far greater than their areal extent. A perennial stream channel shows the cumulative influence of the watershed's geology, climatology, hydrology, and biology, as does the ephemeral channel in a more complex and poorly understood fashion. The constraints imposed by these variables are traditionally categorized as structure, process, and stage.

The structure of a watershed is determined not only by the sequence and configuration of the rocks, but also by their geotechnical properties, such as susceptibility to erosion, mass-failure potential, and infiltrative capacity. Rivers draining watersheds of differing physical characteristics should differ systematically in form, pattern, rate of change, and the capacity to do work (i.e. transport a suspended sediment load, bed load, or solution load). The degree to which a river is adjusted to the system of structural constraints surrounding it is a measure of the degree to which the river system has approached a long-term equilibrium. This quasi equilibrium may have an important, controlling influence over the kinds of short-term changes the system may undergo.

"Process" refers collectively to all geomorphic agents at work shaping the landscape. The agent primarily responsible for shaping a river channel and a river system is the water flowing in the channel. The magnitude, duration, and frequency of recurrence of runoff events can be major factors controlling the character of a river channel. Thus, the erosional form and pattern of the river channel and the form and character of the resulting stream deposits will reflect both the climatic region in which the river occurs and temporal climatic change.

The stage of development or evolution of a landscape or a river system is a function of the passage of time. Accompanying the passage of geologic time is the progressive erosion of the landscape, the reduction of local relief, and, with the completion of a full cycle of erosion (in the order of magnitude of 100 million years), the denudational lowering of the entire region (e.g. the formation of peneplains as used by Alden 1932). When viewed from this geological context, adjustment of channel grade and form is progressive and continuous, and the attainment of a balanced or equilibrium state is only possible at the conclusion of an erosional cycle. For shorter periods of time, it is possible to identify river systems that make small, incremental changes, but, when the river system is viewed as a whole, the relationships between channel form, pattern, and character remain essentially unchanged. During this state of dynamic equilibrium, minor adjustments in channel morphology result from variations in the biophysical nature of the watershed but no progressive changes occur. Thus, the attainment of dynamic equilibrium in the fluvial system represents the delicate adjustment of the river system to the natural rates of change of the region's biophysical system. Among the system of independent variables, the rate of Quaternary climatic change resulting in cycles of glaciation, pluviation, etc. has been the most rapid and, therefore, frequently the controlling natural variable. Man's land-use practices, whether agriculture, urbanization, or resource extraction, are not considered to be natural variables because man-induced changes in the landscape proceed at rates several orders of magnitude more rapid than changes induced from the other variables (Detwyler 1971, Thomas 1956).

STREAM REGIMEN

Stream regimen is the manifestation of the complex interaction of the physical and hydraulic features of the channel-sediment-water system under the external influences of gravity and friction. The fundamental aspects of stream regimen must, of course, rest upon the hydraulic process attendant to flow in an open channel complicated by variations due to local differences in lithology, topography, climate, and vegetation. However, recognizing that a large number of variables are superimposed upon the basic hydraulic system provides a basis for understanding the quality and perhaps quantity of change resulting from man's impact upon his environment.

If at a given time the stream regimen is adjusted to its boundary variables, then we may think of the stream as being graded. This graded condition as envisioned originally by G.K. Gilbert and discussed by Davis (1894) simply implies a condition of balance between degradation and aggradation and as such describes a temporarily static system. The temporary nature and adjustability of this graded condition was emphasized by Mackin (1948), who stated that the

> graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to adsorb the effect of the change.

Thus, it is this temporal condition of equilibrium or near equilibrium which is striven for by the integration of the physical and hydraulic variables.

The graded stream is commonly considered to be a stream in equilibrium, or perhaps more appropriately a stream in dynamic equilibrium (Strahler 1952, Hack 1960) because the system considered is an open system through which there is a continuous passage of material and energy but no change in the form or character of the stream segment itself. Disruption of equilibrium through one or more changes in the variable system results in adjustments in the form and profile of the stream segment. The magnitude of the resultant change is linked to the duration of change (Leopold et al. 1964) as well as to the magnitude and frequency of change (Wolman and Miller 1960).

The morphology of channels and the factors controlling this morphology have been studied at great length with moderate success over the last few decades. Prominent contributors include Leopold, Wolman, Miller, Schumm, Langbein, Hack, Rubey, and Strahler. The study of their combined effort suggests that the morphology of a stable stream channel is determined by the amount of fine-grained, cohesive sediment in the bed and banks of the channel and by the discharge and the sediment load that move through the channel (Schumm 1960, 1968). The greater the discharge (Q), the larger the channel width (W), depth (D), and meander wavelength (L), the smaller will be the channel gradient (S). This is expressed in the following relationship:

$$Q \propto \frac{W,D,L}{S}$$

For a given discharge, channel morphology is chiefly a function of type and amount of sediment load. "A significant increase in the ratio of bed load to total sediment load (Q_s) will cause an increase in channel width, meander wavelength, and slope with a decrease in depth and sinuosity (P; ratio of channel length to valley length)" (Schumm 1968), as follows:

$$Q_s \propto \frac{W,L,S}{D,P}$$

Examining the basic relationships which exist between discharge (Q), width (W), depth (D), and velocity (V) as expressed by the equation

$$Q = WDV$$

Leopold and Maddock (1953) demonstrate that, for consistent sets of at-a-station and between-station hydraulic geometry, simple power function relationships exist in the forms:

$$W = aQ^b$$
$$D = cQ^f$$
$$V = kQ^m$$

Moreover, subsequent researchers (Leopold et al. 1964, Emmett 1976) have shown that streams with mobile alluvial beds and banks adjust their channels to accomodate discharge volumes and durations that occur, on the average, every other year. This bankfull flow frequency recurrence interval (Q_B = 1.5 yrs) has been found to be remarkably consistent in arid, semiarid, and humid temperate regions. The dimensionless ratios of bankfull discharge (Q_B) to channel width at bankfull (W_B), channel area at bankfull (A_B), and channel width-to-depth ratio at bankfull are found to be highly sensitive indicators of the stage of equilibrium or disequilibrium in a watershed served by that channel. For a given geologic substrate, landscape history, and precipitation regime, consistent regional relationships of the type:

$$W_B = 1.37\ {Q_B}^{0.54}\ (r=0.917)$$

$$D_B = 0.25\ {Q_B}^{0.34}\ (r=0.887)$$

$$A_B = 0.35\ {Q_B}^{0.88}\ (r=0.972)$$

where W_B is bankfull width, D_B is bankfull depth, A_B is bankfull area, and Q_B is bankfull discharge may be established by study of the geometry and flow records for stream channels. The above example is derived from ongoing USGS impact work in the White Cloud Peaks area of prospective open pit mining at the headwaters of the Salmon River. Comparative exponents for an average of a large number of midwestern streams yield a width exponent of 0.50 and a depth exponent of 0.40, while in Alaska the same values are 0.50 and 0.35, respectively.

While it has been shown that the absolute size of a stream channel is related to the bankfull flood flow which forms or maintains the channel (Leopold et al. 1964) it appears that the shape of the channel is independent of discharge (Schumm 1960). The ratio of width to depth (F) is, however, a strong function of the percentage of silt-clay in the wetted perimeter of the channel (M). This relationship takes the form:

$$F = gM^h$$

where $$M = \frac{Sc \times W + Sb \times 2D}{W + 2D}$$

Sc = % passing 0.074 mm in bed
Sb = % passing 0.074 mm in bank
D = channel depth
W = channel width
g = coefficient
h = exponent

In addition, Lane (1935) has shown that in channels carrying silt in suspension there is a tendency to deposit this material along the margins of the stream, thus altering the W/D ratio. Stabilization of this stream-bank silt is aided by the growth of vegetation and by the high entrainment velocities required to resuspend this material (Hjulstrom 1935).

Thus, when the stream is graded (i.e., in dynamic equilibrium), channel morphology is affected by a complex set of independent variables, the most important of which is the discharge of sediment and water. The nature and quantity of sediment and water moving through stable alluvial channels largely determines their morphology. Of the independent variables, the nature and quantity of sediment and water supplied to the stream are most readily altered through man's use and modification of the landscape.

Existing situation

VIGIL SITE DOCUMENTATION

The individual Vigil monitoring sites were surveyed, described, and photographed in a manner conformable to the U.S. Geological Survey (USGS) methodology outlined by Emmett and Hadley (1968) to ensure the future utility and retrievability of this data for future researchers. To this end, the Vigil site data have been organized into a standardized format, including a written description of the site, maps, photographs of the site conditions, landscape reference points which will allow a person to find benchmarks in the field, and a tabulation of the original survey data. The complete contents of one folder have been included in this report as appendix C. Copies of the Vigil site folders, readily reproducible, have been submitted to each of the following repositories:

1) Vigil Network Repository
   Library
   U.S. Geological Survey
   Washington, D.C. 20242

2) Water Resources Division
   Montana Department of Natural Resources
   and Conservation
   32 South Ewing
   Helena, MT 59601

3) Geology Department
   University of Montana
   Missoula, MT 59801

Resurvey of these established sites will permit observation of rates of change in stream channel geometry and pattern, stream bank vegetation, and, at some sites, the change in grain-size distribution of bed and bank sediments. Thus, it will be possible to identify and measure the rate and character of geomorphic and hydrologic change which characterize relatively undisturbed watersheds and, through the use of a multiwatershed methodology (Striffler 1965), to compare disturbed watersheds throughout the region.

DATA SYNTHESIS

In the course of establishing the Vigil monitoring sites, the field parties also attempted to determine bankfull stage at each site utilizing such evidence as inflection points in the cross-channel morphology, type and extent of vegetation, limits of flood debris, and floodplain elevation. Partially due to the proximity of modifying influences such as agriculture and grazing, but mainly due to the nature of the streams themselves, the definition of bankfull stage was difficult and subjective. Computation of bankfull discharge (Q_B) or comparative analyses of components of the sites' hydraulic geometry such as width-depth ratios (F) is subject to a considerable amount of nonsystematic error.

In an effort to overcome this problem, yearly peak flow data from 28 crest or recording streamflow gages in the area with a period of record ten years or greater (see figure 37) were compiled. These data were subject to a Log Pearson Type III extreme value analysis and a plot derived of discharge vs. recurrence interval. From this analysis it was possible to determine for the gaging stations used in the analysis the discharge values corresponding to the 1.5-year and 25-year flood recurrence intervals (tables 20 and 21).

In a similar fashion, data from the U.S. Department of Commerce's "Hourly Precipitation Data Summaries" (1948-73) and the data tape CLIMATEMT (Curry 1973) were analyzed and recurrence interval plots for 33 precipitation stations constructed. From this analysis it was possible to determine the 24-hour precipitation event (table 22) which occurs at least once every two years (the median of the distribution). This two-year, twenty-four-hour storm is the storm event frequently chosen to represent a station's precipitation intensity characteristics (Reich 1963). The two-year, one-hour rainfall was also determined for the seven continuous-recording stations in the area (table 23). To facilitate comparison of the precipitation characteristics of watersheds of differing sizes, the 25-year, one-hour rainfall data were also derived.

APPLICABILITY OF DATA

One of the biggest problems in studying streams in southeastern Montana is the lack of discharge data. Most of the larger rivers, such as the Yellowstone or the Tongue, have records of long duration, but a majority of the crest gauges on the smaller streams were not established until the late 1950's or early 1960's. There are, of course, many problems encountered when analyzing a data population using only twelve samples, problems which are compounded by the difficulties involved in evaluating discharge at a crest gage, but that is the extent of the data available at this time.

In an effort to establish a relationship having predictive capabilities, a graph of the 1.5-year discharge versus the drainage basin area (figure 38) was prepared using the data presented in tables 20 and 21. Station 6, the Tongue River at Miles City, was excluded because of the flow regulation effects of the Tongue River Reservoir. This approach was not successful. Stations along line 1 in figure 38 are on streams flowing into this area from the south and east, and most of the discharge they measure is derived from outside the study area. The remaining stations measure runoff from within the region, and it is apparent that not only are their flow characteristics different from those existing on the larger streams, but that they differ considerably among themselves as well. Basins of essentially equal area have widely differing bankfull discharges, as is illustrated by stations 1 (Deep Creek near Kinsey) and 9 (Sand Creek near Broadus). Both drain about thirty square kilometers, but their 1.5-year discharges differ by over four thousand percent. There is also a large scatter when the graph is viewed in terms of equal discharge. Station 1 has a bankfull discharge almost twice that of station 27 (Rosebud Creek near Forsyth), with less than one percent of the drainage area. A significant number of streams plot at these extremes, and do so in such a manner as to delineate an envelope containing most of the data points. Whether or not there is any justification, let alone predictive value, to lines 2 and 3 of figure 38 depends entirely on whether there is any physical meaning to the relationships implied. For purposes of interpretive analysis, the value given by the $Q_{25}/Q_{1.5}$ discharge ratio was assumed to be a rough measure of the variability (skewness) of each

Yellowstone River Basin

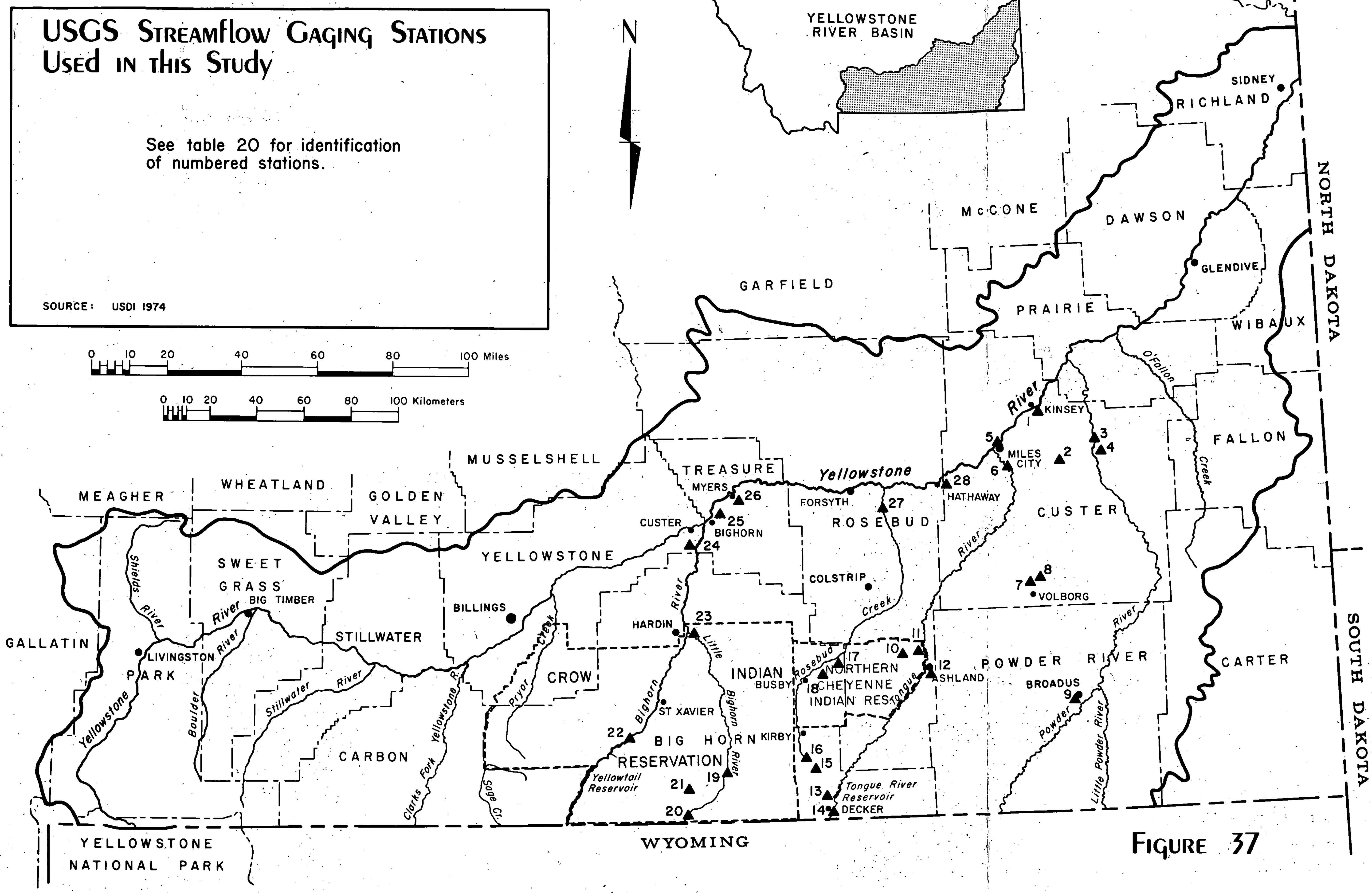


FIGURE 37

TABLE 20. Bankfull discharge ($Q_{1.5}$) for selected USGS Gaging Stations in the Yellowstone River Basin

Map Number	Station Name	USGS Identification Number	Drainage Area (km^2)	Bankfull Discharge ($Q_{1.5}$) in cfs	$\frac{Q_{25}}{Q_{1.5}}$	Period of Record	No. of Years Used
1	Deep Creek near Kinsey[a]	06309080	28.7	540.0	6.30	1962-73	12
2	Ash Creek near Locate[a]	06309090	17.3	10.1	103.90	1962-73	12
3	Powder River near Locate	06326500	34,172.0	7,800.0	3.33	1938-73	36
4	Meyers Creek near Locate[a]	06326400	24.8	190.0	8.95	1962-73	12
5	Yellowstone River at Miles City	06309000	124,975.0	51,003.0	1.71	1923-73	46
6	Tongue River at Miles City	06308500	13,952.0	3,550.0	3.66	1938-73	32
7	Basin Creek Tributary near Volborg[a]	06308200	0.36	13.0	38.46	1955-73	16
8	Basin Creek near Volborg[a]	06308300	28.2	86.0	15.70	1955-73	19
9	Sand Creek near Broadus[a]	06324700	27.5	12.5	66.40	1956-73	17
10	Stebbins Creek near Ashland[a]	06307760	14.0	1.3	38.46	1963-73	11
11	Stebbins Creek at Mouth near Ashland[a]	06307780	53.9	53.0	16.00	1963-73	11
12	Spring Creek near Ashland[a]	06307640	3.8	100.0	14.50	1962-73	12
13	Spring Creek near Decker[a]	06306900	94.0	49.0	28.57	1958-73	16
14	Tongue River near Decker	06306300	3,825.0	3,500.0	2.31	1961-73	13
15	Leaf Rock Creek near Kirby[a]	06306950	15.6	29.0	9.66	1958-73	15
16	Rosebud Creek near Kirby[a]	06295100	88.6	71.0	9.30	1960-73	12
17	Whitedirt Creek near Lame Deer[a]	06295200	4.1	3.6	15.07	1959-73	15
18	Tributary to Rosebud Creek near Busby[a]	06295130	3.0	2.9	12.10	1963-73	11
19	Little Bighorn below Pass Creek	06290500	1,109.0	1,000.0	3.50	1939-73	35
20	Little Bighorn at Stateline	06289000	500.0	900.1	2.77	1939-73	35
21	Lodgegrass Creek above Willow Creek Diversion	06291500	209.0	365.1	3.15	1939-73	35
22	Bighorn River near St. Xavier	06287000	50,938.0	12,801.0	2.77	1935-73	39
23	Little Bighorn near Hardin	06294000	3,351.0	1,500.1	3.60	1953-73	21
24	Andresen Coullee near Custer[a]	06294400	6.1	4.7	10.10	1963-73	11
25	Unknown Creek near Bighorn[a]	06294800	37.8	34.5	40.58	1962-73	12
26	Buckingham Coullee near Meyers[a]	06294850	6.8	13.0	45.38	1962-73	12
27	Rosebud Creek near Forsyth[a]	06296000	3,263.0	275.0	7.09	1948-69	18
28	Snell Creek near Hathaway[a]	06296100	27.2	66.0	6.52	1963-73	11

CONVERSIONS: 1 km^2 = .386 mi^2

[a]Crest gauge

TABLE 21. Little Bighorn River Drainage Basin Components.

Region	Area (km^2)	Maximum Discharge Contributed Every 1.5 years (cfs)	$\frac{Q_{25}}{Q_{1.5}}$
A. Little Bighorn River Basin below the state line to (and including) the Pass Creek Drainage.	609	100	10.00
B. Little Bighorn River Basin below land excluding the Pass Creek Drainage to Hardin, not including the Lodgegrass Creek Drainage.	2,033	135	5.56
C. Little Bighorn River Basin below the state line to Hardin, not including the Lodgegrass Creek Drainage.	2,642	235	7.45

CONVERSIONS: 1 km^2 = .386 mi^2
1 cfs = .0283 m^3/sec.

NOTE: The purpose of this table is to demonstrate how the data in table 20 can be used to calculate the 1.5-year and 25-year discharges, and their ratio, for drainage basins within the area monitored by the stations shown in figure USGS. Values given for the three regions in this table, for example, were calculated as follows (station numbers are given in parentheses):

Q_{An} = Q_n below Pass Creek (#19) - Q_n at state line (#20)

Q_{Bn} = Q_n at Hardin (#23) - Q_n at state line (#20) - Q_n Lodgegrass Creek (#21)

Q_{Cn} = Q_n at Hardin (#23) - Q_n below Pass Creek (#19) - Q_n Lodgegrass Creek (#21)

Where: n = the recurrence interval of interest

Q_{An}, Q_{Bn}, Q_{Cn} = the discharges at recurrence interval n for regions A, B, and C, respectively.

Q_n = the discharge value for recurrence interval n for the indicated gaging station.

TABLE 22. Greatest Two-year, 24-Hour Precipitation Events

Station Number	Station Name	Weather Bureau Number	2-year, 24-hour Precip. (in)	$\frac{P_{25}}{P_2}$	Years of Record Used	No. of Years Used
1	Terry	8165	1.53	1.65	1949-50, 52-72	23
2	Mildred	5666	1.28	2.21	1948-51, 69 1953-66, 72	20
3	Ismay	4442	1.30	2.46	1951, 53-73	21
4	Mizpah 4 NNW	5754	1.17	2.72	1950-72	23
5	Miles City AP	5690	1.30	2.08	1948-72	25
6	Miles City	5685	1.18	2.46	1950-72	23
7	Garland	3383	1.15	3.04	1939-55	16
8	Brandenberg	1084	1.50	1.83	1956-58, 60-72	16
9	Volborg	8670	1.30	2.70	1951-72	22
10	Ashland RS	0330	1.11	2.34	1949-52, 55-60 63-67, 72-73	17
11	Sonnette 4N Sonnette 2WNW[a]	7735 & 7740	1.50	1.77	1951-56, 63, 4N 1965-73, 2WNW	16
12	Broadus	1127	1.23	1.87	1948, 50-72	24
13	Biddle	0739	1.15	2.33	1950-69, 72	21
14	Biddle 8SW	0743	1.67	1.90	1963-73	11
15	Moorhead 9NE	5870	1.34	2.01	1958-61, 63-71	13
16	Otter 9SSW	6287	1.95	1.85	1961-72	12
17	Birney 2SW	0819	1.25	2.08	1955-68, 71-72	16
18	Decker	2266	1.20	2.68	1950-51, 60-70	15
19	Kirby 1S	4701	1.62	2.36	1960-61, 63-72	12
20	Wyola	9175	1.27	1.69	1948-72	25
21	Lodgegrass	5106	1.48	2.03	50-3, 55-61, 63 65-66, 68-73	19
22	Yellowtail Dam	9240	1.30	2.31	1948-49, 63-72	12
23	Crow Agency	2112	1.33	2.78	1948-50, 53-58 1960-63, 65-72	21
24	Hardin	3915	1.13	2.40	1948-51, 53-70	22
25	Busby	1297	1.28	2.00	1948-59, 61-62 1966-70	19
26	Lame Deer	4839	1.17	2.36	1948-55, 57-65 1967-69	20
27	Colstrip	1905	1.44	1.87	1947-72	26
28	Hysham 25SSE	4364	1.45	1.62	1959-63, 65 1968-69, 72-73	10
29	Ballantine	0432	1.18	2.54	1948-1972	25
30	Custer	2158	1.17	2.46	1955, 57-63 1965-68, 70-73	15
31	Hysham	4358	1.32	2.07	1948-53, 55-72	24
32	Vananda 5ESE	8511	1.16	2.07	1950-53, 55, 56 58-64, 66, 72-73	15
33	Forsyth 2E	3099	1.38	1.92	1948, 50-57 59-66, 68-70, 72	21

SOURCE: U.S. Department of Commerce 1948-73, Curry 1973.

CONVERSIONS: 1 inch = 2.54 cm

[a]Records from these two stations were combined.

TABLE 23. Greatest Two-Year, One-Hour Precipitation Events

Station Number	Station Name	Weather Bureau Number	2-Year, 1-Hour Precip. (in.)	$\frac{P_{25}}{P_2}$	$\frac{P_2(1\ hr)}{P_2(24\ hr)^a}$	Years Used	No. of Years Used
3	Ismay	4442	0.60	2.42	0.46	1951-59,61-65, 67-73	20
6	Miles City	5685	0.69	2.32	0.58	1949-53,55,67, 72,57-60,62-64,68	15
10	Ashland RS	0330	0.61	2.62	0.55	1949-52,54,56, 64,58-59,67, 72-73	
12	Broadus	1127	0.56	2.59	0.46	1949-50,52-63 67,69-73	19
21	Lodgegrass	5106	0.55	3.09	0.37	1950-57,59,61, 63,66,68-73	17
30	Custer	2158	0.47	3.40	0.40	1957-63,65-68, 70-73	14
32	Vananda 5 ESE	8511	0.47	3.40	0.41	1950-53,55,58-59,61-63,68, 72-73	13

SOURCE: U.S. Department of Commerce 1948-73

CONVERSIONS: 1 inch = 2.54 cm

[a]From table 22

station's peak flow distribution, representing physically the relative amount by which a twenty-five-year flood exceeds the capacity of the channel to accommodate it. Insofar as the 1.5-year discharge approximates the most frequently occurring value (mode) in these distributions, it represents the magnitude of the excess that appears most frequently when the amount of water supplied to a watershed exceeds its demand by the maximum amount conditions allow. Because this quantity is a measure of the adjustments a watershed has made to the conditions it experiences most of the time, the $Q_{25}/Q_{1.5}$ ratio expresses the degree of assimilation a watershed has achieved between these conditions and the less frequent flood conditions it is subjected to. This analysis yielded grouping of the data into sets similar to those illustrated in figure 38 but with even greater scatter of data points.

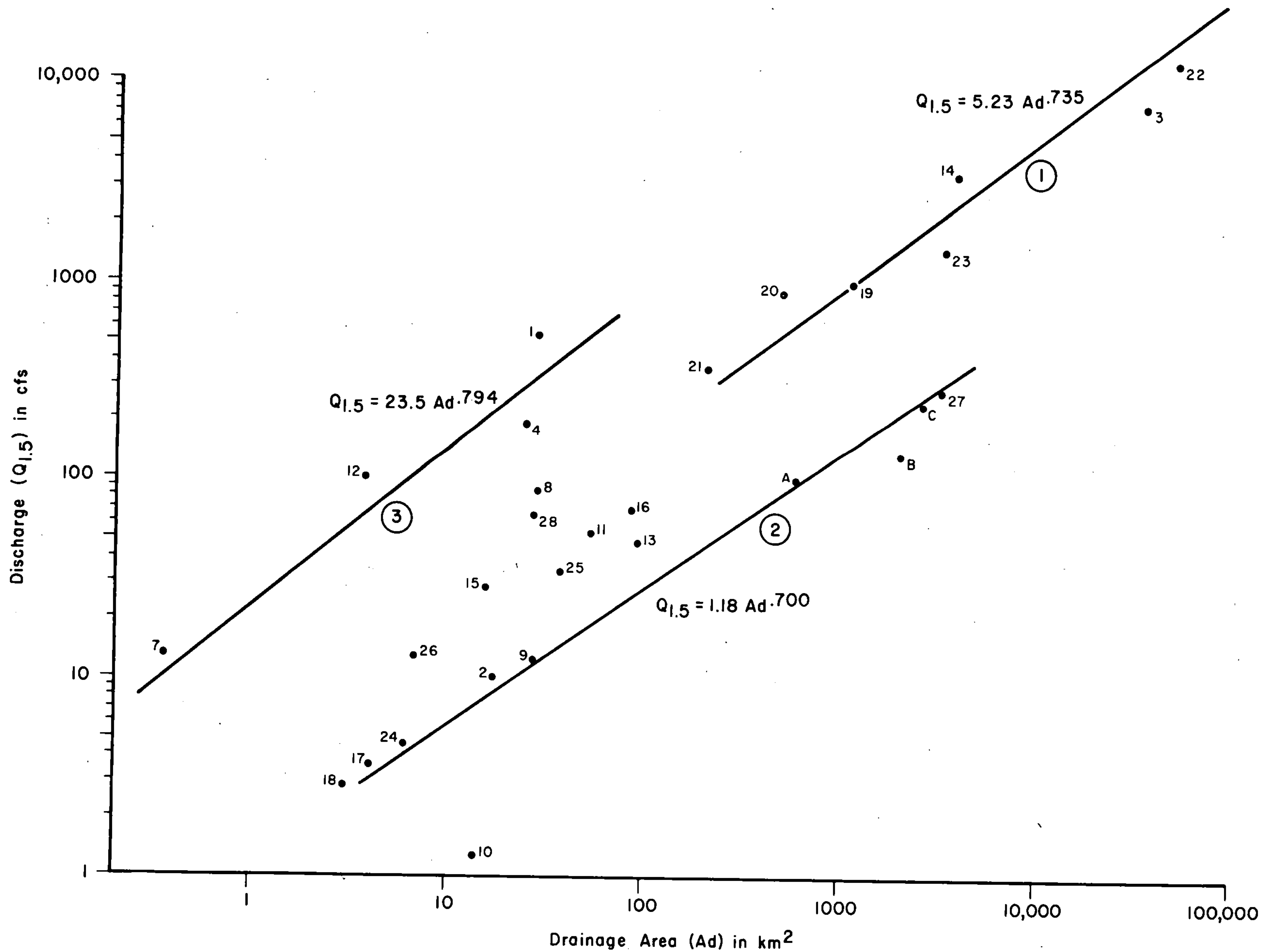


Figure 38. 1.5-year discharge as a function of drainage area.

While there seems to be a distinct grouping of streams which distinguishes the major through-flowing streams from the smaller high-plains streams which derive their flow from regions of lesser precipitation and snowpack, it appears that both $Q_{1.5}$ and a frequency ratio such as $Q_{25}/Q_{1.5}$ are inadequate measures upon which to base a predictive model of discharge per unit of drainage-basin area. A similar broad scatter of data results if the Q_2 or Q_{25} flows are calculated using the regression equations of the USGS "Montana Method" for estimating the magnitude and frequency of floods (Johnson and Omang 1976). Errors of estimate in excess of 3000 percent are common to both methods for similarly sized watersheds in close geographic proximity. From this analysis it appears clear, however, that the small streams of southeastern Montana are at least in part adjusted to the less frequent conditions (intense or long-duration precipitation events) which modify the short-term hydrologic character of the watersheds.

It has already been noted that bankfull discharge is one indicator of the conditions prevailing in a watershed that theoretically results from the set of conditions which occurs most frequently during periods of peak flow. The most frequently occurring short-term conditions, such as local temperature, rainfall intensity, and infiltration rates, presumably exert a powerful influence on the hydrologic character of a watershed, but it would seem that, in this region, the higher-magnitude flows are the ones which accomplish regional integration. Thus, because of the nature of a recurrence interval plot, bankfull discharge ($Q_{1.5}$) may be largely a statistical representation of the interactions between these local conditions and the less frequent regional ones, particularly for ephemeral streams. The statistical analysis suggests that bankfull discharge occurs not only as a discrete event, but also as a result of conditions which lead to flows of higher magnitude. If one basin's 25-year flood flows are very much higher than another's, but their 1.5-year discharge is the same, then their $Q_{25}/Q_{1.5}$ ratios are considerably different, and the nature of the interactions which determine that ratio must also differ. Similarly, when the bankfull discharges of two streams vary, it is because of significant hydrologic differences in their drainage basins. The nature of these differences would determine the type of effects the interactions between the systems responsible for the frequent hydrologic events and the systems responsible for the rare ones would have. If an underlying pattern is apparent in the relationship among the hydrologic variables of a watershed, then changes in parameters describing their different interactions may be systematic. Thus, a certain bankfull discharge may imply the existence of a specific set of local conditions that is different for each subregion and which interacts with the 25-year flood mechanism so as to give those conditions more behavioral homogeneity at high flows than at low. The importance of less frequent flows in semiarid regions is well documented (Wolman and Miller 1960), and studies also indicate that the role of maximum events in determining the characteristics of a region's channel system can be dominant (Chorley and Morgan 1962).

A partial analysis of the precipitation patterns in the area was made in an attempt to isolate some of the possible reasons for the marked contrast in discharge data in seemingly similar watersheds. The geographic distribution of variations in mean annual precipitation, the two-year, 24-hour storm, and its ratio with the 25-year, 24-hour storm show little congruity with the observed local variations in runoff. The distribution pattern resulting from a plot of two-year, one-hour rainfall and the 25/2-year ratio may ultimately be more useful, but, with the relative paucity of data (seven stations), no meaningful correlation could be derived.

Summary

The principal analytical finding of this research has been to demonstrate clearly that variability of hydrologic and hydrographic variables in the region is so high that conventional data synthesis and record extension are not valid. This is a significant finding in considering design and validity of interpretation of records taken from new short-period gaging stations established by state and federal agencies. Standard USGS methods of synthesis will be of dubious value for periods of record that would normally be considered adequate elsewhere in the United States.

The establishment of the Vigil Network in southeastern Montana permits the systematic observation of channel form and pattern with time. Continued observation of these sites will enable future researchers not only to contrast rates of morphologic change at disturbed and relatively undisturbed sites, but also to isolate the functional variables responsible for the region's hydrologic character. The implementation of a carefully designed experimental watershed program would greatly expedite and enhance our understanding of the region's hydrologic character.

Perennial streams, particularly those that head in major mountain ranges in Wyoming and Montana, are amenable to predictable hydraulic geometry relationships. However, the small perennial and ephemeral streams in southeastern Montana do not bear the usual relationship between bankfull stage and recurrence interval. Instead of being characterized by a bankfull flow event on the average of once every 1.5 years like the regional perennial streams, the local ephemeral streams achieve that discharge only once every 15 to 25 years, or even less frequently. Additionally, the streams are highly irregular from site to site so that, for example, the ratio between the 25-year peak discharge and the 1.5-year peak discharge on streams of a fixed drainage size varies by a factor of as much as two orders of magnitude between sites separated by but tens of miles.

Appendixes

Appendix A

PROJECTIONS OF FUTURE USE

FIGURES

TABLES

In order to adequately and uniformly assess the potential effects of water withdrawals on the many aspects of the present study, projections of specific levels of future withdrawals were necessary. The methodology by which these projections were done is explained in Report No. 1 in this series, in which also the three projected levels of development, low, intermediate, and high, are explained in more detail. Summarized below, these three future levels of development were formulated for energy, irrigation, and municipal water use for each of the nine subbasins identified in figure A-1.

ENERGY WATER USE

In 1975, over 22 million tons of coal (19 million metric tons) were mined in the state, up from 14 million (13 million metric) in 1974, 11 million (10 million metric) in 1973, and 1 million (.9 million metric) in 1969. By 1980, even if no new contracts are entered, Montana's annual coal production will exceed 40 million tons (36 million metric tons). Coal reserves, estimated at over 50 billion economically strippable tons (45 billion metric tons) (Montana Energy Advisory Council 1976), pose no serious constraint to the levels of development projected, which range from 186.7 (170.3 metric) to 462.8 (419.9 metric) million tons stripped in the basin annually by the year 2000.

Table A-1 shows the amount of coal mined, total conversion production, and associated consumption for six coal development activities expected to take place in the basin by the year 2000. Table A-2 shows water consumption by subbasin for those six activities. Only the Bighorn, Mid-Yellowstone, Tongue, Powder, and Lower Yellowstone subbasins would experience coal mining or associated development in these projections.

IRRIGATION WATER USE

Lands in the basin which are now either fully or partially irrigated total about 263,000 ha (650,000 acres) and consume annually about 1,850 hm^3 (1.5 mmaf) of water. Irrigated agriculture in the Yellowstone Basin has been increasing since 1971 (Montana DNRC 1975). Much of this expansion can be attributed to the introduction of sprinkler irrigation systems.

After evaluating Yellowstone Basin land suitability for irrigation, considering soils, economic viability, and water availability (only the Yellowstone River and its four main tributaries, Clarks Fork, Bighorn, Tongue, and Powder, were considered as water sources), this study concluded that 95,900 ha (237,000 acres) in the basin are financially feasible for irrigation. These acres are identified by county and subbasin in table A-3; table A-4 presents projections of water depletion.

Three levels of development were projected. The lowest includes one-third, the intermediate, two-thirds, and the highest, all of the feasibly irrigable acreage.

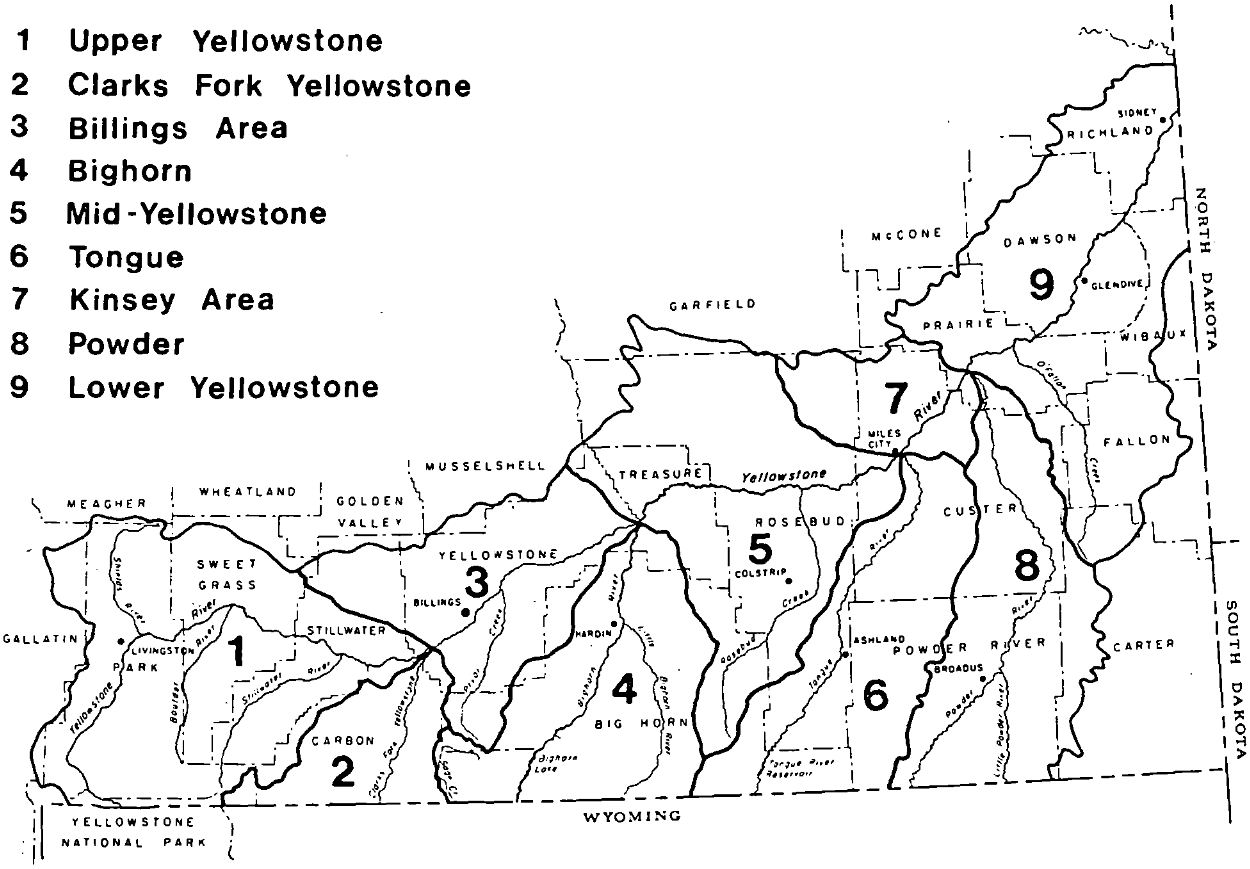


Figure A-1. The nine planning subbasins of the Yellowstone basin.

TABLE A-1. Increased water requirements for coal development in the Yellowstone Basin in 2000.

Level of Development	Coal Development Activity: Electric Generation	Gasification	Syncrude	Fertilizer	Export	Strip Mining	Total
			COAL MINED (mmt/y)				
Low	8.0	7.6	0.0	0.0	171.1		186.7
Intermediate	24.0	7.6	0.0	0.0	293.2		324.8
High	32.0	22.8	36.0	3.5	368.5		462.8
			CONVERSION PRODUCTION				
Low	2000 mw	250 mmcfd	0 b/d	0 t/d			
Intermediate	6000 mw	250 mmcfd	0 b/d	0 t/d			
High	8000 mw	750 mmcfd	200,000 b/d	2300 t/d			
			WATER CONSUMPTION (af/y)				
Low	30,000	9,000	0	0	[a]	9,350	48,350
Intermediate	90,000	9,000	0	0	31,910	16,250	147,160
High	120,000	27,000	58,000	13,000	80,210	22,980	321,190

CONVERSIONS: 1 mmt/y (short) = .907 mmt/y (metric)
1 af/y = .00123 hm^3/y

[a]No water consumption is shown for export under the low level of development because, for that development level, it is assumed that all export is by rail, rather than by slurry pipeline.

TABLE A-2. The increase in water depletion for energy by the year 2000 by subbasin.

Subbasin	INCREASE IN DEPLETION (af/y) Elec. Generation	Gasifi- cation	Syn- crude	Ferti- lizer	Export	Strip Mining	Total
			LOW LEVEL OF DEVELOPMENT				
Bighorn	0	0	0	0	0	860	860
Mid-Yellowstone	22,500	9,000	0	0	0	3,680	35,180
Tongue	7,500	0	0	0	0	3,950	11,450
Powder	0	0	0	0	0	860	860
Lower Yellowstone	0	0	0	0	0	0	0
Total	30,000	9,000				9,350	48,350
			INTERMEDIATE LEVEL OF DEVELOPMENT				
Bighorn	0	0	0	0	4,420	1,470	5,890
Mid-Yellowstone	45,000	9,000	0	0	15,380	6,110	75,490
Tongue	30,000	0	0	0	9,900	7,000	46,900
Powder	15,000	0	0	0	2,210	1,670	18,880
Lower Yellowstone	0	0	0	0	0	0	0
Total	90,000	9,000			31,910	16,250	147,160
			HIGH LEVEL OF DEVELOPMENT				
Bighorn	15,000	0	0	0	11,100	2,050	28,150
Mid-Yellowstone	45,000	18,000	29,000	0	38,700	8,710	139,410
Tongue	45,000	9,000	29,000	0	24,860	10,170	118,030
Powder	15,000	0	0	0	5,550	2,050	22.600
Lower Yellowstone	0	0	0	13,000	0	0	13,000
Total	120,000	27,000	58,000	13,000	80,210	22,980	321,190

CONVERSIONS: 1 af/y = .00123 hm^3/y

NOTE: The four subbasins not shown (Upper Yellowstone, Billings Area, Clarks Fork Yellowstone, Kinsey Area) are not expected to experience water depletion associated with coal development.

TABLE A-3. Feasibly irrigable acreage by county and subbasin by 2000, high level of development.

County	Upper Yellowstone	Clarks Fork	Billings Area	Big Horn	Mid Yellowstone	Tongue River	Kinsey Area	Powder River	Lower Yellowstone	County Totals
Park	21,664									21,664
Sweet Grass	10,204									10,204
Stillwater	6,208									6,208
Carbon		2,160								2,160
Yellow- stone			19,412							19,412
Big Horn				13,037		2,185				15,222
Treasure					9,591					9,591
Rosebud					11,408	9,727				21,135
Powder River								46,853		46,853
Custer					4,230	10,035	3,092	26,438		43,795
Prairie							1,644	1,914	8,231	11,789
Dawson									18,355	18,355
Richland									10,421	10,421
Wibaux									633	633
BASIN TOTALS	38,076	2,160	19,412	13,037	25,229	21,947	4,736	75,205	37,670	237,472

CONVERSIONS: 1 acre = .405 ha

NOTE: The number of irrigable acres for the low and intermediate development levels are one-third and two-thirds, respectively, of the numbers given here. This table should not be considered an exhaustive listing of all feasibly irrigable acreage in the Yellowstone Basin: it includes only the acreage identified as feasibly irrigable according to the geographic and economic constraints explained elsewhere in this report.

MUNICIPAL WATER USE

The basin's projected population increase and associated municipal water use depletion for each level of development are shown in table A-5. Even the 13 hm^3/y (10,620 af/y) depletion increase by 2000 shown for the highest development level is not significant compared to the projected depletion increases for irrigation or coal development. Nor is any problem anticipated in the availability of water to satisfy this increase in municipal use.

WATER AVAILABILITY FOR CONSUMPTIVE USE

The average annual yield of the Yellowstone River Basin at Sidney, Montana, at the 1970 level of development, is 10,850 hm^3 (8.8 million af). As shown in table A-6, the additional annual depletions required for the high projected level of development total about 999 hm^3 (812,000 acre-feet). Comparison of these two numbers might lead to the conclusion that there is ample water for such development, and more. That conclusion would be erroneous, however, because of the extreme variation of Yellowstone Basin streamflows from year to year, from month to month, and from place to place. At certain places and at certain times the water supply will be adequate in the foreseeable future. But in some of the tributaries and during low-flow times of many years, water availability problems, even under the low level of development, will be very real and sometimes very serious.

TABLE A-4. The increase in water depletion for irrigated agriculture by 2000 by subbasin.

Subbasin	Acreage Increase	Increase in Depletion (af/y)
HIGH LEVEL OF DEVELOPMENT		
Upper Yellowstone	38,080	76,160
Clarks Fork	2,160	4,320
Billings Area	19,410	38,820
Bighorn	13,040	26,080
Mid-Yellowstone	25,230	50,460
Tongue	21,950	43,900
Kinsey Area	4,740	9,480
Powder	75,200	150,400
Lower Yellowstone	37,670	75,340
TOTAL	237,480	474,960
INTERMEDIATE LEVEL OF DEVELOPMENT		
BASIN TOTAL	158,320	316,640
LOW LEVEL OF DEVELOPMENT		
BASIN TOTAL	79,160	158,320

CONVERSIONS: 1 acre = .405 ha
1 af/y = .00123 hm^3/y

NOTE: The numbers of irrigated acres at the low and intermediate levels of development are not shown by subbasin; however, those numbers are one-third and two-thirds, respectively, of the acres shown for each subbasin at the high level of development.

TABLE A-5. The increase in water depletion for municipal use by 2000.

Level of Development	Population Increase	Increase in Depletion (af/y)
Low	56,858	5,880
Intermediate	62,940	6,960
High	94,150	10,620

CONVERSIONS: 1 af/y = .00123 hm^3/y

TABLE A-6. The increase in water depletion for consumptive use by 2000 by subbasin.

Subbasin	Increase in Depletion (af/y) Irrigation	Energy	Municipal	Total
	LOW LEVEL OF DEVELOPMENT			
Upper Yellowstone	25,380	0	0	25,380
Clarks Fork	1,440	0	0	1,440
Billings Area	12,940	0	3,480	16,420
Bighorn	8,700	860	negligible	9,560
Mid-Yellowstone	16,820	35,180	1,680	53,680
Tongue	14,640	11,450	negligible	26,090
Kinsey Area	3,160	0	0	3,160
Powder	50,140	860	360	51,360
Lower Yellowstone	25,120	0	360	25,480
TOTAL	158,340	48,350	5,880	212,570
	INTERMEDIATE LEVEL OF DEVELOPMENT			
Upper Yellowstone	50,780	0	0	50,780
Clarks Fork	2,880	0	0	2,880
Billings Area	25,880	0	3,540	29,420
Bighorn	17,380	5,890	300	23,570
Mid-Yellowstone	33,640	75,490	1,860	110,990
Tongue	29,260	46,900	300	76,460
Kinsey Area	6,320	0	0	6,320
Powder	100,280	18,880	600	119,760
Lower Yellowstone	50,200	0	360	50,560
TOTAL	316,620	147,160	6,960	470,740
	HIGH LEVEL OF DEVELOPMENT			
Upper Yellowstone	76,160	0	0	76,160
Clarks Fork	4,320	0	0	4,320
Billings Area	38,820	0	3,900	42,720
Bighorn	26,080	28,150	480	54,710
Mid-Yellowstone	50,460	139,410	3,840	193,710
Tongue	43,900	118,030	780	162,710
Kinsey Area	9,480	0	0	9,480
Powder	150,400	22,600	1,140	174,140
Lower Yellowstone	75,340	13,000	480	88,820
TOTAL	474,960	321,190	10,620	806,770

CONVERSIONS: 1 af/y = .00123 hm^3/y

Appendix B

BIGHORN RIVER MORPHOLOGY PRIOR TO AND AFTER YELLOWTAIL DAM

FIGURES

TABLES

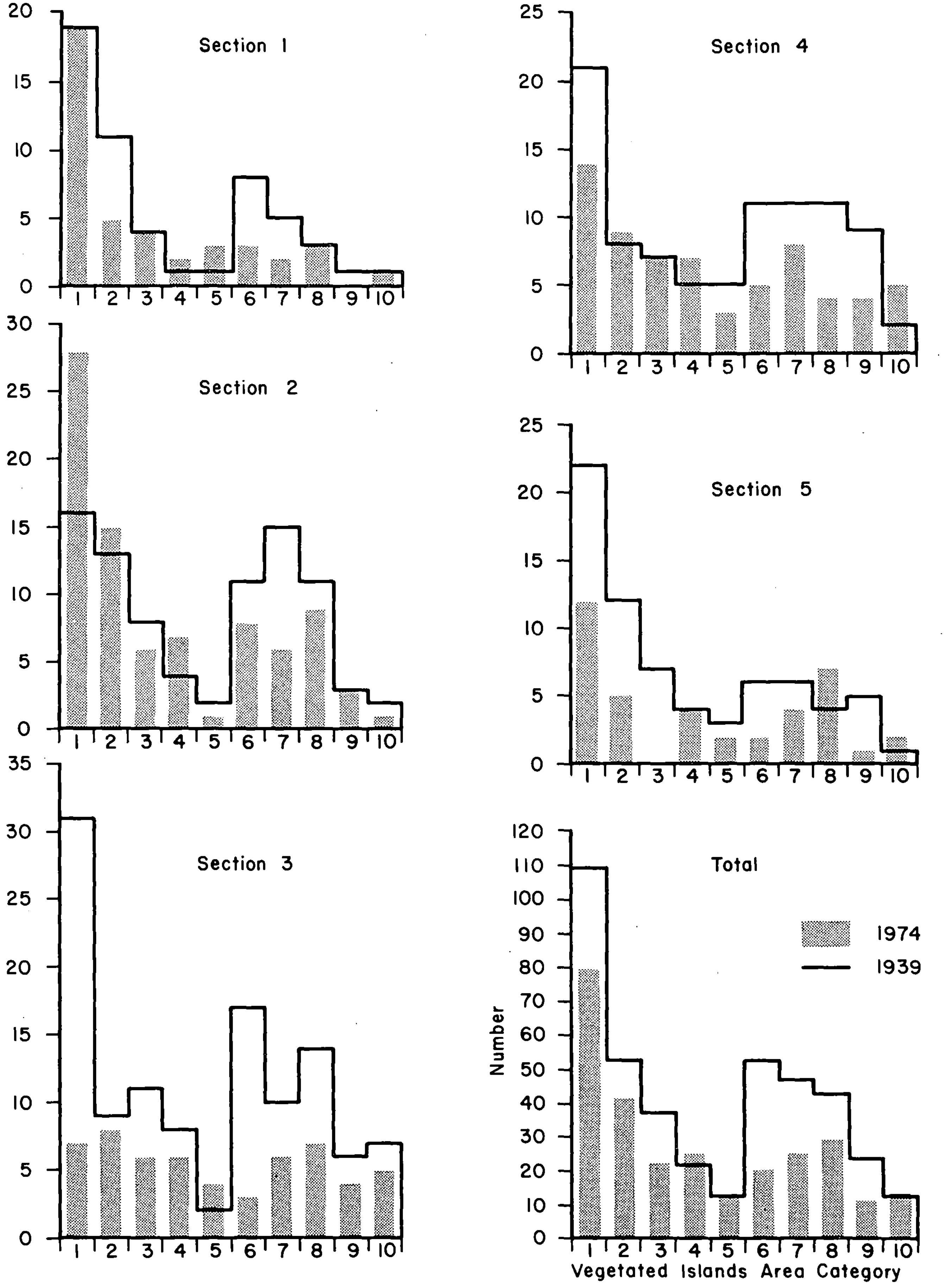


Figure B-1. Vegetated islands on the Bighorn River by area categories prior to and after Yellowtail Dam.

TABLE B-1. Vegetated islands on the Bighorn River prior to and after Yellowtail Dam.

Area Category (acres)		River Section: Prior to Yellowtail Dam[a] 1	2	3	4	5	Total Number	After Yellowtail Dam[b] 1	2	3	4	5	Total Number
1	0 - 1.00	19	16	31	21	22	109	19	28	7	14	12	80
2	1.01 - 2.00	11	13	9	8	12	53	5	15	8	9	5	42
3	2.01 - 3.00	4	8	11	7	7	37	4	6	6	7	-	23
4	3.01 - 4.00	1	4	8	5	4	22	2	7	6	7	4	26
5	4.01 - 5.00	1	2	2	5	3	13	3	1	4	3	2	13
6	5.01 - 10.00	8	11	17	11	6	53	3	8	3	5	2	21
7	10.01 - 20.00	5	15	10	11	6	47	2	6	6	8	4	26
8	20.01 - 50.00	3	11	14	11	4	43	3	9	7	4	7	30
9	50.01 - 100.00	1	3	6	9	5	24	-	3	4	4	1	12
10	100.01 +	1	2	7	2	1	13	1	1	5	5	2	14
	TOTAL NUMBER	54	85	115	90	70	414	42	84	56	66	39	287
	AVERAGE SIZE[c]	8.5	15.2	18.7	17.4	12.6	15.4	8.5	9.8	25.8	20.1	24.2	17.0
	TOTAL AREA[d]	459	1294	2155	1567	884	6360	355	823	1447	1323	942	4891

[a]Taken from 1939 aerial photographs except section 5 taken from 1950 photographs.
[b]Taken from 1974 aerial photographs.
[c]Rounded to the nearest 0.1 acre.
[d]Rounded to the nearest acre.

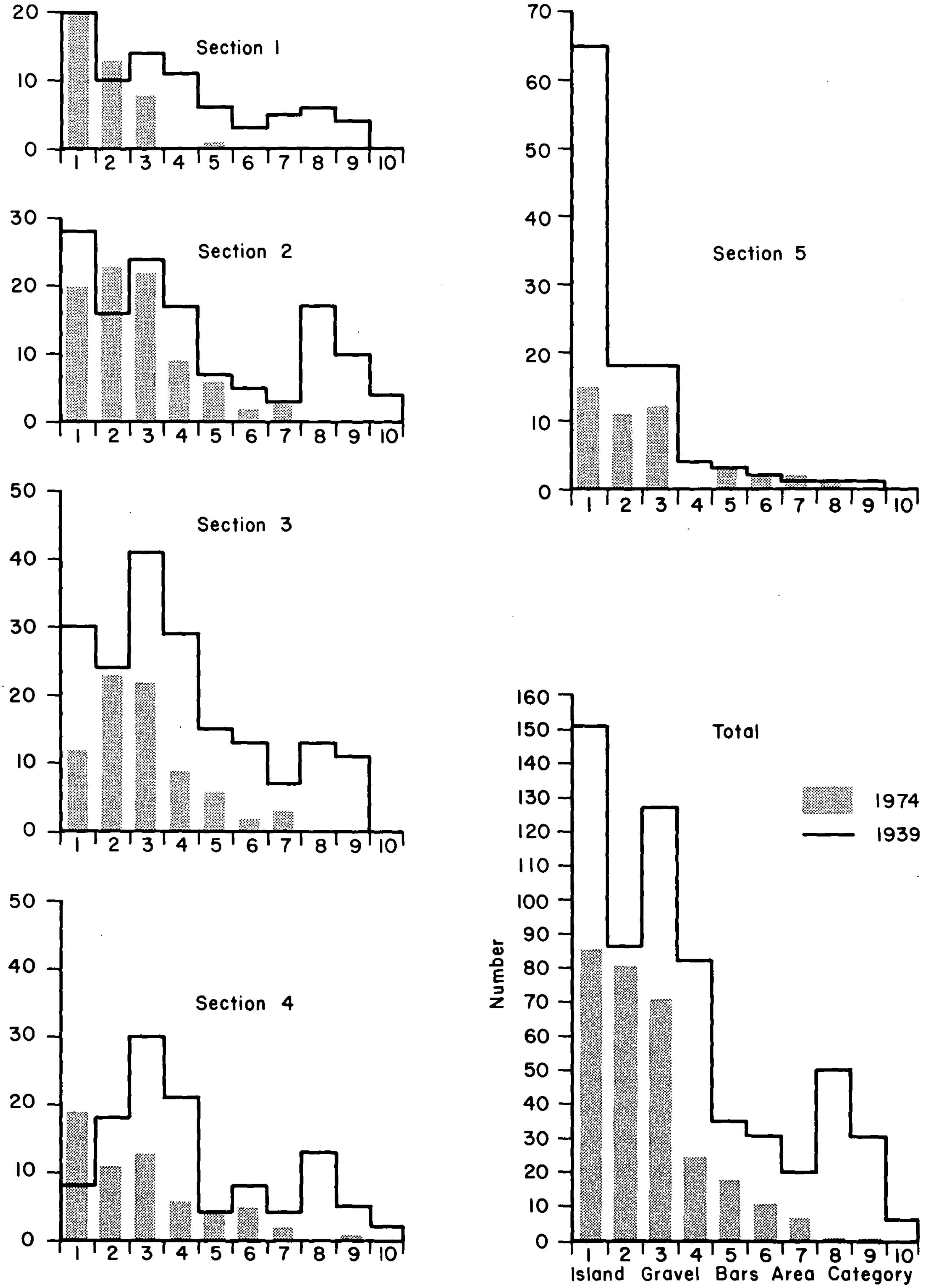


Figure B-2. Island gravel bars on the Bighorn River by area categories prior to and after Yellowtail Dam.

TABLE B-2. Island gravel bars on the Bighorn River prior to and after Yellowtail Dam.

Area Category (acres)		River Section: Prior to Yellowtail Dam[a]						River Section: After Yellowtail Dam[b]					
		1	2	3	4	5	Total Number	1	2	3	4	5	Total Number
1	0 - 0.50	20	28	30	8	65	151	20	20	12	19	15	86
2	0.51 - 1.00	10	16	24	18	18	86	13	23	23	11	11	81
3	1.01 - 2.00	14	24	41	30	18	127	8	16	22	13	12	71
4	2.01 - 3.00	11	17	29	21	4	82	-	10	9	6	-	25
5	3.01 - 4.00	6	7	15	4	3	35	1	4	6	4	3	18
6	4.01 - 5.00	3	5	13	8	2	31	-	2	2	5	2	11
7	5.01 - 6.00	5	3	7	4	1	20	-	-	3	2	2	7
8	6.01 - 10.00	6	17	13	13	1	50	-	-	-	-	1	1
9	10.01 - 20.00	4	10	11	5	1	31	-	-	-	1	-	1
10	20.01 +	-	4	-	2	-	6	-	-	-	-	-	-
	TOTAL	79	131	183	113	113	619	42	75	77	61	46	301
	AVERAGE SIZE[c]	2.8	3.9	3.0	3.8	0.9	2.9	0.7	1.3	1.5	1.7	1.5	1.4
	TOTAL AREA[d]	219	508	548	433	106	1814	30	95	119	103	67	413

[a]Taken from 1939 aerial photographs except section 5 taken from 1950 photographs.
[b]Taken from 1974 aerial photographs.
[c]Average size rounded to nearest 0.1 acre.
[d]Total area rounded to nearest acre.

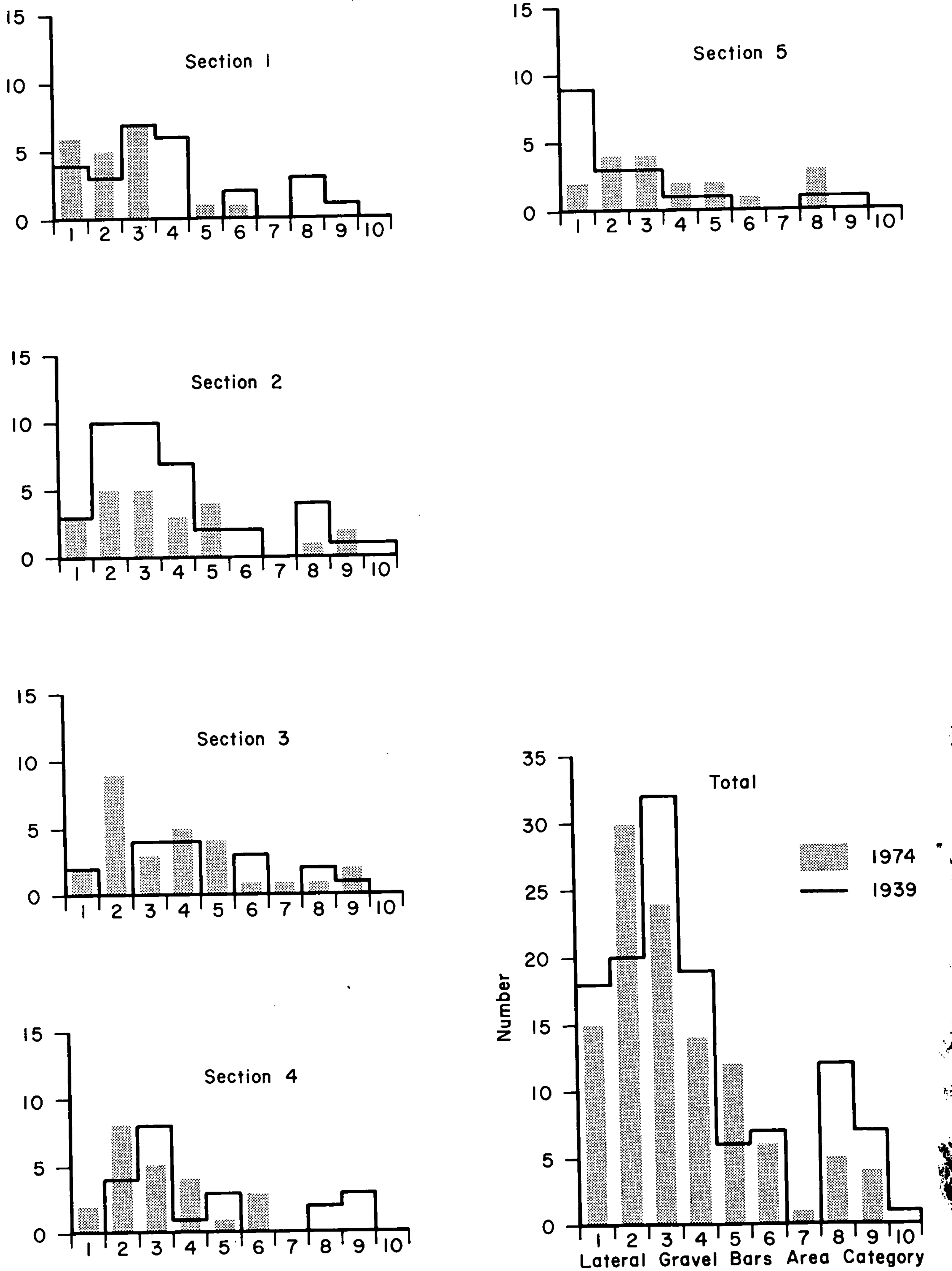


Figure B-3. Absolute numbers of lateral gravel bars on the Bighorn River by area categories prior to and after Yellowtail Dam.

TABLE B-3. Lateral gravel bars on the Bighorn River prior to and after Yellowtail Dam

Area Category (acres)	River Section											
	Prior to Yellowtail Dam[a]						After Yellowtail Dam[b]					
	1	2	3	4	5	Total Number	1	2	3	4	5	Total Number
1 0 - 0.50	4	3	2	-	9	18	6	3	2	2	2	15
2 0.51 - 1.00	3	10	-	4	3	20	5	5	9	7	4	30
3 1.01 - 2.00	7	10	4	8	3	32	7	5	3	5	4	24
4 2.01 - 3.00	6	7	4	1	1	19	-	3	5	4	2	14
5 3.01 - 4.00	-	2	-	3	1	6	1	4	4	1	2	12
6 4.01 - 5.00	2	2	3	-	-	7	1	-	1	3	1	6
7 5.01 - 6.00	-	-	-	-	-	-	-	-	1	-	-	1
8 6.01 - 10.00	3	4	2	2	1	12	-	1	1	-	3	5
9 10.01 - 20.00	1	1	1	3	1	7	-	2	2	-	-	4
10 20.01 +	-	1	-	-	-	1	-	-	-	-	-	-
TOTAL	26	40	16	21	19	122	20	23	28	22	18	111
AVERAGE SIZE[c]	3.1	3.0	3.9	4.3	1.7	3.2	1.2	2.7	2.9	1.8	2.7	2.3
TOTAL AREA[d]	81	120	62	91	32	385	25	61	81	40	48	254

[a]Taken from 1939 aerial photographs except section 5 taken from 1950 photographs.
[b]Taken from 1974 aerial photographs.
[c]Average size rounded to nearest 0.1 acre.
[d]Total area rounded to nearest acre.

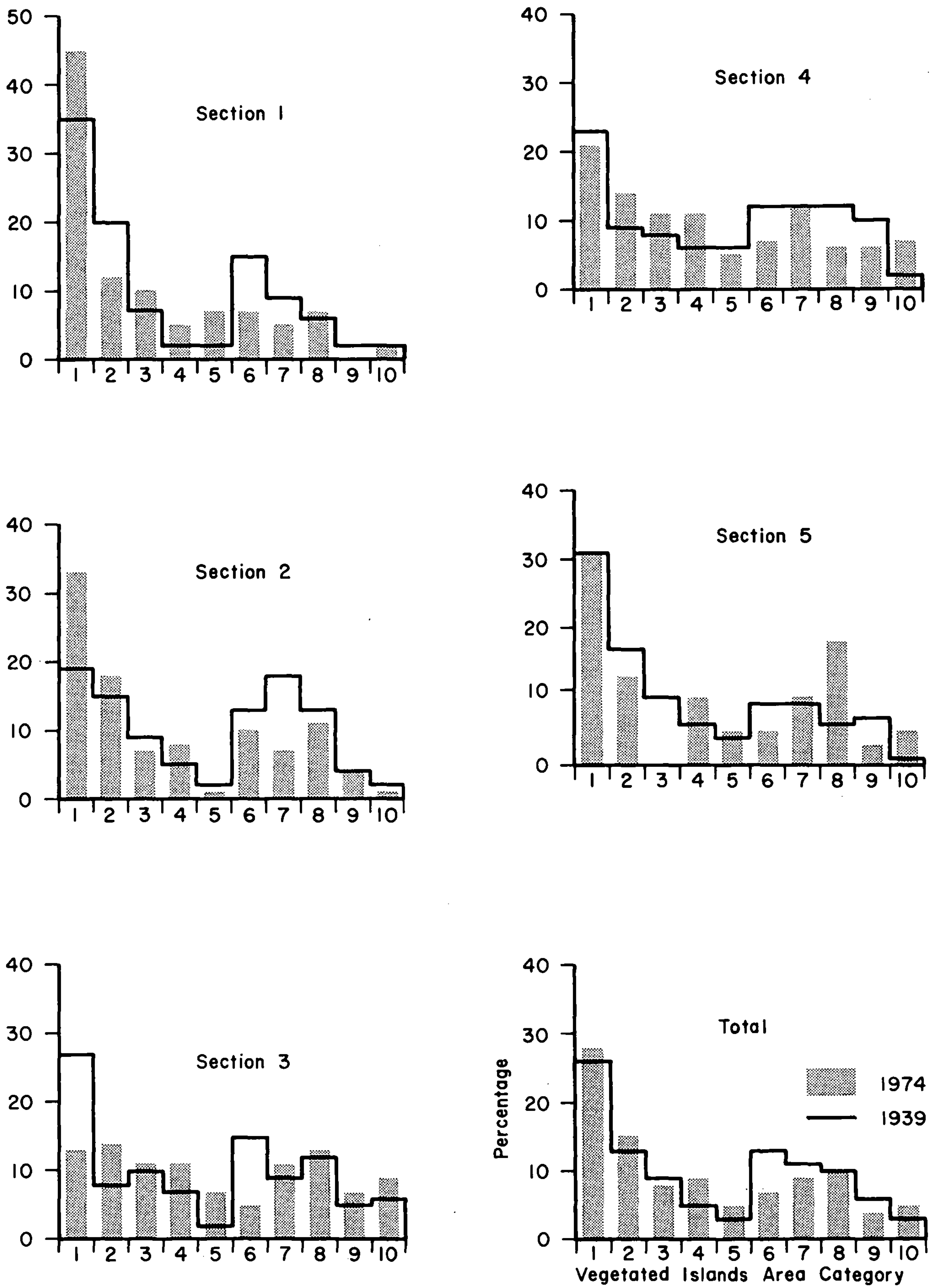


Figure B-4. Percentages of vegetated islands on the Bighorn River by area categories prior to and after Yellowtail Dam.

TABLE B-4. Percentages of vegetated islands on the Bighorn River prior to and after Yellowtail Dam.

Area Category (acres)		River Section											
		Prior to Yellowtail Dam[a]						After Yellowtail Dam[b]					
		1	2	3	4	5	Total	1	2	3	4	5	Total
1	0 - 1.00	35[c]	19	27	23	31	26	45	33	13	21	31	28
2	1.01 - 2.00	20	15	8	9	17	13	12	18	14	14	13	15
3	2.01 - 3.00	7	9	10	8	10	9	10	7	11	11	-	8
4	3.01 - 4.00	2	5	7	6	6	5	5	8	11	11	10	9
5	4.01 - 5.00	2	2	2	6	4	3	7	1	7	5	5	5
6	5.01 - 10.00	15	13	15	12	9	13	7	10	5	7	5	7
7	10.01 - 20.00	9	18	9	12	9	11	5	7	11	12	10	9
8	20.01 - 50.00	6	13	12	12	6	10	7	11	13	6	18	10
9	50.01 - 100.00	2	4	5	10	7	6	-	4	7	6	3	4
10	100.01 +	2	2	6	2	1	3	2	1	9	7	5	5

[a]Taken from 1939 aerial photographs except section 5 taken from 1950 photographs.
[b]Taken from 1974 aerial photographs.
[c]Percentages rounded to nearest whole number.

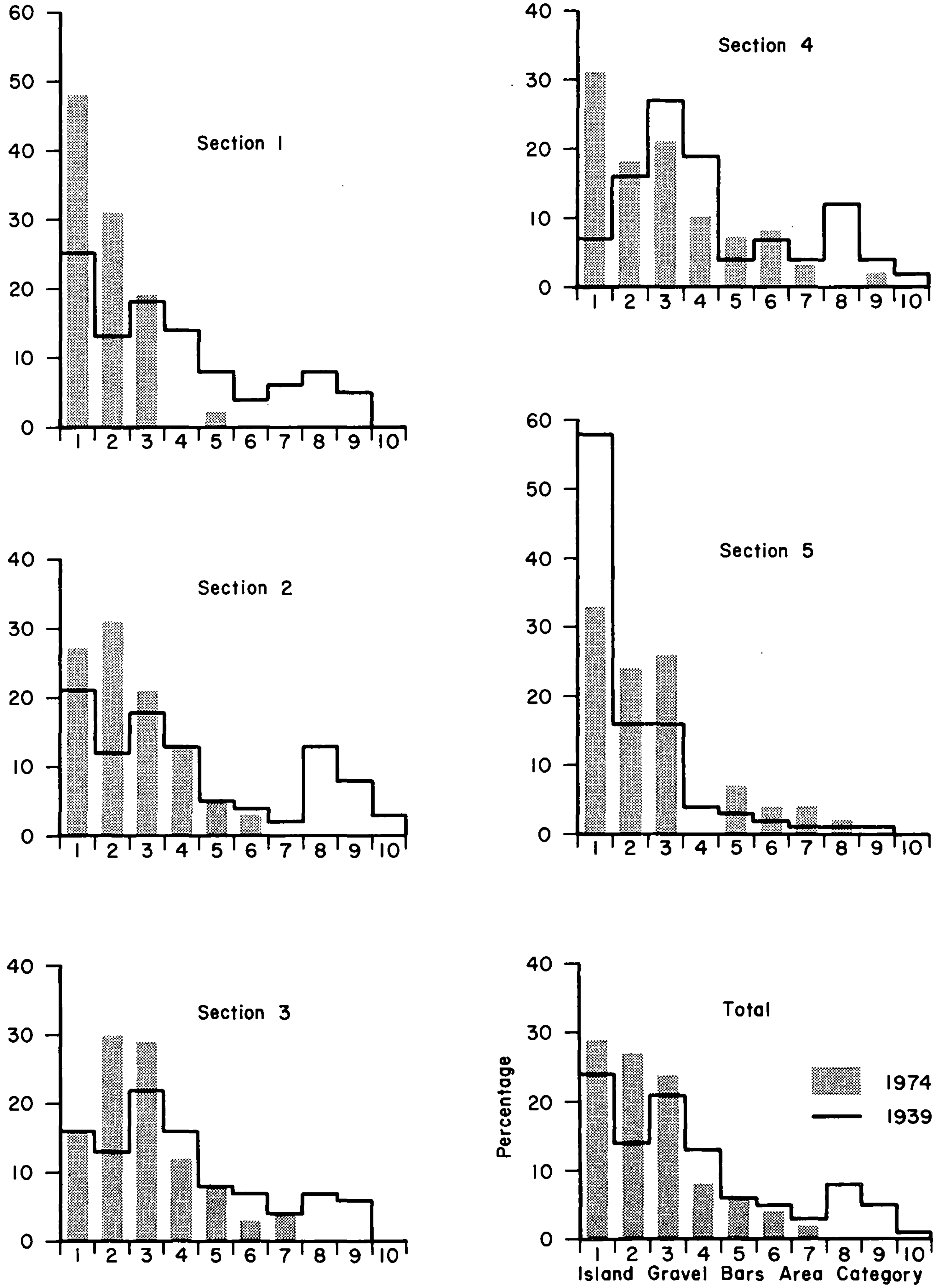


Figure B-5. Percentages of island gravel bars on the Bighorn River by area categories prior to and after Yellowtail Dam.

TABLE B-5. Percentages of island gravel bars on the Bighorn River prior to and after Yellowtail Dam.

Area Category (acres)		River Section											
		Prior to Yellowtail Dam[a]						After Yellowtail Dam[b]					
		1	2	3	4	5	Total	1	2	3	4	5	Total
1	0 - 0.50	25[c]	21	16	7	58	24	48	27	16	31	33	29
2	0.51 - 1.00	13	12	13	16	16	14	31	31	30	18	24	27
3	1.01 - 2.00	18	18	22	27	16	21	19	21	29	21	26	24
4	2.01 - 3.00	14	13	16	19	4	13	-	13	12	10	-	8
5	3.01 - 4.00	8	5	8	4	3	6	2	5	8	7	7	6
6	4.01 - 5.00	4	4	7	7	2	5	-	3	3	8	4	4
7	5.01 - 6.00	6	2	4	4	1	3	-	-	4	3	4	2
8	6.01 - 10.00	8	13	7	12	1	8	-	-	-	-	2	tr[d]
9	10.01 - 20.00	5	8	6	4	1	5	-	-	-	2	-	tr
10	20.01 +	-	3	-	2	-	1	-	-	-	-	-	-

[a]Taken from 1939 aerial photographs except section 5 taken from 1950 photographs.
[b]Taken from 1974 aerial photographs.
[c]Percentages rounded to nearest whole number.
[d]tr = trace; a value less than 0.50 percent.

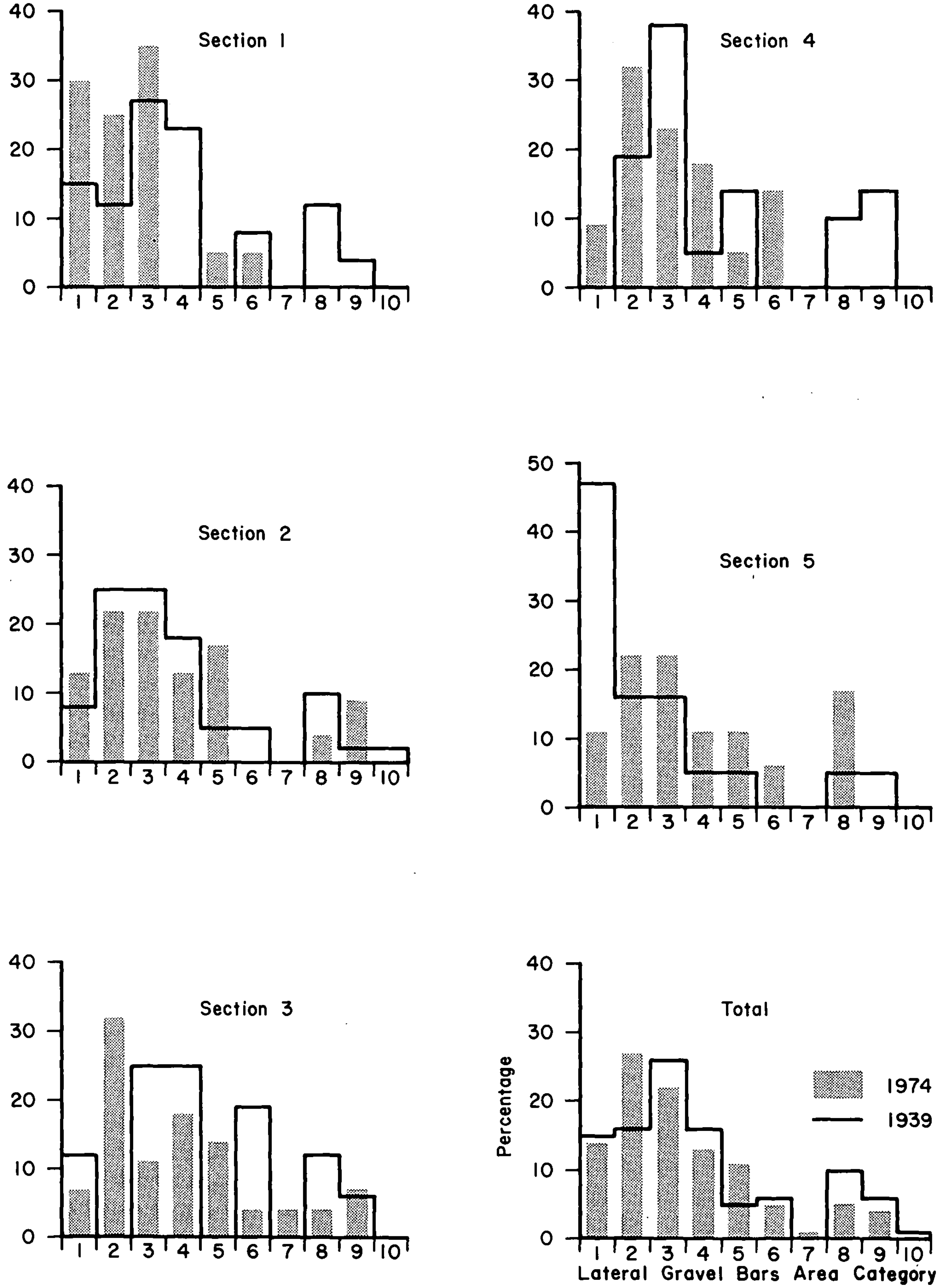


Figure B-6. Percentages of lateral gravel bars on the Bighorn River by area categories prior to and after Yellowtail Dam.

TABLE B-6. Percentages of lateral gravel bars on the Bighorn River prior to and after Yellowtail Dam.

	Area Category (acres)	River Section											
		Prior to Yellowtail Dam[a]						After Yellowtail Dam[b]					
		1	2	3	4	5	Total	1	2	3	4	5	Total
1	0 - 0.50	15[c]	8	12	-	47	15	30	13	7	9	11	14
2	0.51 - 1.00	12	25	-	19	16	16	25	22	32	32	22	27
3	1.01 - 2.00	27	25	25	38	16	26	35	22	11	23	22	22
4	2.01 - 3.00	23	18	25	5	5	16	-	13	18	18	11	13
5	3.01 - 4.00	-	5	-	14	5	5	5	17	14	5	11	11
6	4.01 - 5.00	8	5	19	-	-	6	5	-	4	14	6	5
7	5.01 - 6.00	-	-	-	-	-	-	-	-	4	-	-	1
8	6.01 - 10.00	12	10	12	10	5	10	-	4	4	-	17	5
9	10.01 - 20.00	4	2	6	14	5	6	-	9	7	-	-	4
10	20.01 +	-	2	-	-	-	1	-	-	-	-	-	-

[a]Taken from 1939 aerial photographs except section 5 taken from 1950 photographs.
[b]Taken from 1974 aerial photographs.
[c]Percentages rounded to the nearest whole number.

Appendix C

SAMPLE CONTENTS OF VIGIL NETWORK SITE FOLDER

Site MY-1: Armells Creek at Frieze Ranch

VIGIL NETWORK SITE INDEX CARD

Card No. SITE # MY - 1
Type ______
Date July 23, 1975

Site name Armells Creek - Frieze Ranch
Location Yellowstone River Basin; Southeastern Montana
Principal site investigator Robert R. Curry
Address University of Montana

Purposes (check; if more than one, number in order of importance):
Channel change 1 Erosion 4 Sedimentation 3 Mass movement ____ Vegetation 2

Number and type of observations (if applicable, write number of such installations):

Stream channels

Channel cross sections 3
Scour chains 0
Bed profile 0
Water-surface profile 0
Discharge:
- Crest-stage gage --
- Gaging station no
- Suspended sediment no
- Chemical no

Other (specify) benthic fauna

Vegetation

Transects 3
Quadrats no
Grasses yes, shrubs yes, trees yes
Tree-ring data no
Other (specify) ______

Hillslopes

Erosion stakes ______
Mass-movement pins ______
Painted rock lines ______
Cliff-recession markers ______
Profiles ______
Water runoff ______
Other (specify) ______

Other

Reservoir sedimentation no
Rain gage no
Soil chemistry no
Soil moisture no
Particle size:
- Streambed yes
- Bank yes
- Hillslope no

Pollen --
Other (specify) ______

*Further data**

If a basin, drainage area 807 km^2
If a plot ______
Elev ______
Ann. precipitation ______
Relief ______
Geology:

Vegetation:

Hydrology: w/d @ B.F. Stage 17.3
Slope m/m .0023

Photography: yes; 7 exposures

Other: Griffin Coulee Quadrangle; 7 ½'
A 1973 survey also exists.

* Include units of measurement, metric or English

Stream order n:4

ARMELLS CREEK

L. Frieze Ranch

SITE # MY - 1

Site Location

The site is 17½ miles north of the main turnoff into Colstrip, Montana, or 11.4 miles south of the I-94 exit stop sign, on 315. Go west on the gravel road, crossing the railroad and the first bridge, stopping on the west side of the first cattleguard past the bridge. The owner, L. Frieze, lives north of the site on the first farm to the west of the highway.

This site was originally surveyed by Maxfield and Laudry (University of Montana, 1973, unpublished survey notes, site #25).

Description of Benchmarks

Angles determined by Brunton are followed by a (B), all others were derived from plane table data. Distances determined with a tape are followed by a (T), all others were found using the alidade. The rod is touching the alidade side of the survey point and is centered. Compass compensation is 15½°, ML refers to Maxfield and Laudry, 1973.

All benchmarks are pieces of rebar about 18 inches long driven flush with the ground and spray painted orange.

The Primary reference (P.R.) is the wooden corner fence in the fence which runs from the cattleguard streamward. It is one end of a gate.

The Secondary Regerence (S.R.) is the first, and only, tree south along the fence from the gate.

BM 2 is at about the same elevation as BM 1, being about 1 meter upstream from the edge of a small (approximately 3 m. wide), shallow gully. BM 3 is almost exactly on a line connecting BM 1 and the lone large tree in approximately a 203° dirction from BM 1, being slightly streamward.

BM 1 to BM 3 to BM 5 to tree is not quite a straight line.

See Table 1-1.

Date surveyed = 7/23/75.

Table 1-1

SHOOTING FROM:	TO:	DIRECTION	DISTANCE (m.)
P.R.	BM 1	123°	32
S.R.	BM 1	69°	37
S.R.	BM 3	112° (B)	
S.R.	BM 5	159° (B)	
BM 2	BM 4	180° (T)	17.8
BM 1	BM 2	96°	30 (ML's was 31.3 taped)
BM 1	BM 3	203°	25
BM 1	BM 4	124°	38
BM 1	BM 6	146°	57
BM 1	BM 5	204°	50
BM 3	BM 4	87°	41
BM 3	BM 6	123° (B)	
BM 4	BM 6	181° (B)	27.3 (T)
lone cottonwood 203° from BM 1	BM 5	25°	14
BM 5	BM 6		51

Sediment Samples

BM 1 to BM 2:

#1) Taken on northern most bank (still in water & closest to BM 1).
#2) Taken in midchannel.
#3) Taken on southern most bank (in water & closest to BM 2).

BM 3 to BM 4:

#1 Taken in water on northern bank (closest to BM 3).
#2) Taken in mid channel.
#3) Taken in water on southern bank (closest to BM 4).

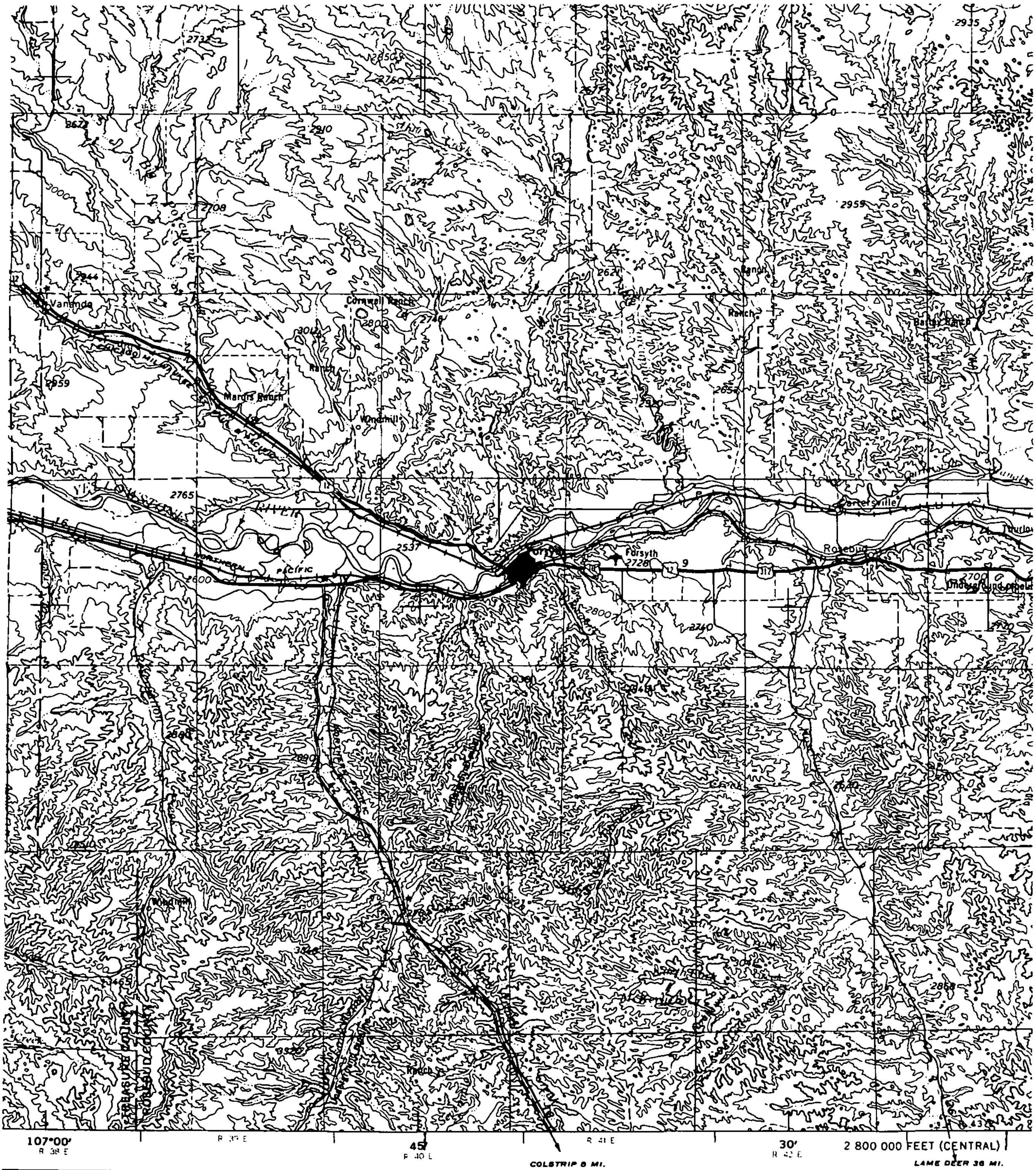
BM 5 to BM 6:

#1) Taken on northern bank, in water closest to BM 5.
#2) Taken on southern bank, in water closest to BM 6.
#3) Taken in midchannel.

These two ended up in the wrong bags, therefore bag #2 reads midchannel, but actually is southern bank closest to BM 6; and bag #3 reads southern bank, but is actually midchannel.

UNIVERSITY OF MONTANA
YELLOWSTONE VIGIL NETWORK SITES

Site Title	Site Number
Armells Creek - L. Frieze Ranch	Site # MY - 1
Rosebud Creek - Helvey Ranch	Site # MY - 2
West Fork Muddy Creek - Cheyenne Reservation	Site # MY - 3
East Fork Sarpy Creek - Pedding Ranch	Site # MY - 4
Ephemeral Tributary to Rosebud Creek - Sweedland Ranch	Site # MY - 5
West Fork Tullock Creek - Crow Reservation	Site # MY - 6
North Fork Rosebud Creek - Anderson Michael Ranch	Site # MY - 7
South Fork Rosebud Creek - Anderson Michael Ranch	Site # MY - 8
Main Stem Rosebud Creek - Anderson Michael Ranch	Site # MY - 9
Lower Tullock Creek - Haynie Ranch	Site # MY - 10
Lower Sarpy Creek - Lyle Ballard Ranch	Site # MY - 11
Lower Owl Creek - Murray Brown Ranch	Site # MY - 12
Sarpy Creek - below bridge on Colstrip Road	Site # MY - 13
Upper Owl Creek - Crow / Scott Land	Site # MY - 14
Mid Owl Creek - Crow / Scott Land	Site # MY - 15
Otter Creek - Trusler Ranch	Site # MY - 16
Otter Creek - Shy Ranch	Site # MY - 17
Logging Creek - Cheyenne Reservation	Site # MY - 18
Pumpkin Creek	Site # MY - 19
Pumpkin Creek - Roger Ranch	Site # MY - 20
Tributary to Hollowwood Creek	Site # MY - 21
	Site # MY - 22



Scale 1:250,000

10 15 20 Statute Miles

10 15 20 25 30 Kilometers

5 10 15 Nautical Miles

R INTERVAL 100 FEET

LOCATION DIAGRAM

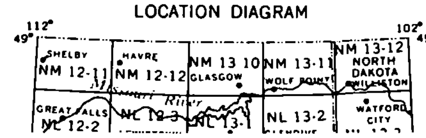


Table 1-2

CROSS SECTIONS: ARMELL'S CREEK SITE # MY - 1

All distances measured with the alidade.

STATION	DISTANCE (m.)	ELEVATION (m.) (relative to:)	REMARKS
BM 1 to BM 2		(BM 1)	
1.	30	-0.09	at BM 2
2.	29	-0.09	
3.	27	-0.30	
4.	26	-0.80	
5.	26	-1.16	
6.	25	-1.24	
7.	25	-1.71	end vegetation
8.	24	-1.97	edge of water
9.	24	-2.12	water surface = 0.15 m.
10.	22	-2.20	
11.	20	-2.16	
12.	--	-2.20	error in readings
13.	19	-2.24	sinking to knees in mud
14.	18	-2.15	
15.	16	-2.12	water surface = 0.15 m.
16.	15	-2.06	edge of water
17.	14	-1.67	top of vertical bank
18.	13	-1.52	
19.	11	-1.52	
20.	8	-0.55	
21.	7	-0.07	one foot from # 20

CROSS SECTIONS: Table 1-2 (cont.)

STATION	DISTANCE (m.)	ELEVATION (m.) (relative to:)	REMARKS
22.	5	+0.06	
BM 3 to BM 4		(BM 3)	
1.	41	-0.05	at BM 4
2.	37	-0.12	top of cut bank
3.	37	-1.18	bottom of cut bank
4.	36	-1.62	
5.	34	-1.78	
6.	33	-2.03	edge of water & vegetation
7.	33	-2.29	water surface = 0.26 m.
8.	31	-2.36	
9.	30	-2.34	
10.	27	-2.18	water surface =.15 m., .35 m. soft mud
11.	28	-2.13	
12.	26	-2.12	water surface = 0.1 m.
13.	25	-2.04	edge of water & vegetation
14.	25	-1.56	
15.	23	-1.35	bankfull
16.	21	-1.33	
17.	17	-1.33	(questionable shot)
18.	13	-1.19	toe basin terrace riser

CROSS SECTIONS: Table 1-2 (cont.)

STATION	DISTANCE (m.)	ELEVATION (m.) (relative to:)	REMARKS
19.	9	-0.06	
20.	5	+0.04	
BM 5 to BM 6		(BM 5)	
1.	51	-0.05	at BM 6
2.	48.5	-0.10	break in slope
3.	48	-1.16	toe of slope
4.	46	-1.65	bankfull
5.	45	-1.98	
6.	44	-2.16	edge of water
7.	42	-2.29	water surface = 0.205 m.
8.	42	-2.36	veg. clump in middle of stream
9.	40	-2.40	veg. clump in middle of stream
10.	38	-2.30	veg. clump, depth of water = .05 m.
11.	38	-2.15	water edge
12.	37	-1.78	break in slope
13.	35	-1.60	estimated bankfull stage?
14.	29	-1.27	
15.	23	-1.11	
16.	15	-0.78	
17.	9	-0.67	toe of terrace

CROSS SECTIONS: Table 1-2 (cont.)

STATION	DISTANCE (m.)	ELEVATION (m.) relative to:	REMARKS
18.	5	-0.12	top of terrace

VEGETATION TRANSECTS ARMELL'S CREEK SITE #MY 1 Table 1-3

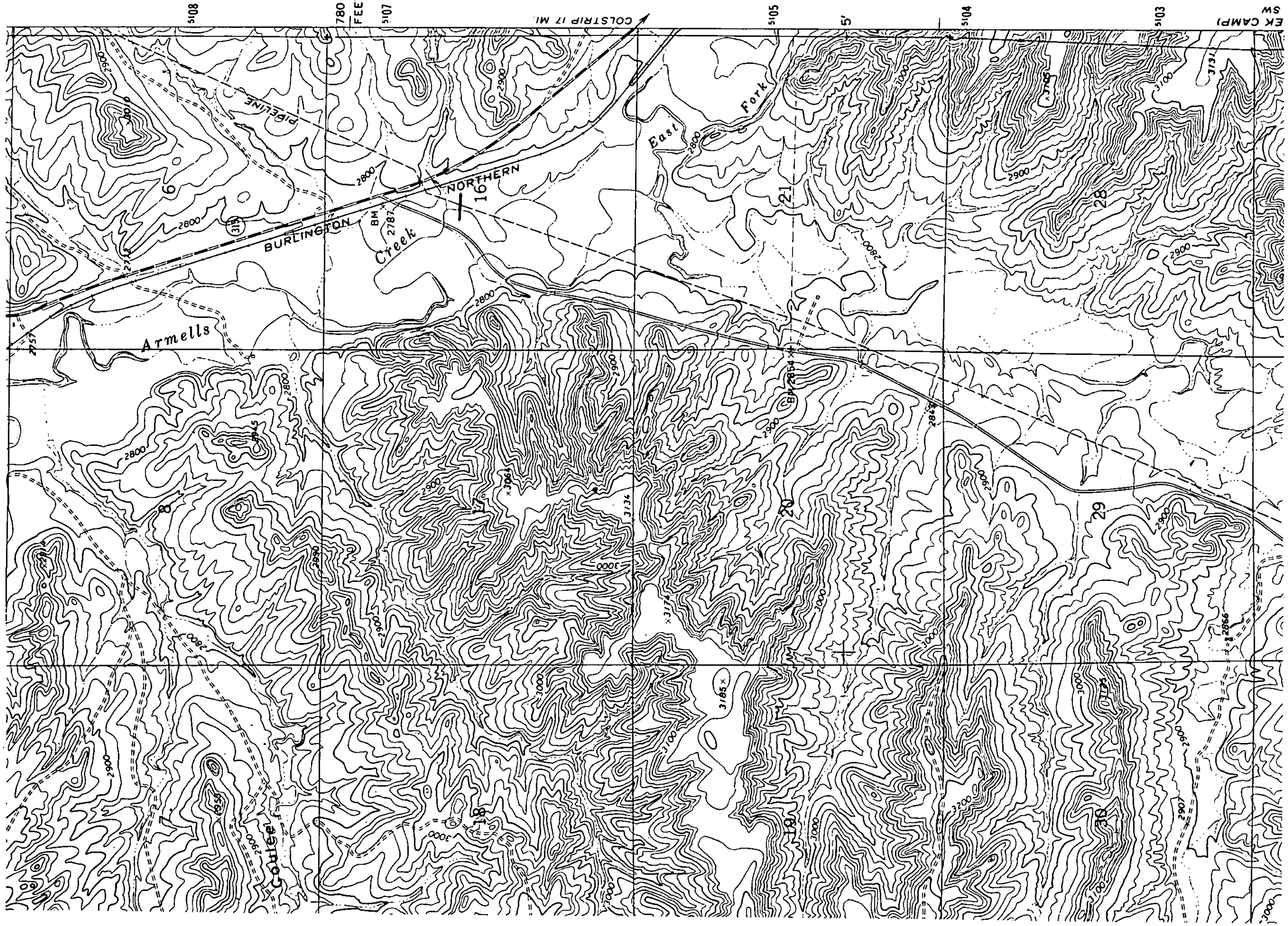
DISTANCE (M)	VEGETATION TYPE	DISTANCE (M)	VEGETATION TYPE
BM 1 to BM 2		BM 3 to BM 4	
1	grass	1	grass
2	bare	2	grass
3	grass	3	grass
4	grass	4	grass
5	grass	5	grass
6	grass	6	grass
7	grass	7	grass
8	bare	8	grass, herbs
9	forb (clover-like)	9	grass
10	forb	10	grass, herbs
11	forb, grass	11	grass, forbs
12	grass	12	grass, forbs
13	grass	13	grass, herbs, forbs
14	sedge, grass	14	herbs, grass
15	sedge	15	grass
16	bare (edge of stream)	16	grass, herb
17	grass	17	sage
18	forb, grass	18	sage, grass
19	grass, forb	19	grass, sage
20	grass, unknown #1	20	forb, grass
21	grass, unknown #1	21	forb, herb, grass
		22	sawgrass, grass

VEGETATION TRANSECTS Table 1-3 (cont.)

DISTANCE (M)	VEGETATION TYPE	DISTANCE (M)	VEGETATION TYPE
23	sawgrass	11	grass
24	sawgrass	12	grass
25	sawgrass, sedge	13	grass
26	sedge (water edge)	14	sage, grass
27	sedge (8.5 edge of water)	15	sage, grass
28	sedge, sawgrass	16	grass, sage
29	sedge, grass	17	grass
30	forb, sage, grass	18	grass
31	bare	19	grass
32	grass, berb (3.9 edge of cutbank)	20	grass
33	grass	21	grass
34	grass	22	grass
		23	grass
BM 5 to BM 6		24	grass, herb
1	sage, grass	25	grass
2	grass, sage	26	grass
3	sage, grass	27	grass, forb
4	grass	28	grass, forb
5	herb, grass	29	grass
6	herb, grass	30	grass, forb, herb
7	grass	31	grass
8	grass, forb	32	grass, herb
9	sage, grass, forb	33	grass, forb
10	grass	34	forb, grass

VEGETATION TRANSECTS Table 1-3 (cont.)

DISTANCE (M)	VEGETATION TYPE	DISTANCE (M)	VEGETATION TYPE
35	grass, sawgrass, sage		
36	sawgrass		
37	sedge		
38	sedge, (edge of water)		
39	sedge, grass (edge of water)		
40	sedge		
41	sawgrass		
42	grass, forb, herb		
43	bare		
44	grass, (3.3 m. top of cutbank)		
45	grass		
46	forbs, grass		


COLSTRIP 17 MI.
780 000 FEET
PIPELINE
BURLINGTON NORTHERN
Armells
Creek
East Fork
Coulee
BM 2787
2800
2900
3000
3100
3200

EXPLANATION

BM.............Benchmark

△.............Instrument Station

⊙.............Benchmark or Reference Point

P.R............Primary Reference

S.R............Secondary Reference

T.R............Tertiary Reference

Q.R............Quaternary Reference

T.N............True North

M.N............Magnetic North

-O-.............Telephone Pole

.............Tree

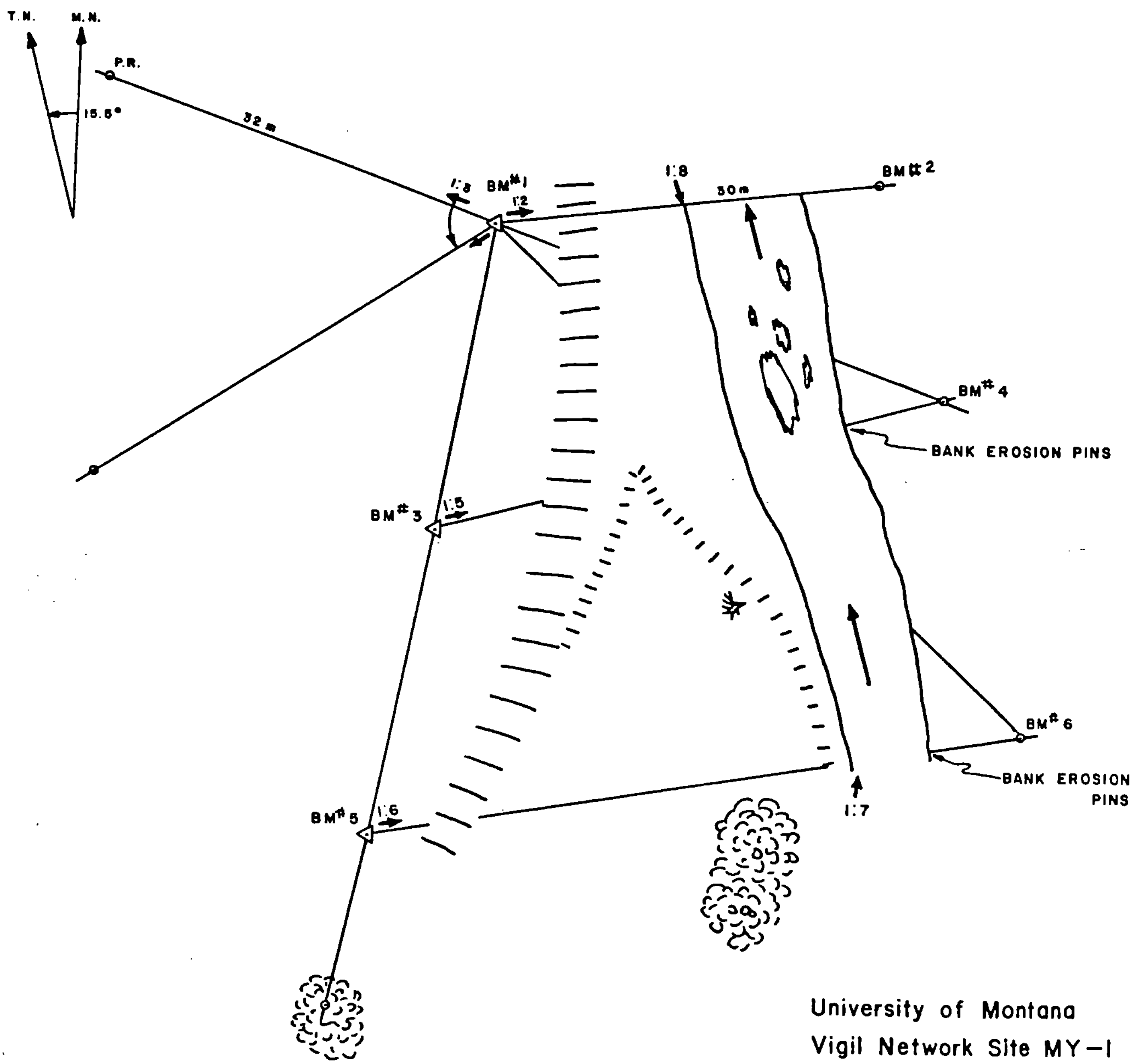
.............Bush or Shrub

← 3:15.............Photograph Sta.
(roll #: exposure #)

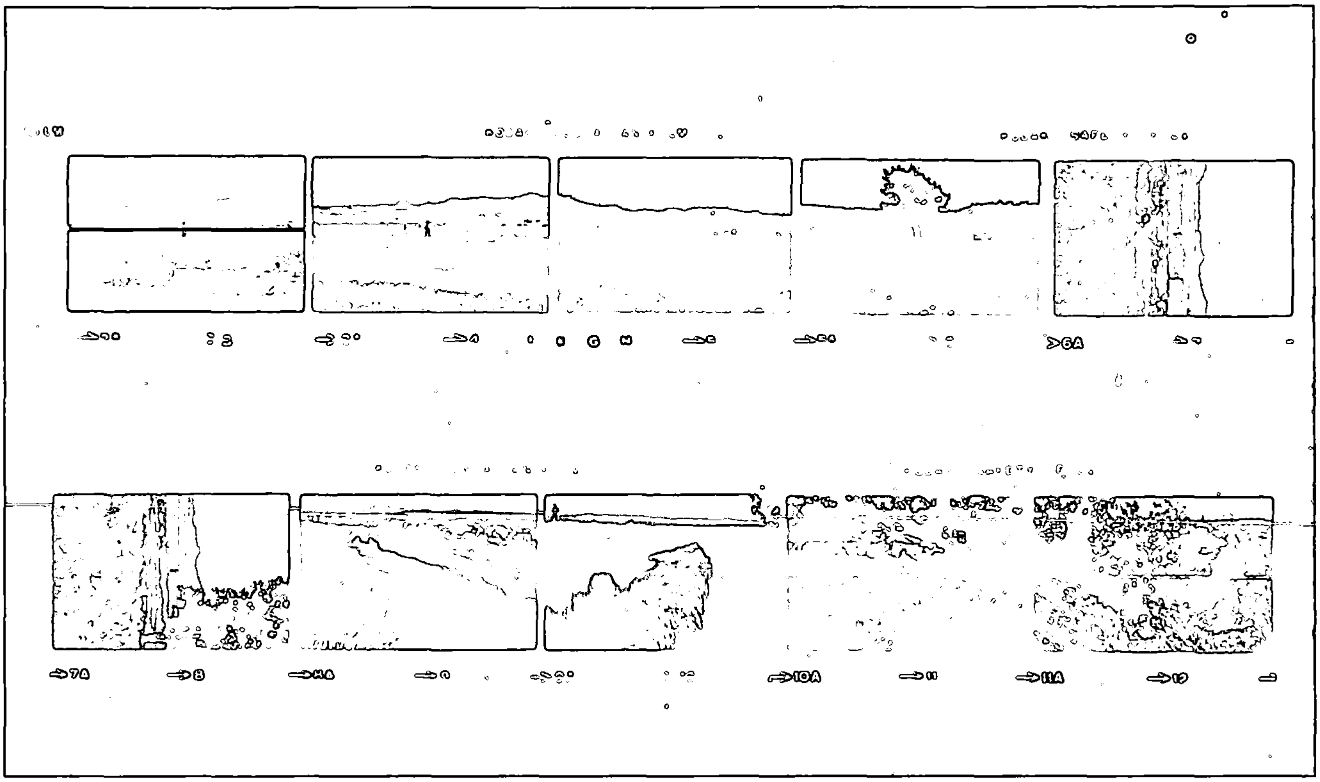
-•-•-•-............Fence

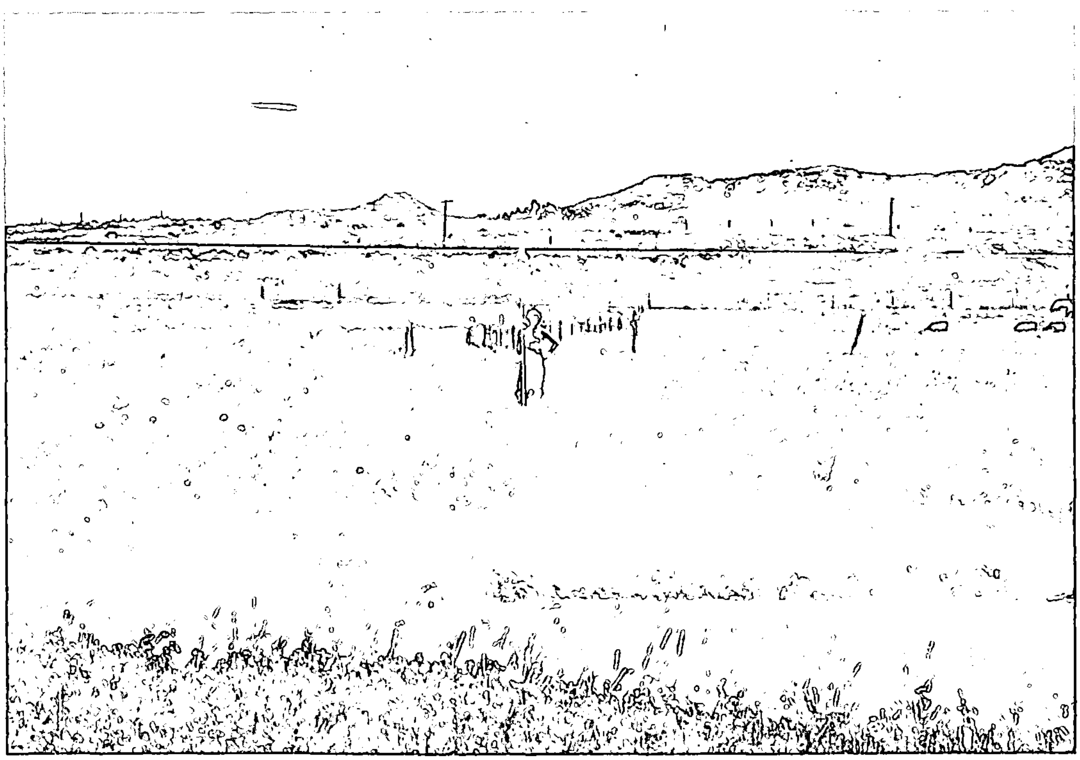
ARMELLS CREEK

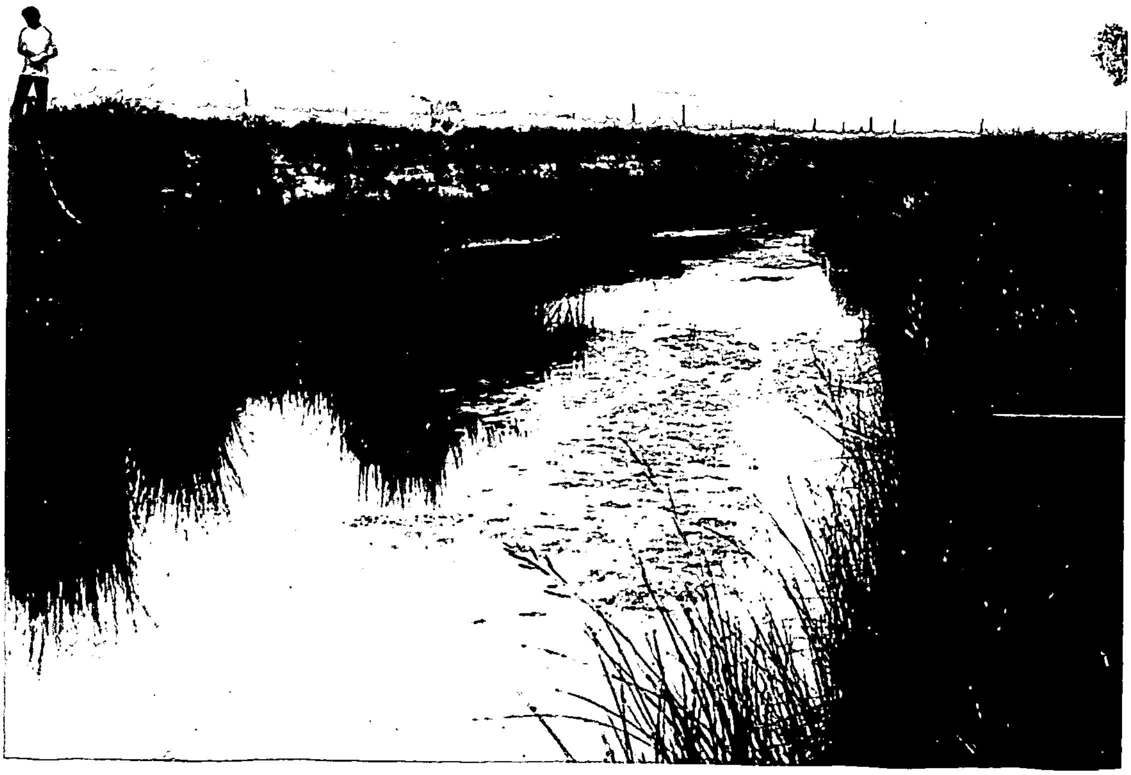
MY—I



University of Montana
Vigil Network Site MY—I
Surveyed: 7/23/75
Located: 17 mi. NW of
Colstrip—GRIFFIN COULEE QUAD.
2 m







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