UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

WATER RESOURCES DIVISION

EROSION AND DEPOSITION OF SEDIMENT IN STOCK RESERVOIRS IN THE POWDER RIVER DRAINAGE BASIN, WYOMING

By

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OPEN-FILE REPORT

Prepared as part of a program of the
Department of the Interior for development of the
Missouri River basin

MAR 10 1958
57-22

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EROSION AND DEPOSITION OF SEDIMENT IN STOCK RESERVOIRS IN THE POWDER RIVER DRAINAGE BASIN, WYOMING

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ABSTRACT

This report gives the results of an investigation by the U. S. Geological Survey and U. S. Bureau of Reclamation of sediment accumulation in stock reservoirs in the Powder River drainage basin upstream from Arvada, Wyo. The study was made to determine the net rates of erosion in the upland areas and the effects of the reservoirs on the amount of sediment transported to the parent stream.

The climate of the area ranges from cold and humid in the high mountains to warm and semiarid on the plains. The average annual precipitation ranges from less than 15 inches on the plains to more than 27 inches in the high mountains, which have a maximum altitude of 13,165 feet. The rocks in the Powder River drainage basin range in age from Precambrian to Recent.

The 25 stock reservoirs that were used in the study have drainage areas of 0.09 to 3.53 square miles, are from 3 to 51 years old, and impound water from areas that have land slopes

averaging from about 3 to 41 percent. The ratio of average reservoir capacity to drainage area ranges from about 2 to nearly 200 acre-feet per square mile.

After adjustment for trap efficiency the average annual sediment yield to the 25 reservoirs ranged from 0.04 to 1.49 acre-feet per square mile and averaged 0.50 acre-foot per square mile of drainage area. The average sediment yield from 6 drainage areas mostly underlain by shale was 0.80 acre-foot per year, 2.3 times greater than the yields from the areas underlain by sandstone or sandy shales.

Correlations show that the sediment yield increased approximately as the 1.5 power of the channel density, the 0.4 power of the shape factor, the 0.7 power of the average land slope, and the -0.25 power of the age of the reservoir.

Empirical equations for sediment yield and trap efficiency for the area studied are given.

INTRODUCTION

Purpose and Scope of Investigation

The investigation of sediment accumulation in stock reservoirs in the Powder River drainage basin upstream from Arvada, Wyo., was undertaken to determine the net rates of erosion in the upland areas and the effects of the reservoirs on the amount of sediment transported to the parent stream.

The relationship between the initial quantity of sediment eroded in a drainage basin above a reservoir and the quantity of sediment deposited in the reservoir during any particular interval depends on the amount of sediment deposited upstream from the reservoir after initial erosion and on the amount of sediment carried through the reservoir by overflow. The quantity of sediment accumulated in a stock reservoir that never spills represents the net rate of erosion for the drainage area above the reservoir. It does not reflect, however, the quantity of sediment that would be transported to the parent stream because of channel and flood-plain degradation or aggradation or both.

The investigation of erosion rates by studies of sediment accumulation in stock reservoirs was started in 1950 by the district office of the U. S. Bureau of Reclamation, Billings, Mont. On the basis of aerial photographs, field reconnaissance, and available geologic maps, the area upstream from Arvada, Wyo., was divided into five physiographic units. These units were selected to determine the relative importance of each with respect to rates of erosion and sources of sediment. Each unit is relatively homogeneous with respect to topography.

In accordance with the conclusions of a conference with the Bureau of Reclamation in Billings, Mont., on April 25, 1951, the Geological Survey undertook to complete the study as a part of an overall sedimentation investigation in the Powder River drainage basin. A field party for May and June 1951 was assigned to survey the reservoirs by the Bureau of Reclamation, Division of Hydrology, through arrangements with the district office. During August and September 1951 the district office assigned a field party to complete the surveys of the reservoirs scheduled for study.

Acknowledgments

Before May 1951 the investigation of erosion rates was conducted by F. P. Dakan under the immediate supervision of E. F. Hower, district hydrologist, U. S. Bureau of Reclamation.

H. V. Peterson, Technical Coordination Branch, acted as consultant and made available the services of M. D. Okerlund and N. J. King, who assisted with the field investigation. M. D. Okerlund also assisted with the reservoir computations.

Field investigations by the Geological Survey were conducted by C. H. Hembree and M. D. Okerlund during May-June 1951 and by C. H. Roach and M. D. Okerlund during July-October 1951.

The investigations by the Geological Survey were conducted under the administrative supervision of C. G. Paulsen, chief hydraulic engineer, Water Resources Division, S. K. Love, Chief of the Quality of Water Branch, Washington, D. C., and under the immediate supervision of P. C. Benedict, regional engineer, Lincoln, Nebr.

POWDER RIVER DRAINAGE BASIN

Location and Extent

The Powder River and its tributaries drain an area of approximately 13,400 square miles (U. S. Congress, 1934, p. 26) in northeastern Wyoming and southeastern Montana. However, this study is restricted to the part of the Powder River drainage basin that is upstream from Arvada, Wyo. (See fig. 1.) This part of the drainage basin has an area of about 6,000 square miles (U. S. Geol. Survey, 1950, p. 237). The area is bounded on the west by the Bighorn Mountains and on the southwest by the northeast flank of the Rattlesnake Range. The remainder of the boundary is formed by low divides that separate the area from the drainage basins of the North Platte, Cheyenne, Belle Fourche, and Little Missouri Rivers.

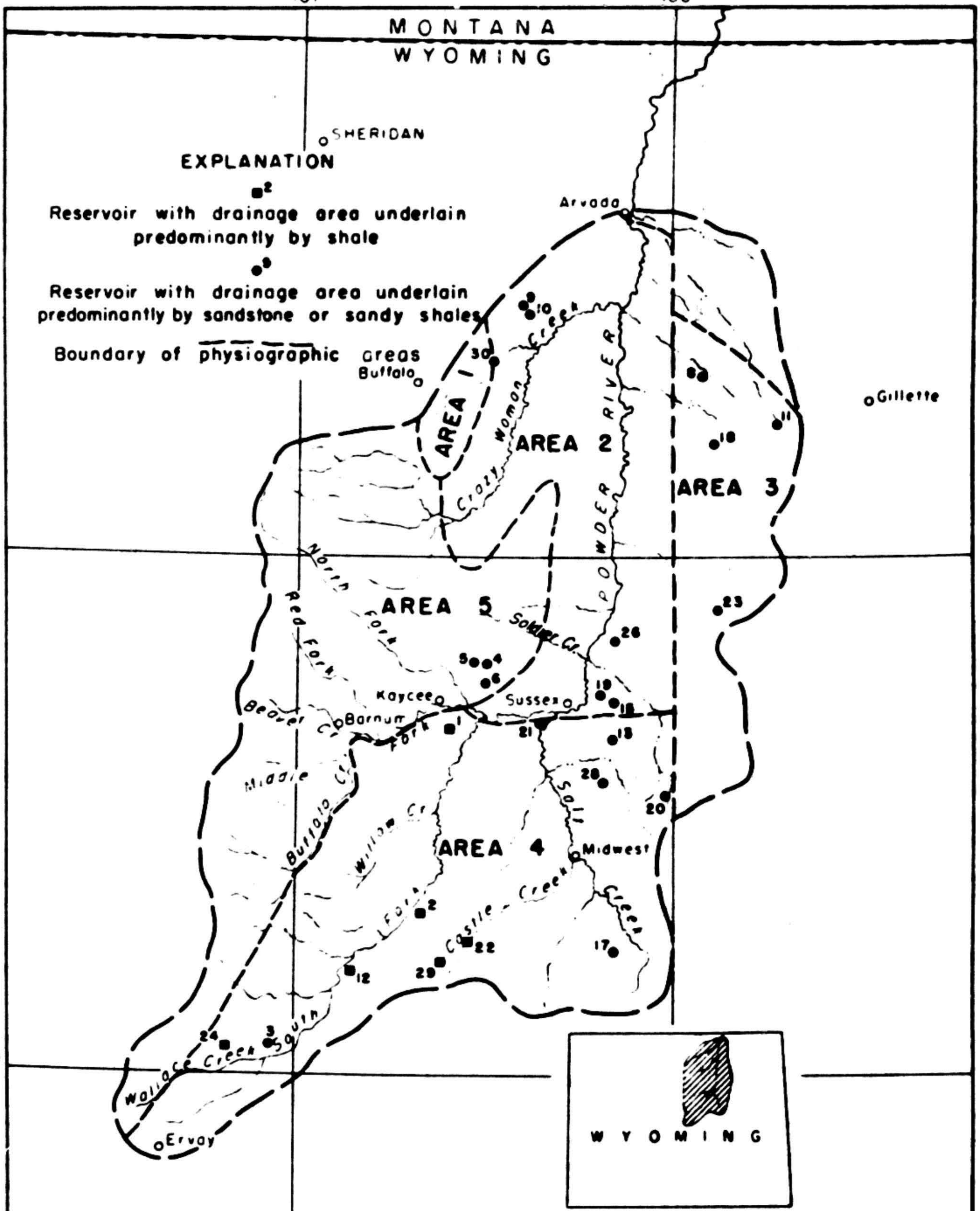


Figure 1.-- Map of the Powder River drainage basin upstream from Arvada, Wyo.

Physiographic Divisions

As a result of the preliminary study that was made of the Powder River drainage basin upstream from Arvada, Wyo., to delineate the different physiographic areas of the basin, five physiographic areas were outlined and are shown in figure 1.

Area 1 is characterized by low conical to pyramidal hills capped by baked clay and shale clinker. These hills rise above the general plain to a height of approximately 250 feet.

The outstanding topographic feature of area 2 is the badland type of topography, known as the Powder River "breaks," along the Powder River between Sussex and Arvada. In some parts of the area the entire surface has been thoroughly dissected to form badlands. The remainder of the area is characterized by sharply rounded hills and steep escarpments.

Area 3 is bounded on the east by the low divide that separates the drainage basin of the Powder River from the drainage basins of the Belle Fourche and Cheyenne Rivers. The area is bounded on the west by parts of the east boundary of areas 2 and 4. Area 3 is characterized by rolling hills, grass- and sage-covered slopes, and shallow drainage systems.

Area 4 includes the Salt Creek and South Fork drainage systems. It is characterized by low, relatively barren hills; sharply cut drainage systems; and wide, shallow meandering channels, some of which are heavily aggraded.

Area 5 includes the mountain and foothill terrain of the Bighorn Mountains west of U. S. Highway 87.

These five physiographic areas were delineated for the purpose of comparing rates of sediment retention in small stock reservoirs with different physiographic areas in the Powder River drainage basin.

Topography

The topography of the Powder River drainage basin ranges from rugged mountains to rolling plains. (See fig. 2.) Four general types of landforms are in the area. They consist of the Bighorn Mountains, the mountain foothills, the sharply rolling plains, and the gently rolling plains (Dunnewald and others, 1939, p. 1).

The Bighorn Mountains form most of the western boundary of the area. The east flank of the mountains rises abruptly from the general level of the plains, which is about 5,000 feet above

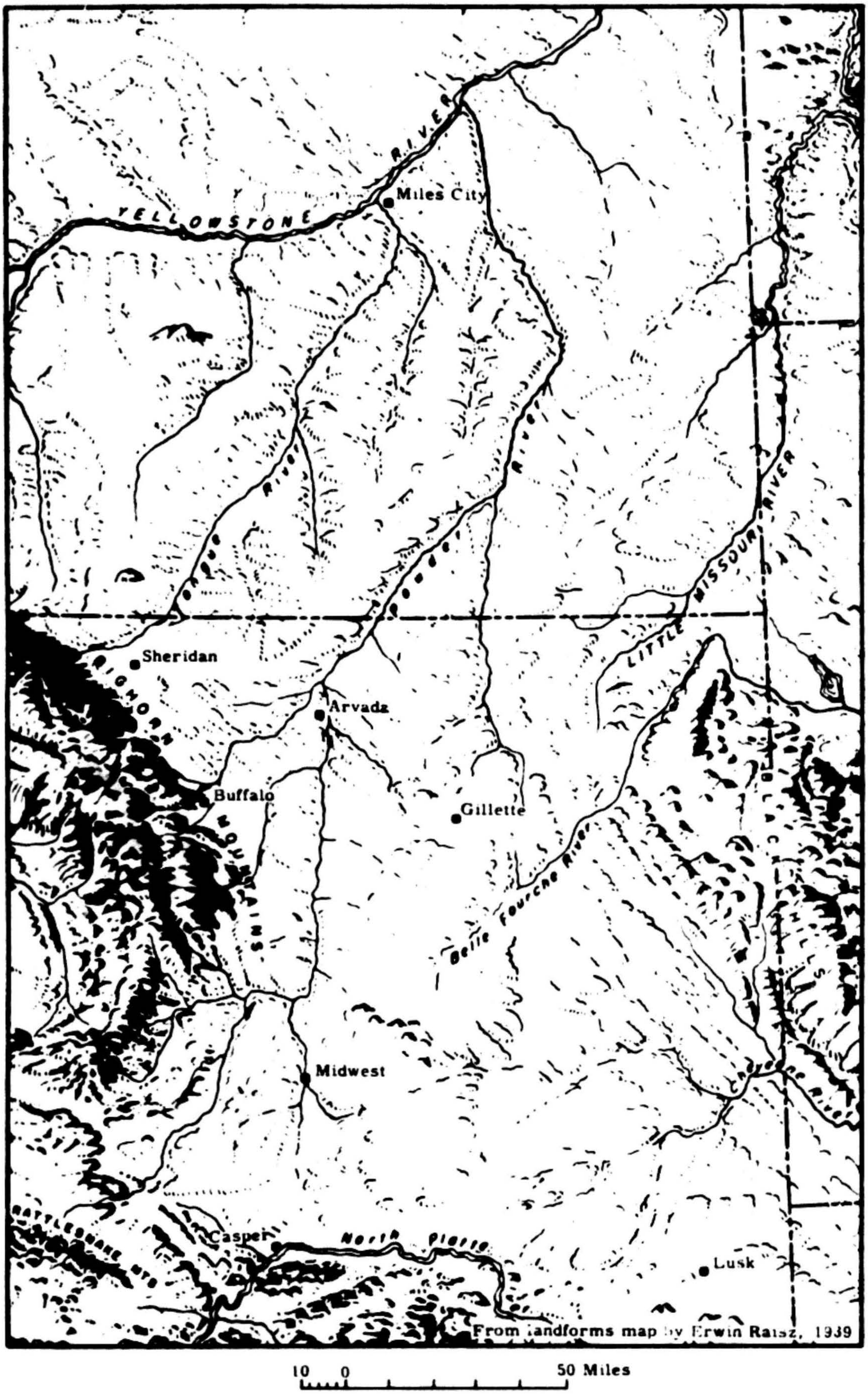


Figure 2.--Map of the landforms of the Powder River drainage basin and surrounding areas.

sea level, and attains an altitude of about 8,000 feet within a distance of several miles. The maximum altitude of 13,165 feet occurs along the Bighorn Divide at the summit of Cloud Peak.

The foothills at the base of the mountains have a great variety of surface features and corresponding soils. The bedrock consists of sandstone, shale, and limestone. The unconsolidated material, derived through glaciation and erosion of the mountain slopes, was brought down by streams and deposited as terraces, flood plains, and alluvial fans of gravel, sand, and clay. The deepening of the valleys has left many benches and mesas. Most of the deposited land has a smooth surface suitable for irrigation. The other land within this area consists of rather steep hills and ridges and a few small flats.

The sharply rolling plains lie generally east of the foothills and are irregularly distributed in the basin. The broad tabular divides separating the larger streams are, relatively speaking, thoroughly dissected by the narrow valleys of the lateral drainageways. The greater part of the plains is characterized by sharply rounded hills, steep escarpments, and small interspersed badlands. The roughest areas are in the "breaks" along the

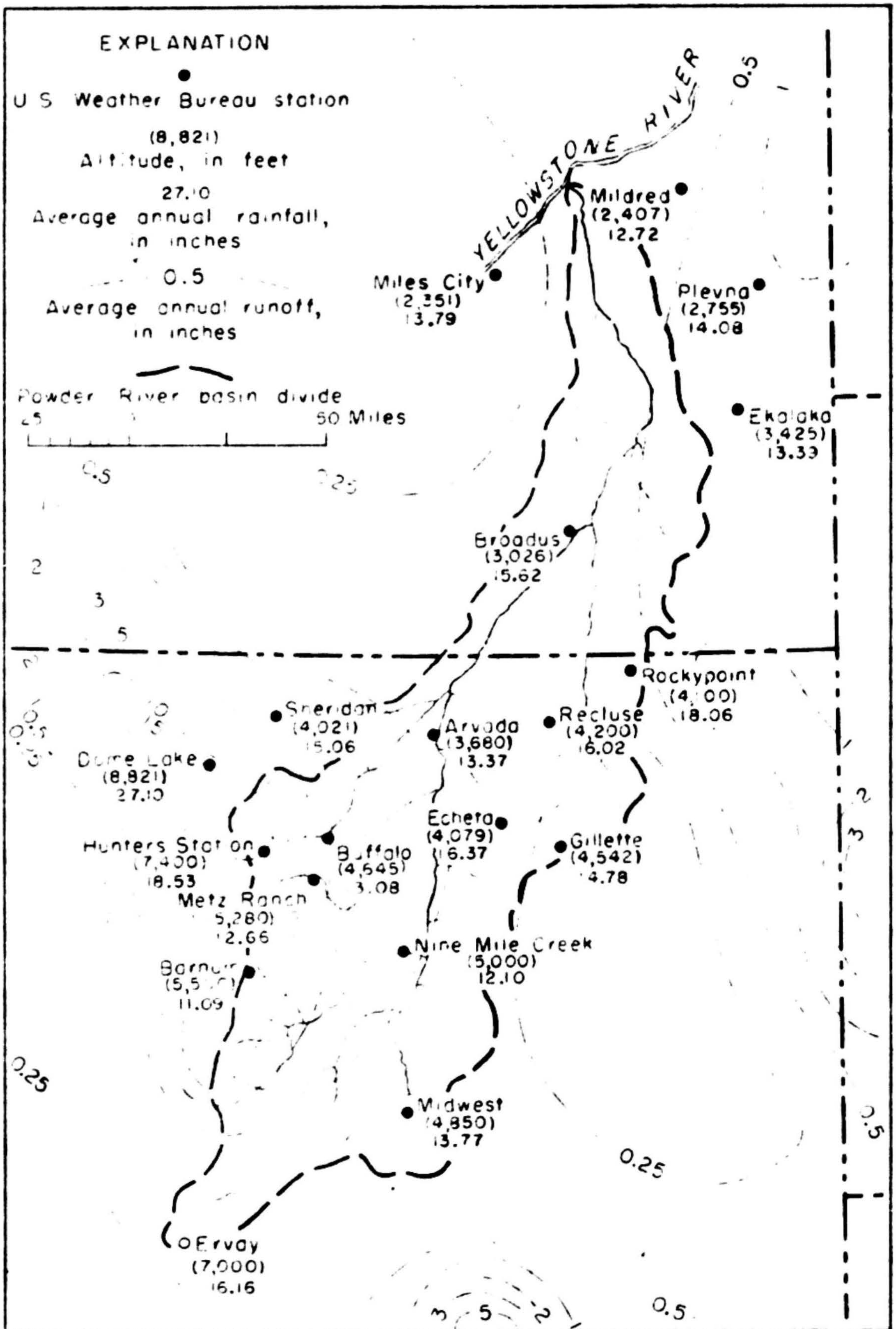
Powder River and Crazy Woman Creek where the land has been carved into rough, sharply rolling ridges and deeply cut valleys; in places, the entire surface has been dissected into badlands.

The gently rolling plains include widely distributed areas that have escaped thorough dissection and are comparatively smooth. The relief of a large part of this land is undulating and favorable for farming, and parts of it are topographically suited for irrigation.

Climate

The altitude of the area ranges from about 3,600 feet at Arvada, Wyo., to 13,165 feet at the summit of Cloud Peak. Large local differences in temperature and precipitation occur in the area because of this range in altitude. A belt of relatively heavy precipitation coincides with the higher mountain districts. (See fig. 3.) Climatological records are not available for these high altitudes, but at some places in the mountains the average annual precipitation is as much as 27 inches.

The lower mountain slopes and foothills are in a less humid belt. Climatic fluctuations occur in this belt because of differences in altitude and topography. This belt is a transition zone between



Lines of average annual runoff from Colby and Oltman, 1948

Figure 3.--Precipitation and runoff in the Powder River basin.

the cold humid climate of the high mountains and the relatively warmer and more arid climate of the plains.

The climate of the rest of the basin is characterized, in general, by less precipitation and greater temperature variation. The plains area has a semiarid climate and an average annual precipitation of less than 15 inches.

Soils and Vegetation

The broad soil groups of the Powder River basin follow vegetational and climatic differences without regard to geological conditions (Thorp and others, 1939, p. 42). They are (1) soils of the humid mountains, (2) soils of the subhumid foothills, and (3) soils of the semiarid plains. In the higher part of the mountains the soils, where found, are well-developed Podzols. The soils in the foothills and semiarid plains are mostly Chernozem and Chestnut soils, but possibly the soils of the more arid part of the plains may be grouped with the Brown soils (Dunnewald and others, 1939, p. 32). The Chernozems are mainly restricted to narrow areas in the foothills. The soil types of the older and younger terraces, as well as of the recent flood plains, are highly variable.

The vegetation of the Powder River basin is as varied as are the landforms and soils. The most common tree in the mountains is lodgepole pine. Western yellowpine, Englemann spruce, alpine fir, limberpine, aspen, and red cedar are common also. Willows fringe some of the mountain streams, and many kinds of pasture grasses grow in the open areas of the forests.

Several kinds of sage and grass grow in the Great Plains section of the Powder River basin. The most common grasses are wheatgrass, gramagrass, buffalograss, and junegrass. Dense thickets of plum, serviceberry, chokecherry, haw, and other bushes grow in the draws near the foot of the mountains. Cottonwood, boxelder, and willow trees border some of the streams of the Great Plains and follow them into the mountain canyons. Western yellowpine and cedar grow on scattered outcrops of sandstone east of the Bighorn Mountains.

General Geology

The Powder River drainage basin is a topographic basin that occupies the western part of the much broader Powder River structural basin. This structural basin is bounded on the west by the Bighorn Mountains, on the south by the Laramie Mountains, on the southeast by the Hartville uplift, and on the east by the Black Hills and associated folds. The structural deformation that formed the basin began with the Laramide revolution in Late Cretaceous time. More recent phases of this deformation are indicated by the unconformable contacts of the conglomerate of the Moncrief member of the Wasatch formation and Oligocene (?) sediments with their underlying formations.

Alluviation of this structural basin began with the Laramide revolution and probably continued until late Tertiary time when the basin was filled to a much greater extent that it is today. A widespread uplift occurred throughout the Rocky Mountain region near the end of Tertiary time (Atwood and Atwood, 1948, p. 606). This regional uplift rejuvenated the streams and started a cycle of erosion that is still in progress and has formed the present topography of the Powder River structural basin. The Powder River drainage basin was formed by the subsequent erosion of the post-Laramide sediments that filled the structural basin to an unknown extent.

The rocks cropping out in the Powder River drainage basin range in age from Precambrian to Recent. (See table 1 and fig. 4.) Igneous and metamorphic rocks of Precambrian age are exposed in the Bighorn Mountains and at the head of the

Table 1.--Summary of exposed rock formations in the Powder River drainage basin

[Darton, 1906, pl. 47; Hares and others, 1946; Love and others, 1945; Thompson and others, 1949; Brown, 1949; Wegemann, 1918, p. 13; Reeside, 1944; Thomas, 1948, p. 79-92; Love and Weitz, 1951]

Age	Formation and member	Remarks
Quaternary		Glacial deposits in the mountains. Terrace and flood-plain deposits of gravel, sand, and silt along the streams.
	Unconformity	
Tertiary: Oligocene	White River (?) formation and younger unnamed rocks.	Sands, volcanic ash, gravels, and boulders.
	Unconformity	
Tertiary: Eocene	Wasatch formation: Moncrief member	Sandstone, drab-colored; drab-colored to variegated claystone and shale; and numerous coal beds. Moncrief member consisting of conglomerate of Precambrian rock fragments, sandstone, and drab shale. Kingsbury conglomerate member consisting of conglomerate of Paleozoic rock fragments, sandstone, and variegated claystone.
	Wasatch formation: Kingsbury conglomerate member	
	Unconformity	
Tertiary: Paleocene	Fort Union formation: Tongue River member	Sandstone, light-colored, massive; gray-colored shale; and numerous coal beds. The Fort Union is, in places, divided into three members: the Tongue River member at the top, the Lebo shale member in the middle, and the Tullock member at the base.
	Fort Union formation: Lebo shale member	
	Fort Union formation: Tullock member	
	Unconformity	
Cretaceous	Lance formation / Hell Creek formation Fox Hills sandstone / Fox Hills sandstone Lewis shale / Bearpaw shale	Sequence of dark marine shales (Lewis, Bearpaw), followed by marine sandstone (Fox Hills), and then by nonmarine dark-colored claystone and shale and coal beds called Lance in Wyoming part of basin and Hell Creek in Montana part of basin.
	Mesaverde formation: Teapot sandstone member	Sandstone, alternating white to buff, massive, cross-bedded, coal-bearing, with a middle zone of marine shales. In northern part of basin Teapot member is not recognized.
	Mesaverde formation: (unnamed middle part)	
	Mesaverde formation: Parkman sandstone member	

Table 1.--Summary of exposed rock formations in the Powder River drainage basin--Continued

Age	Formation and member		Remarks
Cretaceous	Cody shale		Sandstone, shaly; dark-gray marine shales; calcareous shale; thin limestones; and a few thin beds of bentonite.
		Shannon sandstone member	
	Frontier formation	Wall Creek sandstone member	Sandstone and shales, interbedded, gray and black. Thin subbituminous coal beds are present.
	Mowry and Thermopolis shales, undivided		Mowry shale, hard, black, siliceous, weathers silvery gray; underlain by soft black Thermopolis shale that has Muddy sandstone member 200 ft above base.
	Cloverly and Morrison formations, undivided		Conglomerates; gray sandstones and silty shales; lilac claystones and limestone concretions; and variegated shale and claystones, siltstones, and silty sandstones.
Jurassic	Sundance and Gypsum Spring formations, undivided		In descending order, green glauconitic shale, red sandstone and siltstone, gray sandstone, green shale, and lenticular white sandstone. At base is Gypsum Spring formation consisting of red siltstone and gypsum with some white dolomite and limestone beds.
	Unconformity		
Triassic	Chugwater formation	Popo Agie member	Claystone, ocher-colored; purple to red siltstone; and limestone conglomerates.
		Alcova limestone member	Limestone, thin, crinkly light-gray.
		Red Peak member	Siltstone, reddish.

Table 1.--Summary of exposed rock formations in the Power River drainage basin--Continued

Age		Formation and member	Remarks
Triassic and Permian			Undivided Triassic and Permian rocks along the south and west margins of the Powder River basin.
		Unconformity	
Carboniferous	Pennsylvanian	Tensleep sandstone and Amsden formation, undivided	Sandstone, thick; underlain by red shale and limestone and red to gray sandstone.
		Unconformity	
Carboniferous	Mississippian	Madison limestone	Limestone and dolomite, massive, blue-gray, cherty. 1/
		Unconformity	
Ordovician and Cambrian			Bighorn dolomite underlain by equivalents of Gallatin formation, Gros Ventre formation, and Flathead sandstone along west margin of Powder River basin.
		Unconformity	
Precambrian			Granite, schist, and gneiss.

1/ In some localities dolomite and sandstone of Devonian (?) age underlie the Madison.

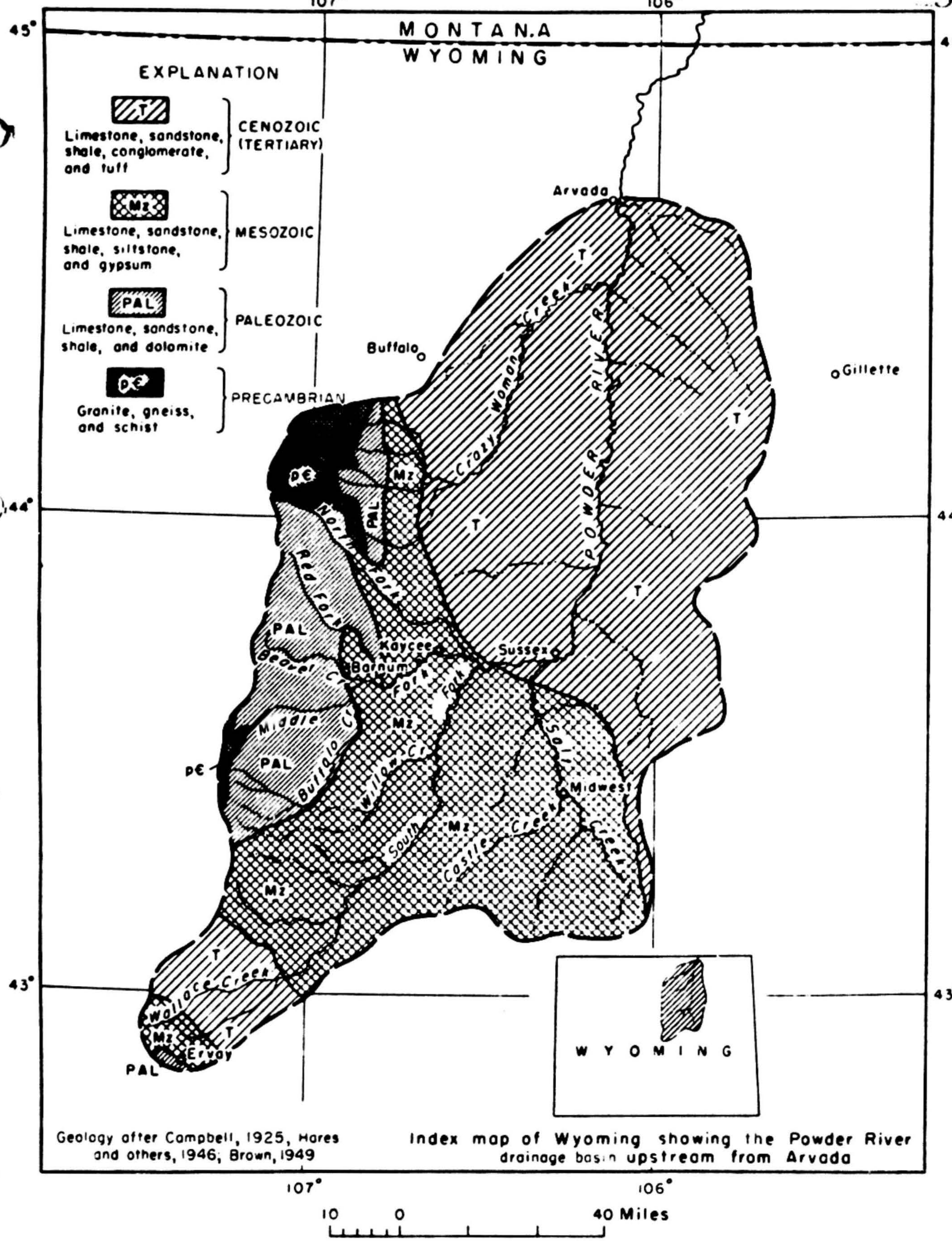


Figure 4.--Geologic map of the Powder River drainage basin upstream from Arvada, Wyo.

South Fork Powder River in the Rattlesnake Range. Paleozoic rocks are exposed along the flanks of the Bighorn Mountains and the Rattlesnake Range. Mesozoic rocks crop out in the foothills of the Bighorn Mountains and along the southern and southeastern parts of the area that is included in this study. Outcrops in the remainder of the area are mainly of Tertiary rocks and relatively minor exposures of Pleistocene glacial debris and Recent alluvial deposits. The Pleistocene deposits are exposed in and near the Bighorn Mountains, and remnants of a once extensive system of Pleistocene terraces can be found in scattered areas of the drainage basin. Recent alluvial deposits are present along practically all the streams in the drainage basin.

The Powder River flows northward and joins the Yellowstone River near Terry, Mont. The principal tributaries upstream from Arvada rise in the Bighorn Mountains and adjacent foothills. The stream pattern throughout the drainage basin is dendritic, and there is very little or no structural control.

STOCK PONDS

During the summer of 1950, a preliminary study was made of the Soldier Creek drainage basin in physiographic area 2 near Sussex, Wyo. (See fig. 1.) The work consisted of surveying

Palmer Reservoir, near the outlet of the Soldier Creek drainage basin, for the purpose of determining the amount of sediment accumulation. Palmer Reservoir was reported in 1950 to have been constructed in 1909. The volume of sediment was determined by drilling with a power auger to establish depths of accumulated sediment. It was recommended that the quantity of sediment accumulated in the stock reservoirs above Palmer Reservoir should be determined so that the rate of sediment yield for the entire drainage basin could be computed.

As a result of the preliminary studies during the summer of 1950, additional field investigations were made in the Soldier Creek drainage basin during May and June 1951. During this period, 22 stock ponds above Palmer Reservoir were surveyed in order to determine the quantity of sediment accumulated in the Soldier Creek drainage basin in addition to that in Palmer Reservoir. Some general information concerning the date of construction of these reservoirs was obtained by personnel assigned to the field investigation at that time.

During a later period of the stock-pond investigations of the Powder River drainage basin upstream from Arvada, Wyo., (July-October 1951) more accurate information was sought concerning the dates of construction of the 22 stock reservoirs and Palmer Reservoir. However, after consulting the three land owners, specific dates of construction could not be obtained for the reservoirs in the Soldier Creek drainage basin. For example, Palmer Reservoir was previously (summer of 1950) reported to have been constructed in 1909; however, during October 1951 the land owner reported that Palmer Reservoir was built in 1902. The range in reported age of each of the 22 reservoirs varied from 1 to 16 years.

If these reported ages were used to compute the annual rate of sediment yield for the drainage areas of the individual reservoirs, the error introduced would range from about 8 to 125 percent. As several of the reservoirs were nested one above another in the same drainage basin, the range of reported ages for the individual reservoirs would not indicate even the relative age of each reservoir. For these reasons the data collected on Palmer Reservoir and the 22 reservoirs above it were not used in the preparation of this report.

The data on 13 additional reservoirs, located throughout the Powder River drainage area upstream from Arvada, Wyo., were not used in this report because the reported age of the reservoir or the original data concerning the operational history of the reservoir or both were unreliable. Also, aerial photographs were not available for three of the drainage areas above the reservoirs.

In summary, about 60 stock reservoirs were surveyed for study of rates of sediment yield. However, information on only 25 of these stock ponds was complete and reliable enough for an investigation of apparent relations between physical characteristics of the drainage basin and the sediment yield at the stock pond.

The drainage areas of the 25 stock ponds range in size from 0.09 to 3.53 square miles, in reported age from 3 to 51 years, and in average land slope from about 3 to 41 percent. The ratio of average reservoir capacity to drainage area ranges from about 2 to nearly 200 acre-feet per square mile. The physical characteristics of the stock ponds are listed in table 2.

Physical Characteristics of the Drainage Basins

A survey was made of the drainage area upstream from each reservoir that was used in this study. Several physical characteristics of the drainage areas and reservoirs were determined. The characteristics and the methods that were used to measured them are discussed here.

Drainage Area

The drainage areas were outlined stereoscopically in the field from aerial photographs, which were furnished by the U. S. Bureau of Reclamation. A map of each drainage area was prepared on transparent tracing film. The accuracy of the outline of the drainage areas was checked thoroughly during the field surveys. The drainage areas were planimetered from the maps and are expressed in square miles.

Shape of Drainage Area

Peak water discharges from a drainage area are a function of many variables, one of which is the shape of the drainage area. Several types of shape factors have been proposed for small drainage areas (Wisler and Brater, 1949, p. 44). A shape factor, to be usable in correlation and analyses, should be computed easily and should be dimensionless. The shape factor chosen for this study is the ratio of the basin length to the basin width. The length used is that of the longest channel in miles. The width was computed by dividing the drainage area, in square miles, by the length of the longest channel in miles. The shape factor is, therefore, the square of the length of the longest channel divided by the drainage area.

Vegetation Density Factor

The density of vegetative cover for each drainage area was estimated in the field. The type and the relative abundance of vegetation were noted. On the basis of these field studies, each drainage area was classified according to relative vegetative density as good (1), fair (2), or poor (3). (See table 2.) Detailed vegetation surveys may be made at a later date by the U. S. Bureau of Land Management.

Infiltration Factor

The character of the outcropping bedrock and soils was noted, and the infiltration rate for each drainage area was estimated and was classified as high (1), medium (1.5), or low (2).

Slope of Land

The slope of the land within the drainage area of each reservoir was determined with the aid of an Abney hand level. Average percentage slope by small areas, and the location of these areas in the basin were recorded on the maps. Individual land slopes within an area are almost infinite in number, and it was necessary to generalize to a great extent in order to obtain land slopes that could be conveniently analyzed. Accordingly, the land slopes were estimated by averaging several individual measurements. Caution was taken to avoid averaging measurements of slopes whose magnitudes differed considerably.

All slope measurements were expressed as percentages, and the percentage of the total drainage area that was occupied by each of several selected ranges of slope was computed. The slopes were weighted by areas to compute average slopes above each reservoir.

Average Distance of Overland Flow

The slope length, as used here, refers to the average distance traveled by overland flow before entering a defined channel. The slope lengths were computed directly from the aerial photographs by averaging several individual measurements of slope length. The individual slope lengths were measured in the direction of overland flow and are expressed in feet.

Drainage Basin Slope

The basin slope of several of the drainage areas was measured with the aid of a compensating aneroid barometer. During the surveys, the barometer was set to read zero at the altitude of the spillway of each reservoir. Relative elevations were determined for different points throughout the basin. The basin slope was computed by dividing the altitude, in feet above the spillway, of a point at the head region of the principal channel by the length of that channel in miles. The basin slope was determined for only half of the drainage areas and was not used in the correlations.

Channel Density

The complete drainage system of the areas was not traced on the maps in the field. Therefore, the drainage densities were computed directly from the aerial photographs with the aid of stereoscopes and reading glasses. The length of all channels within a drainage area was computed, in miles, by expanding a pair of draftsman's dividers in steps along the channels. The total length of channels was divided by the drainage area to obtain the channel density in miles per square mile. The length of raw channels was also measured.

Channel Slope

The slopes of the stream beds were measured at different places in the drainage basins with the Abney hand level. The slope measurements were made from the channel bottoms by sighting the hand level upstream and downstream and using the average reading. The measured slope and the point of measurement were recorded on the maps.

Headcuts

The location of each headcut was noted on the drainage maps during the drainage area surveys. A headcut that had a well-grassed channel below it was considered to be relatively inactive, whereas a raw channel was interpreted to indicate recent head-cutting. The headcut density per square mile above each reservoir was computed by dividing the number of headcuts by the drainage area.

Age of Reservoir

The age of each reservoir was learned by questioning the owner, the builder, or other informed persons. The ages of some of the reservoirs were checked against records of the Production and Marketing Administration.

Measured Accumulations of Sediment

Sediment accumulations in each stock pond were computed from transit and plane table surveys. Depths of sediment were measured by probing with steel rods. The method of computing the sediment volumes consisted of preparing a contour map of the stock pond in its condition at the time of the survey. Dashed or red contour lines were also placed on the map to show the reservoir as it was before any sediment was deposited in it. The areas at contour lines were planimetered. The original and the present capacities below the spillway altitude were then computed separately. The computation was made by adding volumes as computed between contour altitudes. That is, the area at the lowest contour was multiplied by the average depth of water when the water surface was at the contour altitude. Then the areas at pairs of successive contours were averaged, and these average areas were multiplied by the vertical distance between the pairs of contours. The sum of all such products below any given altitude represents the capacity. The volume of sediment was computed by substracting the present capacity from the original capacity unless sediment was deposited above the level of the spillway.

A preferable method of computing volume of sediment perhaps would be the following:

1. Plot depths of sediment on a map of the reservoir.

2. Draw lines of equal depths of sediment.

3. Planimeter areas for each of the lines of equal sediment depth.

4. Plot area against depth of sediment.

5. Planimeter volumes of sediment below any given altitude from the area-depth graph.

This method was used as a check on the computed volumes of sediment in five of the stock ponds. Differences between volumes of sediment as computed by the 2 different methods were as high as 15 percent but were not all in the same direction.

The volume of sediment that was accumulated per year was obtained by dividing the total volume by the reported age of the reservoir to the nearest year. (Some of the reported ages may not be completely accurate.) The rate of sediment accumulation in the 25 stock ponds averaged 0.39 acre-foot per square mile per year. The highest annual rate per square mile was 1.42 acre-feet and the lowest was 0.03 acre-foot. The figure of 0.03 acre-foot per square mile per year is for reservoir 9. The data for this reservoir are out of line on all the correlations and may indicate that the determination of sediment depths in the field was not correct. Six of the stock ponds had drainage areas that were underlain predominantly by shale. In these ponds, sediment accumulated at an average rate of 0.70 acre-foot per square mile per year.

Dry weight per cubic foot of the reservoir sediment was determined for 9 of the stock ponds from the average of 3 or 4 samples of the sediment in place. These samples were collected with a plunger type of sampler. In some reservoirs the samples were taken under water, and in others they were taken from sediment that was exposed to the air. Table 3 shows the average dry weight per unit volume of sediment in place.

Table 3.--Specific weight of the reservoir sediment

Reservoir number	Number of samples	Average dry weight per unit volume (lb per cu ft)
1	3	9.9
2	4	58.2
4	4	55.3
5	4	56.6
10	4	58.8
11	4	57.4
18	4	63.3
23	4	84.0
30	4	66.4

Interpretation of Sediment Accumulations

Time limitations prevented the selection of the stock ponds by the best method to obtain a sample that would be representative either of the entire Powder River drainage basin above Arvada or of stratigraphic divisions. The stock ponds were selected at random with emphasis being placed on the physical condition of the reservoirs, their known date of construction, and their general location within the basin. The trap efficiency of the reservoirs that spill is very indefinite. The few measured specific weights of the sediment deposits in the ponds indicate that the conditions of deposition may have a large effect on the weight per unit of volume. Because of these difficulties, the rates of sediment accumulation may have limited usefulness.

As will be explained later, the average annual measured sediment accumulation of 0.39 acre-foot per square mile for the 25 ponds may indicate a yield to the reservoir sites of about 0.50 acre-foot per square mile per year after adjustment for assumed trap efficiency. If the average weight of the sediment deposits per cubic foot is assumed to be 65 pounds, the total sediment discharge into the 25 reservoirs averaged about 700 tons per square mile per year. The runoff at the stock ponds was not determined, but it probably ranged from about 0.15 inch to perhaps 1.5 inches per year. Probably the runoff to the stock ponds averages at least 0.3 inch per year. On the basis of these estimates, the average concentration of sediment in the water that enters the stock ponds would be only about 3 percent. By comparison, the average annual discharge of suspended sediment of the Powder River at Arvada, Wyo., for the 5-year period that ended September 30, 1950, was about 5,500,000 tons (Hembree and others, 1952, p. 24). This is equivalent to 910 tons per square mile. The average weighted concentration of suspended sediment of the Powder River at Arvada during the 5-year period was 2 percent (Hembree and others, 1952, p. 24). Most of the streamflow of the Powder River at Arvada originates in the Bighorn Mountains, where the streams carry very low concentrations of sediment. Therefore, the computed sediment yields from the drainage areas above the stock ponds seem to be too low as compared with the yield from the Powder River drainage basin above Arvada. The comparison may indicate that much of the sediment at Arvada was obtained from the stream channels outside the mountains or that the sediment accumulations in the stock ponds represent rates of erosion far below the average for the plains area of the Powder River drainage basin upstream from Arvada. However, important sources of sediment may exist in the area between the main stream channels and the upland parts of the drainage basin, where most of the stock ponds are located. For example, the badlands along the Powder River between Sussex and Arvada are important sources of sediment that are not represented in this investigation, because erosion is so serious in that area that essentially no stock ponds have been constructed there. Probably the poor comparison is due to a combination of these factors.

Of course, one should expect that ranchers would try, insofar as possible, to build stock ponds in areas where erosion rates are low. Inspection of aerial photographs and personal interviews with ranchers tend to confirm the idea that some of the stock ponds that were used in this study were in small areas where erosion rates were below average.

Rates of erosion computed from sediment accumulations in the stock ponds do not measure sheet erosion. Appreciable amounts of sediment have been deposited in the drainage areas above some of the ponds, and headcutting and channel widening and deepening provide significant amounts of sediment to some of the ponds.

SEDIMENT ACCUMULATION IN RESERVOIRS

The data are too few and uncertain to establish good correlations between the physical characteristics of the drainage areas and the sediment accumulations in the stock ponds. However, some relationships are tentatively indicated. These relationships are by no means necessarily those of cause and effect. Apparent changes in physical characteristics seem to be associated with changes in sediment yield to the stock ponds in the area of study. Hence, as far as this study has yet shown, the characteristics that do show some sort of relationship to sediment yields are only indicators of these yields. Because a physical characteristic may not cause the change in sediment yield that is associated with it, the tentative relationships that seem to be indicated may not apply to stock ponds in other areas.

The general procedure for correlating the sediment accumulations in the reservoirs with the physical characteristics of the drainage areas and reservoirs was to make tentative correlations and then to improve these tentative correlations by later adjustments. (The basic data for all the correlations are listed in table 2.) First, the average sediment accumulation was computed in acre-feet per square mile per year for the six reservoirs that drain areas underlain predominantly by shale. The average for the other 19 reservoirs, underlain predominantly by sandstone or sandy shales, was also computed. The sediment accumulations in the six reservoirs were adjusted according to the ratio of these averages. Next, the sediment accumulations adjusted only for the difference in underlying rocks(lithology) were plotted against one of the physical characteristics from table 2. The average relationship, or trend line, was drawn on this scatter diagram. All sediment accumulations were expressed in percentage of the sediment accumulation that was indicated by the trend line. Then these percentage sediment accumulations were plotted against another physical characteristic, and another tentative trend line was drawn. Sediment accumulations expressed in percentage of the average that was indicated by this trend were then plotted against another physical characteristic. This procedure was continued until all the physical characteristics that seemed to be significant had been used.

Of course, the first tentative trend line for any particular physical characteristic usually required adjustment. The adjustment was made by repeating the procedure of plotting successive physical characteristics against percentage sediment yields that were indicated by the trend line of the preceding plot. The procedure was continued until no further large adjustments were indicated for any of the physical characteristics. (See figs. 5, 6, and 7.)

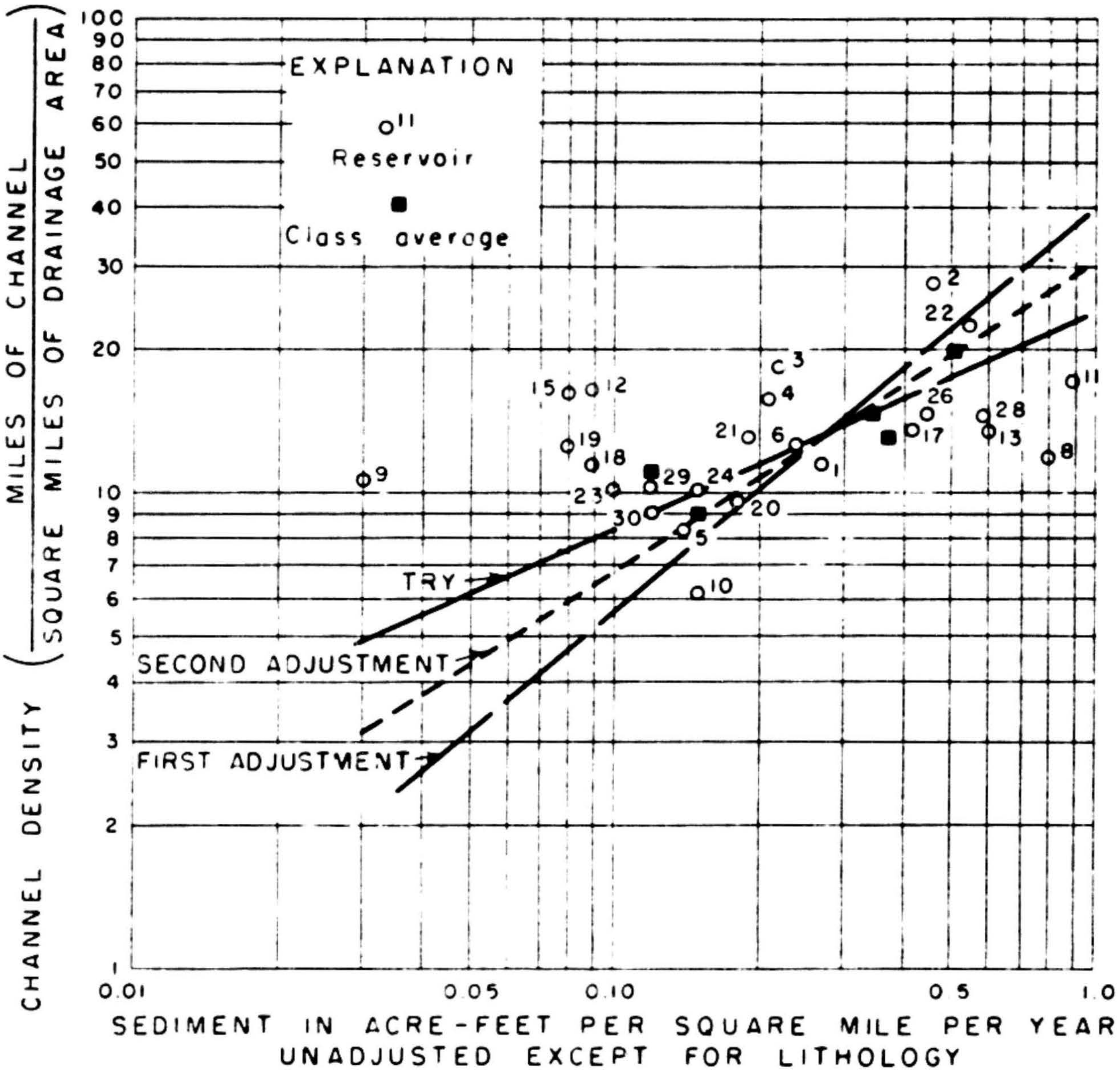


Figure 5.--Correlation of quantity of sediment and channel density.

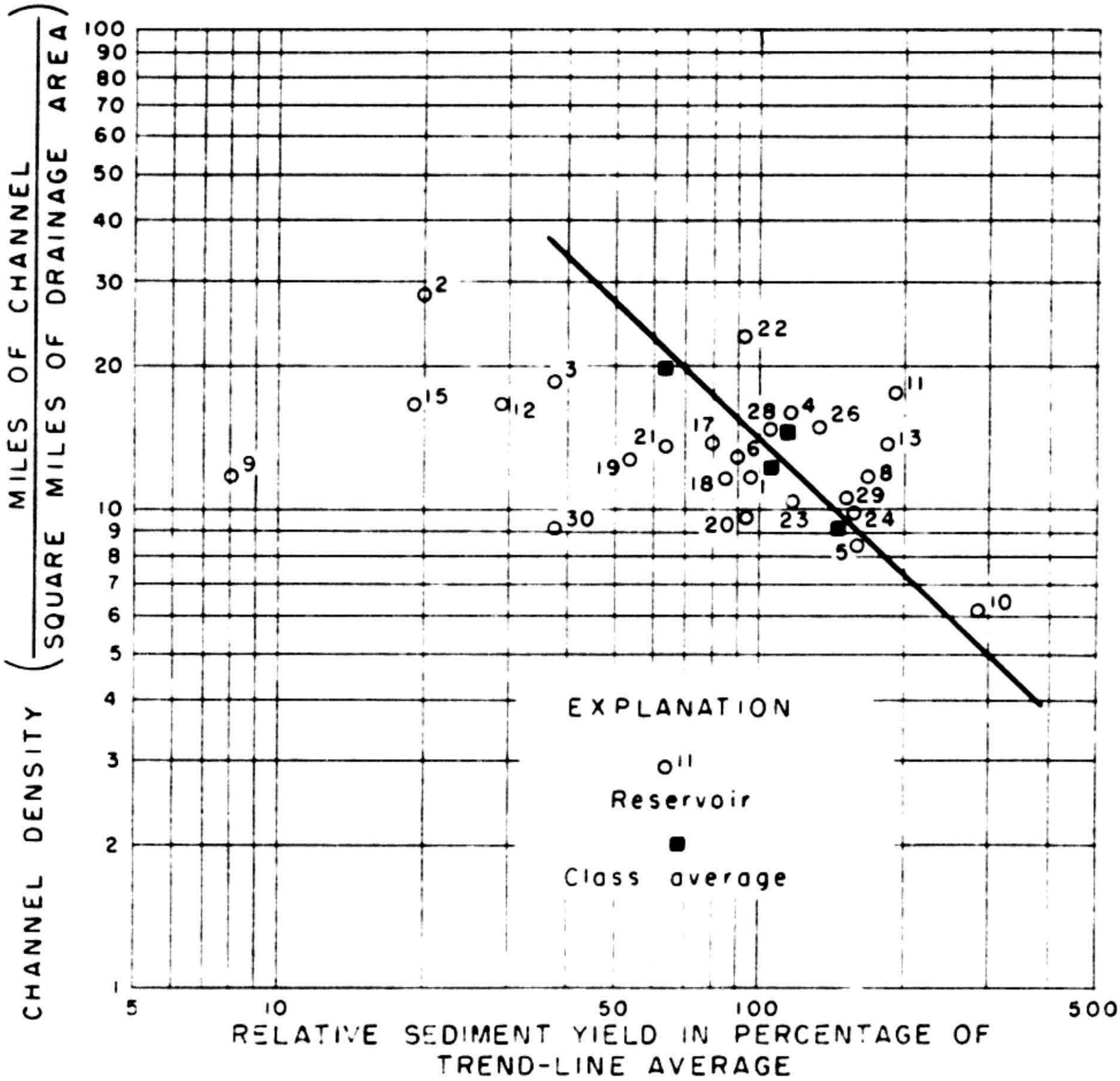


Figure 6.--Second trial plotting of channel density against sediment yields that have been adjusted for first correlations with physical characteristics. The trend line indicates the adjustment to be applied to the trend line of the first trial correlation on figure 5.

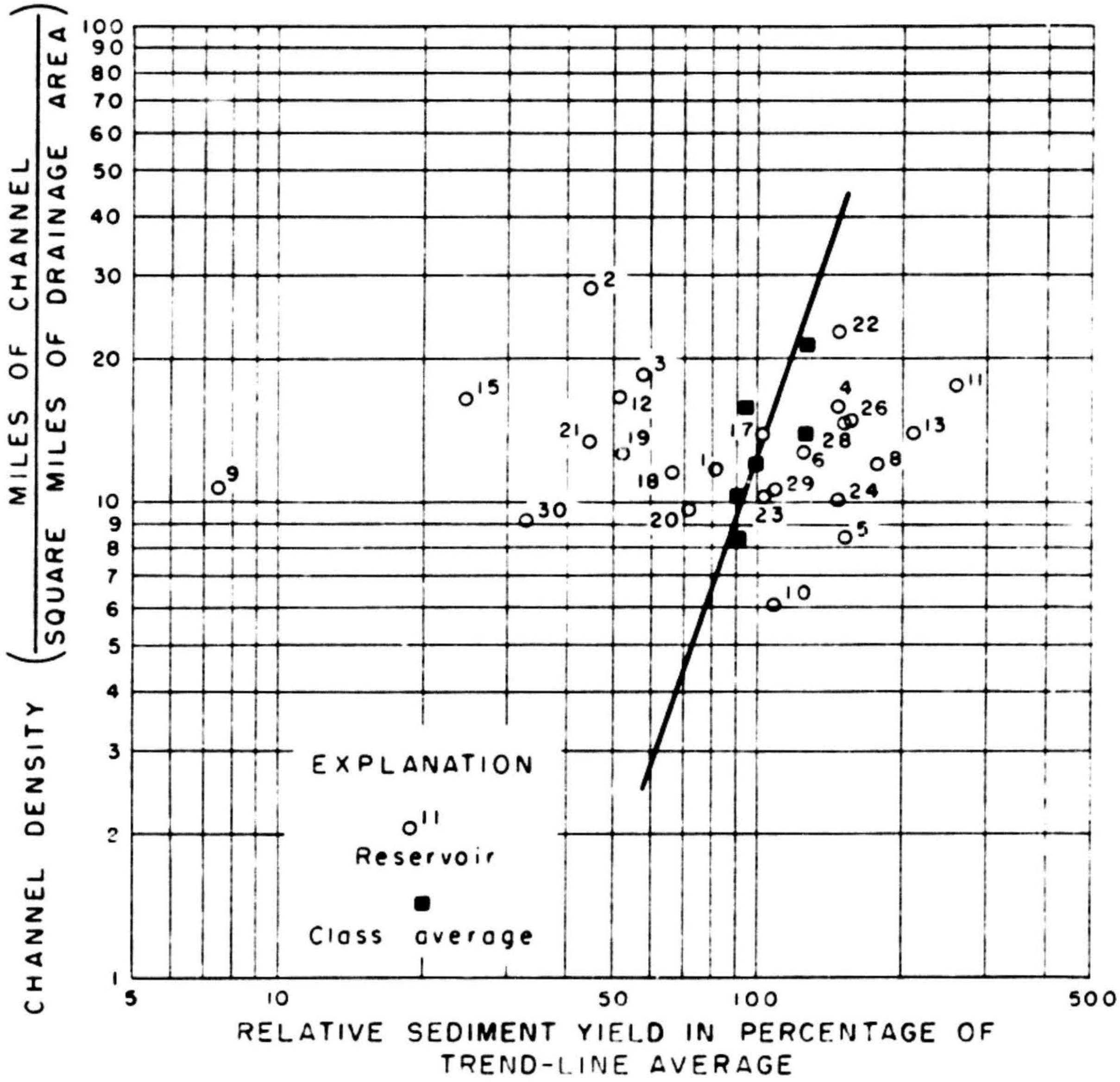


Figure 7.--Third trial plotting of channel density against sediment yields that have been adjusted for the second trial correlations with physical characteristics.

The reservoir capacity per square mile was treated exactly the same as any other physical characteristic except that the trend line of its relationship to the sediment accumulations was assumed to be a curve rather than a straight line when plotted to logarithmic coordinates. This curve was plotted so as to be asymptotic to 100 percent sediment accumulation and was used as a trap efficiency curve. Amounts of sediment adjusted for trap efficiency are referred to in this report as sediment yields at the reservoir site in contrast to sediment accumulations before adjustment for trap efficiency.

All trend lines were determined with sediment accumulations or sediment yields as the independent variable.

Lithology

The drainage areas of stock ponds 1, 2, 12, 22, 24, and 29 are underlain mostly by shale. The annual sediment accumulation in these 6 stock ponds averaged 0.70 acre-foot per square mile as compared to 0.29 acre-foot for the other 19 stock ponds (table 2). The figures for sediment accumulations in the 6 stock ponds were adjusted by a coefficient of 0.4 before any other correlations were tried. Subsequent checks seemed to show that, after correlations with other physical characteristics had been made, the 6 stock ponds in areas that are underlain mostly by shale could be expected to receive sediment inflow at about 2.3 times the rate for the other stock ponds. Other classifications could have been made on the basis of soil and rock types, but none have been made except indirectly through other characteristics.

Channel Density

After the adjustment for difference in lithology had been applied, the sediment accumulations in acre-feet per square mile per year were tentatively correlated with the channel density. The scatter of the individual points and the assumed average relationship are shown on figure 5.

Figure 6 shows the second attempt at correlating sediment yield with channel density. Prior to being plotted on figure 6, the figures for sediment yields had been tentatively adjusted for the first tries at correlations with lithology, channel density, drainage area shape factor, average land slope, age of the reservoir, and reservoir capacity per square mile. The trend line on figure 6 indicates that the line that represents the first tentative correlation should be adjusted somewhat. The adjusted trend line is shown as a dashed line on figure 5. Figure 7 is the scatter diagram of the sediment yield plotted against channel density after the sediment yields have been adjusted for the first two tries at the correlations with the other physical characteristics. The small adjustment indicated by the trend line of figure 7 establishes the position of the dotted line of figure 5. This dotted line is assumed to represent the approximate average relationship between the channel density and sediment yield. It shows that sediment yield increases approximately as the 1.5 power of the channel density.

Shape Factor

Successive attempts at correlation of the sediment yield with the shape factor resulted in a trend line that shows the sediment yield to increase with the 0.4 power of the shape factor.

Average Land Slope

The sediment yield increased considerably with increase in the average slope of the land surface. The rate of increase seemed to be about as the 0.7 power of the land slope.

Age of Reservoir

When the ages of the reservoirs were correlated with sediment yields, the yield was found to vary with approximately the -0.25 power of the age. This relationship may be the result of somewhat greater runoff during recent years than during the drier years from about 1930 to 1940, or greater compaction of sediment in the older reservoirs, or both.

Drainage Area

Although the sediment yields changed as about the -0.2 power of the drainage area, this apparent relationship was not used in the correlations. The average reservoir capacity per square mile of drainage area decreased with an increase in drainage area. Hence, the decrease in sediment yield with an increase in drainage area may have been due to a lower capacity-area ratio rather than to the change in drainage area. Conversely, the relationship finally used between the capacity-area ratio and sediment yield may include some of the effect that should have been ascribed to change in drainage area.

Reservoir Capacity Per Square Mile

The average reservoir capacities per square mile of drainage area were plotted against the sediment accumulations after the first attempts at correlation had been made with lithology, channel density, shape factor, average land slope, and age of the reservoir. An average curve with a logical shape was drawn. Later adjustments based on the subsequent correlations shifted this curve only slightly. The final relationship (fig. 8), when shifted to make it asymptotic to 100 percent, can be expressed reasonably closely by the equation:

$$T = 100 \left[1 - \frac{3.5}{3.5 + (C/A)^{0.8}} \right]$$

in which

T is the trap efficiency in percent

C is the average reservoir capacity in acre-feet

A is the drainage area in square miles

This is the trap efficiency curve as defined during this investigation. Such a curve approximates the percentage of the total sediment inflow that is trapped in a reservoir. However, a trap efficiency curve based on the relation between sediment accumulation and the reservoir capacity per square mile is questionable. The capacity-area ratio is by no means a perfect measure of the trap efficiency of

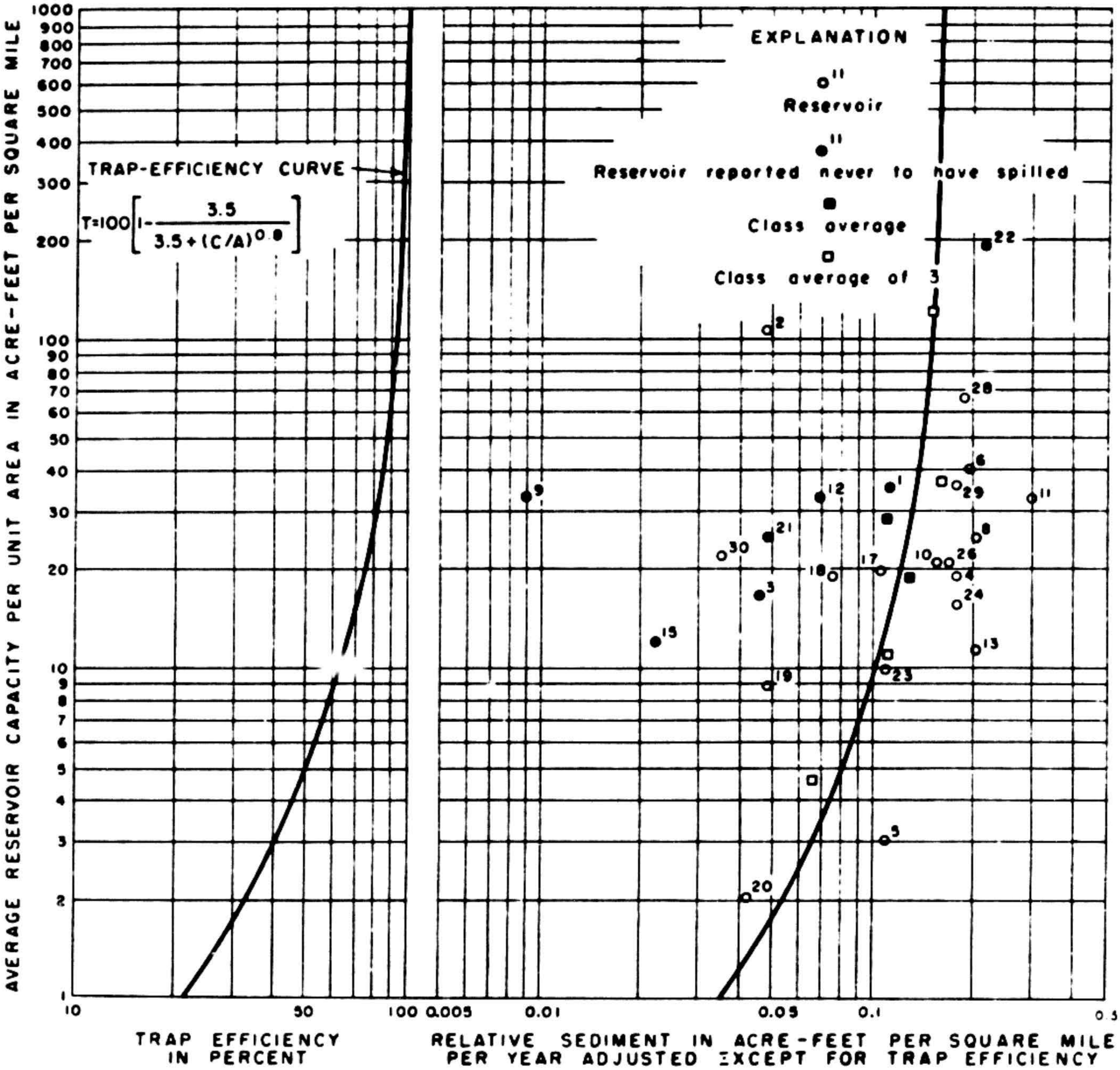


Figure 8.--Trap-efficiency curve based on relationship of adjusted sediment yield and reservoir capacity per square mile.

reservoirs. As figure 8 shows, the average adjusted sediment accumulation in the stock ponds that were reported never to have spilled is not significantly greater than the average adjusted accumulation in the reservoirs that were reported to spill at least occasionally. Perhaps part of the explanation is that most reservoirs reported never to have spilled are in relatively inaccessible areas and are infrequently visited. Therefore, the information concerning the spillage from these reservoirs may be inaccurate.

The wide scatter of the points on figure 8 shows that the curve is not well defined. However, it seems to be as good a curve as can be determined without additional data on runoff, sediment inflow, and sediment outflow at some of the stock ponds.

Relation of Rates of Sediment Accumulation and Yield to Physiographic Divisions

Table 4 shows the average rates of sediment accumulation and yield at the stock ponds in the different physiographic areas. (See fig. 1.)

Table 4.--Rates of sediment accumulation and yield[1/] for the physiographic areas

Physiographic area	Number of stock ponds	Average rate of sediment (acre-ft per sq mile per year)	
		Accumulation	Yield
1	....	....	....
2	6	0.15	0.21
3	4	.47	.60
4	12	.54	.67
5	3	.20	.30

1/ Sediment accumulation adjusted for trap efficiency.

These rates of sediment accumulation and yield do not represent the relative importance of each physiographic area as a source of sediment. It is obvious that stock reservoirs are not normally built in areas where the rates of erosion or runoff are excessively high. For example, the rates of sediment accumulation and yield listed for physiographic area 2 are unreliable because essentially no stock ponds are built in the badlands along the Powder River between Sussex and Arvada, where the rates of erosion are high. Also, economic considerations tend to emphasize the construction of stock ponds on small drainageways, which creates a bias toward the upland areas of a large drainage basin. The number of stock ponds is too small to determine average rates for any of the physiographic areas. Also, no stock ponds from area 1 were used in this study because no ponds were found in this area that had a satisfactory history. The 6 stockponds that are mostly underlain by shale are all in physiographic area 4, and their average annual sediment yield was 0.80 acre-foot per year. For these reasons, the rates listed in table 4 are only indicative of the correct average rates, and much additional study would have to be undertaken before the relative importance of each physiographic area as a source of sediment could be determined.

Other Physical Characteristics

The other physical characteristics listed in table 2 were also considered in relation to sediment yields. Special attention was given to attempts to correlate the number of headcuts per square mile with sediment yields. No significant relationship was found. Also, the very slight indications of relationship between the infiltration factor and the vegetation density factor seemed to be in the wrong direction and were disregarded.

Summary of Correlations

The final correlations that appeared to be significant can be combined and summarized in the equation:

$$Y = KD^{1.5}S^{0.4}s^{0.7}\frac{1}{a^{0.25}}(1 + 1.3L)\left[1 - \frac{3.5}{3.5 + (C/A)^{0.8}}\right]$$

in which

Y is the sediment yield in acre-feet per square mile per year

K is a constant (K is 0.0018 for this study)

D is drainage density in miles per square mile

S is the drainage area shape factor

s is the average land slope in percent

a is age of the reservoir in years

L is a factor to adjust for the higher rates of sediment yield from shale areas (L is 0 for nonshale areas and 1.0 for shale areas)

C is average reservoir capacity in acre-feet

A is drainage area in square miles

This equation is subject to all the errors and inaccuracies in the correlations. It is limited by the range of the base data and by inaccuracies in those data. The relationships indicated by the equation are not necessarily those of cause and effect, so the equation may not be applicable to sediment yields at stock ponds in any other area or even under markedly different conditions within the Powder River drainage area upstream from Arvada, Wyo.

CONCLUSIONS

About 60 stock ponds and their drainage areas were studied in the field. Of these, only 25 seemed to have sufficient information for inclusion in this study.

The annual rate of sediment accumulation in the 25 stock ponds ranged from 0.03 to 1.42 acre-feet per square mile and averaged 0.39 acre-foot per square mile of drainage area. All or most of the drainage area of six of the stock ponds was underlain by shale. The average annual sediment accumulation in these ponds was 0.70 acre-foot per square mile.

After adjustment for trap efficiency, the average annual sediment yield to the 25 reservoirs ranged from 0.04 to 1.49 acre-feet per square mile and averaged 0.50 acre-foot per square mile of drainage area. For the 6 reservoirs whose drainage areas are mostly underlain by shale, the average sediment yield was 0.80 acre-foot per year.

Sediment yields as computed from the data for the 25 stock ponds are not likely to be representative of sediment yields from small drainage areas in the Powder River drainage basin upstream from Arvada, Wyo. The suspended-sediment records for nearly 5 years on the Powder River at Arvada show an average weighted sediment concentration of about 2 percent and an average suspended-sediment discharge equivalent to 910 tons per square mile per year. Of course, most of the flow of the Powder River at Arvada originates in the Bighorn Mountains where little erosion occurs. By comparison with the records at Arvada, the average of about 700 tons per square mile per year from the drainage areas of the 25 stock ponds and the estimated average concentration (weighted with water discharge) of about 2.5 percent in the inflow to the stock ponds seem to be unreasonably low. Also, field observation and inspection of aerial photographs indicate, as might be expected, that some of the stock ponds were constructed in areas where the rates of erosion would be less than average.

The relative importance of each physiographic area as a source of sediment is only indicated. Additional information is required to establish relative average rates of sediment yield from small drainage areas in each of the five physiographic areas. This information should include data on precipitation; runoff; reservoir spillage, including quantity and concentration of sediment that leaves the reservoirs; specific weight of the deposited sediment; range of altitude of the drainage areas; and average altitude of the drainage areas. These data for a selected number of reservoirs should provide a sound basis for determining the trap efficiency. Also, an investigation should be made of those areas in the drainage basin that do not contain stock ponds and, therefore, cannot be investigated by this means. The several areas of badlands fall into this category, and they probably represent one of the major sources of sediment in the Powder River drainage basin.

Correlations by successive steps and by cut-and-try methods indicate the following relationships:

1. Areas underlain predominantly by shale averaged sediment yields that are about 2.3 times greater than the yields from the areas underlain by sandstone or sandy shales.

2. Sediment yield increased approximately as the 1.5 power of the channel density, the 0.4 power of the shape factor, the 0.7 power of the average land slope, and the -0.25 power of the age of the reservoir.

3. The trap efficiency seemed to vary approximately according to the equation:

$$T = 100 \left[1 - \frac{3.5}{3.5 + (C/A)^{0.8}}\right]$$

in which

T is the trap efficiency in percent

C is the reservoir capacity in acre-feet

A is the drainage area in square miles

The results of the correlations may not apply under different conditions or in different areas because they may not represent relationships of cause and effect.

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Table 2.--Physical characteristics of 25 stock pond reservoirs and their drainage areas in the Powder River drainage basin above Arvada, Wyo.

Stock pond number	1	2	3	4	5	6	8	9	10	11	12	13	15	17	18	19	20	21	22	23	24	26	28	29	30
DRAINAGE AREA CHARACTERISTICS																									
Area (sq miles)	1.29	0.77	0.61	0.19	0.52	0.09	0.77	0.18	0.56	0.32	0.38	1.19	0.89	0.63	0.93	1.01	1.80	3.53	0.44	0.68	1.10	1.00	0.19	2.21	0.43
Shape																									
Length of longest channel (miles)	2.60	1.62	1.38	.48	1.59	.47	2.17	.52	.93	.81	1.25	2.31	1.87	1.74	1.31	1.70	2.70	3.16	.93	1.28	2.32	1.99	.76	2.33	1.44
Drainage area divided by length of longest channel	.50	.48	.44	.40	.33	.19	.35	.35	.60	.40	.30	.51	.48	.36	.71	.59	.67	1.12	.47	.53	.47	.50	.25	.95	.30
Shape factor (length squared of longest channel in miles divided by drainage area in square miles)	5.2	3.4	3.2	1.2	4.8	2.5	6.2	1.5	1.6	2.0	4.2	4.5	3.9	4.8	1.8	2.9	4.0	2.8	2.0	2.4	4.9	4.0	3.0	2.5	4.8
Vegetation density factor	2	3	2	2	2	3	2	2	2	2	3	2	3	2	2	2	2	2	3	2	3	2	2	2	2
Infiltration factor	1.5	2	1.5	1.5	2	1.5	1.5	1.5	1.5	1.5	2	1	1.5	1	1.5	1.5	1	1.5	2	1.5	2	1.5	1.5	2	1.5
Average land slope (percent)	8.62	20.00	14.36	6.00	10.14	6.00	14.82	41.20	21.60	10.32	3.18	11.00	8.50	16.05	9.90	8.50	33.00	20.68	6.00	8.50	4.56	9.15	15.00	7.23	24.60
Average distance of overland flow (ft)	374	384	214	366	546	360	570	324	537	[illegible]	280	424	283	284	468	234	372	232	236	339	468	267	252	250	312
Drainage basin slope (ft per mile)	--	129	235	136	90	170	177	713	218	[illegible]	190	--	92	--	190	91	233	--	--	--	73	--	--	--	132
Stream channels																									
Total length (miles)	14.83	21.23	11.18	3.00	4.28	1.13	9.10	1.93	3.41	5.52	6.27	16.29	14.34	3.62	10.60	12.62	17.15	46.18	9.95	6.86	10.92	14.69	2.73	22.75	3.85
Density (miles per sq mile)	11.5	27.6	18.3	15.8	8.3	12.6	11.8	10.7	6.1	17.2	16.5	13.7	16.1	13.7	11.4	12.5	9.5	13.1	22.6	10.1	9.9	14.7	14.4	10.3	9.0
Slope (percent)	2-5	2	2-5	2	2-5	2-5	2-5	5	2-5	2-7	2	2-5	2-5	2-5	2-7	2-5	2-7	2-6	2-5	2-5	1-3	2-5	2-5	2-5	2
Raw channels (miles)	--	--	--	--	--	--	--	--	--	--	--	38.4	--	.26	--	--	4.09	--	--	--	--	--	--	--	--
Number of headcuts																									
In drainage area	17	1	3	1	1	0	6	4	4	[illegible]	0	0	3	18	0	0	31	[illegible]	6	1	0	5	8	21	15
Per square mile	13.2	1.3	4.9	5.3	1.9	0	3.9	22.2	7.1	[illegible]	0	0	3.4	28.6	0	0	17.2	[illegible]	13.6	1.5	0	5.0	42.0	9.5	[illegible]
RESERVOIR CHARACTERISTICS																									
Capacity in acre-ft																									
Original	46.18	89.08	10.50	3.99	2.03	3.69	20.59	5.92	11.94	11.79	12.80	16.90	10.90	13.65	18.34	9.35	4.62	90.20	87.90	7.63	19.50	23.24	13.60	93.70	9.35
Present	43.46	72.91	9.30	3.23	1.15	3.41	17.53	5.85	11.18	[illegible]	11.82	9.80	10.54	11.15	16.28	8.28	2.90	84.12	80.41	5.53	14.80	17.81	11.80	59.40	9.04
Average	44.82	81.00	9.90	3.61	1.59	3.55	19.06	5.88	11.56	[illegible]	12.30	13.35	10.72	12.40	17.31	8.82	3.81	87.56	84.16	6.58	17.15	20.53	12.70	76.55	9.20
Average capacity divided by drainage area (C/A ratio)	34.74	105.19	16.23	19.00	3.05	39.44	24.75	32.67	20.64	32.34	32.37	11.22	12.04	19.67	18.61	8.73	2.01	24.80	191.27	9.65	15.59	20.53	66.84	35.44	21.40
Age (yr)	3	18	9	19	12	13	5	12	9	10	11	10	5	10	24	14	6	8	12	31	11	12	16	51	5
Sediment accumulation																									
Total (acre-ft)	2.72	16.17	1.20	.76	.88	.28	3.06	.07	.76	2.88	.99	7.10	.36	2.64	2.06	1.09	1.92	5.28	7.49	2.10	4.67	5.43	1.78	34.34	.31
Per unit of time and drainage area (acre-ft per sq mile per yr)	.70	1.17	.22	.21	.14	.24	.79	.03	.15	.90	.24	.60	.08	.42	.09	.08	.18	.19	1.42	.10	.39	.45	.59	.31	.12