Chemical Quality of Surface Waters, and Sedimentation in the Grand River Drainage Basin North and South Dakota

By C. H. HEMBREE, R. A. KRIEGER, *and* P. R. JORDAN

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GLOSSARY

Composite is a mixture of two or more samples. Complete chemical analysis of individual daily samples is impractical; therefore, analyses are usually made on composites of several daily samples. Samples of bed material or suspended sediment collected at individual verticals are usually composited for a single analysis.

Depth-integrated sediment sample is a suspended-sediment sample that is accumulated continuously in a sampler that moves vertically at a constant transit rate and that admits the water-sediment mixture at a velocity about equal to the stream velocity at every point of its travel. Present depth-integrating samplers normally collect a water-sediment mixture only from the surface to a point about 0.3 foot from the streambed.

Discharge composite is a composite for which the volume from each sampler is proportional to the streamflow at the time the sample was collected.

Dissolved-solids discharge is the rate at which dry weight of dissolved solids passes a section of a stream or the quantity that is discharged in a given time.

Equal-volume composite is a composite made of equal volumes from each sample.

Equivalents per million (epm) is a unit for expressing the concentration of chemical constituents in terms of the interreacting values of the electrically charged particles, or ions, in solution. One equivalent per million of a positively charged ion will react with one equivalent per million of a negatively charged ion. Parts per million are converted to equivalents per million by multiplying by a factor that is the reciprocal of the combining weight of the ion.

Cations	*Factor*
Calcium (Ca^{+2})	0.04990
Magnesium (Mg^{+2})	.08224
Sodium (Na^{+1})	.04350
Potassium (K^{+1})	.02558

Anions	*Factor*
Carbonate (CO_3^{-2})	0.03333
Bicarbonate (HCO_3^{-1})	.01639
Sulfate (SO_4^{-2})	.02082
Chloride (Cl^{-1})	.02820
Fluoride (F^{-1})	.05263
Nitrate (NO_3^{-1})	.01613

Fluvial sediment is sediment transported by, suspended in, or deposited from water.

Median or **median diameter,** according to Twenhofel and Tyler (1941, p. 110), is "the mid-point in the size distribution of a sediment of which one-half of the weight is composed of particles larger in diameter than the median and one-half of smaller diameter. The median diameter may be read directly from the cumulative curve by noting the diameter value at the point of intersection of the 50 percent line and the curve."

Particle-size classification is the classification recommended by the American Geophysical Union Subcommittee on sediment terminology (Lane and others, 1947, p. 937). According to this classification, clay particles have diameters between 0.0002 and 0.004 mm, silt particles have diameters between 0.004 and 0.062 mm, and sand particles have diameters between 0.062 and 2.0 mm.

Parts per million (ppm) is a unit for expressing the concentration, by weight, of chemical constituents or sediment. Parts per million of chemical constituents is computed as one million times the ratio of the weight of constituents to the weight of the solution. Parts per million of sediment is computed as one million times the ratio of the weight of sediment to the weight of the water-sediment mixture.

Percent sodium is the ratio, expressed in percentage, of sodium to the sum of the positively charged ions (calcium, magnesium, sodium, and potassium)—all ions in equivalents per million.

Residual sodium carbonate is the amount of carbonate plus bicarbonate, expressed in equivalents per million, that would remain in solution if all the calcium and magnesium were precipitated as the carbonate (Eaton, 1950).

$$\text{Residual sodium carbonate} = (CO_3 + HCO_3) - (Ca + Mg)$$

Runoff is streamflow unaffected by artificial diversions, storage, and other works of man in or on the stream channels.

Scheduled sampling station is a location at which water samples are collected on a systematic basis. Three types of stations were operated in this investigation: daily—water sampled once or more each day; periodic—water sampled about once a month; infrequent—water sampled less frequently, usually at 3- to 4-month intervals.

Sediment is fragmental material that originates mostly from rocks and is transported by, suspended in, or deposited from water or air, or is accumulated in beds by other natural agencies.

Sediment discharge is the rate at which dry weight of sediment passes a section of a stream or conduit or is the quantity of sediment, as measured by dry weight or by volume, that is discharged in a given time.

Sediment sample is a quantity of water-sediment mixture that is collected to represent the average concentration of suspended sediment, the average particle-size distribution of suspended or deposited sediment, or the specific weight of deposited sediment.

Sodium-adsorption-ratio is related to the adsorption of sodium by the soil and is an index of the sodium, or alkali, hazard of the water. Concentrations of constituents are in equivalents per million.

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}}$$

Specific conductance is a measure of the ability of a water to conduct an electrical current and is expressed in micromhos per centimeter at 25°C. Because the specific conductance is related to the number and specific chemical types of ions in solution, it can be used for approximating the dissolved-solids concentration of the water. The following general relations are applicable: Specific conductance $\times$ (0.65 ± 0.05) = ppm dissolved solids

$$\frac{\text{Specific conductance}}{100} = \frac{\text{total epm}}{2}$$

Specific weight of a sediment deposit is the weight of solids per unit volume of deposit in place.

Streamflow includes the sediment and dissolved solids that are contained in the water and is the rate at which water passes a section of a stream or is the quantity of water that is discharged in a given time.

Suspended sediment is sediment that is in suspension in water and is maintained in suspension by the upward components of turbulent currents or as a colloid.

Unscheduled sampling point is a location at which samples are collected less frequently and systematically than at a scheduled station; usually only 1 or 2 samples were collected for a specific purpose.

Weighted average represents approximately the chemical character of the water if all the water passing a cross section in the stream during the year were impounded and mixed in a reservoir.

CHEMICAL QUALITY OF SURFACE WATERS, AND SEDIMENTATION IN THE GRAND RIVER DRAINAGE BASIN, NORTH AND SOUTH DAKOTA

By C. H. HEMBREE, R. A. KRIEGER, and P. R. JORDAN

ABSTRACT

An investigation of the chemical quality of surface waters and of the sedimentation in the Grand River drainage basin by the U.S. Geological Survey began in 1946. The chemical quality of the water was studied to obtain information on the nature and amounts of dissolved solids in the streams and on the suitability of the water for domestic, industrial, and irrigation uses. Sedimentation was studied to determine the quantity of sediment that is transported by the streams, the particle sizes of the sediment, and the probable specific weight of the sediment when deposited in a reservoir.

The basin is underlain by consolidated sedimentary rocks of Cretaceous and Tertiary age; along the Grand River and its tributaries these rocks are mantled by alluvium of Quaternary age. The Hell Creek and Fort Union Formations underlie about 4,700 of the 5,680 square miles of drainage area. The climate of the basin is semiarid and is characterized by hot summers and cold winters. Mean annual runoff is about 53 acre-feet per square mile of drainage area and is equal to about 7 percent of the mean annual precipitation. The highest streamflows on the Grand River and major tributaries are caused by melting of snow in March and April. Streamflow is extremely variable from year to year.

Most of the surface waters in the basin are of the sodium sulfate or sodium bicarbonate type. High percent sodium is typical of almost all the surface waters. The streamflow-quality patterns of the Grand River and its two forks are very similar; dissolved-solids concentration, which usually does not exceed 3,000 ppm, is maximum during low-flow periods.

The water in Shadehill Reservoir became stratified during the flood inflow of 1952; about 75 percent of the floodwater, which was of good quality, passed through the reservoir. The quality of the water became almost uniform throughout the reservoir the latter part of July 1952. After the specific conductance became relatively stable in 1956, it fluctuated from about 1,300 to 1,600 micromhos per centimeter and was between 1,400 and 1,500 micromhos per centimeter most of the time.

During the representative period July 1937 to June 1950 the quantity of dissolved solids passing the station near Wakpala was estimated to have been about 140,000 tons per year. Yields computed for different parts of the basin ranged from about 22 to 32 tons per square mile.

Except for sulfate, concentrations of chemical constituents usually do not exceed the maximum concentrations recommended for domestic supplies.

The rather high dissolved solids and hardness of most of the surface waters prevent the use of these waters for most industrial purposes unless the quality is improved by treatment.

Classified for irrigation use according to its specific conductance and sodium-adsorption-ratio, the water stored in Shadehill Reservoir has a high salinity hazard and a medium sodium hazard. The water can be used safely for sustained irrigation on soils of the proposed irrigation unit if adequate leaching is practiced and if gypsum or some other calcium compound is added to the water or land during the high sodium cycle.

Suspended-sediment discharges of the Grand River at Shadehill from March 1946 through July 1950 averaged 700,000 tons per year. Suspended-sediment discharges of the South Fork Grand River near Cash for 1947–50, estimated from periodic measurements, averaged 270,000 tons per year. Sediment discharges during these periods were much greater than normal. Suspended-sediment discharges of the North Fork Grand River for 1947–60, estimated from periodic measurements, averaged 31,000 tons per year at Haley and 140,000 tons per year near White Butte. Suspended sediment is predominantly clay; some silt and a little sand are transported.

The probable specific weights of sediment deposits are about 42 pounds per cubic foot for the North and South Forks and 56 pounds per cubic foot for the Grand River at Shadehill. These specific weights are for deposits that have not been appreciably compacted by overlying deposits or by exposure to the air. At 56 pounds per cubic foot, the sediment that was carried by the Grand River at Shadehill from March 9, 1946, to June 30, 1950, would occupy about 2,500 acre-feet when deposited in a reservoir.

INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATION

The investigation by the U.S. Geological Survey of chemical quality of surface waters and of sedimentation in the Grand River drainage basin was part of the program of the Department of the Interior for the development of the Missouri River basin. The overall plan for the Missouri River basin includes the development of irrigation and hydroelectric power and the storage and regulation of floodwaters.

Information on the chemical quality of the water and on fluvial sediments is one of the requirements for successful planning of economically feasible projects. Successful irrigation depends not only on the type of soils, drainage, and climate but also on water of suitable chemical quality. The suitability of the water for domestic and industrial uses and for the propagation of wildlife depends partly on its chemical quality. A knowledge of the quantity and particle sizes of sediment transported by a stream is necessary for the design and operation of reservoirs and irrigation projects. Moreover, sediment data are used in making estimates of the amount and possible extent of aggradation and degradation upstream and downstream from hydraulic structures.

This report summarizes the results of the investigation to September 30, 1960. The results can be utilized to further the development, control, and use of the water resources of the area.

In the investigation several items were considered: the nature and concentrations of the mineral constituents in solution and of the sediment in transport; the geologic, hydrologic, and cultural factors that influence the chemical quality and the sediment discharge of the streams; the amount of sediment and dissolved minerals discharged by the streams at points of measurement; the probable source of dissolved minerals; the initial specific weight of the sediment after deposition; and the suitability of the water for irrigation, domestic, and industrial uses. Special studies were made of water impounded in Shadehill Reservoir to determine the suitability of the water for irrigation and domestic use.

Chemical-quality data were obtained at Shadehill Reservoir and at six other scheduled chemical-quality stations, which were operated from 2 to 10 years. Supplemental data were obtained on most of the principal tributaries. These data furnish information on the quality of the water that enters Shadehill Reservoir and that leaves the basin.

Studies were made to determine the quantity of sediment transported by the Grand River at Shadehill and the probable initial specific weight of the suspended sediment after deposition in a reservoir. Sediment samples were collected at four scheduled stations and were analyzed for concentration of suspended sediment. Some of the samples were also analyzed for particle-size distribution of suspended sediment. Samples of bed material were collected at several sites and were analyzed for particle size. Field studies made during the investigation provided a background of information that was essential to the understanding and interpretation of the basic data on chemical quality and sediment. Pertinent published reports were reviewed in the study of the relationship of the geology to the sediment and dissolved minerals that are transported by the streams in the Grand River drainage basin.

PREVIOUS INVESTIGATIONS

The U.S. Army Corps of Engineers, measured the suspended-sediment discharge of the Grand River at Wakpala on April 17, 18, 20, and 22, 1931, and collected sediment samples at the surface during the period March 1 to July 31, 1931 (U.S. Congress, 1934, p. 36). Suspended-sediment records were also obtained on the Grand River near Wakpala by the Corps of Engineers from April 1947 to September 1951 (U.S. Army Corps of Engineers, 1951, 1957).

Two samples of water from the North Fork of the Grand River, obtained 9 miles south of Hettinger, N. Dak., were analyzed for dissolved-mineral and sediment content (U.S. Congress, 1934, p. 84).

During October 1941 to September 1945, the Bureau of Reclamation periodically collected and analyzed quality-of-water samples from stations on the Grand River at Shadehill and near Wakpala, S. Dak.

A reconnaissance of geology and ground water in the lower Grand River valley, South Dakota, has been made by the Geological Survey (Tychsen and Vorhis, 1955).

PERSONNEL AND ACKNOWLEDGMENTS

This investigation was made by personnel of the Water Resources Division of the Geological Survey in cooperation with other agencies of the Department of the Interior and was under the successive supervision of P. C. Benedict, regional engineer, and D. M. Culbertson, district engineer.

GRAND RIVER DRAINAGE BASIN

LOCATION AND EXTENT

The Grand River drainage basin (5,680 sq miles) in northwest South Dakota and southwest North Dakota (pl. 1) occupies approximately the north half of Harding and Perkins Counties, all of Corson County, and small parts of Ziebach County, S. Dak., and Bowman and Adams Counties, N. Dak. The drainage basin, which is about 160 miles long and 25 to 60 miles wide, is bounded by low divides that separate it from the drainage basins of the Cannonball River to the north, the Moreau River to the south, and the Little Missouri River to the west.

TOPOGRAPHY

The Grand River basin is in the Missouri Plateau section of the Great Plains province. It has the characteristics of an old plateau modified by valley terraces, local badlands, and isolated buttes. The general topography is a rolling plain broken by the valleys of the mainstream and its tributaries (fig. 1). Buttes and associated badlands are prominent local features of the landscape.

In the eastern part of the basin, the stream valleys are deeply incised below the general level of the land and the stream profiles of the tributaries are very steep. In the western part of the basin, the separation of the valleys from the uplands, although distinct, is not so abrupt as in the eastern part. In general, the valleys are narrow and are bordered by several levels of terraces that parallel the general course of the stream. The flood plain of the Grand River

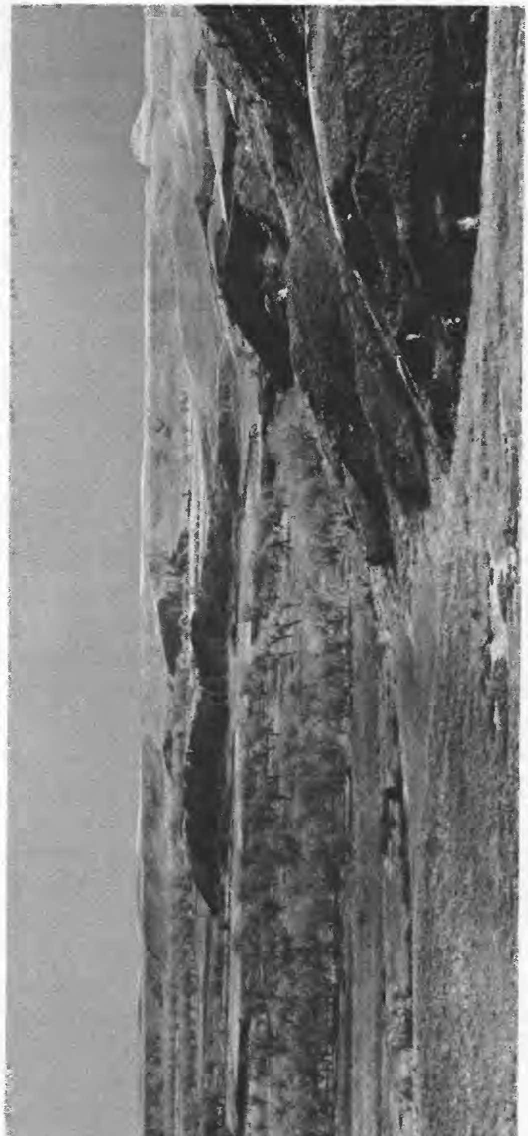

FIGURE 1.—Grand River south of McIntosh along State Route 65. The deep valley, meandering stream, gently rolling uplands, and isolated buttes are representative of much of the Grand River basin.

is from 10 to 20 feet above the stream. Above the valley trench, but still within the valley itself, terraces, which stand from 80 to 180 feet above the stream and are at places several miles wide, slope gently toward the uplands.

Buttes are scattered throughout the basin but occupy large areas only in the western part of the basin. The buttes are capped by resistant sandstones that erode less readily than the softer rocks beneath. Slim Buttes, Table Mountain, and Cave Hills, in Harding County, S. Dak., cover 20 to 30 square miles, and the almost sheer sides of the buttes are as high as 250 feet. The bases of these and other buttes are broken by closely spaced, deeply incised gullies, which together with the narrow divides form the rugged and barren topography of badlands. Badlands are also found along the valley walls of the main stream and deeply incised tributaries in the eastern part of the basin and at the heads of most of the streams in the western part of the basin.

DRAINAGE

The Grand River is formed by the junction of the South Fork and the North Fork in Perkins County, S. Dak., about 2½ miles southwest of Shadehill. The junction of the two streams was submerged by the filling of Shadehill Reservoir. The South Fork heads near the South Dakota-Montana State line west of Buffalo in Harding County. The North Fork heads near the North Dakota-Montana State line west of Haley in Bowman County. From the confluence of these two streams the Grand River flows eastward and joins the Missouri River northwest of Mobridge, S. Dak.

In downstream order the principal tributaries of the South Fork are Sand, Jones, Bull, Nasty, and Lodgepole Creeks; and the principal tributaries of the North Fork are Spring, Lightning, and Buffalo Creeks. The principal tributaries of the Grand River downstream from the confluence of its two forks are Flat, Willow, Black Horse Butte, Cottonwood, Dirty Lodge, Firesteel, Hump, Stink, and High Bank Creeks. (See pl. 1.) All the principal tributaries of the Grand River are intermittent, although there is flow in the lower reaches of Black Horse Butte and Firesteel Creeks during most of the year.

From Shadehill Reservoir to the mouth the gradient of the Grand River changes very little and averages about 3.6 feet per mile. (See pl. 2.) At Shadehill the channel is gravel and sand. From a point north of Athboy, which is a short distance downstream from Shadehill, to the mouth, the bed of the Grand River is mostly sand (fig. 2). Most of the tributaries of the Grand River downstream

FIGURE 2.—Grand River near the mouth, October 1955. The banks are about 12 feet high, and the bed material is mostly sand. The white incrustations on the sandbars are salt deposits formed by capillary action and evaporation.

from Shadehill have drainage basins that are long and narrow, and the long axes of the basins are oriented almost perpendicular to the master stream. The gradients of the tributaries average about three times the gradient of the Grand River. All the tributaries are flowing on or very close to bedrock except where they enter the Grand River valley.

NORTH FORK GRAND RIVER

The North Fork Grand River flows close to the northern border of the plateau to the south and, consequently, receives most of its drainage from the area that lies to the north. In the upper 23 miles of its course the North Fork falls 380 feet, or more than 16 feet per mile. For the remaining 114 miles to the confluence with the South Fork, the North Fork has an average gradient of 5.7 feet per mile. Most of the drainage basin that is not under cultivation is gently to unevenly rolling and grass covered. In the middle reach of the North Fork, the stream meanders over its valley floor, which is about 1 mile wide.

Spring and Buffalo Creeks have gradients that are about equal to the gradient of the upper reach of the North Fork. The principal tributaries to the North Fork drain areas of rolling prairie that is interrupted locally by buttes and low hills and ridges. The valley floors are wide and flat, and the valley walls slope gradually upward to blend into the uplands.

SOUTH FORK GRAND RIVER

The south and west margins of the drainage basin of the South Fork Grand River are rimmed by a series of badlands that start abruptly at the margin of nearly flat prairie, which marks the divide between the Moreau River basin on the south and the Little Missouri River basin on the west. These badlands and buttes are known as The Breaks east of Slim Buttes and as the Jump-off west of Slim Buttes. The minor tributaries that drain The Breaks have eroded deep, narrow valleys that in some places are more than 100 feet below the divides. In the first 32 miles of its course the South Fork drops about 540 feet, or 17 feet per mile. In the remaining 99 miles of its course the South Fork has an average gradient of about 5.5 feet per mile, which is slightly greater than that of the Grand River. Near Buffalo the banks of the stream are low and grass covered, and the stream flows on a bed of sand and fine gravel in a broad sandy valley. Downstream from the mouth of Jones Creek, the streambanks become progressively higher, and the bed material is mostly gravel.

Sand Creek, the only principal tributary that enters the South Fork from the south, has some tributaries, such as Squaw Creek, that drain the area of badlands on the north and west sides of Slim Buttes (fig. 3). The lower reaches of Sand Creek have very low banks, and the bed is mainly sand.

Jones and Bull Creeks rise on the edge of the Jump-off northwest of Buffalo and flow in narrow steep-banked channels. The gently rolling valley slopes rise, sharply in places, from these channels to the bases of the buttes that form Cave Hills. The valleys of both tributaries in the lower reaches are broad and rolling, and the streams meander.

Nasty Creek follows a meandering course in a broad, open valley. Most of the drainage area is uneven and generally grass covered. Lodgepole Creek drains the eastern part of a plateau that lies between Nasty Creek and the North Fork. The valley of Lodgepole Creek is wide and flat and is bordered to the north and south by high rocky ridges that rise above the general level of the plateau.

SHADEHILL RESERVOIR

Shadehill Reservoir is about 12 miles south of Lemmon and near the village of Shadehill. The dam, which is 4 miles downstream from the confluence of the North and South Forks of the Grand River, impounds water that drains from an area of about 3,120 square miles.

FIGURE 3.—Badlands along the base of Slim Buttes south of State Route 8, west of Reva. The vertical cliffs are composed of the Chadron and Arikaree Formations, which are the sources of part of the sediment transported by the South Fork.

Construction of Shadehill Dam was started April 22, 1949, and was completed August 15, 1951 (U.S. Bur. of Reclamation, written communication). Storage of water began July 1, 1950, when the channel of the Grand River was closed. The dam is an earthfill structure, 12,843 feet long, and has a crest (elev 2,318 ft) of 118 feet above the streambed. Dead storage is 58,231 acre-feet below the lowest point of the irrigation canal outlet (elev 2,250.8 ft), conservation storage is 81,400 acre-feet between the bottom of the irrigation canal outlet and the crest of the service spillway (elev 2,272.0 ft), and flood-control storage is 269,400 acre-feet between the service spillway and the maximum service elevation of 2,312 feet (10 ft above the crest of the emergency spillway). The reservoir has a total active capacity of 409,000 acre-feet.

The reservoir was designed for irrigation supply, flood control, wildlife conservation, and recreation. In addition, the reservoir may be used as a municipal supply for the city of Lemmon.

CLIMATE

The Grand River basin has a fairly uniform climate because of its east-west orientation and a small range in altitude (about 1,500 to 3,300 ft). Average annual precipitation increases from about 15 inches in the west to a little more than 16 inches in the east. The annual precipitation for the basin averages about 15 inches and the temperature about 44° F. (See pl. 1.)

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The climate of the basin is semiarid and is characterized by hot summers and cold winters. The temperature ranges from about −30° to 115° F. Snow covers the ground during most of the winter and totals about 3.6 inches of precipitation, or about 24 percent of the average annual precipitation. About one-third of the precipitation for the year falls during May and June, which are normally the months of greatest precipitation.

SOILS AND VEGETATION

The characteristics of a soil depend on the parent material, climate, organisms, topography, and time. The Grand River basin is in a zone of Chestnut soils, which are characteristic of predominantly short-grass country that has a mean annual precipitation of less than about 18 inches (U.S. Cong., 1941, p. 276, 1117). Chestnut soils are characterized by a dark-grayish-brown or dark-brown surface horizon, a lighter colored blocky to prismatic B horizon, and a zone of carbonate accumulation at a depth of about 18 to 30 inches. The soils are commonly neutral or slightly acid at the surface and alkaline in the subsoil (Edwards and Ableiter, 1951, p. 26).

Soils in numerous areas in the basin have been affected by salts—mostly sodium salts. Most of the sodium-rich soils are along the streams on nearly flat terraces or on gentle valley or upland slopes. These soils were developed as the result of flooding by saline water of depressions or poorly drained areas. Areas where the soil is impregnated with sodium salts are generally known as scab spots or scabby land.

Grassland is typical of the entire drainage basin where the land is not cultivated. The Slim Buttes, Pine Hills, and Cave Hills are parts of the Custer National Forest and have a scanty growth of yellow pine and juniper. Cottonwood is the most common tree along the streams. Other trees and shrubs that grow along the stream valleys are ash, dogwood, boxelder, willow, wild rose, sweetbrier, buffalo berry, and juneberry. The most common grasses are blue grama, needle grass, wheat grass, threadleaf sedge, big and little bluestem, and buffalo grass. Small pricklypear, gumweed, saltgrass, and seepweed are associated with the scabby land. Gray and pasture sagebrush, clubmoss, plantain, sand grass, peppergrass, and Russian-thistle are locally abundant.

STREAMFLOW

Mean annual runoff in the Grand River drainage basin as measured at Grand River near Wakpala is about 53 acre-feet per squre mile of drainage area and is about 7 percent of the mean annual precipitation. Annual runoff per square mile of drainage area varies only slightly for different areas. Although the heaviest rain normally falls in May and June, the highest streamflow rates on the Grand River and major tributaries are caused by melting of snow in March and April. On the small tributaries, peak streamflow rates are caused by intense rainstorms in summer. For example, H. M. Erskine (written communication), district engineer of the U.S. Geological Survey, Bismarck, N. Dak., reported that the highest streamflow rates ever measured in the region were in the extreme headwaters of the North Fork Grand River and of Bull Creek during the night of July 28–29, 1951. Precipitation of 5 to 10 inches was reported by residents in the area. Streamflow rates were as high as 7,500 cfs (cubic feet per second) from 5.2 square miles of drainage area.

Extremes in streamflow are characteristic of the Grand River. For the period of record, the streamflow of Grand River near Wakpala before closure of Shadehill Dam ranged from zero about 12 percent of the time to 82,200 cfs. Most of the tributaries are ephemeral streams that flow only after heavy rainfall or when snow is melting. The reservoir regulates the flow from about 55 percent of the Grand River basin. Records are available for seven streamflow stations and one reservoir in the basin (table 1).

TABLE 1.—*Periods of streamflow records in the Grand River basin*

Gaging stations	Drainage area (sq mi)	Period of record
North Fork Grand River:		
At Haley, N. Dak	509	May 1908 to September 1917. October 1945 to September 1960.
Near White Butte, S. Dak	1,190	October 1945 to September 1960.
South Fork Grand River:		
At Buffalo, S. Dak	148	August 1955 to September 1960.
Near Cash, S. Dak	1,350	October 1945 to September 1960.
Shadehill Reservoir: At Shadehill, S. Dak	3,120	June 1950 to September 1960.
Grand River:		
At Shadehill, S. Dak	3,120	February 1943 to September 1960.
At Little Eagle, S. Dak	5,370	July 1958 to September 1960.
Near Wakpala, S. Dak.[1]	5,510	April 1912 to March 1918 August 1928 to September 1960.

[1] Before Mar. 18, 1918, gaging station was 12 miles downstream from present site. From Aug. 26, 1928, to Mar. 30, 1944, gaging station was 17 miles downstream from present site.

The use of long-term records to derive a duration curve of daily streamflow is the most accurate method of defining the flow characteristics of a stream. Unfortunately, such records are seldom available. The longest period of record is for Grand River near Wakpala, but only the period March 1931 to June 1950 can be used for a duration curve of daily streamflow because before March 1931 daily records were not available for some periods and after June 1950 the streamflow was regulated. Although the longest usable period may fairly well represent the long-term streamflow, it included 5 years of extreme drought; therefore, a shorter period, if correctly chosen, may be even more representative. The period chosen was based on the assumption that a period representative for an area having similar climate, topography, and geographic location would also be representative for the Grand River near Wakpala.

The part of the drainage basin of the Missouri River between the Garrison and Fort Randall damsites include the Grand River basin and has similar climate and topography, and streamflow records (furnished in part by the U.S. Army Corps of Engineers, Omaha District) are available for 1898 through 1954. Figure 4 shows that runoff from this area follows the same trend as runoff from the Grand River basin. Frequency distributions of annual runoff between Fort Randall and Garrison were plotted for the water years 1898 through 1954 and for various periods during which streamflow records for the Grand River were available. The

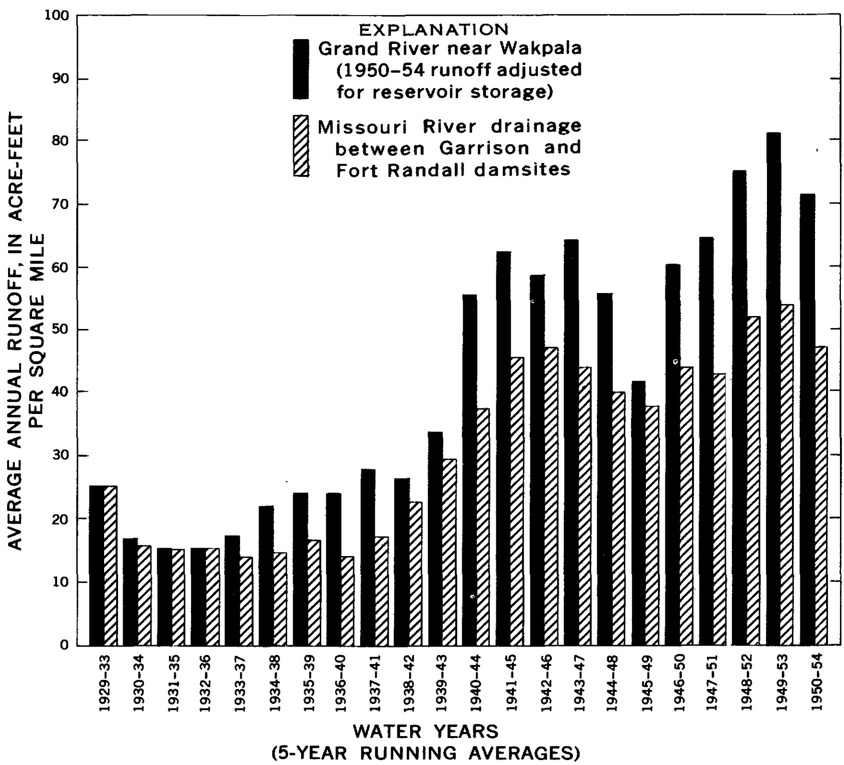

FIGURE 4.—Runoff from the Grand River basin and from the drainage area tributary to the Missouri River between Garrison and Fort Randall damsites.

frequency distribution for July 1, 1937, to June 30, 1950, is almost the same as that for the long period (fig. 5); therefore, the flow for July 1, 1937, to June 30, 1950, is probably representative of the long-term unregulated flow of Grand River near Wakpala (fig. 6).

For the stations upstream from Wakpala, representative duration curves could not be obtained in the same way as for Wakpala. Concurrent records are available for the stations at Haley, near White Butte, and near Cash for water years 1947 through 1960, and streamflow-duration curves were constructed for this period (fig. 7). The period included several years of high streamflow and several years of low streamflow; therefore, the duration curves may not differ greatly from those for a longer, more representative period.

Periods of record for South Fork Grand River at Buffalo and for regulated streamflow of Grand River at Shadehill are composed almost entirely of years of below-normal streamflow; therefore, the curves for these stations (fig. 8) are not comparable with the curves for the other stations. For Grand River at Shadehill, the slope of the curve from 15 to 250 cfs probably represents the normal slope for unregulated streamflow. The less-than-normal slope of the curve above 4,000 cfs shows that the magnitude of the highest streamflows was reduced by storage in the reservoir. The steeper-

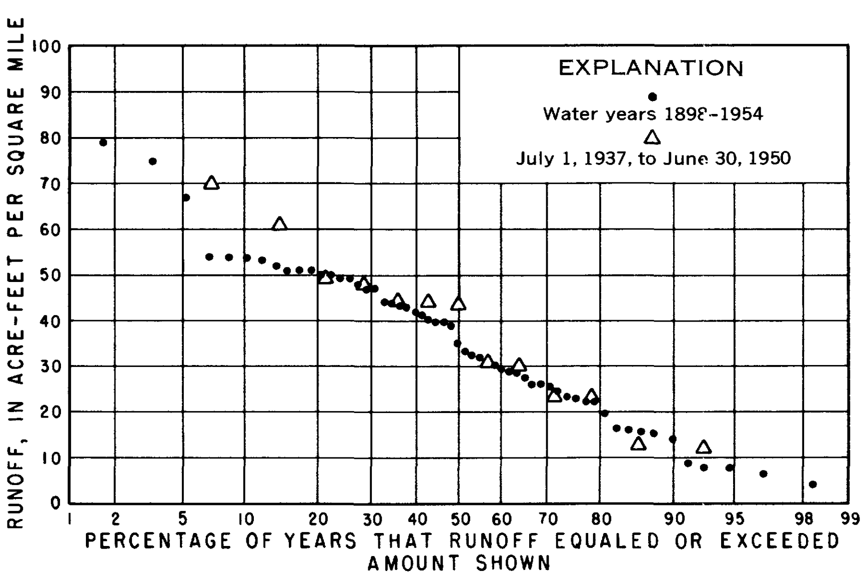

FIGURE 5.—Frequency distribution of annual runoff from drainage area tributary to the Missouri River between Garrison and Fort Randall damsites.

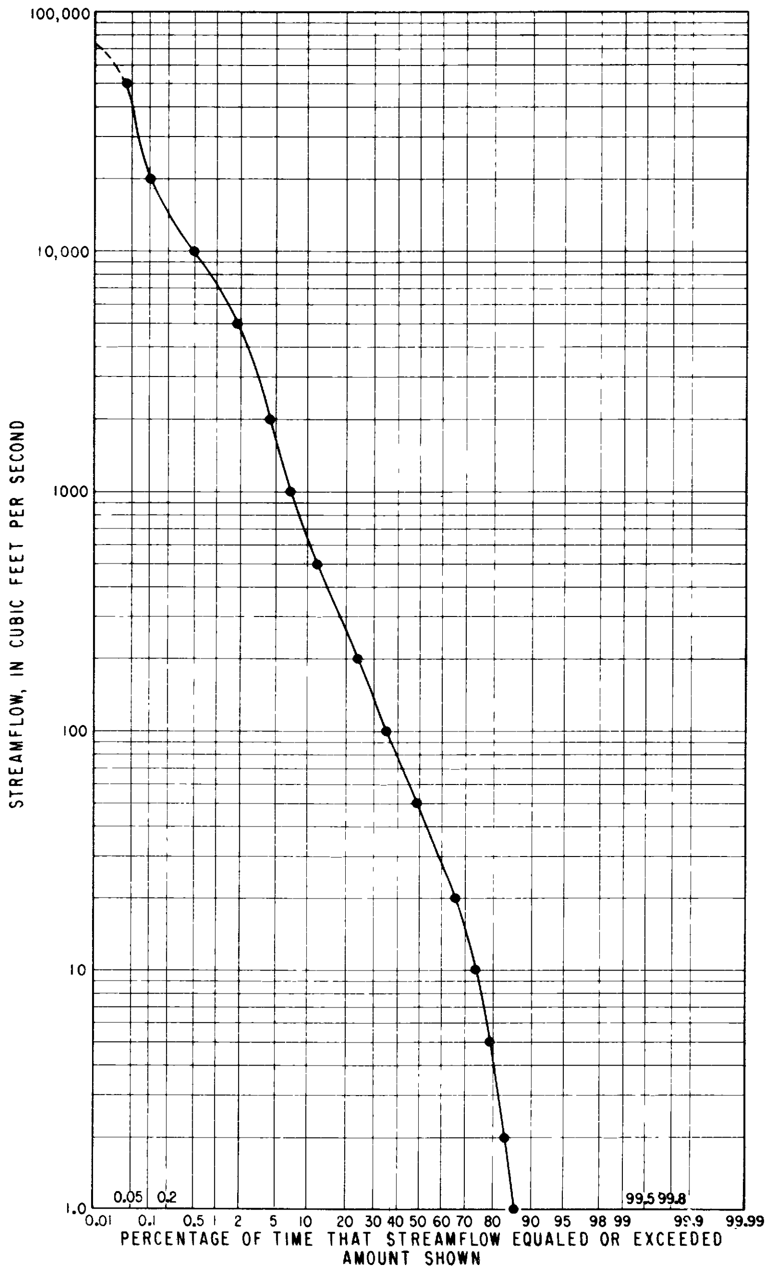

FIGURE 6.—Duration curve of daily flows for Grand River near Wakpala, July 1, 1937, to June 30, 1950.

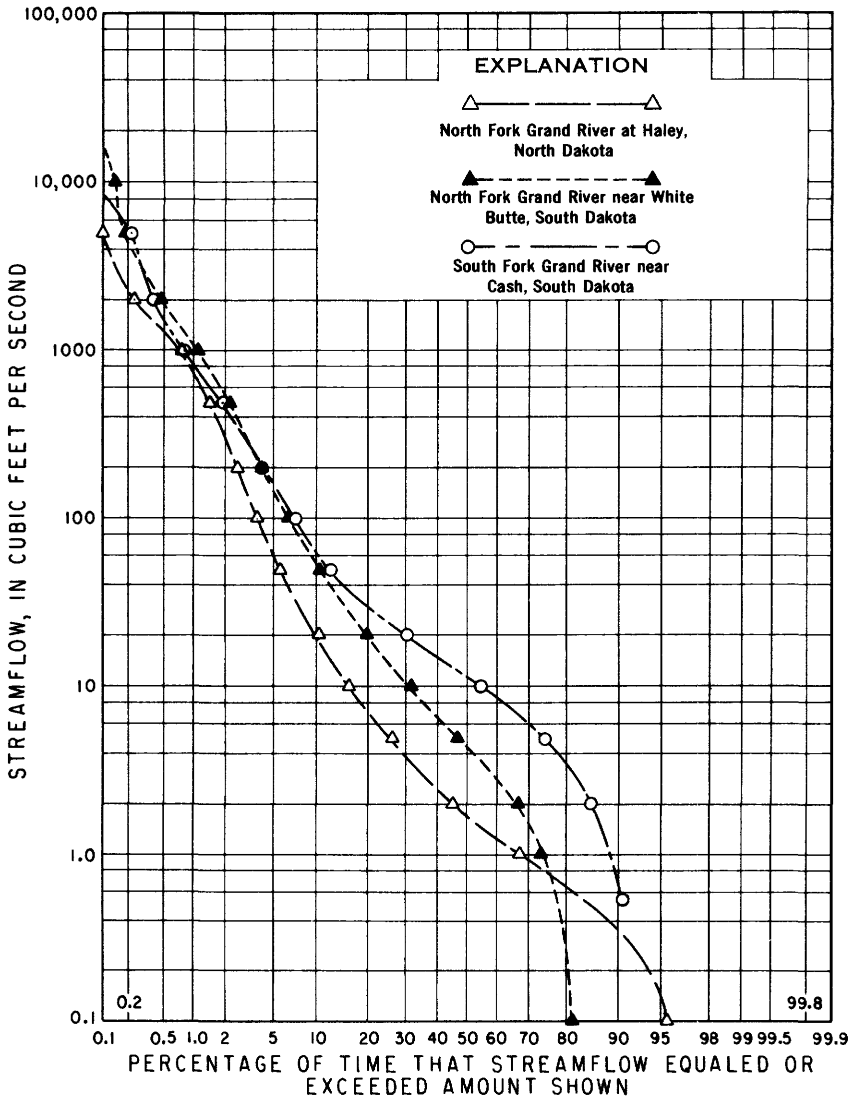

FIGURE 7.—Duration curves of daily streamflow, North Fork Grand River at Haley and near White Butte, and South Fork Grand River near Cash, water years 1947–60.

than-normal slope of the curve between 250 and 4,000 cfs shows that the duration of streamflows of more than 4,000 cfs was increased by releases from storage. The less-than-normal slope of the curve between 8 and 15 cfs shows that the duration of streamflows of 8 to 15 cfs was increased by releases from storage.

The streamflow that is typical, or most common, is represented approximately by the median (the streamflow exceeded 50 percent of the time). The total volume of water available for storage is

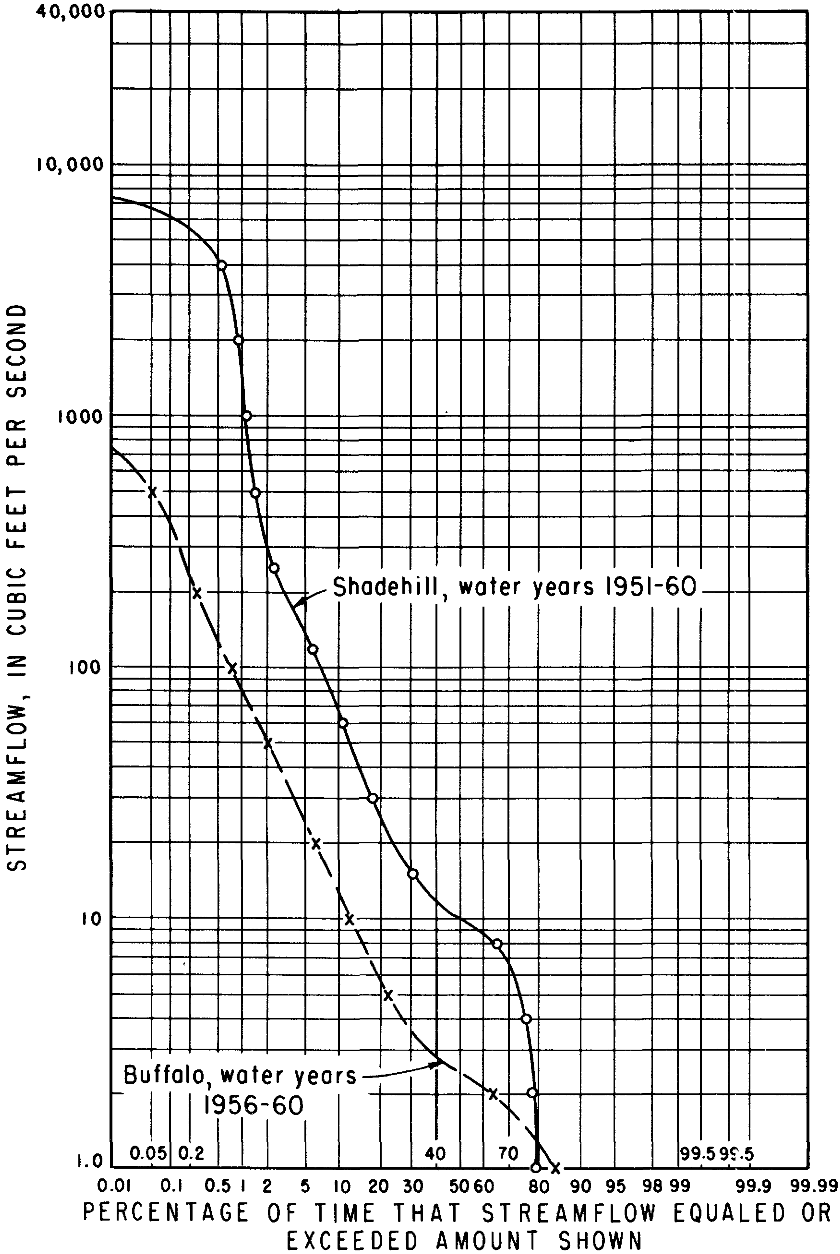

FIGURE 8.—Duration curves of daily streamflow, South Fork Grand River at Buffalo and Grand River at Shadehill.

represented by the mean streamflow, in cubic feet per second or in acre-feet per year. For streams such as those in the Grand River basin, the mean is much larger than the median because it is influenced by the very large volumes that are discharged during short periods of high streamflow. The median and mean streamflows at four locations are shown in the following table:

Summary of streamflow characteristics

Location	Water years or period	Median streamflow (cfs)	Mean streamflow: Cubic feet per second	Mean streamflow: Acre-feet per year	Mean streamflow: Acre-feet per square mile per year
North Fork at Haley	1947–60	1.7	37	27,000	53
North Fork near White Butte	1947–60	4.4	71	52,000	44
South Fork near Cash	1947–60	11	64	46,000	34
Grand River near Wakpala	July 1937 to June 1950	47	400	290,000	53

Because the drainage areas for the stations near Cash and White Butte are of similar size (see table 1), their streamflow characteristics may be compared without an adjustment for drainage area. Although the mean streamflow of the North Fork near White Butte is slightly higher than that of the South Fork near Cash, the streamflow of the South Fork near Cash exceeded the streamflow of the North Fork near White Butte at least 90 percent of the time. (See fig. 7.) The higher mean streamflow for the North Fork is due to a few days of very high streamflow. Although the mean streamflow of the North Fork near White Butte for the period was 71 cfs, this streamflow was exceeded less than 9 percent of the time, and the median streamflow was only 4.4 cfs. (See fig. 7.)

Although the mean streamflow represents the volume of water available for storage over a large number of years, the streamflow in any one year may be considerably more or less than the mean. The extreme variability of yearly streamflows at two selected locations in the basin is shown in figure 9. In this figure, the streamflow for Grand River near Wakpala after 1950 has been partly regulated by Shadehill Reservoir.

Before Shadehill Reservoir was constructed, the streamflow of the Grand River was greater near Wakpala than at Shadehill except for some periods of low streamflow (fig. 10). During very low streamflows in the summer the Grand River between Shadehill and Wakpala lost more water than it gained. Some of the water was lost by infiltration, but probably the greater part was lost through evaporation.

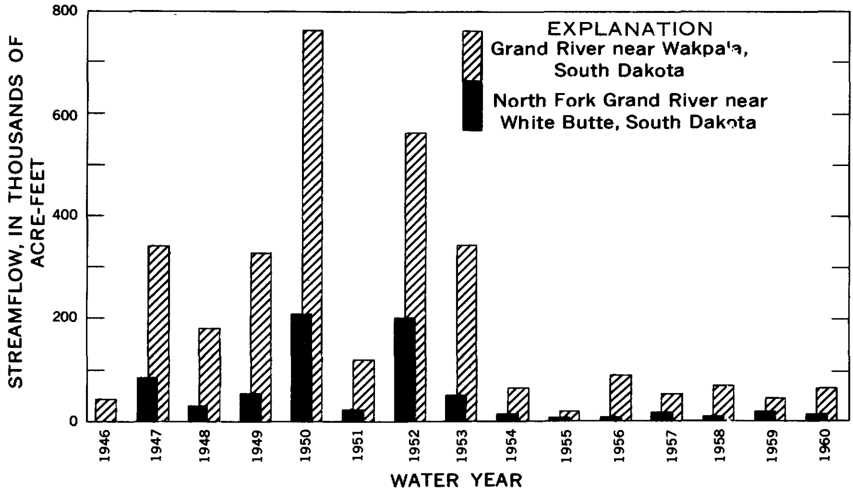

FIGURE 9.—Variability of annual streamflow at selected stations.

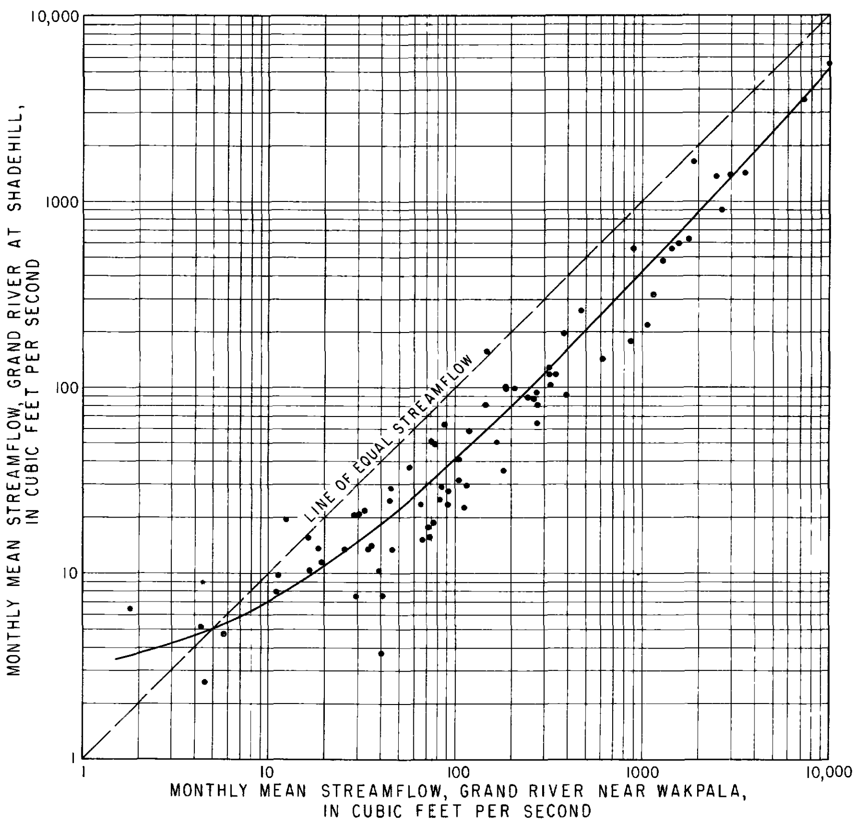

FIGURE 10.—Relation of monthly mean streamflow of the Grand River at Shadehill and near Wakpala, March 1, 1943, to June 30, 1950.

On April 3, 1958, water right filings for irrigation in the Grand River basin totaled about 2,500 acre-feet. This amount of water was to be used on an estimated 22,872 acres of land (South Dakota Water Resources Commission, written communication). Data from the 1950 census (U.S. Dept. Commerce, 1952) indicate that many of the filings do not represent use of water. According to the census, the area irrigated in 1950 was less than 1,000 acres. Irrigation is predominantly by diversion or pumping from the streams and is mostly in Harding County, S. Dak. The amount of irrigation has not increased appreciably since 1950. Although Shadehill Reservoir has been in operation since 1950, the only land irrigated from this source has been about 28 acres on the Shadehill Development Farm (U.S. Bur. Reclamation, written communication).

CHEMICAL QUALITY OF THE WATER

The water that falls on the earth as rain or snow is nearly devoid of dissolved constituents except for small amounts of dissolved gases, such as carbon dioxide. The water in streams, lakes, oceans, and ground-water reservoirs contains dissolved solids in variable amounts. These dissolved solids are derived from the rocks and soils with which the water has been in contact. Differences in the chemical composition and dissolved-solids concentration of waters are due to differences in the mineral composition of rocks and in the solubility of minerals.

Water that enters a stream or lake from surface runoff generally has a lower dissolved-solids concentration than water that enters from the ground-water reservoir. The concentration is lower because water that flows over the surface reaches the streams quickly, is in contact with the rocks and soils only briefly, and thus dissolves relatively small amounts of material. On the other hand, subsurface water increases its solvent power by dissolving carbon dioxide while percolating through the soil, is in contact with the minerals a long time because it travels slowly, and thus may be highly mineralized.

The chemical composition of surface water may, and usually does, fluctuate. Some of the environmental factors that cause fluctuations or differences in chemical composition of surface waters at one location or between two locations are climate, geology, tributary inflow, and such activities of man as regulation of flow and industrial development.

RELATION TO GEOLOGY

The total mineralization and the proportional amount of each mineral in the streams depend mainly on the physical and chemical properties of the rocks and soils in the drainage basin. The availability of the minerals in the rocks and soils is decreased by leaching, and the rate of leaching depends on the solubility of the minerals, length of time the water is in contact with the minerals, and temperature of the water. The amount of dissolved products of weathering carried by the streams depends also on the climate. In arid or semiarid regions, most soils and the rocks from which they originated are incompletely leached and still contain large amounts of readily soluble material.

Fine-grained rocks, such as siltstone and shale, expose large areas to the solvent action of water, and water in contact with these rocks may dissolve and carry in solution large amounts of dissolved solids. The cementing material of many rocks is calcium carbonate, which is easily dissolved in water that contains carbon dioxide.

The Grand River basin is underlain by shale, siltstone, sandstone, and limestone of Cretaceous and Tertiary age. Alluvium of Quaternary age partly mantles these consolidated rocks along the Grand River and its tributaries. The formations exposed at the surface are the Pierre Shale, Fox Hills Sandstone, and Hell Creek Formation of Late Cretaceous age and the Ludlow, Cannonball, and Tongue River Members of the Fort Union Formation (Paleocene), the White River Group (Oligocene), and the Arikaree Formation (Miocene) of Tertiary age.

Clarke (1924, p. 69) pointed out that a river water is the average, or composite, of all its tributaries. Similarly the chemical composition of a river water reflects the physical and mineral composition of the rocks in the drainage basin. The quadrilaterals in plate 3 illustrate the effect of geology on the chemical characteristics of the water. The kite diagrams (quadrilaterals) are from analyses of samples collected during periods of low flow.

The size of the diagrams shows the concentration of the ions in solution, and the size and shape show the suitability of the water for irrigation (Colby, Hembree, and Rainwater, 1956, p. 118). The dissolved-solids concentration in equivalents per million is equal to the sum of the lengths of the horizontal and vertical axes, which are of equal length. The inclusion of potassium with sodium in the lower vertical axis is not in absolute agreement with the agricultural definition of percent sodium, but potassium is usually present in such small quantities that its inclusion is insignificant in percent-sodium interpretation from plate 3. If the major part of the quadrilateral is above the horizontal axis, the water has a low percent sodium; the percent sodium is approximately equal to the ratio of the length of the sodium-and-potassium line to the total length of the vertical axis expressed in percentage. If the major part is in the upper left, the water is the most desirable type for irrigation; sulfates and chlorides of calcium and magnesium predominate. If the major part is in the upper right, percent sodium is low but residual sodium carbonate may be present. The slope of the line joining the plots of calcium plus magnesium and carbonate plus bicarbonate is the ratio of these constituents and indicates the presence or absence of residual sodium carbonate. If the slope is greater than 45 degrees, there is no residual sodium carbonate; as the slope decreases from 45 degrees, residual sodium carbonate increases. Location of the larger area in the lower right quarter indicates water least desirable for irrigation; high percent sodium and residual sodium carbonate are both present. The significance of these water-quality characteristics is discussed further in the section on suitability of the waters for irrigation.

Exposed rocks in the drainage area of the North Fork are the Hell Creek Formation and the Fort Union Formation. (See pl. 3.) The Hell Creek Formation consists of continental deposits of alternating strata of sandstone, shale, bentonite, and thin beds of coal. The formation is light to dark gray and contains manganese and iron concretions, which weather out and give a distinctive appearance to the areas underlain by the formation. Clay beds that were fired by burning lignite beds form red bands around some of the hills and buttes.

In the Grand River basin the Fort Union Formation consists of three members: Ludlow, Cannonball, and Tongue River. The Ludlow and Tongue River Members are of continental origin and interfinger with the Cannonball Member of marine origin. The Cannonball Member, which is the marine equivalent of the Ludlow and the lower part of the Tongue River, crops out mostly to the east of Haley. The Ludlow Member consists of sandstone, shale, clay, and lignite and is characterized by its yellowish color. The Cannonball Member is composed of dark-gray sandstone and shale and is difficult to distinguish from the underlying Hell Creek Formation because of the similarity in lithology and color. The Tongue River Member consists of gray to brown clay, shale, sandstone, and lignite; some thin limestone is present locally.

Water of the North Fork at Haley is of the sodium sulfate type and has a high percent sodium. The water at Haley is a mixture of waters draining from areas consisting mostly of exposed Hell Creek Formation and the Ludlow and Tongue River Members of the Fort Union Formation. Waters draining from areas of these exposed rocks are represented individually on figure 19 by diagrams for other parts of the basin: South Fork at Buffalo drains rocks of the Hell Creek Formation; Nasty Creek near Ralph drains an area consisting mostly of exposed Ludlow Member; and Flat Creek at Haynes drains rocks of the Tongue River Member. Waters draining from areas of exposed Ludlow Member are of about the same type as those draining from areas of the exposed Tongue River Member.

Water of the North Fork south of Hettinger and farther downstream at the station near White Butte has higher percentages of calcium than the water at Haley. The increase in the percentage of calcium downstream is probably due to the decreased influence of the Hell Creek Formation and the increased effect of the Fort Union Formation, particularly the Cannonball Member.

Most of the headwater drainage area of the South Fork consists of exposed Hell Creek Formation. Waters from the South Fork at Buffalo and from Sand Creek are of the sodium bicarbonate type and have a very high percent sodium. Waters from Bull Creek and Jones Creek, which drain areas of exposed Hell Creek Formation and Ludlow Member, are mixtures of sodium sulfate and sodium bicarbonate types (pl. 3). The water has about equal proportions of sulfate and bicarbonate. The sodium bicarbonate waters of the South Fork between the mouth of Jones Creek and Shadehill Reservoir progressively decrease in percentage of bicarbonate and increase in percentage of sulfate, calcium, and magnesium. The change in the type of water is effected by inflow from tributaries draining areas of exposed Ludlow Member.

About 1 percent of the drainage area upstream from the Cash station consists of exposed rocks of the Arikaree Formation and White River Group. The White River Group overlies both the Fort Union and Hell Creek in the western part of the basin (Gill and Moore, 1955, p. 252). The Chadron and Brule Formations of the White River Group are restricted mostly to the Slim Buttes area, but a few small remnants remain on the tops of several other buttes. The lower part of the Chadron Formation consists of medium-yellow to dark-yellowish-orange sandstone and siltstone, and the upper part is mainly white sandstone and light-olive-gray bentonite. The Brule Formation is composed of well-cemented sandy claystone and tuffaceous sandstone. The Arikaree Formation consists mostly of yellowish-gray tuffaceous sandstone and locally contains basal beds of conglomerate.

The water of Shadehill Reservoir is a mixture of waters of the North Fork and South Fork, and the waters of each fork, in turn, are mixtures of waters draining from several different types of rocks. Of the 3,120 square miles of drainage area upstream from Shadehill, about 30 percent consists of exposed Hell Creek and about 70 percent consists of exposed members of the Fort Union Formation. The effect of the Hell Creek on the chemical composition (high residual sodium carbonate) of water in Shadehill Reservoir seems to be disproportionate to the area of the exposed formation. (See pl. 3.) However, this effect may be due to differences in the amounts of ground-water inflow to the streams from the Hell Creek and Fort Union Formations.

Approximate drainage areas of exposed formations upstream from the gaging station at Shadehill

Formation	Area in square miles			
	Upstream from Cash station	Upstream from White Butte station	Downstream from Cash and White Butte stations	Upstream from Shadehill station
Arikaree Formation and White River Group, undifferentiated	16	1	0	17
Fort Union Formation:				
Tongue River Member	75	660	85	820
Cannonball Member	26	120	130	270
Ludlow Member	500	330	270	1,100
Hell Creek Formation	730	85	99	920

Flat Creek and East Flat Creek join near Shadehill upstream from where Flat Creek empties into the Grand River. The drainage basin of Flat Creek is in the Tongue River Member in the upper reaches and in the Cannonball Member in the lower reaches. The drainage basin of East Flat Creek is mostly in the Cannonball Member. Waters from East Flat Creek and Flat Creek Lake are of the sodium sulfate type, but the percentage of sodium plus potassium is about equal to the percentage of calcium plus magnesium.

Downstream from Shadehill, water samples from tributaries of the Grand River that drain areas of exposed Hell Creek Formation are of the sodium sulfate type; however, the percentage of sulfate is only slightly greater than the percentage of bicarbonate. In the upper part of the basin, water from areas of exposed Hell Creek are of the sodium bicarbonate type. The reason the waters from the two areas differ is that the waters collected from an unnamed tributary near Athboy, Willow Creek near Morristown, and Hump Creek near McIntosh, all downstream from Shadehill, represent surface runoff, and the waters collected from upper South Fork and Sand Creek represent ground-water inflow. Analyses of water from two wells in the Hell Creek indicate that the ground water is of the sodium bicarbonate type and increases in dissolved solids with depth (table 2).

TABLE 2.—*Results of chemical analyses of ground water from the Hell Creek Formation in the eastern part of the basin*

Location	Depth of well (ft)	Dissolved solids (ppm)	Equivalents per million			
			Calcium and magnesium	Sodium and potassium	Bicarbonate and carbonate	Sulfate, chloride, and nitrate
SW¼ sec. 1, T. 20 N., R. 18 E.	30	732	2.26	9.39	7.19	4.76
NE¼ sec. 24, T. 20 N., R. 18 E.	80	1,260	.22	20.06	12.22	8.82

High percent sodium is typical of almost all the water in the Grand River basin. Most of the surface water is of the sodium sulfate or sodium bicarbonate type. Ground waters, however, generally contain greater proportions of bicarbonate than sulfate.

In the eastern part of the basin the Pierre Shale and the Fox Hills Sandstone are exposed. The Pierre Shale consists principally of very dark gray to black clay and shale. Beds of marl and impure chalk, as well as calcareous and gypsiferous concretions, are in the formation. Bentonite, an alteration product of volcanic dust, occurs in thin beds and is interspersed in the shaly facies. In general, the Fox Hills Sandstone consists of brown to yellow fossiliferous sandstone and sandy shale. In some exposures the basal beds of the Fox Hills consist of sandy shale that is gradational from the dark-gray shale of the underlying Pierre. In some exposures, however, a distinct difference in color and texture marks the contact between the two formations.

Water that drains from the Fox Hills Sandstone is similar in type to water that drains from the Hell Creek Formation except that water from the Hell Creek generally is more mineralized. Water from Stink Creek near Bullhead is a mixture of water from the Hell Creek Formation and Fox Hills Sandstone.

Water draining from areas of exposed Pierre Shale generally has higher dissolved-solids concentration than water draining from areas of other formations in the basin. Because the Pierre Shale contains the minerals gypsum, calcite, and pyrite in quantity, the water draining from it is of the calcium or sodium sulfate type. Generally the percent sodium is somewhat lower in water draining from the Pierre Shale than in water draining from the Hell Creek and other formations in the basin. The analyses in the following table are for waters from a well in alluvium, which was derived mostly from the Pierre Shale, and from Snake Creek, which drains an area of exposed Pierre Shale.

Chemical characteristics of water from areas of exposed Pierre Shale

Origin of water sample	Dissolved solids (ppm)	Equivalents per million			
		Calcium and magnesium	Sodium and potassium	Bicarbonate and carbonate	Sulfate, chloride, ant nitrate
Well, Little Eagle Day School, Little Eagle, S. Dak	2,510	19.80	19.21	10.41	28.98
Snake Creek near Wakpala, S. Dak	1,540	14.98	7.54	1.57	21.59

The chemical quality of the water that is contributed to the Missouri River by the Grand River depends mainly on the action of weathering on the Fort Union and Hell Creek Formations. The areas of outcrop of the different formations are indicative of their relative importance to the quality of water. However, the effects of the different formations are not necessarily proportional to their areas.

Approximate drainage areas of the exposed formations in the Grand River basin

Formation	*Drainage area (sq mi)*
Arikaree Formation and White River Group undifferentiated	17
Fort Union Formation:	
Tongue River Member	1,000
Cannonball Member	440
Ludlow Member	1,100
Hell Creek Formation	2,200
Fox Hills Sandstone	620
Pierre Shale	280

RELATION TO STREAMFLOW

The patterns and characteristics of streamflow affect the chemical characteristics of the water in the streams; two of the most important are velocity and quantity. Concentration of mineral constituents generally varies inversely with the stream velocity because the solution of minerals is more dependent on the time that the water is in contact with the rocks than on the stream energy. For example, if two streams are flowing over the same type of material, the one having the lower gradient will pick up the greater amount of dissolved solids from a unit area of stream channel. The quantity of streamflow is closely related to velocity and varies from day to day and hour to hour. Likewise, the chemical quality of the stream varies from day to day generally in inverse proportion to the stage of the stream. The base flow, or low sustained flow, of a stream is generally predominantly water that has entered the stream from the ground-water reservoir. This water has been in contact with rock and soil particles and has leached the soluble

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minerals. At high stages the more mineralized ground water entering the stream is diluted by surface runoff. Figure 11 shows the differences in the mineral content and chemical composition of some of the streams at different streamflow rates.

The general streamflow-quality patterns of the Grand River and its two forks are very similar. The dissolved-solids content varies greatly, especially at high streamflow rates (fig. 12). Nevertheless, the quality of the water clearly improves as streamflow increases. The dissolved-solids concentration is maximum during low-flow periods and generally does not exceed 3,000 ppm (parts per million).

Waters of the North and South Forks have about the same dissolved-solids concentration most of the time. Moreover, the waters at the five scheduled stations do not vary greatly in dissolved-solids concentration most of the time (table 3). Dissolved-solids concentration is maximum at low streamflow and minimum at high streamflow. Low flows are mostly from ground-water inflow, and during high flows the normal and base flows are diluted by overland runoff.

The effect of ground-water inflow and overland runoff on the chemical composition of the water is shown by figures 11 and 13. At flows of more than 1,000 cfs the water was of the calcium bicarbonate type, and at flows of less than 20 cfs the water was of the sodium sulfate type (fig. 13). For most flows the water in the Grand River at Shadehill was of the sodium sulfate type.

TABLE 3.—*Percentages of time concentration and streamflow were equaled or exceeded*

[Partly based on estimated data]

Station	Equaled or exceeded values for indicated percentage of time					
	Dissolved-solids concentration (ppm)			Streamflow (cfs)		
	99 percent	50 percent	20 percent	1 percent	50 percent	80 percent
North Fork Grand River at Haley, 1947–60	190	1,670	1,750	760	1.7	0.6
North Fork Grand River near White Butte, 1947–60	380	1,670	1,830	1,100	4.4	.3
South Fork Grand River near Cash, 1947–60	340	1,740	2,500	850	11	3.5
Grand River at Shadehill, 1944–49	262	1,480	2,200	3,300	25	5.7
Grand River near Wakpala, 1937–50	220	1,250	1,400	7,200	47	4.0

SHADEHILL RESERVOIR

WATER IN THE RESERVOIR

After storage began in July 1950, the reservoir filled slowly until the spring runoff of 1952 and then filled rapidly. No water was discharged from the reservoir until April 4, 1952, when the water

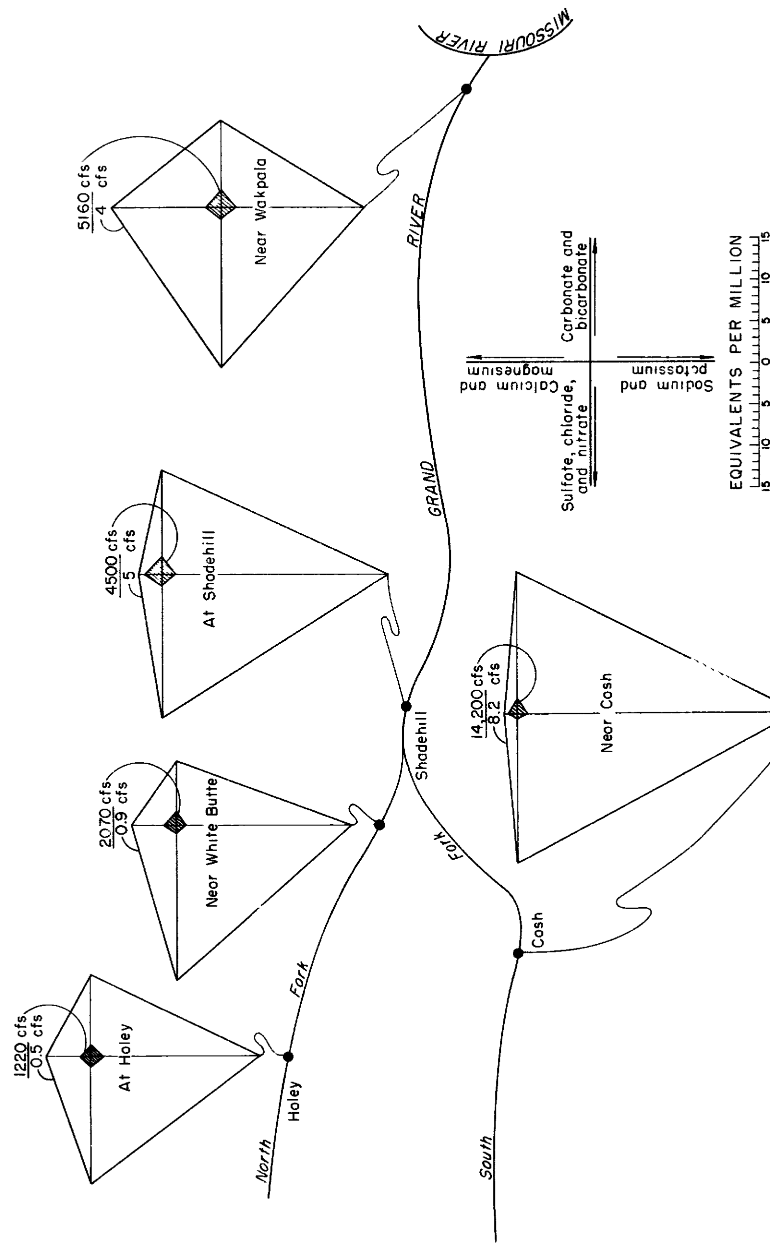

FIGURE 11.—Chemical quality of water at high and low streamflow rates.

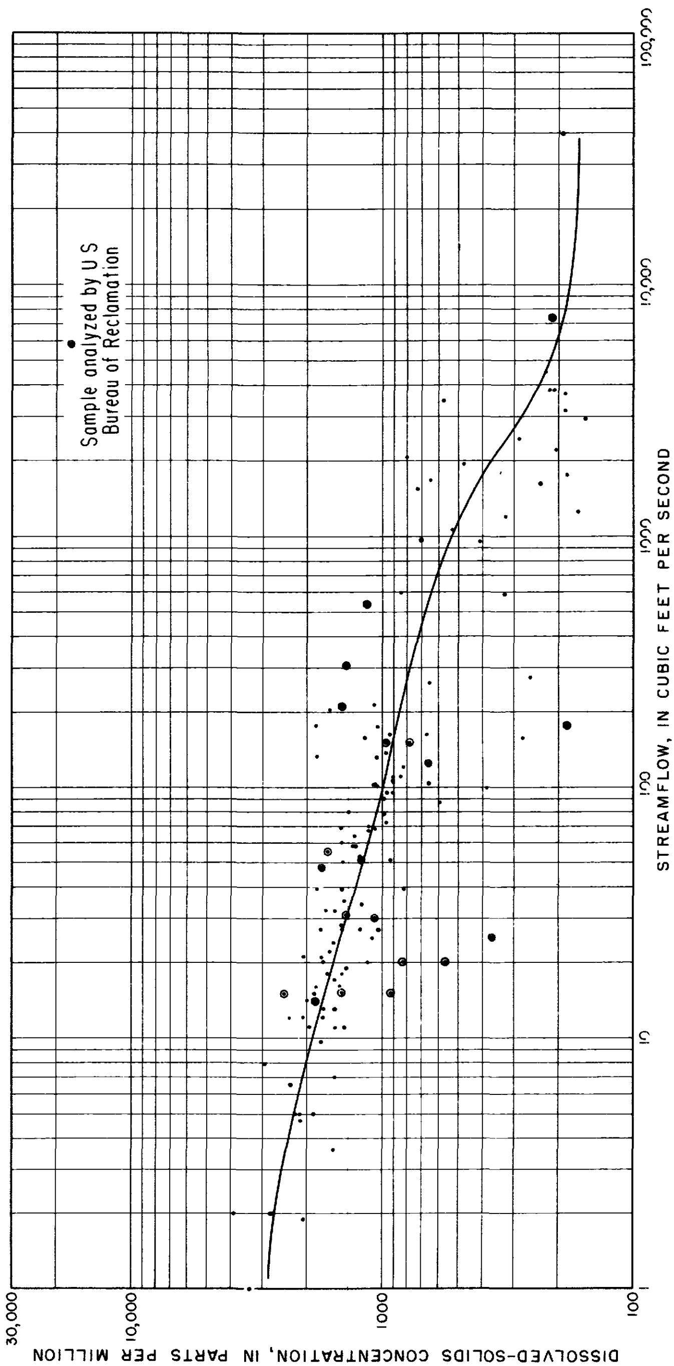

FIGURE 12.—Relation of dissolved-solids concentration to streamflow, Grand River at Shadehill, S. Dak.

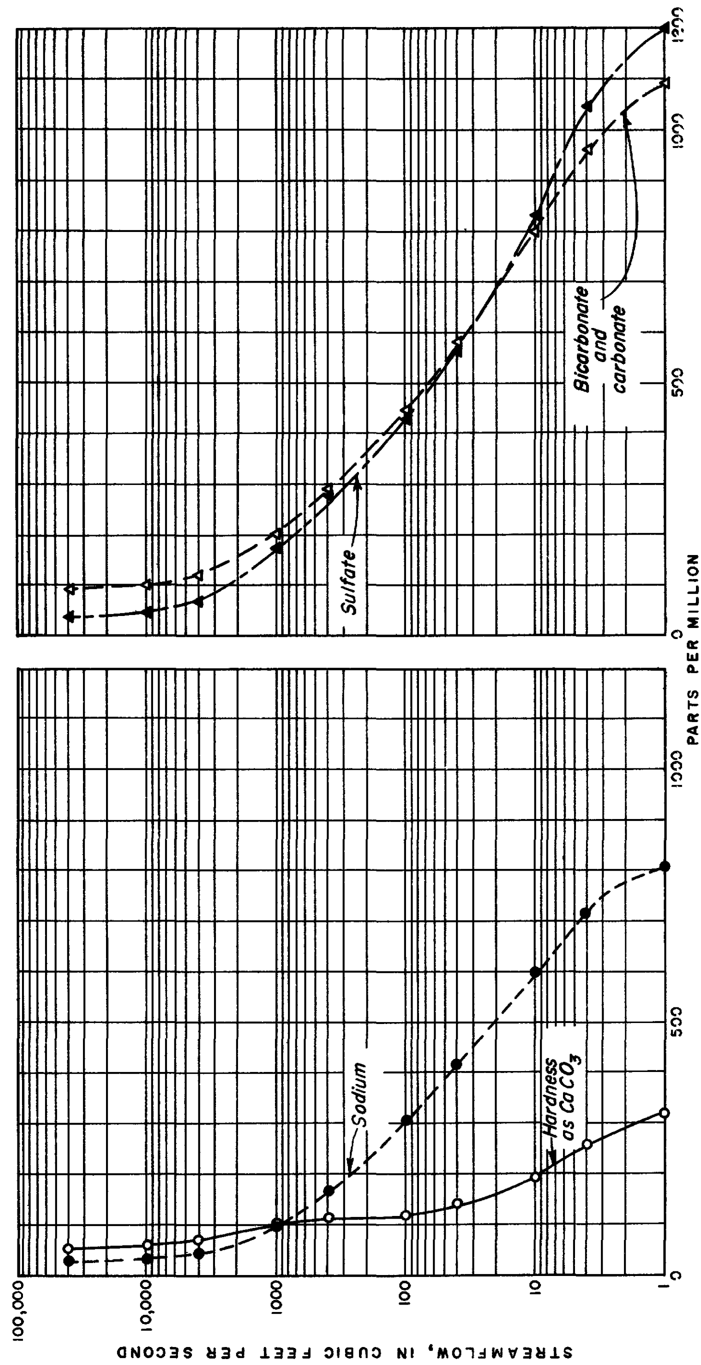

FIGURE 13.—Relations of concentrations of dissolved constituents to water discharge, Grand River at Shadehill, S. Dak. Points derived from plots of concentrations versus specific conductance (as in fig. 20) and streamflow versus specific conductance (as in fig. 18).

reached the spillway crest. (Because the water has never reached the emergency spillway, for convenience in this and following sections the term "spillway" refers to the service spillway.) Therefore, samples collected from the reservoir during the period of rapid filling represent the accumulated total runoff for 21 months from the upper Grand River basin. The quality of the stored water probably changed during the period because of evaporation, direct precipitation on the surface of the reservoir, solution, and possibly some precipitation of salts.

Before the closure of the dam, range lines across various parts of the reservoir were established by the Bureau of Reclamation (pl. 4) for use in measuring sediment accumulations. Samples of water were collected at several different depths at each sampling site on the range lines. The sites were selected over the old stream channel and at as many other points along the range lines as was necessary for adequate sampling of the reservoir in the vertical. (See pl. 4.)

Samples of water from the reservoir at different sites and depths defined lateral and vertical variations in the quality of the water. These samples, which were taken at different times during a period of several years at the same locations, show changes in the quality of water with season and with inflow.

Only during a relatively short time in the year is the dissolved-solids concentration of the inflow as low as that of the water in the reservoir. Except at the points of inflow and during floodflows, the water in the reservoir is well mixed and is uniform in composition.

Runoff was below normal from July 1950 to March 1952. On March 7, 1952, Shadehill Reservoir contained only 56,000 acre-feet of water mostly from low flows, and the specific conductance of the water was about 1,500 micromhos per centimeter and percent sodium was 79. By March 30, 1952, the spring runoff from snowmelt had begun to enter the reservoir. From March 30 to April 17, water entering the reservoir amounted to more than 327,800 acre-feet (the sum of the flows for the North Fork Grand River near White Butte and the South Fork Grand River near Cash). Because this water was mainly snowmelt, it was low in dissolved solids. Water discharging from the spillway outlet had decreased in conductance to 472 micromhos per centimeter and in percent sodium to 74 by April 5. Conductance of the water in the spillway outlet decreased gradually to a low of 333 micromhos per centimeter by April 7, and percent sodium reached a low of 65 by April 9.

On April 17, 1952, the specific conductance of the water varied both horizontally and vertically. The horizontal variation of surface samples was not great; the conductance ranged only from 240 to 346 micromhos per centimeter on range lines 1, 2, 4, and 21. However, the measured vertical variations in conductance ranged from 240 micromhos per centimeter at the surface to 1,820 micromhos per centimeter near the bottom. The decrease in specific conductance from the bottom of the reservoir upward is similar to that noted in Lake Mead by Anderson and Pritchard (1951). The dilute floodwaters apparently moved over the top of the concentrated residual water and out the spillway without being entirely mixed. On April 17 the water on the bottom at range lines 1 and 2 probably had been in the reservoir before the floodflows; at range lines 4 and 21, the floodwater had displaced the residual water.

Although on March 7, 1952, the reservoir contained 56,000 acre-feet of water, by April 17 the surface of the reservoir was 20 feet higher than the spillway crest, and the reservoir contained 83,600 acre-feet of floodwater below the spillway elevation. Because 2,200 of the 83,600 acre-feet of floodwater was below the irrigation outlet, the 2,200 acre-feet would not be available for irrigation.

From March 31 through May 18, 1952, at least 340,000 acre-feet of water entered the reservoir, and probably about 75 percent of this water of low specific conductance passed through the reservoir and out by way of the spillway. The reservoir was sampled on May 19, 1952, after most of the excess water had passed from the reservoir. Samples taken at different depths and locations on the range lines indicate that mixing of the water was fairly complete laterally but not vertically. Specific conductances in the deeper areas of the lake, along range lines 1 and 2, were constant to a depth of about 40 feet and then increased rapidly with greater depth (fig. 14). The data collected on May 19 indicate that the boundary line between the dilute upper layer and the more concentrated lower layer of water was not horizontal but sloped slightly upward away from the dam. The fact that the water was still stratified 6 weeks after floodflows filled the reservoir can be explained by the effect of temperature on the circulation of waters in reservoirs.

In a study of the hydrology of Indiana lakes, Perrey and Corbett (1956, p. 16) discussed the temperature data collected at Maxinkuckee, Ind., by Evermann and Clark (1920) as follows:

> When lakes are open and water temperatures are between 32°F and 39.2°F any tendency for the water to become warmer will increase its density, as fresh water reaches its maximum density at 39.2°F; consequently, the heavier water will move downward and be replaced by colder and lighter water from below, thus maintaining a nearly constant temperature at the water surface. Of course, if this process continues long enough, the whole body of water will

eventually become warmed to 39.2°F and the temperature at the water surface will gradually increase.

During the spring and summer months when the water temperature of the lake surface is above 39.2°F, daily variations of 6°, 8°, and 10°F in the water at the surface are not uncommon. These variations are possible because of a greater differential existing between surface temperatures and those a short distance below the surface. The top few inches of water may be warmed very rapidly under the hot summer sun, and because the water becomes lighter as its temperature increases it will remain on top. Consequently there will be very little mixing with the water underneath, particularly on calm days.

On March 7, 1952, the temperatures measured in Shadehill Reservoir were from 38° to 40°F, which is near 39.2°F, the temperature at which water reaches maximum density. On April 17, the water temperature was still near 39.2°F except at the surface where temperatures were higher. On May 19, 1952, temperatures had risen from 10 to 20 degrees throughout the profile, and the warmest water was at the surface. On July 23, 1952, the water in the reservoir was almost uniform in chemical quality, and temperatures of the water at all depths were generally higher than those in May. The mixing that took place between May 19 and July 23 was due to wave action and currents.

WATER DISCHARGED FROM THE RESERVOIR

After the reservoir began to spill on April 4, 1952, samples at the spillway outlet were collected daily, or at intervals of a few days, when the water level was above spillway elevation. Samples were also collected at the irrigation outlet, usually when the water level was below spillway elevation. From available analyses of water in the reservoir and of water leaving the reservoir (table 4), the suitability of the water for irrigation and other uses can be determined.

Figure 15 shows that the spread between the maximum and minimum conductances of the water in the reservoir from September 1950 to October 1952 was only slight until the end of March 1952. When the reservoir started to spill in early April, the more dilute water in the top part of the reservoir (see fig. 14) was discharged through the spillway outlet. Water discharged through the spillway was not representative of all the water in the reservoir until July when mixing in the reservoir was complete. The maximum and minimum specific conductances as represented by the lines in figure 15 gradually began to converge in April 1952; the conductance of water in the reservoir and the conductance of the water discharged through the spillway were the same by late July.

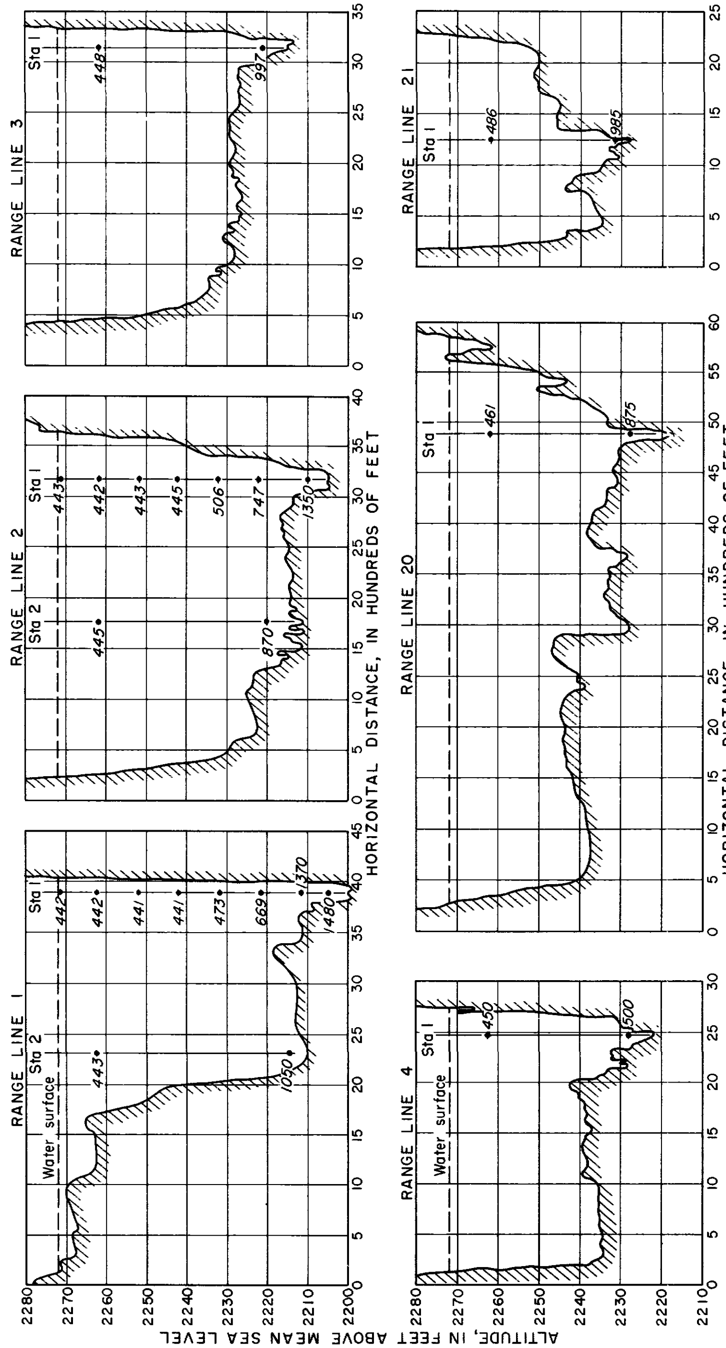

FIGURE 14.—Cross sections of Shadehill Reservoir showing sampling points and relationship of specific conductance to depth, May 19, 1952.

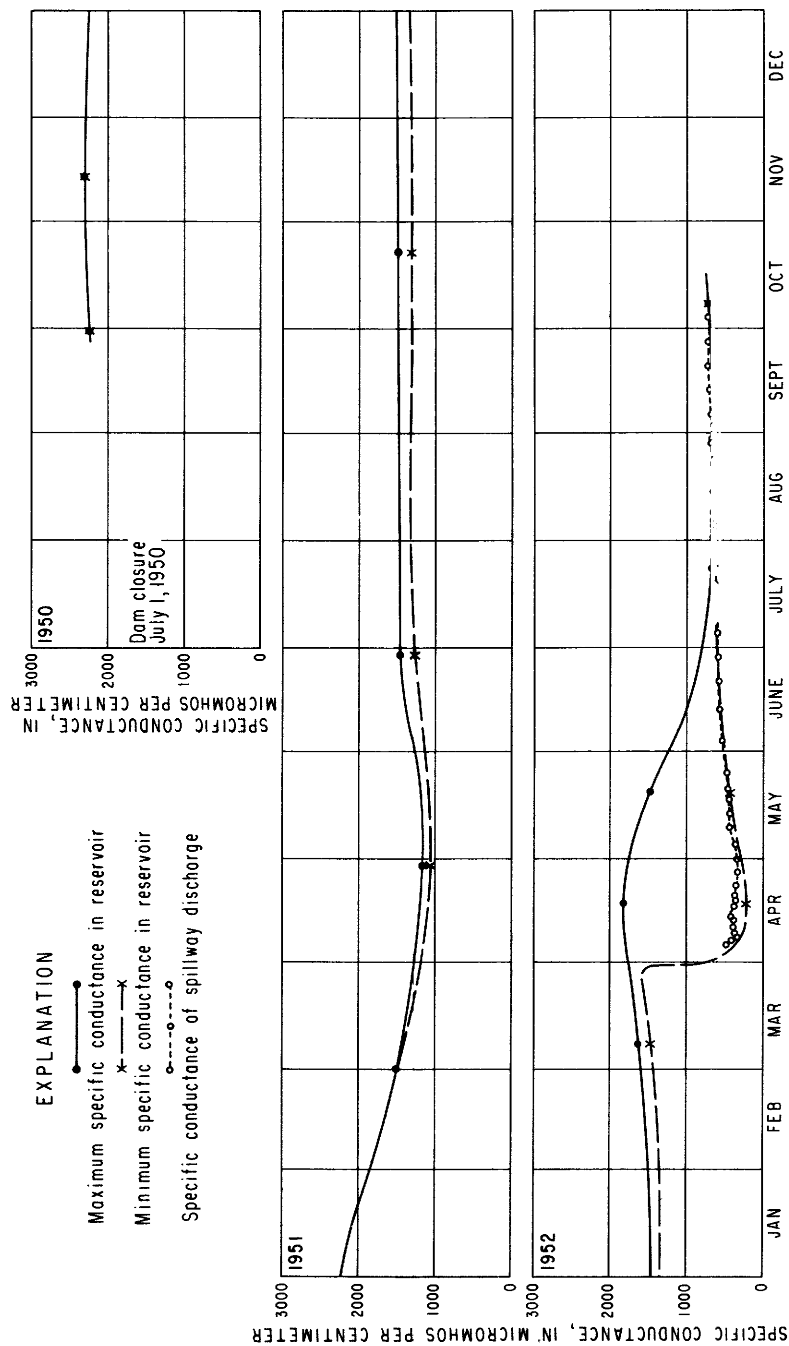

FIGURE 15.—Maximum and minimum specific conductances of the water from Shadehill Reservoir and spillway.

TABLE 4.—*Weighted-average chemical analyses, Grand River near Shadehill, S. Dak.*

[Samples collected at reservoir outlets. Mean discharge at gaging station, 1 mile downstream from dam. Results in parts per million except as indicated]

Water year	Mean streamflow (cfs)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Boron (B)
1952 [1,2]	380	--	--	--	56	--	--	--	--	--
1953 [3]	115	--	--	--	--	--	--	--	--	--
1954 [1,4]	23.4	--	--	--	177	--	--	--	--	--
1955 [5]	7.36	5.1	32	17	221	7.5	[6] 354	337	4.6	0.32
1956 [4]	25.6	--	--	--	232	--	[6] 367	347	--	.35
1957 [4]	30.2	--	--	--	257	--	[6] 397	--	--	.39
1958 [4]	20.5	--	--	--	274	--	[6] 412	--	--	--
1959 [4]	27.9	--	--	--	299	--	[6] 437	--	--	--
1960 [4]	32.2	--	--	--	291	--	423	--	--	--

Water year	Dissolved solids			Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Percent sodium	Sodium-adsorption ratio	Specific conductance (micromhos per cm)
	Residue on evaporation at 180° C	Tons per acre-foot	Tons per day					
1952 [1,2]	256	0.35	--	56	--	69	3.3	374
1953 [3]	--	--	--	--	--	--	--	[1] 858
1954 [1,4]	667	.91	42.1	147	--	72	6.4	1,030
1955 [5]	812	1.10	--	151	0	76	7.8	1,230
1956 [4]	858	1.17	59.3	147	0	76	8.3	1,290
1957 [4]	915	1.24	74.6	147	0	79	9.2	1,360
1958 [4]	955	1.30	52.9	144	0	81	9.9	1,420
1959 [4]	--	--	--	141	0	82	11	1,510
1960 [4]	973	1.32	85.1	132	0	83	11	1,440

[1] Includes estimated data.
[2] Analytical results represent 99.9 percent of flow for water year.
[3] Analytical results represent 99.8 percent of flow for water year.
[4] Analytical results represent 100 percent of flow for water year.
[5] Analytical results represent 97.0 percent of flow for water year.
[6] Includes carbonate as bicarbonate.

From September 1950 to April 1952 while the reservoir was filling to spillway level, the quality of water in the reservoir improved in the late winter and spring and deteriorated in the summer and fall (fig. 16). During this period specific conductance ranged from about 350 to 2,300 micromhos per centimeter. After the reservoir filled, the quality of the water became almost uniform throughout the reservoir by the latter part of July 1952, and the specific conductance of the water gradually increased and became relatively stable in 1956. Thereafter, the specific conductance fluctuated from about 1,300 to 1,600 micromhos per centimeter and was between 1,400 and 1,500 micromhos per centimeter most of the time (fig. 16). The gradual increase of specific conductance was affected very little by seasonal changes in the quantity and quality of the inflow. The below-normal inflows of the 1954, 1955, and 1956 water years may have lessened the time required for the quality of the water in the

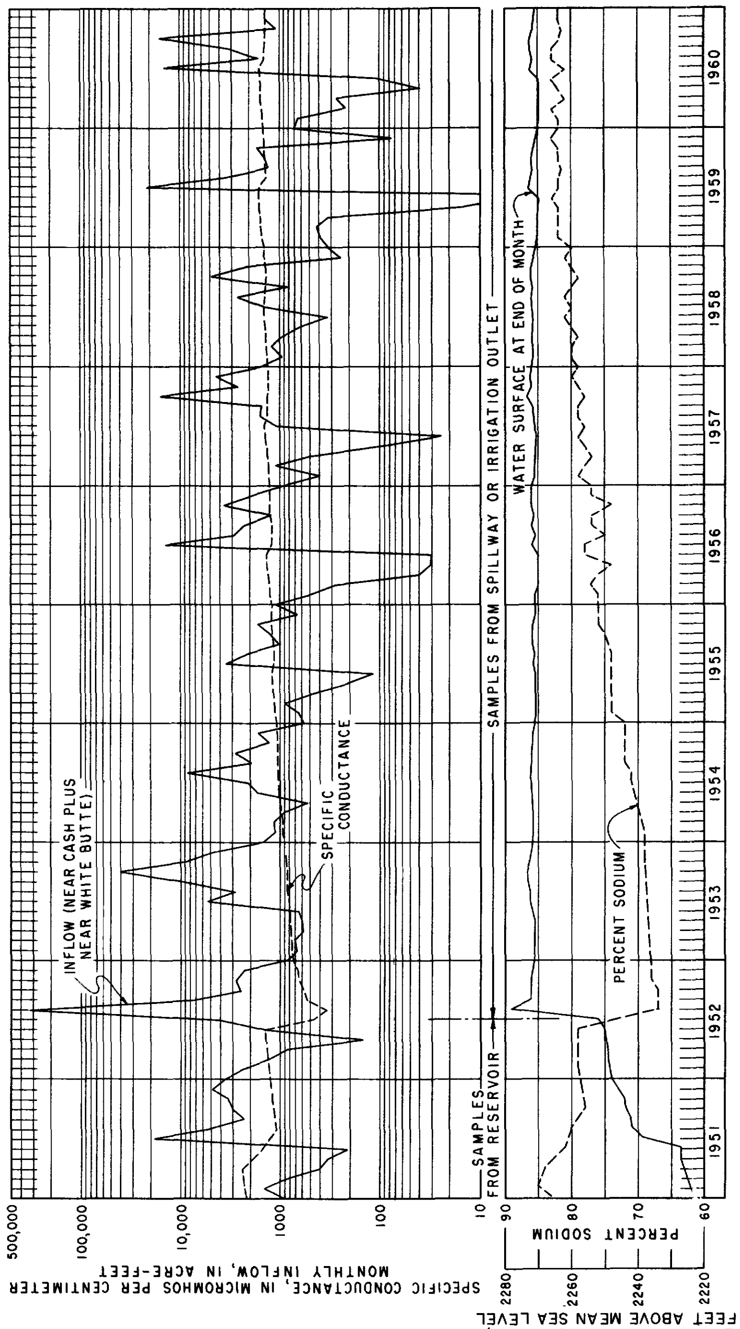

FIGURE 16.—Relation of chemical quality of water, inflow, and surface elevation, Shadehill Reservoir, 1951–60 water years.

reservoir to reach probable maximum concentration after the abnormally high flows in the spring of 1952. However, the slope of the specific-conductance curve in figure 16 is fairly uniform for the water years 1953–55.

CHEMICAL-QUALITY RECORDS

In addition to samples collected at scheduled stations (fig. 17), one or two samples have been collected on most of the remaining principal streams in the basin. (See pl. 1.) Chemical analyses of samples from scheduled stations are published in the annual series of U.S. Geological Survey water-supply papers entitled "Quality of Surface Waters of the United States," and chemical analyses of samples from unscheduled stations are given in table 5. Analyses furnished by the Bureau of Reclamation for the period October 1941 to September 1945 are given in table 6.

Periods of streamflow records are given in table 1. The mean annual runoff was greater for the periods represented by the chemical-quality records than for the period July 1, 1937, to June 30, 1950, which is probably representative of the long-term period.

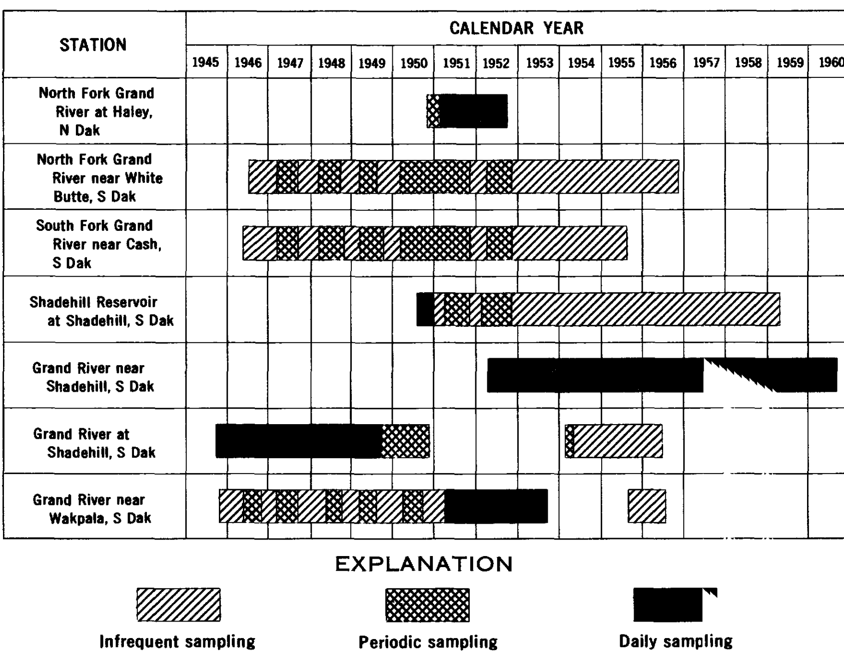

FIGURE 17.—Duration of chemical-quality records and sampling frequency at scheduled stations.

TABLE 5.—*Chemical analyses at unscheduled sampling points in Grand River drainage basin*

[Results in parts per million except as indicated]

Date of collection	Streamflow (cfs)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids: Calculated	Dissolved solids: Residue on evaporation at 180°C	Dissolved solids: Tons per acre-foot	Dissolved solids: Tons per day	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Percent sodium	Sodium-adsorption-ratio	Specific conductance (micromhos per cm)	pH
North Fork Grand River south of Hettinger (SE¼ sec. 8, T. 22 N., R. 12 E.)																								
Oct. 14, 1955	[1] 1	7.0	0.01	32	35	354	8.5	473	0	610	7.5	0.6	1.0	0.82	1,290	1,320	1.80	3.56	224	0	77	10	1,890	8.1
North Fork Grand River above junction with South Fork Grand River near Shadehill																								
Apr. 26, 1949	60.2	8.5	0.02	51	27	224		336	0	424	5.0	0.2	0.8	0.36	----	942	1.28	153	239	0	67	6.3	1,340	7.8
Mar. 15, 1951	----	----	----	----	----	628	----	727	0	890	14	----	----	----	----	----	----	----	----	----	89	21	2,780	7.6
South Fork Grand River at Buffalo																								
Apr. 26, 1949	4.53	12	0.05	14	7.2	394		681	36	276	9.5	0.2	0.6	0.22	1,090	1,080	1.47	13.2	65	0	93	21	1,620	8.6
Aug. 1, 1950	----	----	----	----	----	466	6.6	----	----	----	----	----	----	----	----	1,350	1.84	----	46	----	95	30	1,920	----
Oct. 14, 1955	1.7	16	----	13	1.8	430	3.9	760	51	283	7.0	.6	1.0	.33	1,180	1,200	1.63	5.51	40	0	95	30	1,820	8.8
July 25, 1956	1.8	14	.08	13	3.0	402	5.5	745	30	280	6.5	.4	2.6	.36	1,120	1,180	1.60	5.73	45	0	94	26	1,780	8.6
Sand Creek near Buffalo (NE¼ sec. 35, T. 19 N., R. 6 E.)																								
Oct. 14, 1955	[1] 2	34	----	10	1.2	436	3.3	712	79	285	7.0	0.7	0.8	0.29	1,210	1,200	1.63	6.48	30	0	97	35	1,840	9.0
July 25, 1956	.35	9.3	0.08	10	2.2	438	4.8	748	63	285	6.0	.4	10	.38	1,200	1,250	1.70	1.18	34	0	96	33	1,[illegible]00	8.9

Squaw Creek near Buffalo (NW¼ sec. 10, T. 18 N., R. 7 E.)																								
Oct. 14, 1955	1 0.05	------	------	------	------	1,120	11	1,160	216	1,300	------	------	------	0.54	------	3,290	4.47	0.44	80	0	96	54	4,470	9.0
Sand Creek at mouth near Buffalo																								
Apr. 27, 1949	3.83	12	0.05	18	7.9	421		713	36	316	12	0.4	0.7	0.15	1,180	1,140	1.55	11.8	78	0	92	21	1,690	8.6
Jones Creek at mouth near Buffalo																								
Apr. 27, 1949	1.27	9.1	0.05	27	13	337		517	16	376	8.0	0.1	1.1	0.22	1,050	1,070	1.46	3.67	121	0	86	13	1,570	8.3
Bull Creek near Ludlow (NE¼ sec. 31, T. 21 N., R. 6 E.)																								
Oct. 14, 1955	1 0.5	18	------	20	8.3	588	5.2	730	35	710	5.0	0.7	1.5	0.76	1,750	1,760	2.39	2.38	84	0	93	28	2,540	8.6
July 25, 1956	.20	12	0.23	23	5.5	214	5.5	336	0	270	.0	.2	2.3	.30	------	734	1.00	.40	80	0	84	10	1,110	8.1
Bull Creek at mouth near Buffalo																								
Apr. 27, 1949	3.85	11	0.02	24	9.5	339		443	40	384	28	0.3	1.4	0.59	1,030	1,060	1.44	11.0	99	0	88	15	1,560	8.7
Nasty Creek near Ralph																								
Apr. 25, 1949	3.91	9.2	0.02	67	46	376		408	0	796	6.0	0.3	1.1	0.62	1,510	1,580	2.15	16.7	356	21	70	8.7	2,090	7.9
South Fork Grand River near Prairie City (NW¼ sec. 26, T. 20 N., R. 11 E.)																								
Oct. 14, 1955	1 10	------	------	------	------	558	5.2	730	94	513	11	0.8	1.9	0.50	------	1,620	2.20	43.7	48	0	96	35	2,360	8.8
July 25, 1956	6.0	12	0.08	21	5.5	360	7.7	514	13	425	6.5	.4	3.0	.42	1,110	1,160	1.58	18.8	75	0	90	18	1,740	8.5
South Fork Grand River near Bison (NE¼ sec. 13, T. 19 N., R. 13 E.)																								
Oct. 17, 1955	1 18	12	------	13	7.7	594	6.6	730	79	620	11	0.8	1.1	0.52	1,700	1,740	2.37	84.6	64	0	95	32	2,530	8.8
July 26, 1956	6.6	12	0.11	22	5.1	283	6.7	406	12	350	4.0	.4	2.1	.37	------	944	1.28	16.8	76	0	88	14	1,420	8.4

See footnotes at end of table.

TABLE 5.—*Chemical analyses at unscheduled sampling points in Grand River drainage basin*—Continued

[Results in parts per million except as indicated]

Date of collection	Streamflow (cfs)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids: Boron (B)	Dissolved solids: Calculated	Dissolved solids: Residue on evaporation at 180°C	Dissolved solids: Tons per acre-foot	Tons per day	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Percent sodium	Sodium-adsorption-ratio	Specific conductance (micromhos per cm)	pH
Lodgepole Creek at mouth near Shadehill																								
Apr. 26, 1949	1.49	7.9	0.03	111	67	399		474	0	972	12	0.5	0.7	0.30	1,810	1,910	2.60	7.68	553	164	61	7.4	2,440	7.9
South Fork Grand River above confluence with North Fork River near Shadehill																								
Apr. 26, 1949	44.8	11	0.05	41	22	352		489	15	496	10	0.3	0.9	0.37	1,190	1,220	1.66	148	193	0	80	11	1,740	8.2
Mar. 15, 1951	--	--	--	--	--	474	--	582	0	725	11	--	--	--	--	--	--	--	--	--	83	14	2,270	7.6
Flat Creek at Haynes																								
Apr. 5, 1958	0.7	9.1	0.07	37	45	172	17	301	0	366	27	0.5	10	0.29	--	863	1.17	1.63	276	29	56	4.5	1,260	7.2
Flat Creek Lake near Shadehill																								
Nov. 18, 1947	--	1.0	0.05	67	51	198	10	326	0	514	8.0	0.3	1.0	--	1,010	1,030	1.40	--	377	110	52	4.4	1,520	8.0
Oct. 17, 1955	--	5.8	--	44	42	247	12	290	0	555	8.5	.4	3.7	0.31	1,060	1,070	1.46	--	282	44	64	6.4	1,550	7.6
July 20, 1956	--	2.2	.02	31	31	174	12	216	0	405	6.0	.4	5.1	.24	--	807	1.10	--	205	28	63	5.3	1,190	7.5
East Flat Creek near Shadehill																								
Apr. 26, 1949	0.17	8.4	0.02	194	61	449		438	0	1,280	12	0.4	0.9	0.32	2,220	2,350	3.20	1.08	735	376	57	7.2	2,880	7.5

Flat Creek below Flat Creek Lake near Shadehill																								
Apr. 26, 1949	3.43	5.5	0.02	53	28	158		250	0	360	6.0	0.1	1.2	0.23	-------	758	1.03	7.02	248	43	58	4.4	1,090	7.6
Grand River near Athboy (SE¼ sec. 8, T. 20 N., R. 18 E.)																								
Oct. 13, 1955	[1]25	2.3	0.02	24	22	263	7.8	390	6	393	8.0	0.5	0.6	0.42	-------	937	1.27	63.2	149	0	78	9.4	1,400	8.3
July 26, 1956	10.6	3.2	.04	20	16	274	8.8	385	0	405	7.5	.5	.7	.42	-------	972	1.32	27.8	117	0	82	11	1,460	8.3
Unnamed tributary to Grand River near Athboy (NE¼ sec. 17, T. 20 N., R. 18 E.)																								
Oct. 13, 1955	[2]0	------	11	-----	------	129	4.9	214	0	139	5.0	-----	1.1	0.13	-------	-------	------	-------	40	0	86	8.9	632	7.8
Willow Creek near Morristown																								
Oct. 13, 1955	[2]0	------	10	-----	------	95	4.0	178	0	103	2.0	-----	1.3	0.08	-------	-------	------	-------	46	0	80	6.1	495	7.8
Black Horse Butte Creek near Morristown																								
June 14, 1957	[1]1	14	0.10	19	3.0	165	5.7	257	0	185	8.5	0.4	2.0	0.32	-------	543	0.74	1.47	60	0	84	9.3	819	8.0
Grsnd River near Morristown (SE¼ ser. 19, T. 20 N., R. 20 E.)																								
Aug. 7, 1948	-------	6.0	0.02	14	18	674		754	47	808	25	0.7	1.0	0.65	1,970	2,070	2.82	-------	109	0	93	28	2,680	8.8
Oct. 13, 1955	[1]20	2.3	.02	24	22	283	8.2	405	9	415	8.5	.5	1.0	.42	-------	988	1.34	53.4	152	0	79	10	1,480	8.3
July 19, 1956	19.5	4.1	.04	22	15	274	8.8	374	7	400	7.5	.4	1.1	.46	-------	959	1.30	50.5	118	0	82	11	1,450	8.4
Grand River near McIntosh (SW¼ sec. 18, T. 20 N., R. 23 E.)																								
Oct. 12, 1955	[1]20	3.2	0.02	28	16	310	8.8	422	0	470	10	0.5	0.8	0.39	1,060	1,070	1.46	57.8	136	0	82	12	1,580	8.1
July 19, 1956	15.0	7.2	.06	28	9.2	278	8.0	331	0	445	8.0	.1	1.7	.44	-------	995	1.35	40.3	108	0	84	12	1,490	8.1

See footnotes at end of table.

TABLE 5.—*Chemical analyses at unscheduled sampling points in Grand River drainage basin*—Continued

[Results in parts per million except as indicated]

Date of collection	Streamflow (cfs)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids: Calculated	Dissolved solids: Residue on evaporation at 180°C	Dissolved solids: Ton per acre-foot	Dissolved solids: Ton per day	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Percent sodium	Sodium-adsorption-ratio	Specific conductance (micromhos per cm)	pH
Hump Creek near McIntosh (sec. line, secs. 19–24, T. 21 N., Rs. 22–23 E.)																								
Oct. 12, 1955	[1] 1	------	8.1	------	------	58	3.6	130	0	101	2.0	------	3.1	0.05	------	------	------	------	86	0	58	2.7	415	7.6
July 19, 1956	[2] 0	26	.77	11	2.1	146	4.2	192	0	190	1.0	0.2	4.7	.15	------	532	0.72	------	36	0	88	11	739	7.8
Stink Creek near Bullhead (NW¼ sec. 23, T. 21 N., R. 24 E.)																								
Oct. 12, 1955	[1] 0.50	10	0.05	42	19	169	8.9	338	0	273	6.0	0.5	1.9	0.25	------	709	0.96	0.96	182	0	66	5.4	1,050	7.6
July 19, 1956	.2	14	.18	27	7.2	115	5.3	292	0	115	.5	.0	2.0	.24	------	453	.62	.24	97	0	71	5.1	696	7.8
High Bank Creek near Little Eagle (NW¼ sec. 30, T. 19 N., R. 26 E.)																								
May 2, 1957	3.9	8.8	0.06	56	22	110	4.1	425	12	102	3.2	0.6	0.5	0.20	------	552	0.75	5.81	231	0	50	3.2	841	8.5
Grand River at Little Eagle (sec. line, secs. 28–33, T. 20 N., R. 27 E.)																								
Oct. 11, 1955	[1] 8	9.0	0.03	42	16	302	8.3	404	0	490	11	0.5	1.3	0.30	1,080	1,100	1.50	23.8	170	0	78	10	1,590	8.0
July 18, 1956	18	11	.07	41	10	259	8.2	344	0	415	8.5	.3	1.5	.33	------	961	1.31	46.7	145	0	78	9.4	1,410	8.0
Snake Creek near Wakpala																								
July 18, 1956	2.5	17	0.03	194	64	164	16	96	0	1,030	4.0	0.6	2.4	0.20	1,540	1,650	2.24	11.1	747	668	32	2.6	1,970	7.3

[1] Estimated.
[2] Practically no flow.

TABLE 6.—*Chemical analyses by the U.S. Bureau of Reclamation*

[Results in parts per million except as indicated]

Date	Streamflow (cfs)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Choloride (Cl)	Nitrate (NO_3)	Total dissolved solids	Percent sodium	Specific conductance (micromhos per cm)	pH
Grand River at Shadehill, S. Dak.														
Oct. 9, 1941	20	23	9.0	142	9.0	243	0	203	4.3	6.2	560	75	885	7.7
Dec. 1	15	22	22	448	18	515	36	615	12	3.7	1,452	85	2,100	8.6
Jan. 19, 1942	15	66	43	711	58	921	24	1,090	30	4.3	2,488	79	3,400	7.8
Mar. 17	25	16	5.8	79	12	160	0	102	1.8	5.0	364	68	533	7.0
Apr. 11	20	28	11	251	------	------	----	------	------	------	830	82	1,260	7.8
June 3	150	42	12	205	------	------	----	------	------	------	784	75	1,150	8.1
July 20	150	24	9.4	285	------	------	----	------	------	------	972	86	1,460	7.7
Sept. 19	15	58	13	246	------	------	----	------	------	------	926	73	1,420	7.9
Apr. 12, 1943	123	39	23	174	------	------	----	------	------	------	658	66	1,010	8.3
Mar. 14, 1945	7,450	22	5.4	34	------	140	0	40	.0	.0	214	49	299	7.4
Apr. 9	176	19	5.5	35	------	134	0	35	7.1	.1	184	52	285	7.7
May 29	60	33	21	430	------	527	19	629	16	.1	1,454	85	2,072	8.2
June 5	210	51	28	393	------	442	23	687	11	.1	1,442	78	2,038	8.3
June 7	306	58	27	382	------	421	20	653	11	.2	1,400	76	1,947	8.1
June 9	540	36	20	331	------	364	4	552	11	.4	1,174	81	1,700	8.1
June 23	55	44	30	455	------	468	36	764	16	.1	1,642	81	2,277	8.4
June 25	30	68	30	264	------	423	10	467	3.5	.2	1,084	66	1,537	8.0
July 7	32	31	28	517	------	578	24	759	18	.1	1,690	92	2,420	8.3
July 24	47	18	17	580	------	665	35	730	16	.2	1,754	92	2,540	8.6
Sept. 20	14	12	16	621	------	690	58	735	21	.1	1,842	93	2,680	8.1
Grand River near Wakpala, S. Dak.														
Oct. 10, 1941	40	23	6.7	138	7.8	242	0	183	6.0	5.0	530	76	878	7.7
Dec. 1	50	37	23	343	32	395	24	576	14	3.1	1,274	76	1,740	8.3
Jan. 21, 1942	40	97	54	651	63	744	21	1,170	29	8.7	2,646	72	3,330	7.6
Mar. 17	330	31	8.6	102	13	157	0	188	7.1	16	494	63	711	7.5
Mar. 21	475	27	5.8	171	------	------	----	------	------	------	658	80	864	8.7
Apr. 10	350	20	4.4	78	------	------	----	------	------	------	314	72	460	8.1
May	3,000	28	7.1	99	------	------	----	------	------	------	434	69	686	7.6
July 28	1,180	34	7.5	115	------	------	----	------	------	------	512	68	730	7.8
Nov. 5	25	17	15	515	------	------	----	------	------	------	1,536	92	2,270	8.5
Apr. 20, 1943	100	65	11	193	------	------	----	------	------	------	838	67	1,190	8.1

EXTENSION OF RECORDS

Mean water discharges at Shadehill for each month from July 1937 to February 1943 were estimated from a relation of measured mean streamflow for each month from March 1943 to June 1950 for Grand River at Shadehill and near Wakpala. (See fig. 10.) Chemical-quality records for the period July 1937 to June 1950 were computed for Grand River at Shadehill from chemical-quality data collected after October 1945 and from measured and estimated monthly mean streamflows for the period.

Specific conductance was plotted against streamflow (fig. 18) and against parts per million of sodium, bicarbonate plus carbonate, and sulfate (fig. 19). From the curves and mean streamflows, monthly chemical-quality records were computed for the Grand River at Shadehill, and weighted averages for each year and for the period were computed (table 7). Yearly weighted averages

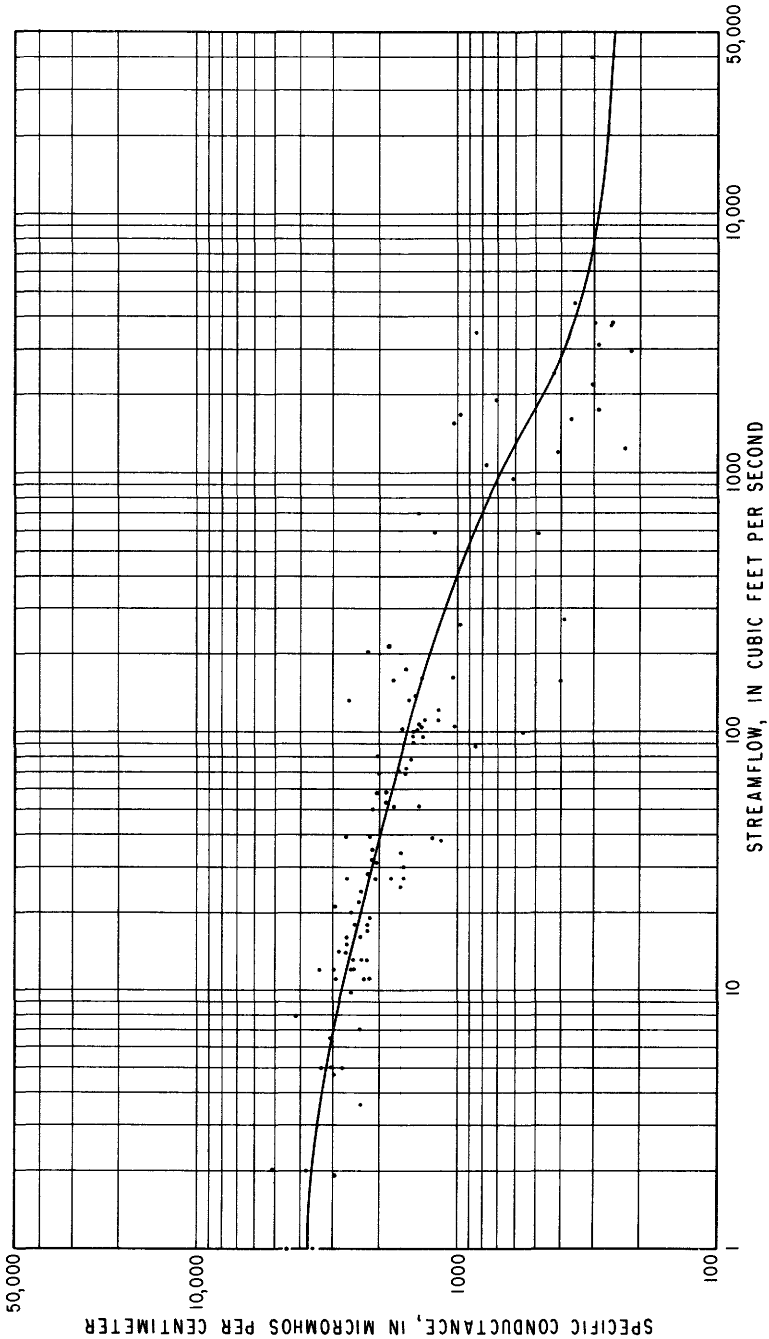

FIGURE 18.—Relation of specific conductance to streamflow, Grand River at Shadehill, S. Dak.

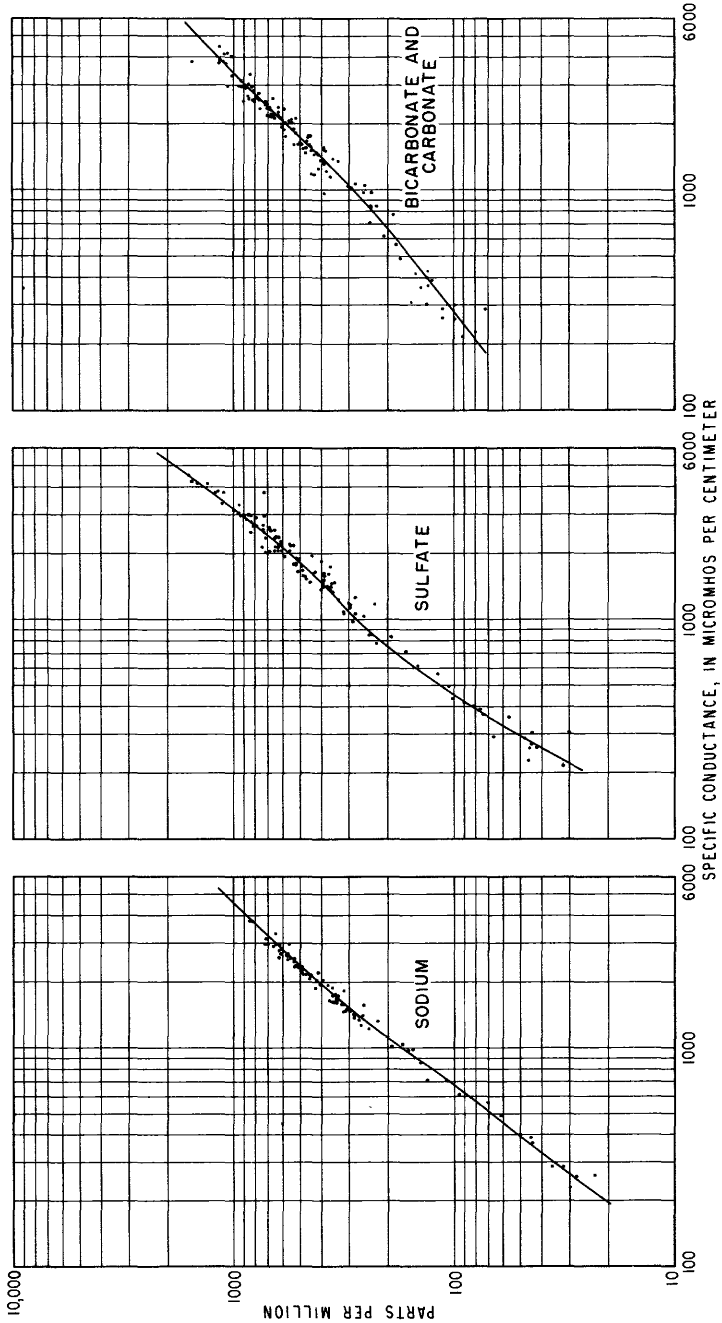

Figure 19.—Relation of concentrations of sodium, sulfate, and bicarbonate plus carbonate to specific conductance, Grand River at Shadehill, S. Dak.

for July 1945 to June 1950 that were computed compare favorably with weighted averages that were measured. (See table 7.)

TABLE 7.—*Chemical quality of Grand River at Shadehill*

Fiscal year	Mean streamflow (cfs)	Specific conductance (micromhos per cm)	Calcium plus magnesium as $CaCO_3$		Sodium (Na)		Bicarbonate plus carbonate as HCO_3		Sulfate (SO_4)		Percent sodium	Sodium-adsorption-ratio
			Ppm	Epm	Ppm	Epm	Ppm	Epm	Ppm	Epm		
Computed, July 1937 to June 1950 [Chemical-quality records are based on data collected after October 1946 and streamflow records; streamflows before March 1943 are based on streamflow measured at Wakpala]												
1938	65	1,430	122	2.4	281	12.2	420	6.9	403	8.4	84	11
1939	124	1,060	119	2.4	190	8.3	310	5.1	290	6.0	78	7.6
1940	44	1,570	133	2.7	313	13.6	457	7.5	442	9.2	83	12
1941	93	1,110	123	2.5	201	8.7	326	5.3	307	6.4	78	7.8
1942	98	1,300	122	2.4	245	10.7	377	6.2	361	7.5	82	9.8
1943	231	900	105	2.1	155	6.7	267	4.4	242	5.0	76	6.5
1944	411	560	86	1.7	85	3.7	176	2.9	132	2.7	69	4.0
1945	177	930	110	2.2	168	7.3	282	4.6	254	5.3	77	7.0
1946	31	1,880	156	3.1	387	16.8	546	8.9	529	11.0	84	13
1947	283	820	107	2.1	136	5.9	245	4.0	217	4.5	74	5.8
1948	105	1,270	126	2.5	240	10.4	371	6.1	350	7.3	81	9.3
1949	178	820	108	2.2	136	5.9	246	4.0	216	4.5	73	5.6
1950	542	440	78	1.6	63	2.7	146	2.4	97	2.0	63	3.0
1938–50	183	814	101	2.0	140	6.1	246	4.0	212	4.4	75	6.1
Measured, July 1945 to June 1950 [Chemical-quality data for July, August, and September 1945 estimated; October 1949 to June 1950 partially estimated]												
1946	31	1,760	108	2.2	375	16.3	520	8.5	491	10.2	88	16
1947	283	759	108	2.2	123	5.4	239	3.9	191	4.0	71	5.1
1948	105	1,290	136	2.7	255	11.1	383	6.3	361	7.5	80	9.6
1949	178	567	88	1.8	93	4.0	176	2.9	142	3.0	69	4.2
1950	542	448	78	1.6	64	2.8	145	2.4	99	2.1	64	3.1
1946–50	228	656	93	1.9	109	4.7	205	3.4	163	3.4	71	4.8

The weighted-average analysis indicates the chemical character of the water if all the water passing through a cross section in the stream during the year or period were impounded and mixed in a reservoir and if no water were lost by evaporation or were added by direct precipitation. Although table 7 indicates that the long-term average specific conductance of water in Shadehill Reservoir might be about 800 micromhos per centimeter, the concentration of dissolved solids in a reservoir would be likely to increase through evaporation and by the passage of dilute floodwater through the spillway before mixing with residual water. The concentration in the reservoir could be expected to increase through the years until a relatively stable concentration was reached, and this concentration would be higher than that indicated by a weighted-average concentration of the inflow. Data on the quality of water in Shadehill Reservoir for the water years 1951–60 indicate that the average specific conductance of the water in Shadehill Reservoir will probably be substantially greater than 800 micromhos per centimeter.

Data on the quality of water in Shadehill Reservoir indicate that the specific conductance ranges from about 1,400 to 1,500 micromhos per centimeter most of the time. (See fig. 16.) Between December 1955 and September 1960 the specific conductance at the spillway was usually not less than 1,200 micromhos per centimeter and did not exceed 1,630 micromhos per centimeter. Runoff during most of this period had been below normal; consequently, the dissolved-solids concentration of the water in the reservoir probably was above normal.

Data in table 7 were used to compute the quality of water in Shadehill Reservoir if the date of closure had been on July 1, 1937 (table 8). The period July 1, 1937, to June 30, 1950, is probably representative of a long-term period. The yearly inflows, residual water, and specific conductance were adjusted for evaporation, outflow through the service spillway, and releases through the irrigation spillway. An average factor of 1.83 feet net evaporation was applied to the surface area of the reservoir. This average factor was based on the long-term (1898–1945) net evaporation as calculated by the Corps of Engineers (written communication) for the Oahe Reservoir. Shadehill Reservoir releases for irrigation, when available, were estimated to be 29,100 acre-feet per year. For the period July 1937 to June 1950 the specific conductance of the reservoir water would have ranged from about 900 to 1,500 micromhos per centimeter after the reservoir was filled to a level that would be sufficient to meet demands for irrigation water. The weighted-average specific conductance of the reservoir water for the period would have been about 1,200 micromhos per centimeter, or the dissolved solids would have been about 840 ppm (fig. 20). The minimum and maximum for the period would have been 74 and 83 for percent sodium and 6.4 and 12 for sodium-adsorption-ratio, and the average would have been 77 percent and 7.7, respectively. The measured specific conductance, dissolved solids, percent sodium, and sodium-adsorption-ratio of water leaving the reservoir in July 1960, after several years of abnormally low flow, were 1,400 micromhos per centimeter, 955 ppm, 82 percent, and 11, respectively.

TABLE 8.—*Computed quality of water in Shadehill Reservoir, July 1937 to June 1950*

[July 1937 to June 1950 is considered to be representative of a long-term period. Chemical quality of inflow is based on data collected after October 1946 and streamflows; streamflows before March 1943 are based on streamflows measured at Wakpala]

Fiscal year	Inflow (acre-feet)	Specific conductance of inflow (micromhos per cm)	Reservoir releases	Estimated net evaporation	Reservoir contents	Specific conductance of reservoir water (micromhos per cm)	Percent sodium	Sodium-adsorption-ratio
			Acre-feet					
1938	23,700	1,430	0	3,100	20,600	1,640	83	12
1939	45,500	1,060	2,950	4,950	58,200	1,330	80	9.2
1940	16,100	1,570	10,430	5,670	58,200	1,530	81	10
1941	33,900	1,110	27,600	6,300	58,200	1,450	79	9.5
1942	35,800	1,300	29,100	6,480	58,420	1,520	80	10
1943	84,300	900	29,590	8,800	104,330	1,150	78	7.9
1944	150,000	560	112,100	8,800	133,430	930	75	6.4
1945	64,600	930	55,800	8,800	133,430	1,000	75	6.7
1946	11,300	1,880	31,600	8,800	104,330	1,170	76	7.7
1947	103,200	820	65,300	8,800	133,430	1,080	75	7.0
1948	38,400	1,270	29,600	8,800	133,430	1,210	77	7.9
1949	65,000	820	56,200	8,800	133,430	1,180	76	7.5
1950	197,800	440	189,000	8,800	133,430	1,050	74	6.6
1938–50	869,000	814	639,270	96,900	----------	1,170	77	7.7

DISSOLVED-SOLIDS DISCHARGE

The total dissolved-solids content of a stream is usually expressed in terms of concentration. Because most dissolved solids impart no color to the water, the large quantities carried by streams are not readily apparent. However, the transportation of material in solution is an important part of the overall degradation of the land surface. Actually, the dissolved-solids discharge of many streams exceeds the sediment discharge manyfold. The quantity of dissolved solids transported by a stream is proportional to the product of the concentration of the dissolved solids and the streamflow. Although a large river may have low concentrations of dissolved solids, the total dissolved-solids discharge is a very large quantity.

The dissolved-solids discharges at five locations in the basin (table 9 and fig. 21) were estimated from chemical-quality and streamflow records. The computation procedure is indicated by table 10. The quantity passing the station near Wakpala for the long-term representative period July 1937 to June 1950 was 140,000 tons per year. The yield from the basin as measured at the station near Wakpala was about 25 tons per square mile per year. For the stations at Haley, near White Butte, and near Cash for 1947–60 the computed annual yields were about 22, 28, and 25 tons per square mile, respectively. At Shadehill for 1944–49, the computed annual yield was about 28 tons per square mile.

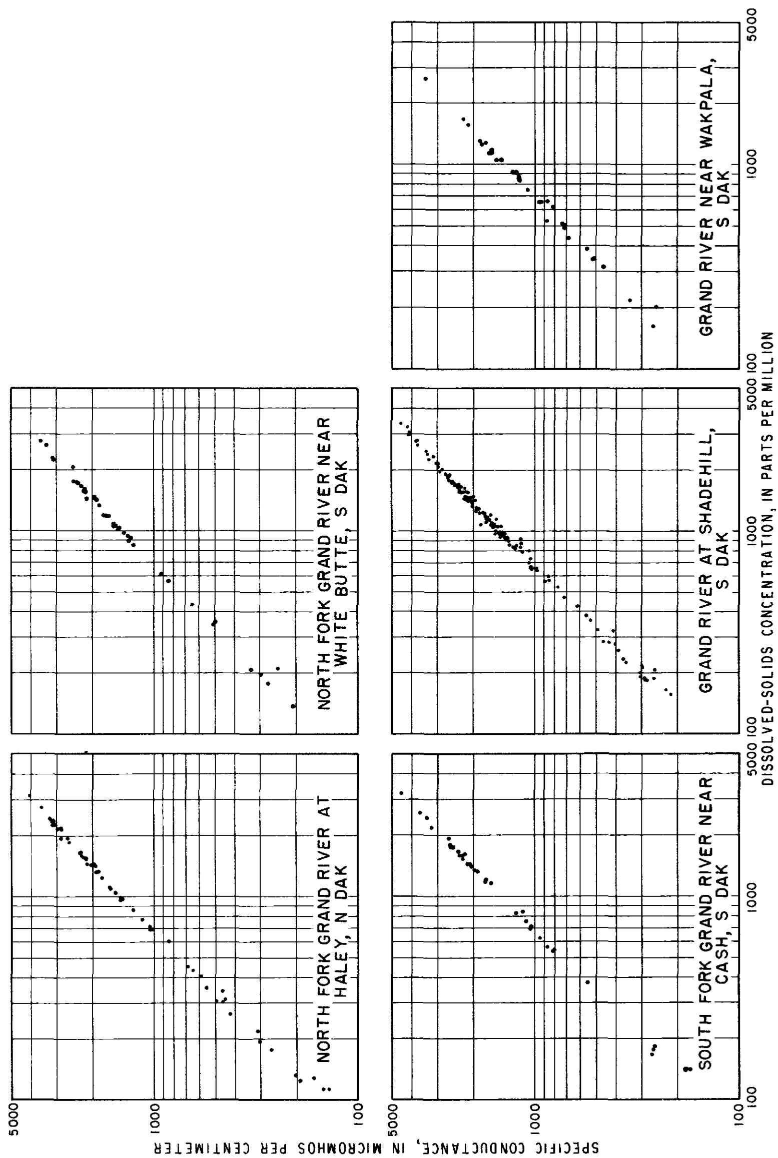

FIGURE 20.—Relation of specific conductance to dissolved-solids concentration.

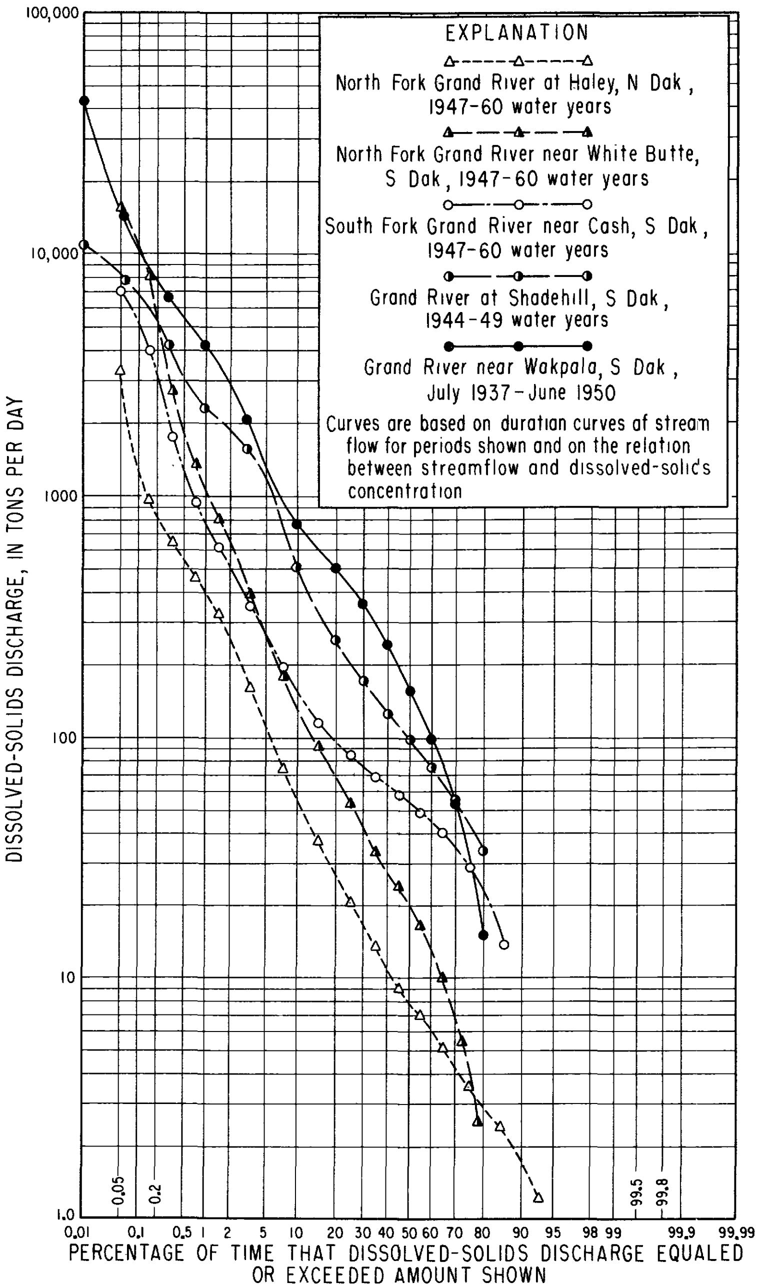

Figure 21.—Duration curves of dissolved-solids discharge of Grand River and North and South Forks.

TABLE 9.—*Summary of estimated dissolved-solids discharge for stations in the Grand River drainage basin*

[Estimated from duration curves of streamflow for periods shown and on the relation between streamflow and dissolved-solids concentration]

Station	Mean streamflow (cfs)	Dissolved-solids discharge		
		Tons per day	Tons per year	Tons per sq mi per year
North Fork Grand River at Haley, N. Dak., 1947–60 water years	37	30	11,000	22
North Fork Grand River near White Butte, S. Dak., 1947–60 water years	71	91	33,000	28
South Fork Grand River near Cash, S. Dak., 1947–60 water years	64	93	3[illegible],000	25
Grand River at Shadehill, S. Dak., 1944–49 water years	175	238	87,000	28
Grand River near Wakpala, S. Dak., July 1937–June 1950	400	384	140,000	25

TABLE 10.—*Estimated dissolved-solids discharge of Grand River at Shadehill, S. Dak., 1944–49 water years*

[Estimated from duration curve of streamflow for period and on the relation between streamflow and dissolved-solids concentration]

Time limits	Time interval	Mean of interval	Streamflow	Increment of mean streamflow	Dissolved solids		
					Concentration (ppm)	Discharge	Increment of mean discharge
Percent			Cubic feet per second			Tons per day	
0.00–0.02	0.02	0.01	24,000	4.8	168	10,886	2.18
.02–.1	.08	.06	17,000	13.6	170	7,803	6.24
.1–.5	.4	.3	8,600	34.4	182	4,226	16.9
.5–1.5	1.0	1.0	3,300	33	262	2,334	23.3
1.5–5.0	3.5	3.25	1,200	42	490	1,588	55.6
5–15	10	10	230	23	830	515	51.5
15–25	10	20	96	9.6	1,000	259	25.9
25–35	10	30	56	5.6	1,160	175	17.5
35–45	10	40	36	3.6	1,310	127	12.7
45–55	10	50	25	2.5	1,480	99.9	9.99
55–65	10	60	17	1.7	1,650	75.7	7.57
65–75	10	70	11	1.1	1,860	55.2	5.52
75–85	10	80	5.7	.6	2,200	33.9	3.39

Mean streamflow	cfs	175
Dissolved-solids concentration (Computed from dissolved-solids discharge and streamflow)	ppm	504
Dissolved-solids discharge	tons per day	238
	tons per year	87,000
	tons for period	522,000
	tons per sq mi per year	28

The dissolved-solids discharges in tons per square mile per year given in table 9 are fairly uniform because they are for cumulative drainage areas; however, the discharges for small areas are not so uniform. For example, the annual yield was 22 tons per square mile from the area upstream from Haley but was 32 tons per square mile between Haley and the White Butte station. Differences in yields are caused by a combination of factors—principally, differences in slope, geology, and proportion of the ground-water inflow to total surface-water outflow. The North Fork upstream from Haley has a slope of 11 feet per mile, and most of the intervening reach between Haley and the White Butte station has a slope of about 5.5 feet per mile. (See pl. 2.) The Hell Creek Formation and the Ludlow, Cannonball, and Tongue River Members of the Fort Union Formation underlie about 17, 54, less than 1, and 29 percent, respectively, of the drainage area upstream from Haley. These same formations underlie less than 1, 8, 17, and 75 percent, respectively, of the intervening area between Haley and the White Butte station. (See pl. 3.)

WATER QUALITY AND USE

Water is unquestionably one of the most widely used resources of our land. The adjectives good and bad are often used to describe waters; however, whether a water is good or bad depends on how the water is to be used. For example, a high-sodium water may be bad for irrigation use but good for domestic use.

DOMESTIC USE

Concentrations of iron, chloride, and fluoride in the surface waters of the Grand River basin are well below the maximum concentrations recommended by the U.S. Department of Health, Education, and Welfare (1962). The limits in the following table have been recommended for all public water supplies as well as for water supplies used by interstate carriers subject to U.S. Public Health Service regulations:

Constituent	*Maximum concentration (ppm)*
Iron	0.3
Manganese	.05
Sulfate	250
Chloride	250
Fluoride	[1] 1.5
Dissolved solids	500

[1] Based on temperature records for Lemmon, S. Dak.

Sulfate and dissolved solids in most of the streams exceed the maximum except during high flows. Impoundments, which would be required for a dependable supply of water, would improve the sulfate composition of the water for most of the year by diluting the water of high concentration. For example, in the 1952 water year the water of the North Fork Grand River at Haley contained as much as 1,490 ppm of sulfate for a streamflow of 3 cfs but only 18 ppm for a streamflow of 11,080 cfs. The weighted-average concentration of sulfate for the water year was 49 ppm.

Shadehill Reservoir has been proposed as a source of public water supply for Lemmon, S. Dak. Concentrations of sulfate and dissolved solids exceed the limits recommended; usually sulfate is present in concentrations of 350 to 450 ppm, and dissolved-solids concentration is about 900 to 1,000 ppm.

A comparison of the classification of hardness in the following table and chemical analyses of the surface water shows that most of the water in the Grand River basin is hard or very hard.

Hardness (ppm)	*Rating*	*Usability*
0–60	Soft	Suitable for many uses without further softening.
61–120	Moderately hard	Usable except in some industrial applications. Softening profitable for laundries.
121–180	Hard	Softening required by laundries and some other industries.
181+	Very hard	Softening desirable for most purposes.

INDUSTRY

The mineral constituents in water and the properties and characteristics of water determine if the water is suitable for industrial use. Water-quality tolerances for some industrial applications are given in table 11. In the Grand River basin any large quantity of water for processing would require impoundment, such as in the Shadehill Reservoir. Comparison of the chemical analyses of the Grand River near Shadehill (table 4) with the data in table 11 will indicate the possible industrial application of the water.

The turbidity of water is due to suspended inorganic and organic material. Because the turbidity of the water in Shadehill Reservoir is usually low, it would not adversely affect the use of the water for industry.

The dissolved solids and hardness of most of the surface waters of the Grand River basin prevent the use of these waters for most industrial purposes unless the quality is first improved by treatment.

IRRIGATION

The successful use of water for irrigation depends on many factors, such as: texture, structure, and internal drainage of the soil and subsoil; management of the soil or farming practices; crops; climate; and the chemical quality of the water. High concentrations of total dissolved solids in the water may drastically reduce crop yields by decreasing the ability of plants to take water and essential plant nutrients from the soil solution and by adversely affecting the soil structure. The importance of individual ions depends on their effect on the structure of the soil, their physiological effect on the plants, and their combination with other ions after the water is applied to the land.

TABLE 11.—*Water-quality tolerances for industrial use*

[Adapted from American Water Works Association, 1950. Symbols: A, No corrosiveness; B, No slime formation; C, Conformance to Federal drinking water standards necessary; D, NaCl=275 ppm. Limits in parts per million except as indicated]

Industry	Turbidity	Color	Color + O_2 consumed	Dissolved oxygen (ml/l)	Odor	Hardness	Alkalinity (as $CaCO_3$)	pH	Total solids	Ca	Fe	Mn	Fe+Mn	Al_2O_3	SiO_2	Cu	F	CO_3	HCO_3	OH	$CaSO_4$	Na_2SO_4 to Na_2SO_3 ratio	General
Air conditioning [1]											0.5	0.5	0.5										A, B
Baking	10	10				(2)					.2	.2	.2										C
Boiler feed:																							
0–150 psi	20	80	100	2		75		8.0+	3,000–1,000					5	40			200	50	50		1 to 1	
150–250 psi	10	40	50	.2		40		8.5+	2,500–500					.5	20			100	30	40		2 to 1	
250 psi and up	5	5	10	0		8		9.0+	1,500–100					.05	5			40	5	30		3 to 1	
Brewing: [3]																							
Light	10				Low		75	6.5–7.0	500	100–200	.1	.1	.1				1				100–200		C, D
Dark	10				Low		150	≧7.0	1,000	200–500	.1	.1	.1				1				200–500		C, D
Canning:																							
Legumes	10				Low	25–75					.2	.2	.2										C
General	10				Low						.2	.2	.2				1						C
Carbonated beverages [4]	2	10	10		0	250	50		850		.2	.2	.3				.2						C
Confectionary					Low			(5)	100		.2	.2	.2										
Cooling [6]	50					50					.5	.5	.5										A, B
Food, general	10				Low						.2	.2	.2										C
Ice (raw water) [7]	1–5	5					30–50		300		.2	.2	.2		10								C
Laundering						50					.2	.2	.2										
Plastics, clear, uncolored	2	2							200		.02	.02	.02										
Paper and pulp: [8]																							
Groundwood	50	20				180					1.0	.5	1.0										A
Kraft pulp	25	15				100			300		.2	.1	.2										
Soda and sulfite	15	10				100			200		.1	.05	.1										
Light paper, HL-Grade	5	5				50			200		.1	.05	.1										B
Rayon (viscose) pulp:																							
Production	5	5				8	50		100		.05	.03	.05	<8.0	<25	<5							
Manufacture	.3					55		7.8–8.3			.0	.0	.0										
Tanning [9]	20	10–100				50–135	135	8.0			.2	.2	.2										
Textiles:																							
General	5	20				20					.25	.25											
Dyeing [10]	5	5–20				20					.25	.25	.25										
Wool scouring [11]		70				20					1.0	1.0	1.0										
Cotton bandage [11]	5	5			Low	20					.2	.2	.2										

[1] Waters with algae and hydrogen sulfide odors are most unsuitable for air conditioning.

[2] Some hardness desirable.

[3] Water for distilling must meet the same general requirements as for brewing (gin and spirits mashing water of light-beer quality; whiskey mashing water of dark-beer quality).

[4] Clear, odorless, sterile water for syrup and carbonization. Water consistent in character. Most high quality filtered municipal water not satisfactory for beverages.

[5] Hard candy requires pH of 7.0 or greater, as low value favors inversion of sucrose, causing sticky product.

[6] Control of corrosiveness is necessary as is also control of organisms, such as sulfur and iron bacteria, which tend to form slimes.

[7] $Ca(HCO_3)_2$ particularly troublesome. $Mg(HCO_3)_2$ tends to greenish color. CO_2 assists to prevent cracking. Sulfates and chlorides of Ca, Mg, Na should each be less than 300 ppm (white butts).

[8] Uniformity of composition and temperature desirable. Iron objectionable as cellulose absorbs iron from dilute solutions. Manganese very objectionable, clogs pipelines and is oxidized to permanganates by chlorine, causing reddish color.

[9] Excessive iron, manganese or turbidity creates spots and discoloration in tanning of hides and leather goods.

[10] Constant composition; residual alumina 0.5 ppm.

[11] Calcium, magnesium, iron, manganese, suspended matter, and soluble organic matter may be objectionable.

The sodium ion and its relation to other ions is generally of most concern. The U.S. Salinity Laboratory Staff (1954) has made extensive studies of the sodium problem and has set up criteria for predicting the suitability of the water for irrigation on various soils and various types of crops. The Salinity Laboratory Staff also introduced the sodium-adsorption-ratio (SAR) as a measure of the sodium or alkali hazard of water used for irrigation and prepared a diagram for classifying water with respect to salinity hazard and sodium hazard on the basis of specific conductance and SAR. The criteria and classification system of the Salinity Laboratory are used in the following discussion.

The surface waters throughout the Grand River basin are similar in quality; therefore, the water of Shadehill probably is typical and representative of water that might be impounded anywhere in the basin. The annual weighted averages of conductance and SAR for several years for the water of Shadehill Reservoir are shown on figure 22. The location of the points on the diagram indicates that the water has a high-salinity hazard and a medium- to high-sodium hazard. According to the U.S. Salinity Laboratory criteria, water having a high-salinity hazard should be used only on well-drained soils and on crops having a good salt tolerance. Even under these conditions, special management for salinity control may be required. Water having a medium-sodium hazard is generally satisfactory for use on coarse-textured soils, but it may be troublesome or fine-textured soils unless gypsum is present in the soils or is added to the water or the soil.

Original plans by the Bureau of Reclamation (written communication) for development of irrigation in the Grand River basin were for irrigation of about 23,700 acres of land in the main stream valley in Perkins and Corson Counties, S. Dak., which included land in the Standing Rock Indian Reservation. Although 66,000 acres of land in the basin can be classified as irrigable, the water from the surface supply would be sufficient for the development of only about 24,000 acres. Shadehill Reservoir, which was completed in 1950, and Blue Horse Reservoir, which was to be constructed downstream from Shadehill, were to supply the water to the irrigable land. About 9,900 acres, mostly on the north side of the river between the two reservoirs, were to be irrigated.

Early in the planning for the Shadehill unit of the Grand Division, the Bureau of Reclamation recognized that the water to be stored in Shadehill Reservoir could cause problems when used for irrigation; J. T. Maletic and W. H. Yarger (Bureau of Reclamation, written communication) summarized the basic problem as follows:

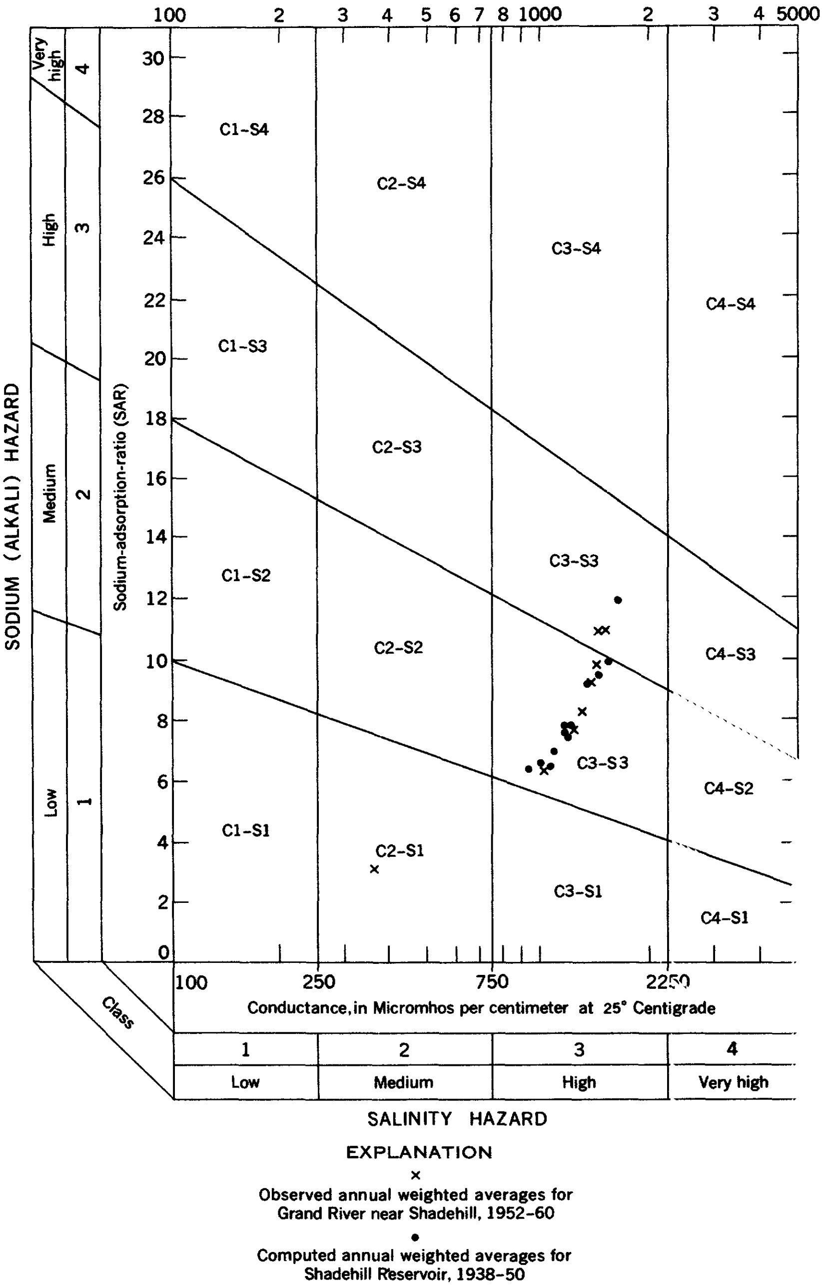

FIGURE 22.—Classification of water from Shadehill Reservoir for irrigation use (diagram from U.S. Salinity Laboratory Staff, 1954).

Irrigation with the poor quality of water available from the Shadehill Reservoir may result in excessive deterioration of soil structure caused by an increase in the ESP level of the soils. This increase will be related to: (1) SAR [sodium-adsorption-ratio], RSC [residual sodium carbonate], and concentration of the irrigation water, (2) reactions in the soil that tend to solubilize calcium, (3) cropping practices including use of fertilizers, organic matter and chemical amendments, (4) irrigation practices including amount of leaching, and (5) climatic influences such as rainfall and frost action.

In 1952 the Shadehill Development Farm was established to attain the threefold objective (Bureau of Reclamation, written communication):

To determine the effect of the application of low-quality irrigation water from Shadehill Reservoir upon the accumulation of salts and alkali in the soils of the Shadehill Unit and upon crop production.

To determine the effect of leaching and chemical amendments upon the movement of water into and through the root zone, and upon the removal of exchangeable sodium and soluble salts.

To compare irrigated and dryland crop production.

Data from the Development Farm for 1952–59 show that the sodium-adsorption-ratio and residual sodium carbonate of the irrigation water ranged from 3.5 to 12 and 1.0 to 6, respectively. Although water was best for irrigation during the first 2 years of operation, the exchangeable-sodium percentage in the soils increased as the result of the use of the water. At the end of the 1958 irrigation season, the upper 12 inches of the soils in the plots that were not treated with gypsum had an exchangeable-sodium percentage of about 10. The increase of exchangeable sodium in the soils of the Development Farm is shown in table 12. The values for exchangeable sodium in table 12 can be changed to approximate exchangeable-sodium percentage by dividing by 20 (the soils in the Shadehill Project have exchange capacities between 20 and 24) and multiplying by 100. The highest exchangeable-sodium percentage (12.8 percent) was in 1959 in the 6- to 12-inch soil zone of the plot for frequent irrigation at field capacity. The sodium in the upper 18 inches was still increasing in the later years but at a slower rate than in the earlier years.

In December 1959, representatives of the Bureau of Reclamation (written communication), the State Agricultural Experiment Station, and the Agricultural Research Service reviewed the water-quality data and the data from the Development Farm and concluded that water from Shadehill Reservoir could be used safely for sustained irrigation on the coarser textured and well-drained soils of the irrigation unit if irrigation practices were carefully controlled and if provision was made for periodic addition of gypsum.

TABLE 12.—*Annual summary of exchangeable sodium content (milliequivalents per 100 grams) by increments of depth*

[From Bur. Reclamation, written communication. 1958 was the last year of scheduled irrigation treatments]

Depth (inches)	1952	1953	1954	1955	1956	1957	1958	1959
No irrigation								
0-6	0.19	0.32	0.21	0.21	----------	----------	----------	----------
6-12	.21	.31	.21	.29	----------	----------	----------	----------
12-18	.21	.19	.16	.17	----------	----------	----------	----------
18-24	.22	.19	.13	.18	----------	----------	----------	----------
24-30	.24	.16	.13	.16	----------	----------	----------	----------
30-36	.24	.18	.12	.15	----------	----------	----------	----------
Optimum irrigation								
0-6	0.16	0.63	1.59	1.77	1.70	1.60	1.79	2.11
6-12	.19	.45	1.27	1.95	1.97	2.06	2.23	2.49
12-18	.20	2.6	.87	1.49	1.69	1.65	1.92	2.14
18-24	.24	.17	.53	1.09	1.23	1.52	1.77	1.80
24-30	.23	.18	.31	.75	.93	1.18	1.35	1.56
30-36	.23	.16	.27	.50	.57	.86	.95	1.20
Optimum irrigation with gypsum								
0-6	0.15	0.75	1.37	1.30	1.40	1.12	1.29	1.70
6-12	.15	.48	1.19	1.59	1.72	1.55	1.67	1.94
12-18	.17	.32	.76	1.20	1.49	1.36	1.62	1.83
18-24	.20	.22	.41	.99	1.09	1.32	1.43	1.69
24-30	.22	.18	.26	.63	.69	1.09	1.14	1.30
30-36	.23	.16	.22	.44	.48	.87	.82	1.01
Frequent irrigation at field capacity								
0-6	0.19	0.63	1.51	1.85	1.90	1.71	1.86	2.20
6-12	.20	.40	1.20	1.85	2.16	1.93	2.22	2.57
12-18	.27	.26	.88	1.37	1.72	1.71	1.83	2.21
18-24	.23	.17	.58	.99	1.25	1.46	1.47	1.77
24-30	.24	.15	.39	.68	.84	1.25	1.09	1.32
30-36	.24	.20	.29	.61	.54	.83	.84	1.31

FLUVIAL SEDIMENT

COLLECTION OF DATA

Sediment data for streams in the Grand River basin include daily determinations of suspended-sediment discharge, periodic determinations of sediment discharge, and particle-size analyses of suspended sediment and bed material. The data were obtained for one daily station (Grand River at Shadehill, from March 1946 to June 1950) and from three periodic stations (North Fork Grand River near White Butte, S. Dak., and South Fork Grand River near Cash, S. Dak., from May 1946 to September 1951 and North Fork Grand River at Haley, N. Dak., from December 1950 to July 1952). Fairly accurate estimates were made of the yearly sediment discharges at Haley and near White Butte for 1947–60 and near Cash for 1947–50.

Particle-size analyses were made of many of the suspended-sediment samples and were used in computing the initial specific weight of a deposit of the sediment. A few samples of bed material were collected and analyzed. Depth-integrated suspended-sediment samples were obtained with U.S. D-43 and U.S. DH-48 samplers except on very cold days when a Colorado River bucket sampler was used; low temperatures do not permit use of a sampler having a nozzle.

A local resident collected samples each day at a single vertical on the Grand River at Shadehill and obtained additional samples on some days of rapidly changing concentration and discharge. Personnel of the U.S. Geological Survey made periodic determinations of sediment discharge on the Grand River and on the two forks by collecting samples at several representative verticals in the stream cross section. These samples were collected biweekly during normal flow and more frequently during high flow.

COMPUTATION OF SEDIMENT DISCHARGE

The discharge of suspended sediment was computed by multiplying the suspended-sediment concentration by the streamflow and by a constant to convert to tons per day. The concentration in parts per million by weight was determined in the laboratory by filtration or evaporation of the samples. The streamflow was measured with a current meter or was determined from the relationship of gage height to streamflow. Because concentrations at a single vertical at Shadehill may not have been representative of the concentration of the entire stream cross section, they were adjusted on the basis of periodic samples collected at several verticals.

For the North Fork Grand River at Haley and near White Butte, periodic sediment discharges plotted against streamflow showed a fairly good relationship (fig. 23). This relationship was used to estimate the sediment discharge for the periods of no sediment record during 1947–60. Both this relationship and the sediment discharges determined from periodic sampling were used to estimate the sediment discharge for days of no samples during the periods of sediment record. Frequent sampling during high flow contributed to the accuracy of the estimates of yearly sediment discharge during the periods of sediment record.

For the South Fork Grand River near Cash, sediment discharges plotted against streamflow resulted in a graph having considerable scatter. This graph obviously would not give reliable estimates of the sediment discharges even with adjustments based on periodic sampling; therefore, the records of streamflow and sediment discharge for the North Fork, South Fork, and main stem were studied together. Many times a rise occurred on the South Fork and main stem but not on the North Fork; during these times the relation of sediment discharge to streamflow for the South Fork would be simi-

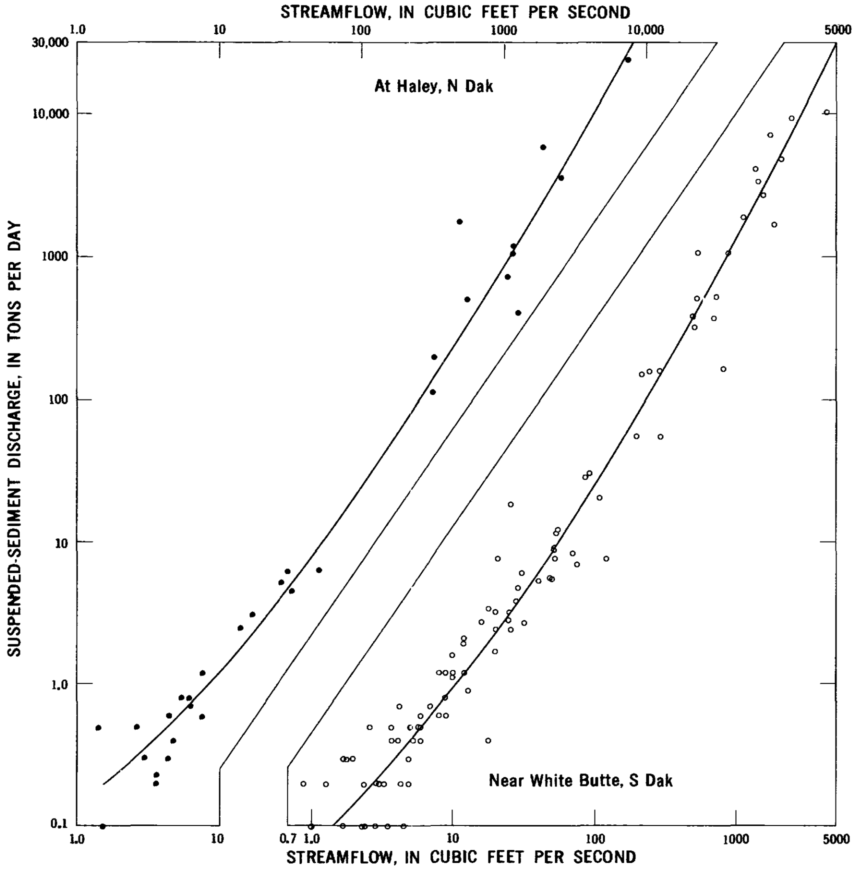

FIGURE 23.—Relation of suspended-sediment discharge to streamflow, North Fork Grand River at Haley and near White Butte.

lar to that for the main stem because the South Fork was contributing most of the sediment load to the main stem. Figure 24 shows the relation between sediment discharge and streamflow for selected rises on the Grand River at Shadehill and for a rise on the South Fork when several samples were collected. The graph shows a hysteretic effect; the sediment discharges in relation to the streamflow are greater after the peak of the rise than before the peak. This hysteretic effect was used in estimating the sediment discharges for many of the rises on the South Fork. The estimates seem to be reasonable because the sum of the sediment discharges of the North Fork and the South Fork for each month is in about the same proportion to the sediment discharge at Shadehill as the sum of the drainage areas is to the drainage area for Shadehill.

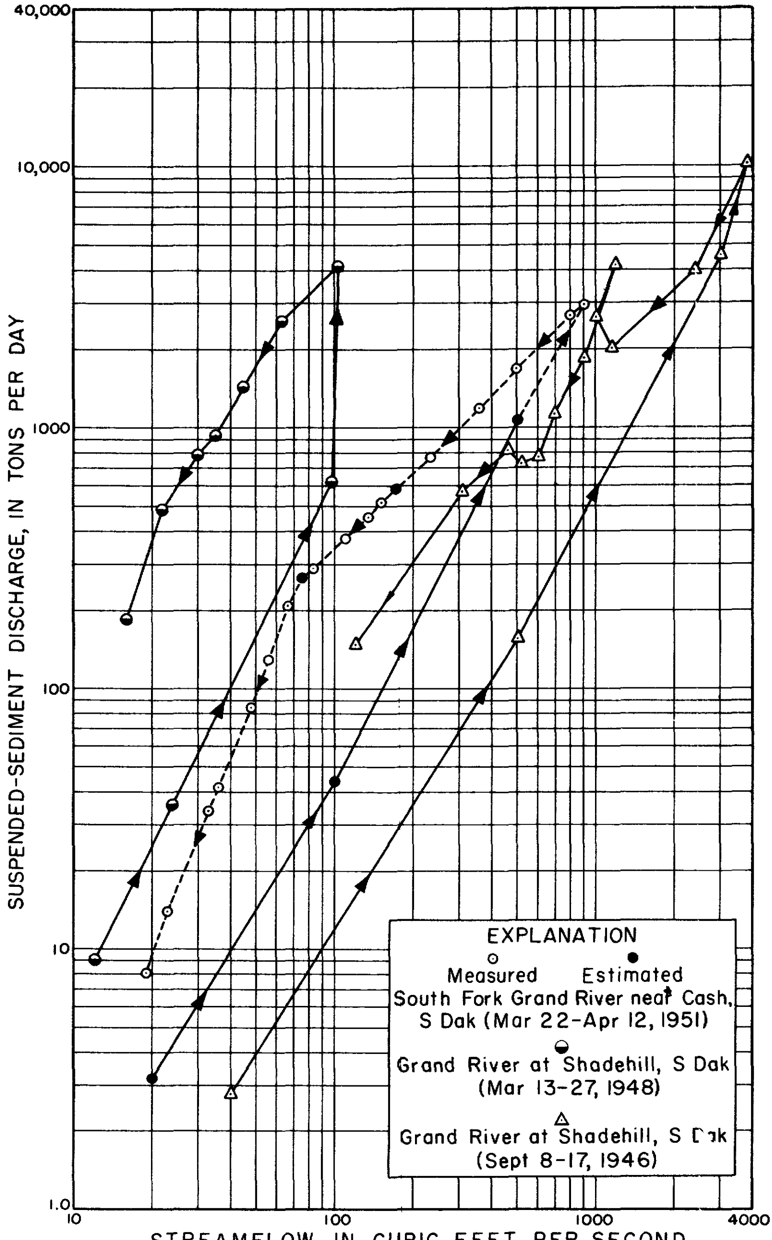

Figure 24.—Change of the relation between sediment discharge and streamflow with time.

SUSPENDED-SEDIMENT DISCHARGE

Because yearly sediment discharges are even more variable than yearly streamflow, a very long period of record would normally be required for an accurate determination of the average sediment discharge. The extreme variability of yearly sediment discharges is shown in figure 25, which also shows that sediment discharge can be very low for several years in succession. Successive years of low sediment discharge increase the length of record necessary for an accurate determination of the long-term average.

For the periods for which the sediment discharge near Cash was estimated and for which the sediment discharge at Shadehill was measured, the mean sediment discharge was undoubtedly much greater than normal because the water discharge was much greater than normal. For the period 1947–60, the mean water discharges at Haley and near White Butte were probably reasonably close to normal; therefore, the mean sediment discharge probably is fairly close to normal.

Estimated suspended-sediment discharges at Haley, near White Butte, and near Cash, and measured suspended-sediment discharges at Shadehill are summarized in the following table:

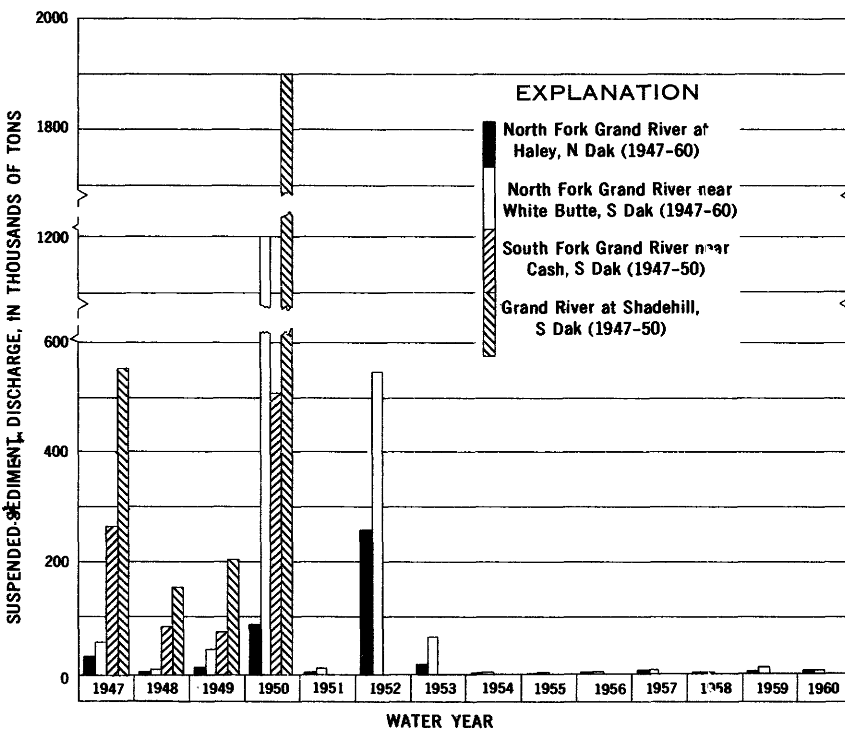

FIGURE 25.—Variability of yearly suspended-sediment discharges.

Mean and extreme suspended-sediment discharges

Location	Water years or period	Suspended-sediment discharge				
		Mean (tons per year)	Minimum		Maximum	
			Tons	Year	Tons	Year
North Fork at Haley	1947–60	31,000	130	1955	230,000	1952
North Fork near White Butte	1947–60	140,000	180	1955	1,200,000	1950
South Fork near Cash	1947–50	270,000	78,000	1949	510,000	1950
Grand River at Shadehill	Mar. 9, 1946–June 30, 1950.	700,000	160,000	1948	[1] 1,900,000	1950

[1] Oct. 1, 1949, to June 30, 1950. Equivalent to sediment discharge for entire water year.

For some uses, relatively small amounts of water are pumped or diverted from a stream at a fairly uniform rate. For such uses of the water, a knowledge of the frequency distribution of suspended-sediment concentration is desirable. Information for directly determining frequency distributions of concentration is not available except at Shadehill before closure of the dam, where such information would no longer be useful. However, frequency distributions of concentration have been determined indirectly for North Fork Grand River at Haley and near White Butte and for South Fork Grand River near Cash (fig. 26).

For the stations at Haley and near White Butte, the curves in figure 26 were derived from the relation of concentration to streamflow and from the streamflow-duration curves. Because the average relation of concentration to streamflow was used, the curves do not show the extremely low concentrations that occurred a small fraction of the time.

For the station near Cash, a concentration for each day during 1947–50 was computed from the streamflow and the estimated sediment discharge. Because 1947–50 was a period of unusually high flow, the concentrations for this station shown in figure 26 are much higher than normal.

The lower parts of the curves for all three stations may be somewhat inaccurate because of the unreliability of concentration data during periods of very low flow. Suspended-sediment concentration is not necessarily zero when flow stops. Each curve was extended, however, to a point representing the probable concentration when flow stopped or started and the percentage of time of flow in each stream.

PARTICLE SIZE

Samples of suspended sediment were analyzed with sieve, pipet, or bottom-withdrawal tube. They were analyzed in distilled water, with or without dispersing agents, or in the native water. Particle-

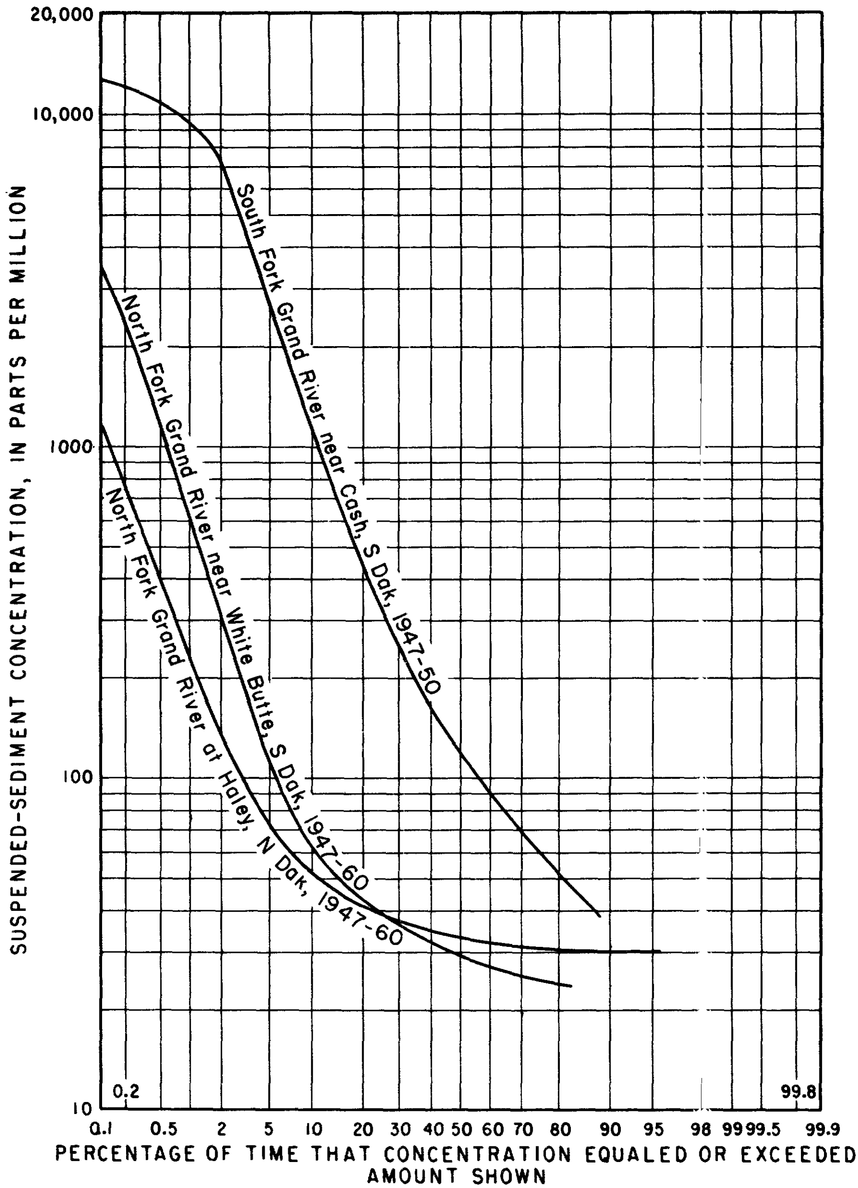

FIGURE 26.—Duration curves of suspended-sediment concentration, North and South Forks Grand River.

size distributions of samples that were analyzed in native water were coarser than those of duplicate samples analyzed in distilled water because some small particles flocculated in the native water. A small amount also flocculated when distilled water without a chemical dispersing agent was used as the settling medium. Because of the flocculation, only samples analyzed in distilled water with chemical dispersing agent were used for computing the average particle-size distributions in figure 27.

The curves of finest and coarsest particle-size distributions in figure 27 show that the particle size at any location on the Grand River is extremely variable. The average curves of figure 27 represent only the arithmetic averages of the analyses; they do not necessarily represent the particle-size distributions that occur most of the time nor the distributions that an accumulation of several years of sediment discharge would have if deposited in one place, as in a reservoir. The main reason for qualifying the average curves is that they represent generally higher-than-average discharges. Also, the curve for Grand River at Shadehill is based on data only from the high-flow period of March to May 1950.

In the average particle-size distributions, clay predominates; some silt and a little sand are present. The average of 26-percent sand for the Grand River at Shadehill probably is much higher than the normal.

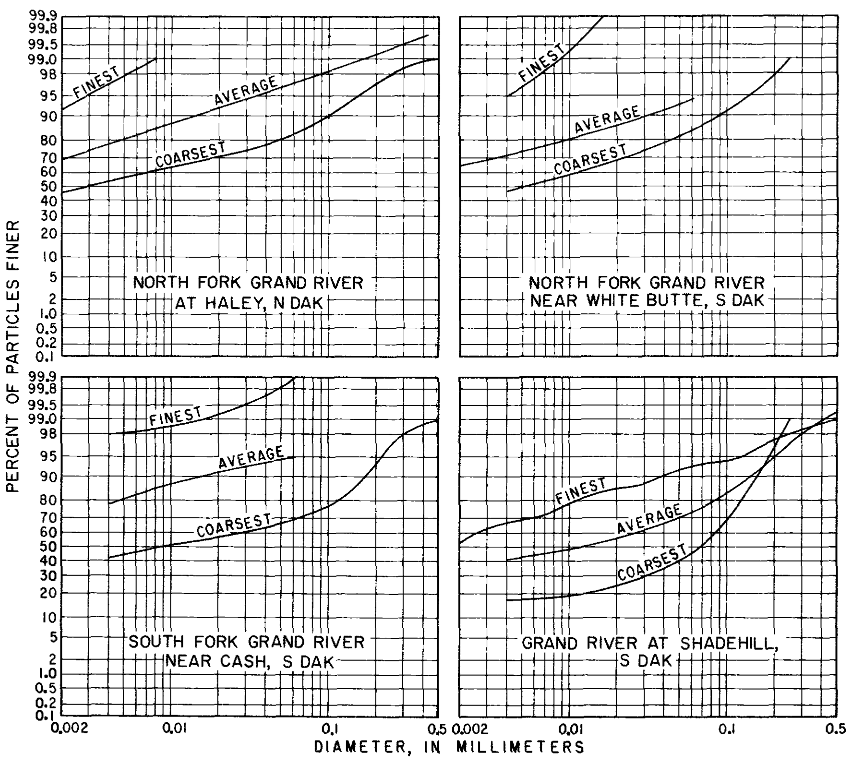

FIGURE 27.—Average, finest, and coarsest particle-size distributions of samples analyzed in distilled water with chemical dispersing agent.

SPECIFIC WEIGHT OF SEDIMENT DEPOSITS

One of the principal uses of sediment data is to estimate rates of depletion of reservoir capacity by sediment deposition. Such estimates require a knowledge of the probable location and specific weight of the sediment deposits. The location of sediment deposits depends on the elevation of water surface in the reservoir, sedimentation diameters of particles in transport, mineral constituents in solution, and effects of density currents. The specific weight of sediment deposits depends on the type of material deposited, particle-size distribution, and amount of consolidation.

The particle-size distribution is the factor that has the most influence on the specific weight of a sediment deposit; it has been determined from the sediment records (fig. 27). The relation between the median particle diameter and the specific weight of sediment deposits in a large number of reservoirs in several drainage basins (Hembree and others, 1952) is shown in figure 28. Because the data given in figure 28 are for samples that were collected near the surface of submerged sediment deposits, the specific weights are representative of natural deposits that have been formed probably within a few years of the sampling time and that have not been compacted materially by overlying deposits.

Table 13 shows the computation of the specific weight of a loosely compacted deposit that might be formed from the suspended sediment transported by the Grand River at Shadehill during the period of record. The median size of each sample that was analyzed in a dispersed state was plotted against the instantaneous suspended-sediment discharge, and an average curve was drawn. For predetermined class intervals of suspended-sediment discharge, the corresponding median particle sizes were taken from the curve. The specific weights for the median particle sizes were determined from figure 28. The specific weight was found to be 56 pounds per cubic foot.

TABLE 13.—*Specific weight based on median particle size for the Grand River at Shadehill, March 9, 1946, to June 30, 1950*

[Specific weight in lb per cu ft$=\frac{3,022,600}{54,382}=56$]

Suspended-sediment discharge			Median particle size (mm)	Specific weight (lb per cu ft)	Total tons divided by specific weight
Class interval (tons per day)	Middle of class interval	Total tons			
0-8,000	4,000	518,700	0.0060	53	9,787
8,000-50,000	29,000	728,000	.0073	55	13,236
50,000-300,000	175,000	649,900	.0088	56	11,605
300,000-800,000	550,000	1,126,000	.0100	57	19,754
Total		3,022,600			54,382

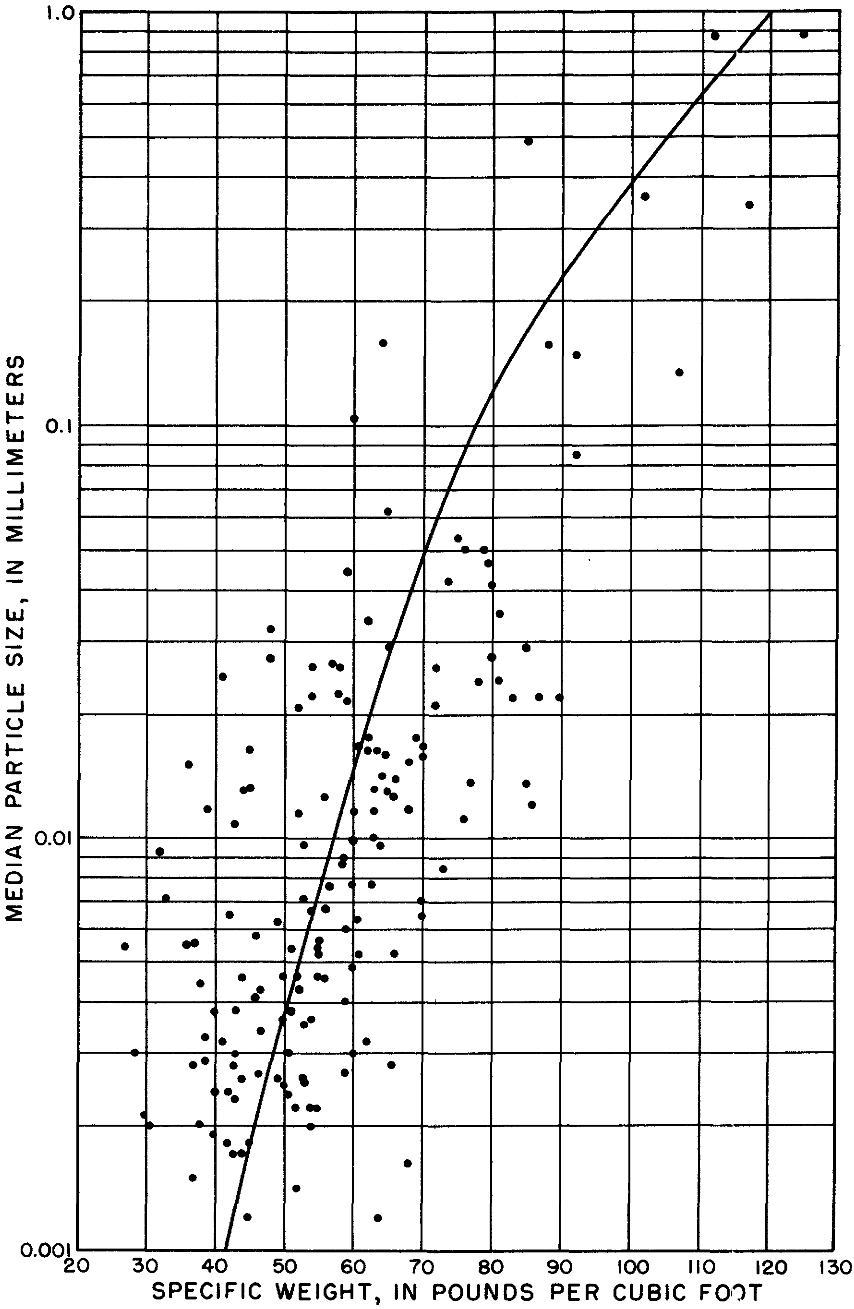

FIGURE 28.—Relation of specific weight of sediments deposited in reservoirs to median particle size.

This specific weight was used to convert the weight of sediment in tons for Grand River at Shadehill to the volumes of deposit given in the following table.

Period	*Suspended-sediment discharge (tons)*	*Volume of deposited sediment (acre-feet)*
Mar. 9 to Sept. 30, 1946	150, 000	120
Water year 1946–47	560, 000	460
Water year 1947–48	160, 000	130
Water year 1948–49	210, 000	170
Oct. 1, 1949, to June 30, 1950	1, 900, 000	1, 600
Total (rounded)	3, 000, 000	2, 500

The computed volume, 2,500 acre-feet, indicates the probable maximum space that would be occupied by the suspended sediment discharged by the Grand River at Shadehill from March 9, 1946, to June 30, 1950, after deposition in a reservoir.

For the North Fork Grand River at Haley and near White Butte and for the South Fork Grand River near Cash, the median particle diameters in the average particle-size distributions were all less than 0.002 mm. The median diameters for individual analyses were all less than 0.005 mm for the two stations on the North Fork and less than 0.01 mm for the South Fork near Cash. From this particle-size information, a specific weight of 42 pounds per cubic foot was estimated for loosely compacted deposits of the suspended sediment transported by the North Fork Grand River at Haley and near White Butte and by the South Fork Grand River near Cash.

BED MATERIAL

The small amount of data available on the particle-size distribution of bed material (table 14) indicates that the bed of the South Fork generally has coarser material than the bed of the main stem. (The data are for times of low streamflow or no streamflow.) The median size for the South Fork was about 2 mm, whereas the median size for all three locations on the main stem was about 0.20 to 0.25 mm.

For the Grand River near Wakpala, bed-material samples were obtained several years before and after closure of Shadehill Dam. Analyses of these samples (see fig. 29) show that if the dam has had any effect on the bed material near Wakpala, the effect has been very small. The small difference between the particle-size distributions could be due entirely to the fact that the samples in 1931 were obtained about 13 miles downstream from the 1960 location.

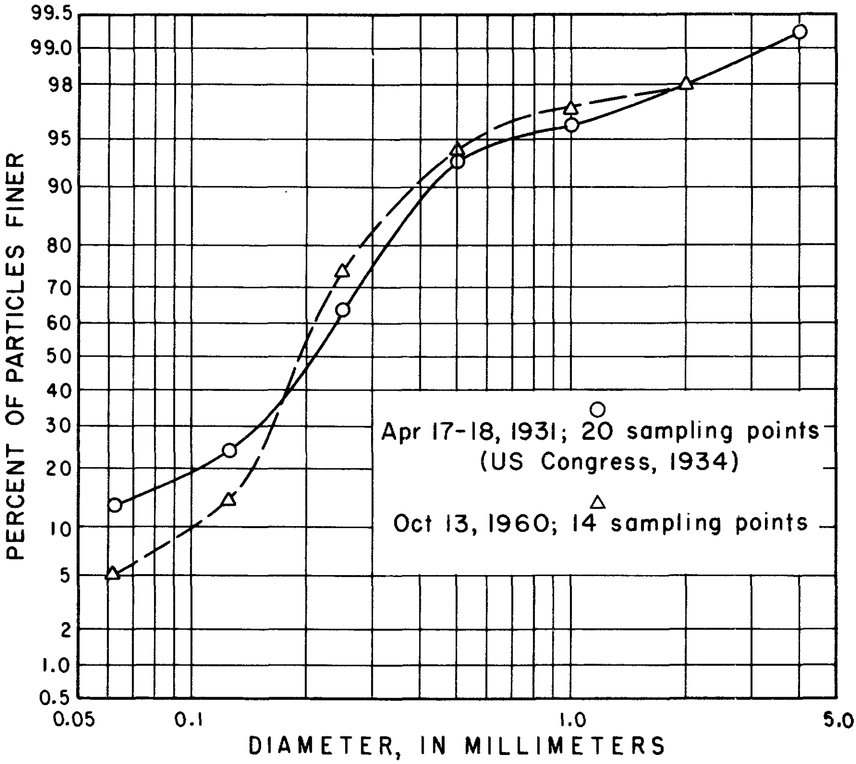

FIGURE 29.—Particle-size distributions of bed material, Grand River near Wakpala.

TABLE 14.—*Particle-size analyses of streambed material*

[Method of analysis, sieve and visual accumulation tube]

Date	Percent of streambed material finer than indicated size (millimeters)									Remarks
	0.062	0.125	0.250	0.500	1.000	2.000	4.000	8.000	16.000	
South Fork Grand River near Bison										
Oct. 17, 1955	4	5	8	12	33	50	68	84	97	One-fourth of width from right bank.
	3	4	6	12	32	48	66	84	96	One-fourth of width from left bank.
Grand River south of Morristown										
Oct. 13, 1955	0	6	87	100	------	------	------	------	------	One-third of width from right bank.
	0	8	83	98	99	100	------	------	------	Middle of stream.
	1	6	76	93	96	97	99	100	------	One-third of width from left bank.
Grand River south of McIntosh										
Oct. 12, 1955	1	13	86	93	95	98	99	100	------	One-third of width from right bank.
	1	3	24	35	45	58	78	91	96	Middle of stream.
	2	5	37	62	73	84	93	98	100	One-third of width from left bank.
Grand River near Wakpala										
Oct. 13, 1960	5	14	74	94	97	98	100	------	------	Average for 14 sampling points. No flow.

TOTAL SEDIMENT DISCHARGE

The concentration of suspended sediment in a stream varies in a vertical direction; the minimum concentration is at the surface, and the maximum concentration is at the bed. Concentrations of particles finer than sand are nearly uniform throughout the depth, but the concentrations of sand and coarser particles are much greater near the bed than near the surface. The lower 3 to 5 inches of the stream (called the unsampled zone) cannot be sampled by suspended-sediment samplers currently in use; therefore, the concentration of a depth-integrated sample is less than the mean concentration in the entire depth.

Suspended-sediment discharge is computed by multiplying the concentration determined from depth-integrated samples by the streamflow for the entire depth and by an appropriate units-conversion factor; this discharge is called the measured suspended-sediment discharge. However, because the streamflow is for the entire depth, the measured suspended-sediment discharge includes part of the suspended-sediment discharge in the unsampled zone. All sediment discharge not computed as measured suspended-sediment discharge is called unmeasured sediment discharge and consists of sediment rolling or sliding on the bed, sediment moving in short skips or leaps near the bed, and part of the suspended sediment in the unsampled zone. Nearly all the material finer than sand, because of its uniform vertical distribution, is included in the measured suspended-sediment discharge; therefore, the unmeasured sediment discharge is composed mostly of sand or coarser particles. In sand-bed streams, unmeasured sediment discharge is usually a large part of the total sediment discharge unless the stream is deep, velocities are low, or discharges of sediment finer than sand are so high that the unmeasured sediment discharge is very small in relation to the total.

Colby (1957) has developed a method for computing the unmeasured sediment discharge principally from its relationship to mean velocity. The method does not require a bed-material analysis nor the slope of the energy gradient but requires only the width, mean depth, mean velocity, and measured concentration of suspended sand. The method is sufficiently accurate for determining the relative magnitude of the unmeasured sediment discharge with respect to the total sediment discharge.

Computations for North Fork Grand River near White Butte, South Fork Grand River near Cash, and Grand River near Shadehill indicate that at low streamflow the measured suspended-sediment discharges are more than 99 percent of the total sediment discharges. At streamflow well above the average, the measured suspended-sediment discharges are lowest—about 70 to 80 percent of the total sediment discharges for the Grand River at Shadehill and about 80 to 85 percent for the North and South Forks. The percentages for the Grand River at Shadehill are lower than those for the South Fork near Cash, probably because the available material in the bed at Shadehill is finer and more easily transported; the percentages are also lower than those for the North Fork near White Butte, probably because at high flows the depths at Shadehill are shallower and therefore a smaller fraction of the total depth is sampled. At peak streamflows, the measured suspended-sediment discharges at all three stations are from 85 to 95 percent of the total.

SUMMARY AND CONCLUSIONS

The effects of environmental factors—such as type of rocks and soils, climate, topography, and vegetation—are fairly uniform throughout the Grand River basin. Therefore, differences in the chemical composition of surface waters from one part of the basin to another are not great, and physical and chemical erosion is almost uniform. The quantity of dissolved solids transported by the streams is closely related to the amount of streamflow. On the other hand, the chemical type of the water depends on the material over and through which the water moves.

Mean annual runoff in the basin is about 53 acre-feet per square mile of drainage area and is about 7 percent of the mean annual precipitation of about 15 inches. The highest streamflow rates on the larger streams have been due to snowmelt. In localized areas the peak streamflow rates are caused by intense summer rains.

The chemical quality of the water that is contributed to the Missouri River by the Grand River depends mainly on the action of weathering on the Fort Union and Hell Creek Formations. The areas of outcrop of the different formations are indicative of their relative importance to the quality of water. However, the effects of the different formations are not necessarily proportional to their areas of outcrop. The Fort Union and the Hell Creek Formations crop out in areas covering about 2,500 and 2,200 square miles, respectively, of the 5,680 square miles of area in the Grand River basin.

High percent sodium is typical of almost all the waters in the Grand River basin. Most of the surface waters are of the sodium sulfate or sodium bicarbonate type. The general streamflow-quality patterns of the Grand River and its two forks are similar. The dissolved-solids content varies greatly, especially at high streamflow rates. Nevertheless, the quality of the water improves as the streamflow increases. The dissolved-solids concentration is maximum during low flows but usually does not exceed 3,000 ppm. During high flows the normal and base flows, which are mostly from ground-water inflow, are diluted by overland runoff. The effect of overland runoff on the chemical composition of the water is pronounced. At peak flows the water of the Grand River at Shadehill is of the sodium bicarbonate type, and at extremely low flows the water is generally of the sodium sulfate type.

After storage began in July 1950, Shadehill Reservoir filled slowly until the spring of 1952 when runoff caused the reservoir to fill rapidly and to spill in April 1952. After the reservoir had filled and the quality of the water became almost uniform throughout the reservoir by the latter part of July 1952, the specific conductance gradually increased and became relatively stable in 1956. Thereafter, the specific conductance fluctuated from about 1,300 to 1,600 micromhos per centimeter and was between 1,400 and 1,500 micromhos per centimeter most of the time. The gradual increase of specific conductance was affected very little by seasonal changes

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in the quantity and quality of inflow. Only during a short time, usually in March and April, is the concentration of dissolved solids in the inflow as low as that of the water in the reservoir. Except at the points of inflow and during floodflows, the water in the reservoir is well mixed and is uniform in composition.

Chemical-quality records that were computed for the Grand River at Shadehill for the representative period July 1937 to June 1950 compare favorably to measured data for the period October 1945 to June 1950. If the runoff at Shadehill during the period July 1937 to June 1950 had been stored in Shadehill Reservoir, the specific conductance of the water probably would have averaged about 1,200 micromhos per centimeter, or the dissolved solids would have been about 840 ppm. The minimum and maximum for this period would have been 74 and 83 for percent sodium and 6.4 and 12 for sodium-adsorption-ratio, and the average would have been 77 percent and 7.7, respectively. The measured specific conductance, concentration of dissolved solids, percent sodium, and sodium-adsorption-ratio of water leaving the reservoir in July 1960, after several years of abnormally low flow, were about 1,400 micromhos per centimeter, 955 ppm, 82 percent, and 11, respectively.

The dissolved-solids discharge at the station near Wakpala for the long-term representative period July 1937 to June 1950 is estimated to have been 140,000 tons per year, and the yield from the basin was about 25 tons per square mile per year. For the stations at Haley, near White Butte, near Cash, and at Shadehill, the computed yields were about 22, 28, 25, and 28 tons per square mile, respectively.

Except for sulfate, concentrations of chemical constituents usually do not exceed the maximum concentrations recommended for domestic supplies. The high dissolved-solids and hardness of most of the surface waters of the Grand River basin prevent the use of these waters for most industrial purposes unless the quality is improved by treatment.

The water from Shadehill Reservoir, when classified for irrigation use according to specific conductance and sodium-adsorption-ratio, has a high salinity hazard and a medium sodium hazard. The effects of using the water for irrigation on experimental plots have been studied by the Bureau of Reclamation and other agencies. According to the Bureau, the water can be used safely for sustained irrigation on loamy sand, sandy loam, and the lighter-textured loams if provision is made for gypsum application in the range of 4.5 tons per acre during the high sodium cycle and if adequate leaching is practiced.

Suspended-sediment discharges of the Grand River at Shadehill during the period of record were much greater than normal. They ranged from 160,000 tons in 1948 to 1,900,000 tons in 1950 and averaged 700,000 tons per year.

Suspended-sediment discharges of the North Fork at Haley and near White Butte and the South Fork near Cash were estimated from periodic sampling. Estimated discharges of the North Fork at Haley for 1947–60 averaged 31,000 tons per year and ranged from 130 tons in 1955 to 260,000 tons in 1952. Estimated discharges of the North Fork near White Butte for 1947–60 averaged 140,000 tons per year and ranged from 180 tons in 1955 to 1,200,000 tons in 1950. Estimated discharges of the South Fork near Cash for 1947–50 averaged 270,000 tons per year and ranged from 78,000 tons in 1949 to 510,000 tons in 1950. Sediment discharges during the period of record for the South Fork near Cash were much greater than normal.

The suspended sediment is predominantly clay; some silt and a little sand are transported. The amount of sand in the suspended sediment in the North and South Forks averaged about 5 percent. The average of 26 percent of sand in suspended sediment in the Grand River at Shadehill probably is much higher than normal because samples were for a high-flow period.

The probable specific weights of sediment deposits are about 42 pounds per cubic foot for the North and South Forks and 56 pounds per cubic foot for the Grand River at Shadehill. These specific weights are for deposits that have not been appreciably compacted by overlying deposits or by exposure to the air. At 56 pounds per cubic foot, the sediment that was carried by the Grand River at Shadehill from March 9, 1946, to June 30, 1950, would occupy about 2,500 acre-feet when deposited in a reservoir.

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