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CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

1925

NATHAN C. GROVER, Chief Hydraulic Engineer

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CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES, 1925

N. C. GROVER, Chief Hydraulic Engineer

WATER POWER AND IRRIGATION IN THE MADISON RIVER BASIN, MONTANA

By JOHN F. DEEDS and WALTER N. WHITE

INTRODUCTION

During July and August, 1923, field studies were undertaken to obtain information needed in assembling and correlating data in the files of the Geological Survey regarding the utilization of water in the Madison River basin, Mont. The work consisted of reconnaissance investigations, including a plane-table survey to determine potential power resources along two sections of the river, one 18 miles long and the other 34 miles long, and a compilation of county classification records showing irrigated areas. Records of the Montana State engineer were helpful in obtaining data concerning projected irrigation development, and considerable information concerning hydroelectric power was obtained from the Montana Power Co., which owns or controls the principal hydroelectric plants in the Missouri River basin. Private engineers, business men, and many others who were interviewed in connection with the field work displayed a notable spirit of cooperation and furnished many valuable data. J. Q. Peterson, of the Geological Survey, aided in preparing the agricultural discussion, and G. R. Mansfield, also of the Survey, reviewed the section on geography and physiography and prepared the section on geology.

The principal trading points in the basin are at Three Forks, Ennis, and Norris, but there are post offices also at Cameron, Cliff Lake, Jeffers, Lyon, McAllister, Varney, Grayling, and Yellowstone. Transportation in the lower part of the river basin is afforded by the Northern Pacific and Chicago, Milwaukee & St. Paul railways. The most accessible shipping point for the remainder of the basin is at Norris, the terminus of a branch line of the Northern Pacific Railway. Fairly good highways are to be found throughout the settled parts of the basin. The Vigilante Trail to Yellowstone National Park extends into the valley across the watershed on the west side from Virginia City to Ennis, thence up the east side of the river to the Hebgen reservoir, and thence south to the west entrance of the park. The trail known as the Great White Way runs from Three Forks to Norris and Ennis, thence over the same route as the Vigilante Trail to the Hutchins ranch, in sec. 10, T. 11 S., R. 1 E., whence it crosses the river and proceeds up the west side of Madison Valley, crosses the Continental Divide to Henrys Lake, Idaho, and runs back across this divide to the west entrance of Yellowstone Park. The Banff-Grand Canyon Trail follows the same route as the Vigilante Trail. Highway bridges are located near the mouth of the river on the road from Three Forks to Logan; at a point in sec. 11, T. 3 S., R. 1 E., on the road from Norris to Bozeman; in sec. 36, T. 8 S., R. 1 W., near the mouth of Indian Creek; and at Ennis, Varney, Lyon, and the Hutchins ranch.

SUMMARY

The Madison River basin contains the internationally famous geysers of Yellowstone National Park, which are at its headwaters, and it is also well known for its trout fishing, which brings large numbers of tourists to the basin each season. In an economic sense, however, the basin is of particular interest because of its water supply, as it yields annually more than 1,400,000 acre-feet which can be used for the development of hydroelectric energy and for irrigation. The power resources are now partly developed by power plants having an installed capacity of 18,000 horsepower and storage reservoirs having a total capacity of 386,000 acre-feet. It is estimated that the undeveloped power resources on the river amount to 136,000 horsepower of electric energy. This estimate does not include potential power resources of considerable magnitude at the headquarters of the basin within Yellowstone National Park, as the scenic value of that area is regarded as sufficient to prevent present consideration of commercial development of its potential power, and such development has been prohibited by law.

Agriculture is practiced in the basin to a certain extent, but the area suitable for diversified farming is relatively small, and stock raising is the principal agricultural industry. Adverse climate, poor soil, and unfavorable topography are the limiting factors to agriculture. About 2.1 per cent of the drainage area is irrigated, and an additional 2.3 per cent is included in irrigation projects, at least part of which probably will be constructed eventually. Near the lower end of the basin certain favorably located bench lands are cultivated by dry farming and produce successful crops of small grains during

good years. In parts of the basin are flood-plain areas that may be susceptible of successful reclamation by drainage, diking, and irrigation.

GEOGRAPHY AND PHYSIOGRAPHY

Madison River is formed in Yellowstone National Park by the junction of Gibbon and Firehole rivers and flows thence a distance of approximately 140 miles to Three Forks, in southwestern Montana, where it joins Jefferson and Gallatin rivers to form Missouri River. The drainage area tributary to the river (fig. 1) is 2,590 square miles, consisting of mountain ranges, high plateaus, and relatively small areas of valley lands. The watershed for the basin, beginning at the mouth of the river on the west side, extends to and along the crest of the Jefferson Mountains, thence along the Continental Divide on the south, thence northward across plateaus and minor mountain ranges and along the Madison Range and low-lying hills to the mouth of the river.

The river basin comprises five natural subdivisions having distinct physiographic and economic features—the headwater area above the Hebgen dam, including Upper Madison Valley; the upper canyon section, which extends about 7 miles below the Hebgen dam; the middle valley section, which extends 57 miles below the upper canyon; the lower canyon section, which extends 20 miles below the middle valley; and the lower valley, which extends 18 miles below the lower canyon to the mouth of the river. These five subdivisions are convenient units for discussing the utilization of water along the river, and frequent reference to them will appear in subsequent parts of this report.

Topographically the headwater area is composed for the most part of high plateaus and mountains, with a comparatively small amount of open valley. In this area Gibbon Falls, having a head of 80 feet, and the cascades of the Firehole, with a fall of 300 feet within 2 miles, furnish potential power resources of considerable magnitude. The only water utilization in this area that is possible without encroaching on Yellowstone National Park, however, is at the Hebgen reservoir, the flow line of which extends to the park boundary. The investigations in connection with the present paper therefore practically ignored the park section of the basin.

The upper canyon section lies in a gorge walled with massive gneissic rocks rising almost vertically to an estimated height of over 500 feet above the river. Throughout this section the river channel lies along or near the left wall of the gorge, but on the opposite side of the gorge rock in place is not exposed at any point near the river, and the precipitous cliffs of the main canyon wall are in places half a mile back from the water's edge. The slopes leading to this right wall are covered with a mantle of rock fragments of undetermined

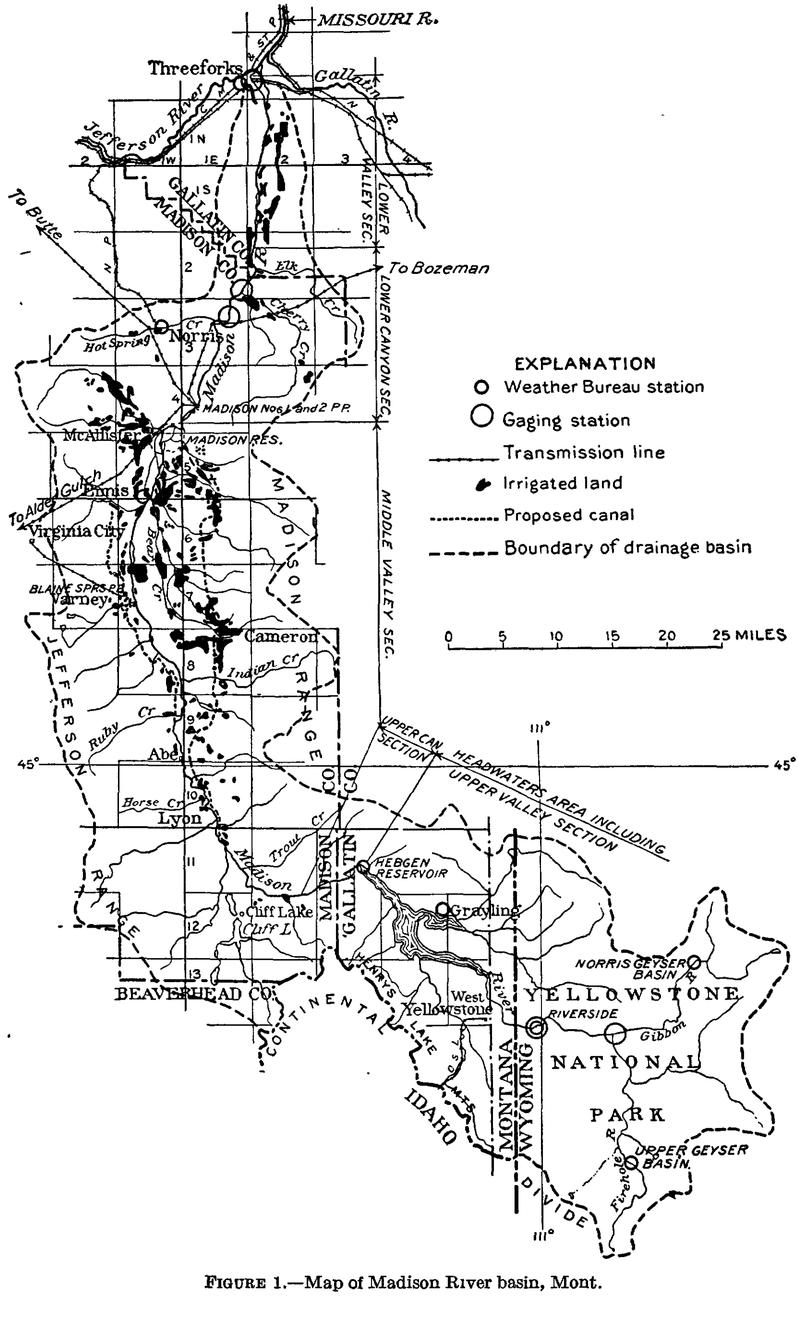

FIGURE 1.—Map of Madison River basin, Mont.

depth except at the upper end of the canyon, where the excavations for the Hebgen dam extended into solid rock at a depth of 34 feet below the river bed. Israel Hutchins, an early settler living near the upper end of the middle valley, reported that he was engaged about 15 years ago to make explorations in the upper canyon in connection with a contemplated power development. This work consisted in sinking a 74-foot shaft on the right bank about 1 mile above the mouth of the canyon at a point 100 feet higher than the water surface and 200 yards back from the river. The shaft failed to reach solid rock.

The middle valley section consists of a basin between the upper and lower canyon sections having a maximum width of 8 to 10 miles from the foothills of the Jefferson Mountains on the west to the base of the Madison Range on the east. The trough of the valley is near its west side, leaving an area on the east side which in places attains a width of 7 miles. Madison River flows through the trough of the valley in a flood plain that ranges in width from a few hundred feet in certain places near its upper end to about 3 miles at its lower end. For the most part the flood plain is flanked by a series of coarse gravel terraces stepped up to a maximum height of 150 feet above the river. The terraced topography is modified on one or both sides of the river in a stretch extending from sec. 24, T. 11 S., R. 1 E., to a point in sec. 1, T. 10 S., R. 1 W., owing to the occurrence of rhyolite. In this stretch the river occupies a channel through a valley so narrow at places as apparently to present economical cross sections for dam sites. Where the river channel follows the line between T. 10 S., R. 1 E., and T. 10 S., R. 1 W., prominent palisades of rhyolite 3 miles in length occur along the west bank. In sec. 25, T. 11 S., R. 1 E., at 50 feet above the river the width of the valley is 575 feet, and at 90 feet above the river the estimated width is 775 feet. At this point rhyolite is present on both sides of the river. Near the center of sec. 14, T. 11 S., R. 1 E., the left bank of the river follows the base of a rocky ridge 500 feet or more in height, and on the right bank there is a series of characteristic Madison Valley terraces, one 25 feet, a second 75 feet, and a third 100 feet above the river. At 60 feet above the water surface the valley is 250 feet wide, and at 100 feet above it is about 500 feet wide.

In the SW. ¼ SE. ¼ sec. 33, T. 10 S., R. 1 E., about halfway between Squaw and Second Standard creeks, the width of the valley at the water surface is 225 feet and at 30 feet above the river it is 375 feet. The left bank here is a steep talus slope 75 feet or more high, and the right bank is a typical terrace 450 feet wide leading to a second terrace about 70 feet high. In the SE. ¼ NW. ¼ sec. 18, T. 10 S., R. 1 E., the width of the valley at 30 feet above the water surface is about 450 feet and at 50 feet above about 650 feet. At this point the left bank consists of a talus slope of moderate gradient, and the right bank is a steep terrace slope 70 feet high. In the NE. ¼ sec. 12, T. 10 S., R. 1 E., the width of the valley at 30 feet above the water surface is about 400 feet; the left bank is formed by rhyolite talus spalled off from closely adjacent cliffs and the right bank by the usual gravel-covered terrace. In the SW. ¼ sec. 25, T. 9 S., R. 1 W., terraces on opposite sides of the river, the one on the left bank 100 feet high and the one on the right over 60 feet high, form narrows having a width of about 800 feet at 60 feet above river level.

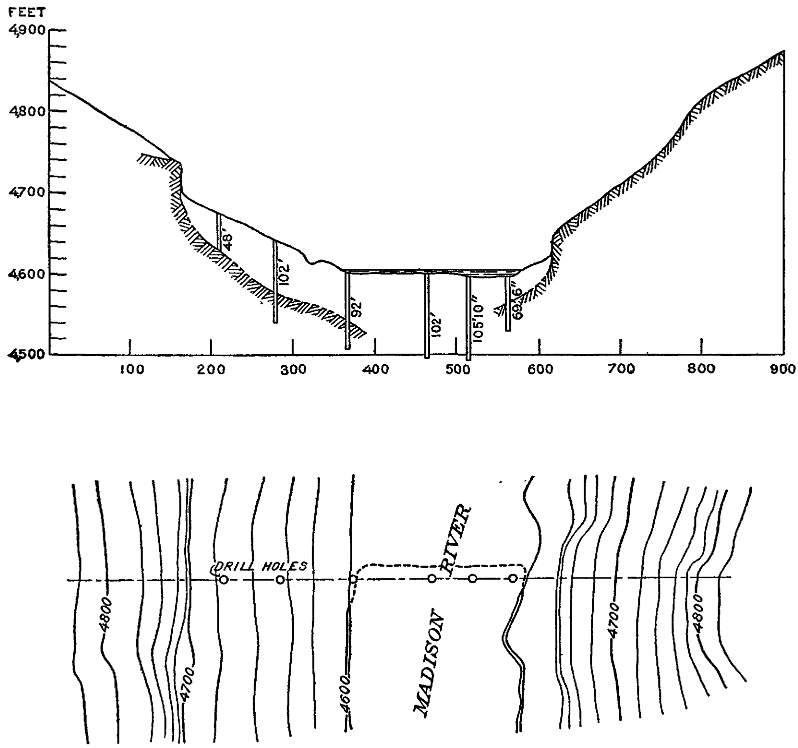

FIGURE 2.—Cross section of Madison River in lower canyon section, showing drill holes made by Montana Power Co.

The lower canyon section is a narrow rock-walled gneissic gorge similar to the upper canyon in that the walls of the gorge furnish a solid foundation for dam abutments. The river bed occupies practically the whole bottom of the canyon and consists of rock débris of undetermined depth. Through the courtesy of the Montana Power Co. a cross section of the canyon at a point in lots 3 and 4, sec. 34, T. 3 S., R. 1 E., and data obtained through exploratory boring operations along the axis of a possible dam at this point are presented in Figure 2. The drill used in these operations penetrated to a maximum of 105 feet 10 inches but failed to reach solid rock. This condition of a favorable cross section for a dam site but lack of bedrock foundations at a moderate depth has been disclosed by similar explorations of the power company in secs. 11, 27, and 33, T. 3 S., R. 1 E., and apparently prevails throughout the lower canyon.

The lower valley is a wide plain which is in places almost level. The river is intrenched in this plain to a depth of only a few feet, and near its lower end the rapid fall that prevails throughout the greater part of the river course diminishes so much that the stream flow appears comparatively sluggish.

GEOLOGY

With respect to its general geologic and physiographic features the Madison Valley as a whole appears to be much like many intermontane valleys farther south in Idaho. These valleys were formed by erosion and perhaps in part by downwarping or faulting in middle or earlier Tertiary time and were excavated to considerably greater depths than the present valleys. They were largely filled by middle or later Tertiary sediments (gravel, marl, etc.), partly lacustrine and partly fluviatile, which formed the so-called lake beds that are so common in these valleys and that locally overspread adjoining hills. During this epoch volcanic activity gave rise to flows of rhyolite or basalt and beds of volcanic ash. These materials are now interbedded here and there with the Tertiary sediments. With the revival of erosion some streams cut through the thin cover of Tertiary sediments into an underlying ridge of older rocks, forming canyons, whereas the thicker sediments up and down stream were excavated so that wide valleys were developed in them. Similarly when flows of rhyolite or basalt were cut through, canyons or palisaded reaches were formed, with open reaches in the weaker lake beds upstream. The wide valleys in the lake beds have passed through several partial erosion cycles, which are marked by the terraces that are so conspicuous here and there, and together with their connecting canyons have been eroded to depths which are likewise greater than those of the present valleys. This erosion, which presumably occurred in early Pleistocene time, was succeeded by an epoch of aggradation, induced in part at least by more arid climatic conditions, in which the valleys and connecting canyons were partly refilled to unknown depths but in some places 200 feet or more. Since this time the climate has again become more moist, and the streams are now engaged in scouring away these fillings, though they have thus far made little progress in this work.

In the middle valley area there are narrow places with palisades of rhyolite that suggest favorable positions for dam sites. These rhyolite flows are probably to be regarded as members of the lake-bed series and are therefore doubtless underlain by Tertiary beds.

Where rhyolite appears in these palisades it has in all probability been cut through by the later stream erosion so that it does not now underlie the river bed and would therefore not be available for dam foundations. However, if at any place the flows were exceptionally thick they may not have been completely eroded through and in that event would serve for dam foundations if not too porous. Drilling would be necessary to determine the presence or absence of the rhyolite at any particular locality.

METEOROLOGY

Data on the growing season, precipitation, and temperature recorded by the United States Weather Bureau for the Madison River basin are given below. At the headwaters of the basin records have been obtained at the Hebgen dam and Grayling, in Montana, and at Norris Geyser Basin and Upper Geyser Basin, in Wyoming. The average annual precipitation along the river channel as disclosed by these records is about 20 inches. The rainfall at the crests of the mountain ranges in the basin is considerably higher, but no records of it are available. The growing season averages 24 days in length at Grayling and 78 days at the Hebgen dam. At the Upper Geyser Basin and Norris Geyser Basin stations frost records obtained in 1915 show a growing season of 53 days and 32 days respectively, but during the years 1910 to 1914 and 1916 at Norris and 1909 to 1914 and 1916 at Upper Geyser Basin frost occurred every month in the year. These data seem to be inconsistent in that the growing season at the Hebgen dam is made to appear as of excessive length in comparison to that at the other stations, but it is believed that the moderating influence of the large body of water in the Hebgen reservoir, supplied in part from hot springs, operates to lengthen the frost-free period at this station.

The remaining Weather Bureau stations in the Madison River basin are at lower altitudes—at Ennis, Meadow Creek, Norris, and Three Forks, Mont. According to the records the average growing season is 98 days long at Ennis and longer at the other stations. The precipitation, on the other hand, in general decreases with the altitude to a minimum of 11.58 inches a year at Three Forks, the least recorded in the basin. At Norris the record shows a mean annual precipitation of 17.36 inches, which has proved adequate in this area to produce successful crops of wheat and oats under dry-farming methods. A growing season of 98 days is sufficient for the production of general farm crops, but where the annual precipitation is as small as at Three Forks irrigation is necessary for successful farming.

Temperature records show prolonged periods of weather below the freezing point throughout the Madison River basin, and operation of hydraulic structures during the winter may be difficult because of interference from frazil or "slush" ice. Frazil ice will disappear when introduced into a reservoir under an ice cover and will not form for a considerable distance downstream from the outlet of the reservoir. On Madison River the operation of the Hebgen reservoir effectively eliminates frazil ice in the upper canyon, and in this section power can be developed without the possibility of interference from this source. In the middle valley frazil ice will form unless preventive measures are taken, either by the construction of reservoirs above the intakes to the power plants or by some other means of eliminating the difficulty.

Precipitation, in inches, at stations in Madison River basin

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
Ennis, Mont.													
1918				2.13	0.80	0.32	1.68	2.15	2.40	1.51	0.65	1.72	
1918–19	1.30	0.83	0.48	.16	.80	.26		.50		.10		.36	
1919–20		.80	2.24	.08	.88	1.92	1.64	1.40	2.75	.55	.30		
1920–21		.32	.48	.64				2.20	1.05	.45	.70	1.00	
1921–22	1.00		.40	.72	.12	.56	1.22	2.06	1.50	2.06	3.00	.50	
1922–23			.44					1.02	2.01	2.05	1.40	.25	
1923	.40	.48	.72										
Average	.90	.61	.79	.75	.65	.76	1.51	1.56	1.94	1.12	1.21	.77	12.57
Meadow Creek, Mont.													
1909												0.12	2.06
1909–10	0.16	1.76	1.15	0.50	1.40	Tr.	0.69	0.63	0.33		.08		
Grayling, Mont.													
1904									1.17	1.67	1.18	0.59	
1904–5	1.12	Tr.	1.01	0.57	0.34	1.31	0.49	2.58	1.75	1.21	.66	1.02	12.06
1905–6	.74	0.90	.69	1.37	.97		.71	2.56		.53	1.40	.73	
1906–7	.61	.36	2.11	2.07	.48	3.01	.42	1.57	2.18	1.81	1.14		
1907–8	.81	.13	.88						3.24	1.30	2.67	1.40	
1908–9	2.14	.17			1.80	.27	.39	1.86	1.19	1.74	1.05	3.08	
1909–10	.61	1.87	1.15	2.85	.56	.13	.76		.29	1.16	.24		
1910–11		1.92	1.07	2.50	.60	.79	.54	2.65	2.57	1.12	.56	.94	
1911–12	1.20	1.09	1.01	.95	.49		1.62	1.55	2.01	4.14	1.92	.47	
1912–13	2.16	.64	.40										
Average	1.17	.79	1.04	1.72	.75	1.10	.70	2.13	1.80	1.64	1.20	1.18	15.22
Hebgen dam, Mont.													
1913				3.98	1.03	2.84	2.56	2.35	3.90	4.53	0.79	1.35	
1913–14	1.89	1.23	0.61	2.26	2.11	.48	.63	1.34	4.26	1.39	Tr.	1.36	17.56
1914–15	1.75	.15	1.17	2.64	2.05	1.71	2.01	5.15	2.00	3.05	.95	3.53	26.16
1915–16	.68		3.06	3.63	1.91	2.50	.95	2.71	1.61	1.23	.68	1.04	
1916–17	2.84	2.25	3.41	2.63	2.35	1.79	3.14	1.77	1.82	.32	.50	2.71	25.53
1917–18	.38	.99		4.24	2.42	2.31	1.37	1.65	2.37	3.58	1.65	3.01	
1918–19	2.70	.63	.85	1.14	3.25	1.84	1.01	1.77	.09	.77	.74	3.15	17.94
1919–20	3.76			.93		3.23	2.36	3.19	2.46	1.18	1.45	2.39	
1920–21	2.53	1.64		3.91	1.44		1.86	4.54	1.45	.78	1.79	1.12	
1921–22	.88	2.53	2.01	2.84	2.74	2.39	2.11	2.15	1.10	1.65	3.47	.25	24.12
1922–23	.40	.98	3.00	2.66	1.25	1.90	2.71	1.94	4.06	3.66	2.03	.72	25.31
1923–24	1.71	.84	2.50		2.38	2.27	.91						
Average	1.77	1.25	2.08	2.81	2.08	2.11	1.80	2.60	2.28	2.01	1.28	1.88	23.95

Precipitation, in inches, at stations in Madison River basin—Continued

Norris, Mont.

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1908				0.22	1.05	1.76	0.55	10.37	4.37	0.65	0.78	1.37	
1908-9	1.05	.04	.60	.05	.02	2.09	1.00	6.04	1.02	2.34	2.83	4.54	21.62
1909-10	.70	1.57	1.85	2.53	.51	.35	1.50	2.64	1.19	.88	1.96	2.06	17.74
1910-11	1.80	1.98	.35										
1911-12				.10	.12	1.35	1.71	2.91	1.73	.60	1.50	1.96	
1912-13	2.41	.20	.22	.19	.45	.91	.75	1.94	5.72	2.17	.27	2.54	17.77
1913-14	3.60	.34	.19	.29	.32	.18	1.29	2.15	3.77	1.18	.06	2.74	16.11
1914-15	1.04	.09	.05	.46	.04	.60	1.59	4.03	3.97	2.92	2.07	2.58	19.44
1915-16	.71	1.25	.56	.73	.57	.87	1.76	3.10	3.40	2.16	.72	1.10	16.93
1916-17	2.52	.29	.34	.55	.81	.61	2.45	3.20	2.09	.73	.13	3.08	16.80
1917-18	1.34	.25	.23	.92	.74	.49	2.24	2.30	1.45	1.33	1.25	1.29	13.83
1918-19	1.23	1.06	.36	.21	1.11	.48	1.47	1.98	.12	.09	.64	.71	9.46
1919-20	3.18	.79	.89	.37	1.06	1.70	2.29	3.74	2.58	.67	1.10	1.08	19.45
1920-21	.16	.54	.37	.42	.36	1.31	1.78	4.65	2.11	.93	.58	2.09	15.30
1921-22	.34	1.52	1.84	.64	.51	.66	3.19	3.45	2.02	1.96	2.51	.59	19.23
1922-23	.39	1.64	.80	.31	.38	1.15	1.48	2.60	2.85	1.45	1.21	1.44	15.70
1923-24	1.80	.45	.65	.46	.97	1.97	1.47						
Average	1.48	.80	.62	.53	.56	1.03	1.66	3.67	2.56	1.34	1.17	1.94	17.36

Three Forks, Mont.

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1910					0.45	0.34	1.36	1.67	1.24	0.68	0.53		
1910-11					.23	.02	.48	1.89	2.68	.27		1.34	
1911-12	1.08	0.30											
1912-13				0.21	.48	.50	1.35	1.93	3.37	2.42	.37	.42	
1913-14	1.98	1.26	0.08	.25	.31	.17	1.97	1.97	3.34	1.49	0	2.21	
1914-15	2.24	.02	.12	.28	.02	.97	.57	1.81	4.43	2.53	1.00	2.66	16.65
1915-16	.12	.63	.70	.41	.51	.38	88	.79	2.91	1.02	.80	.94	10.09
1916-17	1.21	Tr.	.59	.65	.42	.31	.97	2.18	1.33	.11	.46	1.90	10.13
1917-18	.17	.19	.45	.43	.10	.61	.37	1.13	1.39	1.22	.85	1.99	8.90
1918-19	.85	.89	.04	.11	.65	.16	.20	.44	.34	0		.44	
1919-20	1.35	.58	1.13			.36		2.70	2.27	1.41	1.00	.63	
1920-21			.06	.14		.13	.57	1.61	2.76	1.48	.93	1.81	
1921-22	.07	.81	1.30	.60	.85	.48	2.62	1.62	2.06	2.00	1.79	.81	15.01
1922-23	.31		.48	.42	.40	Tr.	.54	2.23	3.85	2.27	1.20	.47	
1923-24	.14	0			.62	.80	1.65						
Average	.87	.47	.50	.35	.42	.37	1.04	1.69	2.46	1.30	.81	1.30	11.58

Norris Geyser Basin, Wyo.

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1908				0.95	1.02	0.61	0.14					0.36	
1908-9	2.01	0.85	1.03	2.60	2.67	.48	1.28	0.60	0.73	2.25	0.84	1.92	17.26
1909-10	.69	2.11	.96	3.51	1.63	.50	.77	2.77	.19	2.06	.20	.68	16.07
1910-11	1.18	2.95	1.50	5.70	.60	1.93	2.24	2.92	2.26	.46	.68	.60	23.02
1911-12	1.35	2.79	1.08	1.18	1.35	1.74	1.05	3.23	.75	2.00			
1912-13	2.45		1.88		1.04	3.80	1.10	3.00	2.79	3.44	.25	1.81	
1913-14	2.48	2.48	.88	1.02	1.43	.48		1.50	2.04	1.51	Tr.	1.52	
1914-15			.18	.88	.48	.89	1.00	2.74	2.03	1.47		1.70	
1915-16	.80												
1918-19												2.46	
Average	1.56	2.24	1.07	2.26	1.28	1.30	1.08	2.39	1.54	1.88	.39	1.38	18.37

Riverside, Wyo.

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1908				1.26	1.24	0.59	Tr.		3.35	Tr.	2.92	0.70	
1908-9	0.72	0.55	1.71	3.60	2.26	0.74	1.19	1.57	1.33	1.81	1.12	2.74	19.34
1909-10	.83	4.53	1.09	2.63	2.46	.46	1.15	2.63	.41	.74	.12	.85	17.90
1910-11	.20	1.47	1.26	4.21	1.90			.12	3.95	1.95	1.15	.55	
1911-12	1.11	2.95					2.73	2.14	.92	1.25	1.07	.69	
1912-13	1.00	.68	1.67	2.82	.05	1.18	.40	1.81	2.37	4.02	1.25	.96	18.21
1913-14	1.44	2.90	.40	2.40	.66	.20		.38	2.59	.46	.03	2.55	
1914-15	.83	.52	.50	1.47	.80	.88	1.05		2.63	1.30	1.30	2.30	
1915-16	.70	2.59	2.10										
1918-19												3.19	
1919-20	3.74	1.20	2.27	.78	.76	2.63	1.08		2.12	1.26	1.50	2.23	
1920-21	1.29	.84		1.78	.50		2.71	3.63	.99	.72	1.48	1.32	
1921-22			2.64	1.87						1.44	2.47		
1922-23	.32	1.25		2.81	.64			2.52	2.10		.70	1.03	
1923	1.19	.57	2.09										
Average	1.11	1.67	1.57	2.33	1.13	.95	1.29	1.85	2.07	1.36	1.26	1.59	18.18

Precipitation, in inches, at stations in Madison River basin—Continued

Upper Geyser Basin, Wyo.

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1908	------	------	------	2.15	1.10	2.01	0.80	2.83	2.85	0.39	2.02	0.56	------
1908–9	4.46.	0.44	------	------	1.80	.30	.55	.65	------	1.10	1.10	2.50	------
1909–10	.70	.59	0.50	2.81	1.80	.45	------	2.05	------	.94	.19	1.10	------
1910–11	.93	2.75	1.60	5.70	.84	1.02	.95	2.35	1.96	Tr.	Tr.	1.55	19.65
1911–12	.90	2.19	1.87	1.30	2.00	4.04	1.18	2.90	1.40	1.00	7.30	------	------
1912–13	1.90	------	1.40	3.65	1.44	1.30	.12	------	2.90	4.92	.85	1.43	------
1913–14	1.43	2.59	.40	------	.54	------	------	------	1.30	.08	.02	2.01	------
1914–15	.49	1.05	.62	3.30	1.21	1.20	1.30	3.18	2.01	2.01	2.37	2.88	21.62
1915–16	2.03	3.70	1.98	------	------	------	------	------	------	------	------	------	------
Average	1.60	1.90	1.20	3.15	1.34	1.52	.82	2.33	2.07	1.30	1.73	1.72	20.60

Frost data at stations in Madison River basin

Norris, Wyo.

[1910–1914, 1916, frost every month.]

Year	Last killing frost in spring	First killing frost in fall	Interval (days)
1915	July 4	Aug. 5	32

Upper Geyser Basin, Wyo.

[1909–1914, 1916, frost every month.]

1915	July 19	Sept. 10	53

Riverside, Wyo.

[1909–1917, rost every month.]

Ennis, Mont.

1918	June 1	Sept. 4	95
1919	June 2	Sept. 22	112
1920	June 4	Aug. 29	86
1921	May 28	Sept. 10	105
1922	June 1	Sept. 8	99

Grayling, Mont.

1909	June 25	July 7	12
1910	July 13	July 24	11
1911	July 13	Aug. 3	21
1912	July 10	Aug. 20	41

Hebgen dam, Mont.

1913	July 14	Sept. 10	58
1914	June 22	Sept. 1	71
1915	June 27	Sept. 9	74
1916	June 11	Sept. 14	95
1917	June 14	Sept. 1	79
1918	June 30	Sept. 16	78
1919	June 2	Sept. 22	112
1920	June 24	Aug. 29	66
1921	July 3	Sept. 5	64
1922	June 11	Sept. 8	89

Frost data at stations in Madison River basin—Continued

Norris, Mont.

Year	Last killing frost in spring	First killing frost in fall	Interval (days)
1909	June 11	Sept. 23	104
1910	May 2	Aug. 24	114
1911	May 11	Sept. 17	129
1912	May 7	Sept. 21	137
1913	May 19	Sept. 24	128
1914	May 12	Oct. 5	146
1915	Apr. 9	Oct. 6	180
1916	May 11	Sept. 28	140
1917	May 31	Oct. 17	139
1918	May 29	Sept. 27	121
1919	May 6	Oct. 8	155
1920	June 1	Oct. 21	142
1921	May 14	Sept. 10	119
1922	May 12	Oct. 14	155
1923	May 15	Oct. 12	150

Three Forks, Mont.

Year	Last killing frost in spring	First killing frost in fall	Interval (days)
1910	June 3	Aug. 25	83
1911	May 31	Sept. 19	111
1913	May 17	Sept. 20	126
1914 [a]	May 5	Oct. 7	155
1915 [a]	May 6	Sept. 20	137
1916 [a]	June ?	Sept. 14	?
1917 [a]	June 5	Oct. 17	134
1918 [a]	May 22	Sept. 16	117
1918	May 29	Sept. 4	98
1919 [a]	June 2	Sept. 22	112
1920 [a]	July 8	Aug. 19	42
1921 [a]	May 14	Oct. 7	146
1922 [a]	May 31	Sept. 29	121

[a] Record obtained near Three Forks.

Mean monthly temperature, in degrees Fahrenheit, at stations in Madison River basin

Norris Geyser Basin, Wyo.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1904	------	------	------	33.4	41.2	------	------	------	48.6	------	------	------	------
1905	------	15.1	------	------	------	------	56.8	57.2	49.0	35.4	25.4	8.4	------
1906	11.6	14.8	13.8	33.6	42.4	46.1	55.8	54.0	46.6	38.4	22 6	25.4	33.8
1907	14.5	24.4	26.4	32.5	39.4	48.0	57.2	54.6	45.6	40.8	25.6	16.8	35.5
1908	13.0	21.4	22.1	34.8	40.2	43.3	54.2	50.0	44.2	32.9	24.0	------	------
1909	18.8	------	22.0	24.0	33.8	------	54.4	55.2	44.4	36.0	28.2	7.6	------
1910	7.2	10.2	30.8	37.7	42.0	49.7	54.8	50.4	46.4	37.6	25.4	15.4	------
1911	13.2	10.0	23.0	28.2	39.8	49.0	51 8	49.5	43.8	30.5	16.6	------	------
1912	14.7	13.6	15.2	29.2	37.2	------	50.8	------	------	38.6	------	------	------
1913	------	------	15.3	30.8	40.1	49.0	51.6	53.2	------	30.0	25.6	11.4	------
1914	17.6	15.0	22.8	33.5	43.4	47.8	55.4	51.7	42.5	39.9	30.6	10.9	34.3
1915	12.0	19.6	25.3	40.0	40.5	44.4	50.0	50.6	42.5	32.1	------	------	------
1916	------	------	------	33.9	39.4	53.5	50.7	49.8	41.0	------	------	------	------
1917	------	------	------	------	------	------	------	------	------	33.2	29.6	------	------
1919	------	------	------	------	------	------	------	------	44.0	------	------	------	------
Mean	13.6	16.0	21.7	32.6	40.0	47.9	53.6	52.4	44.9	35.5	25.4	13.7	33.1

Riverside, Wyo.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1905	------	------	------	------	------	------	55.9	57.5	50.2	31.8	26.2	13.2	------
1906	17.6	21.1	20.6	34.2	43.2	45.9	55.9	55.2	47.6	38.2	23.8	24.9	35.7
1907	13.1	24.6	27.0	33.0	39 4	46.3	56.6	------	47.0	42.6	25.1	16.0	------
1908	12.6	19.9	23.7	35.2	41.2	46.8	57.8	52.1	44.8	34.5	23.6	14.6	33.9
1909	20.8	19.0	25.8	28.7	38.6	51.2	56.8	58.2	47.7	35.8	28.0	8.5	34.9
1910	10.4	12.2	------	------	43.5	52.0	59.9	53.7	49.4	40.8	29.9	17.4	------
1911	------	11.6	24.8	------	42.2	53.0	52.7	52.0	49.2	36.2	18.9	------	------
1912	------	------	------	33.0	41.1	53.6	54.8	53.6	41.6	32.2	20.6	11.2	------
1913	------	------	------	------	------	46.6	------	51.4	49.0	33.0	25.7	12.4	------
1914	19.9	17.8	25.8	37.4	47.2	49.4	68.4	54.5	46.8	40.5	28.6	9.9	37.2

Mean monthly temperature, in degrees Fahrenheit, at stations in Madison River basin—Continued

Riverside, Wyo.—Continued

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1915	13.4	24.1	28.2	41.5	41.4	46.3	52.6	56.4	45.0	40.8	21.2	14.2	35.4
1916	8.1	19.8	28.0	33.6	37.0	46.4	57.2	53.9	45.0	33.8	17.2	11.9	32.7
1917	7.2	16.3	12.4	------	38.8	------	58.4	53.8	49.0	34.6	29.2	------	------
1918	------	------	30.3	33.4	45.4	------	------	------	------	------	------	------	------
1919	------	------	------	------	------	------	------	------	48.0	27.6	18.4	9.6	------
1920	14.8	15.2	19.6	25.8	38.4	47.3	55.9	53.8	44.6	34.3	24.0	16.1	32.5
1921	15.4	17.6	26.2	28.2	41.8	51.6	55.2	53.1	41.4	------	------	20.8	------
1922	------	------	------	30.0	43.0	------	57.0	57.1	------	------	18.2	------	------
1923	------	------	------	------	41.5	46.4	55.2	48.8	46.2	32.6	24.8	9.0	------
Mean	13.9	18.3	24.4	32.8	41.5	48.8	56.9	54.1	46.6	35.6	23.7	13.9	34.2

Upper Geyser Basin, Wyo.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1904	------	------	------	------	41.6	48.0	54.6	55.2	48.2	40.4	30.7	18.4	------
1905	19.0	21.2	32.0	34.6	39.2	49.8	57.9	62.1	50.0	30.2	26.5	12.2	36.2
1906	17.4	20.6	19.8	33.8	41.2	45.6	55.5	54.6	52.4	41.9	23.3	------	------
1907	12.1	22.3	25.4	31.4	38.6	44.4	56.0	55.1	48.6	43.6	28.2	77.8	35.3
1908	16.6	20.4	22.2	36.3	40.6	46.2	58.2	53.8	47.3	34.0	26.6	------	------
1909	------	------	21.8	------	34.2	47.2	------	------	44.3	35.4	28.2	8.7	------
1910	------	13.4	------	38.6	43.2	53.2	59.2	53.5	49.5	42.0	26.0	15.4	------
1911	11.2	3.6	21.6	25.8	40.8	51.4	54.5	50.9	48.0	35.3	19.8	------	------
1912	19.5	11.1	21.4	29.9	40.3	52.5	50.6	51.8	38.2	34.2	------	13.0	------
1913	9.4	------	19.4	30.7	43.2	55.4	------	------	47.2	35.4	25.9	18.0	------
1914	16.2	18.1	26.3	35.8	45.3	48.7	------	54.3	46.2	39.0	34.2	11.4	------
1915	15.4	22.4	29.2	41.9	39.8	44.2	51.0	56.2	45.8	38.5	23.8	14.2	35.2
1916	9.6	21.7	28.2	34.6	36.7	46.2	57.2	54.2	46.8	------	------	------	------
Mean	14.6	17.5	24.3	33.9	40.4	48.7	55.5	54.7	47.1	37.5	26.6	14.3	34.6

Ennis, Mont.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1918	22.1	23.6	37.8	38.2	47.1	64.4	64.4	60.8	55.4	49.2	32.1	27.2	43.5
1919	29.2	23.4	33.8	45.6	52.3	63.8	69.9	66.1	55.4	35.3	29.3	19.5	44.5
1920	27.4	26.6	28.3	36.9	48.2	56.4	66.2	63.2	55.7	43.2	30.8	27.8	42.6
1921	26.8	30.6	36.1	40.6	49.4	62.2	65.6	65.1	51.2	49.4	33.4	23.8	44.5
1922	16.4	17.7	30.4	38.8	49.5	62.2	64.0	66.7	59.4	49.3	30.4	20.6	42.1
1923	26.6	21.0	29.2	40.0	51.0	56.8	67.6	61.8	57.2	39.5	35.9	22.0	42.4
Mean	24.8	23.8	32.6	40.0	49.6	61.0	66.3	64.0	55.7	44.3	32.0	23.5	43.1

Grayling, Mont.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1904	------	------	------	------	------	47.9	53.4	53.6	46.0	39.2	28.4	14.6	------
1905	------	8.5	27.8	33.8	42.0	47.5	53.8	55.0	46.4	31.0	24.0	6.6	------
1906	12.9	16.6	------	33.4	43.2	45.7	54.6	53.0	46.0	35.0	21.4	22.4	------
1907	------	19.4	26.5	32.4	41.2	46.1	53.4	50.4	------	41.2	24.4	13.4	------
1908	------	------	------	------	------	46.0	55.5	51.2	46.0	34.2	23.6	------	------
1909	------	14.8	23.4	27.3	39.2	50.8	54.3	55.3	47.1	36.7	25.4	5.0	------
1910	8.6	9.4	30.6	38.4	------	50.9	57.8	51.0	47.4	------	26.2	13.8	------
1911	14.5	7 9	23.4	30.6	42.2	51.4	52.5	51.2	43.6	32.4	15.8	14.6	------
1912	14.3	14.0	------	31.8	39.8	51.1	52.0	50.2	37.8	33.0	25.0	14.7	------
Mean	12.6	12.9	26.3	32.5	41.3	48.6	54.1	52.3	45.0	35.3	23.8	13.1	33.2

Hebgen dam, Mont.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1913	------	------	21.0	36.8	46.0	53.8	56.4	59.6	------	27.8	24.1	12.4	------
1914	18.9	16.0	27.2	37.8	48.8	52.1	61.3	60.7	48.4	40.6	30.6	7.6	37.5
1915	13.0	23.3	29.4	44.4	44.4	50.3	57.4	61.6	47.4	42.4	26.2	15.6	38.0
1916	4.7	18.8	30.2	37.8	41.0	50.6	63.3	60.8	51.5	36.5	20.0	8.6	35.3
1917	7.3	16.5	14.8	30.6	41.7	51.4	65.4	60.6	54.8	40.2	34.2	------	------
1918	12.6	14.7	28.4	32.7	43.4	58.6	59.6	56.8	52.6	42.8	26.4	15.2	37.0
1919	12.7	16.5	27.2	39.0	48.5	59.4	------	63.0	54.2	32.4	19.8	------	------
1920	15.6	12.4	22.6	30.4	42.6	53.6	62.3	59.4	49.4	37.6	24.8	------	------
1921	15.6	19.1	------	32.6	44.4	57.2	61.6	59.6	46.0	43.6	31.2	17.6	------
1922	6.0	11.4	27.3	29.5	43.3	56.5	59.5	61.6	54.0	43.4	23.7	15.8	36.0
1923	16.6	8.4	14.6	33.0	44.6	51.5	62.8	58.1	54.3	36.6	29.6	12.0	35.2
Mean	12.3	15.7	24.3	35.0	44.4	54.1	61.0	60.2	51.3	38.5	26.4	13.1	36.4

Mean monthly temperature, in degrees Fahrenheit, at stations in Madison River basin—Continued

Norris, Mont.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1908	30.8	30.8	35.4	49.8	49.8	56.0	70.7	65.8	59.8	44.4	37.2	27.4	46.5
1909	21.8	28.9	35.6	39.8	48.8	61.4	67.6	68.5	57.5	47.8	35.0	17.3	44.2
1910	21.2	22.5	44.9	50.4	55.1	------	71.2	66.6	------	52.3	------	30.9	------
1911	27.8	25.0	41.2	42.6	50.3	61.2	65.1	62.4	------	43.3	30.7	24.9	------
1912	26.8	30.6	22.6	43.1	51.6	61.9	64.8	64.5	50.7	43.2	40.9	27.5	------
1913	25.2	18.8	29.8	46.4	52.6	60.7	66.4	68.7	57.6	42.9	39.4	27.0	------
1914	33.3	28.4	39.2	44.7	54.2	58.6	69.7	67.8	58.0	48.8	43.6	23.4	47.5
1915	28.0	35.5	37.8	51.0	49.3	55.7	61.2	68.1	53.6	51.8	36.0	29.6	46.5
1916	10.4	30.5	40.3	45.4	46.9	57.4	69.2	66.4	57.6	40.9	32.2	21.2	43.2
1917	20.9	26.2	26.9	38.8	49.0	59.0	71.6	67.4	60.6	48.3	43.0	34.1	45.5
1918	24.6	26.5	41.0	40.2	49.1	66.6	66.4	64.6	54.2	49.4	33.3	28.6	45.4
1919	31.2	26.6	35.6	44.6	54.2	65.8	72.4	69.9	59.2	39.4	30.2	21.6	45.9
1920	28.9	26.6	28.8	34.7	47.8	55.4	66.7	65.8	54.8	43.8	31.2	28.0	42.7
1921	28.5	31.4	34.3	39.5	44.6	57.8	65.4	68.0	52.8	52.1	37.2	26.5	44.8
1922	19.1	20.2	35.2	41.2	51.7	65.6	68.1	70.8	63.8	51.6	32.8	21.0	45.1
1923	29.4	21.6	32.0	42.7	52.4	58.8	69.4	64.2	58.6	41.0	37.0	23.7	44.2
Mean	25.5	26.9	35.0	43.4	50.5	60.1	67.9	66.8	57.1	46.3	36.0	25.8	45.1

Three Forks (near), Mont.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1910	------	------	46.6	50.0	54.2	63.2	68.0	61.4	------	------	------	------	------
1911	------	23.1	41.6	44.0	52.6	64.8	65.7	------	------	------	------	------	------
1912	23.5	28.8	------	------	------	------	------	------	------	------	------	------	------
1913	23.0	16.8	28.8	45.4	53.8	61.9	64.5	67.0	55.9	41.2	36.0	20.2	------
1914	31.5	28.0	37.6	43.8	52.2	56.0	66.0	62.6	54.0	43.4	37.6	16.9	44.1
1915	21.4	31.1	34.6	49.4	48.4	52.8	58.4	65.0	49.7	47.2	31.1	24.0	43.8
1916	−3.0	23.2	37.2	42.6	44.0	54.2	65.6	62.2	52.0	37.8	26.2	12.8	37.9
1917	15.0	17.0	19.6	37.6	47.3	55.0	69.5	64.4	58.7	44.3	37.2	24.7	40.9
1918	19.4	20.7	37.2	39.1	47.4	65.0	63.6	62.2	54.2	47.4	26.6	25.8	42.4
1919	28.8	19.4	30.8	44.7	52.6	64.4	69.3	67.2	55.4	33.4	25.4	12.4	42.0
1920	27.5	31.8	31.9	40.0	54.0	59.6	66.6	64.5	55.2	40.3	25.1	27.2	43.6
1921	27.6	32.4	38.1	40.8	50.7	61.3	67.0	65.8	51.0	50.8	33.0	21.8	45.0
1922	19.2	16.2	32.6	42.6	52.3	60.8	62.9	67.3	59.4	48.0	------	20.0	------
1923	30.0	17.0	34.4	42.4	52.9	59.7	70.0	67.0	56.8	43.2	37.0	------	------
Mean	22.0	23.5	34.7	43.3	51.0	59.9	65.9	64.7	54.8	43.4	31.5	20.6	42.9

SOILS AND DRAINAGE

The character of the soil is one of the limiting factors to water utilization in the Madison River basin. Large areas of land that is otherwise valuable for agriculture and susceptible of irrigation are nonarable because of poor soil or almost total absence of soil, and the same condition is a source of difficulty in the operation of canals. Drainage problems arise where arable land in the flood plain is overflowed as a result of slush-ice gorges during winter. The scope of this paper does not contemplate a detailed analysis of either soils or drainage conditions, and the discussion of these factors will be limited to a general sketch based on reconnaissance observations in the middle and lower valleys.

The flood plain of the middle and lower valleys has a surficial cover which ranges from cobblestones to fine alluvium, but the alluvium is confined chiefly to the lower end of the middle valley and the greater part of the lower valley. The terraces of the middle valley have in general a surficial cover of coarse gravelly soil, which in places rests upon a poorly cemented aggregate of sand, gravel, and boulders.

Streams tributary to Madison River that flow across these terraces have built up alluvial fans which extend out from the base of the mountains and foothills on either side of the valley. The soil of these alluvial fans is in part similar to the river-bottom alluvium, being friable and having considerable fertility. The cobblestone and gravelly areas have practically no agricultural value except for grazing.

Canals constructed through the terrace gravel are subject to a high rate of seepage loss, as disclosed by two measurements made July 30, 1923, by Fred C. Scobey and F. M. Ingerson, of the Department of Agriculture, in cooperation with the authors of the present paper. These measurements were made at points in the Valley Garden ditch, which was constructed prior to 1890 to convey water from a point near the Blaine Springs power plant, in T. 7 S., R. 1 W., to land northwest of Ennis. In the section measured the ditch is excavated in terrace gravel and cemented gravel and boulders. The measurements were made almost simultaneously in wooden box flumes approximately 2.3 miles apart, and the computed discharge at the upper point was 12.5 second-feet and at the lower point 11.4 second-feet. The difference, 1.1 second-feet, represents a reduction in flow of 8.8 per cent, which is due entirely to seepage losses. At a point on the east side of the valley below the mouth of Indian Creek, in T. 8 S., R. 1 W., an attempt was made at one time to divert water from Madison River through a canal to terrace land on the east side. The canal was constructed for several miles through characteristic terrace gravel but has been abandoned, apparently because of the perviousness of this material.

In the flood-plain areas of the middle and lower valleys the water table is maintained at shallow depths to a considerable extent, if not entirely, by flooding from slush-ice gorges during winter. The result is beneficial to farming in places, but in most of the area the water table lies so near the surface as to render the land moist and incapable of producing remunerative crops, and therefore the land is used only for grazing. The subsurface material of the moist areas is coarse gravel, cobblestones, and boulders, through which water percolates easily; hence the land apparently could be efficiently drained by open canals excavated to this material. Some drainage has already been accomplished with satisfactory results, but a large part of the land is not reclaimed, and it is believed that diking and drainage of such land is a meritorious project which should receive more careful study.

WATER SUPPLY

Stream-flow records in Madison River basin obtained by the Geological Survey are summarized on pages 17–22. The run-off from about half of the headwater area is shown by the record for the gaging station at Riverside station, near Yellowstone. An interesting feature disclosed by this record is the comparatively uniform flow of the river throughout the year. Apparently, this uniformity is due to the fact that the drainage area above the gaging station contains a large number of geysers and hot springs that have a fairly constant flow throughout the year and that eliminate ice interference except during periods of extraordinary cold weather, by maintaining a water temperature above freezing. Discharge records obtained at Hebgen by the Montana Reservoir & Irrigation Co. are available for the period October, 1909, to September, 1923. The annual run-off as determined from these records is about twice that shown by the Riverside record of the Geological Survey for the years that simultaneous records are available. The records also indicate that the ratio between the discharges at the two stations varies widely during the year, but in the absence of other data equally satisfactory the flow at Hebgen has been taken as double that at Riverside. The discharge 90 per cent of the time at Riverside is 413 second-feet or more, and the discharge 50 per cent of the time is 510 second-feet or more. The corresponding discharges at Hebgen are therefore about 825 second-feet and 1,020 second-feet. These figures are approximate only but are used in preference to the record obtained by the Montana Reservoir & Irrigation Co. because information is lacking that would show to what extent that record was affected by the operation of the Hebgen reservoir.

The records for the Red Bluff and Norris gaging stations show the run-off from practically the same drainage area, the only difference being that the flow of the small stream called Cherry Creek is not included in the earlier records for the station near Red Bluff. The drainage area of Cherry Creek is 90 square miles, or less than 4 per cent of the total area above the two stations, and the run-off per square mile from the creek basin is small in comparison to that from the larger area. Estimates of water supply can therefore be made from these records on the assumption that they were obtained at the same point, as the error of less than 4 per cent involved in such an assumption can be disregarded. Most of the records for these stations were obtained prior to the storage development, which would affect any records now obtained at the same stations. They indicate a discharge of 1,200 second-feet or more 90 per cent of the time during the periods 1890 to 1893 and 1897 to 1906. The discharge 50 per cent of the time is 1,430 second-feet or more for the first period and 1,570 second-feet or more for the second period; the mean is 1,500 second-feet.

The Geological Survey records are as follows:

Monthly discharge of Madison River near Yellowstone, Mont., for the years ending September 30, 1913–1922

[Location, Riverside station, about 4 miles east of Yellowstone, Mont.]

Month	Discharge in second-feet			Run-off in acre-feet
	Maximum	Minimum	Mean	
1913				
June 16–30	1,180	974	1,050	31,200
July	1,570	681	917	56,400
August	1,020	681	759	46,700
September	775	635	704	41,900
The year	1,570	635	831	176,000
1913–14				
October	823	635	711	43,700
November	775	635	699	41,600
December	635	546	586	36,000
January	676	522	582	35,800
February	625	522	572	31,800
March	574	471	531	32,600
April	882	522	656	39,000
May	1,400	625	1,030	63,300
June	1,240	676	895	53,300
July	676	574	605	37,200
August	625	522	537	33,000
September	882	522	579	34,500
The year	1,400	471	667	482,000
1914–15				
October	882	574	637	39,200
November	574	471	517	30,800
December	522	471	510	31,400
January	522	471	474	29,100
February	522	471	482	26,800
March	522	471	484	29,800
April	831	522	670	39,900
May	882	522	678	41,700
June	1,040	471	636	37,800
July	574	370	447	27,500
August	574	420	451	27,700
September	522	420	452	26,900
The year	1,040	370	537	389,000
1915–16				
October	522	420	447	27,500
November	471	420	441	26,200
December	471	420	456	28,000
January	522	420	455	28,000
February	471	420	431	24,800
March	574	420	489	30,100
April	728	471	579	34,500
May	1,110	676	873	53,700
June	1,770	994	1,290	76,800
July	1,210	558	736	45,300
August	666	518	556	34,200
September	574	471	526	31,300
The year	1,770	420	606	440,000
1916–17				
October	728	522	562	34,600
November	574	471	510	30,300
December	522	471	520	32,000
January	574	420	499	30,700
February	625	471	524	29,100
March	625	522	539	33,100
April	707	451	548	32,600
May	1,410	440	885	54,400
June	1,950	780	1,310	78,000
July	1,300	640	863	53,100
August	642	497	542	33,300
September	579	497	513	30,500
The year	1,950	420	652	472,000

Monthly discharge of Madison River near Yellowstone, Mont., for the years ending September 30, 1913–1922—Continued

Month	Discharge in second-feet			Run-off in acre-feet
	Maximum	Minimum	Mean	
1917–18				
October	543	462	496	30,500
November	491	440	477	28,400
December 1–8	491	491	491	7,790
July	682	497	572	35,200
August	497	486	496	30,500
September	682	462	488	29,000
1918–19				
October	816	492	570	35,000
November	545	400	483	28,700
December	503	392	445	27,400
January	458	376	386	23,700
February	416	376	391	21,700
March	530	416	444	27,300
April	750	416	541	32,200
May	972	570	764	47,000
June	684	370	472	28,100
July	420	316	366	22,500
August	450	370	388	23,900
September	450	370	393	23,400
The year	972	316	471	341,000
1919–20				
October	524	360	432	26,600
November	503	376	419	24,900
December	532		396	24,300
January	408	353	380	23,400
February	392	353	388	22,300
March	432	353	401	24,700
April	458	376	410	24,400
May	1,220	432	779	47,900
June	1,440	662	1,050	62,500
July	723	491	548	33,700
August	546	400	450	27,700
September	513	400	437	26,000
The year	1,440	353	507	368,000
1920–21				
October	491	410	441	27,100
November	570	392	442	26,300
December	476		442	27,200
January	476		438	26,900
February	458	392	413	22,900
March	476	392	429	26,400
April	589	392	469	27,900
May	1,350	506	994	61,100
June	1,370	590	993	59,100
July	686	480	541	33,300
August	535	440	479	29,500
September	579	450	485	28,900
The year	1,370	392	548	397,000
1921–22				
October 1–8	460	450	451	7,160
June	1,160	590	869	51,700
July	638	430	529	32,500
August	568	410	453	27,900
September	430	335	379	22,600

Monthly discharge of Madison River near Red Bluff, Mont., for the years ending September 30, 1890–1893, 1897–1903

[Location, 1890–1893, 1½ miles below Hot Springs Creek, 4 miles from Red Bluff, at Hayward Bridge; moved in May, 1897, to point below Cherry Creek, at Black's ranch.]

Month	Discharge in second-feet			Run-off in acre-feet
	Maximum	Minimum	Mean	
1890				
January			[a] 1,200	73,800
February			[a] 1,200	66,600
March			[a] 1,200	73,800
April 4–30	2,580	1,370	1,620	96,400
May	6,420	3,060	4,820	297,000
June	6,360	3,780	4,980	296,000
July	3,660	1,720	2,520	155,000
August	1,640	1,380	1,540	94,500
September	1,580	1,420	1,470	86,300
1890–91				
October	1,520	1,420	1,500	92,300
November	1,470	1,280	1,380	82,200
December	1,520	1,280	1,400	86,200
January	1,580	1,240	1,410	86,500
February	1,580	1,260	1,440	79,700
March	1,790	1,470	1,630	100,000
April	1,960	1,640	1,770	106,000
May	4,260	1,790	3,390	208,000
June	4,620	3,780	4,170	248,000
July	3,660	1,160	2,040	126,000
August	1,640	1,200	1,430	87,900
September	1,380	1,240	1,310	77,900
The year	3,660	1,160	1,910	1,380,000
1891–92				
October	1,470	1,240	1,350	83,100
November	1,470	1,280	1,400	83,300
December	1,240	1,070	1,140	69,900
January	1,380	1,240	1,300	80,300
February	1,640	1,330	1,500	86,500
March	1,640	1,330	1,490	91,500
April	1,420	1,240	1,300	77,100
May	2,580	1,330	1,450	89,400
June	5,940	2,820	4,900	292,000
July	5,340	1,790	3,220	198,000
August	1,880	1,280	1,520	93,400
September	1,420	1,330	1,360	80,900
The year	5,940	1,070	1,850	1,330,000
1892–93				
October	1,420	1,280	1,330	81,600
November	1,420	1,330	1,420	84,700
December	1,420	1,240	1,320	81,400
January	1,380	1,160	1,230	75,600
February	1,960	1,030	1,290	71,400
March	1,200	1,030	1,080	66,500
April	1,240	910	1,020	60,600
May	1,520	1,070	1,330	81,500
June	3,180	1,580	2,420	144,000
The period	3,180	910	1,380	747,000
1897				
January			[a] 1,600	98,400
February			[a] 1,600	88,900
March			[a] 1,600	98,400
April			[a] 1,900	113,000
May 2–17, 27–31	8,610	3,300	4,930	205,000
June	8,610	2,700	4,430	264,000
July	3,000	2,000	2,550	157,000
August	2,000	1,600	1,680	103,000
September	1,600	1,520	1,540	91,900

[a] Estimated.

Monthly discharge of Madison River near Red Bluff, Mont., for the years ending September 30, 1890–1893, 1897–1903—Continued

Month	Discharge in second-feet			Run-off in acre-feet
	Maximum	Minimum	Mean	
1897–98				
October	1,800	1,450	1,630	100,000
November			[a] 1,700	101,000
December			[a] 1,700	105,000
May 7–31	6,380	2,960	4,830	297,000
June	8,000	3,450	6,000	357,000
July	4,420	2,800	3,620	223,000
August	3,120	2,150	2,680	165,000
September	2,800	2,150	2,260	134,000
1898–99				
October	2,310	2,150	2,160	133,000
November 1–14			2,150	128,000
April 16–30	2,960	2,640	2,840	169,000
May	6,050	1,180	3,050	188,000
June	10,300	6,050	8,380	499,000
July	8,650	2,800	5,160	317,000
August	3,610	2,150	2,730	168,000
September	2,150	2,150	2,150	128,000
1899–1900				
October	1,820	1,820	1,820	112,000
November [a]			1,820	109,000
March [a]			860	52,900
April	2,530	860	1,760	105,000
May	5,660	3,000	4,260	262,000
June	5,380	2,080	3,600	214,000
July	2,080	1,640	1,860	114,000
August	1,850	1,640	1,670	102,000
September	1,850	1,640	1,690	101,000
1900–1901				
October	1,850	1,850	1,850	114,000
November	1,850	1,640	1,660	98,800
December	1,640	1,640	1,640	101,000
April	2,280	1,900	1,960	117,000
May	8,320	2,820	5,080	313,000
June	5,400	2,400	3,360	200,000
July	2,400	1,650	2,010	124,000
August	1,900	1,480	1,560	96,000
September	1,480	1,480	1,480	87,800
1901–2				
October	1,480	1,480	1,480	90,700
November	1,650	1,480	1,520	90,200
December			1,480	90,700
March 23–31			[a] 910	16,200
April	2,080	910	1,440	85,400
May	6,140	1,570	3,000	185,000
June	6,440	2,880	4,340	258,000
July	3,450	1,570	2,440	150,000
August	1,570	1,180	1,360	83,700
September	1,360	1,360	2,360	80,900
1902				
October	1,360	1,360	1,360	83,600
November 1–8			1,360	21,600

[a] Estimated.

Monthly discharge of Madison River near Norris, Mont., for the years ending September 30, 1903–1906, 1910, and 1911

[Location, 3 miles below Red Bluff station, including Cherry Creek]

Month	Discharge in second-feet			Run-off in acre-feet
	Maximum	Minimum	Mean	
1903				
January			[a] 1,300	79,900
February			[a] 1,300	72,200
March			[a] 1,300	79,900
April	1,700	1,440	1,620	96,500
May	3,360	1,700	2,280	140,000
June	6,140	3,510	5,060	301,000
July	3,510	1,700	2,140	132,000
August	1,440	1,050	1,260	77,400
September	1,220	1,050	1,100	65,200
The period	6,140	1,050	2,450	1,040,000
1903-4				
October	1,220	1,050	1,210	74,300
November	1,220	1,220	1,220	72,600
December			[a] 1,200	73,800
January			[a] 1,200	73,800
February			[b] 1,200	69,000
March	1,760	1,100	1,290	79,200
April	2,010	1,100	1,430	85,300
May	6,740	2,010	3,740	230,000
June	6,740	3,860	5,610	334,000
July	3,860	1,760	2,670	164,000
August	1,760	1,410	1,530	94,200
September	1,520	1,300	1,360	80,600
The year			1,980	1,430,000
1904-5				
October	1,410	1,300	1,350	82,800
November	1,300	1,300	1,300	77,400
December			[a] 1,200	73,800
March 12-31	1,540	1,320	1,460	58,000
April	1,540	1,540	1,540	91,600
May	2,120	900	1,570	96,500
June	3,970	2,000	3,200	190,000
July	3,000	800	1,840	113,000
August	1,320	1,100	1,180	72,400
September	1,210	1,100	1,170	69,700
1906				
October	1,100	1,100	1,100	67,600
November 1-25	1,100	1,100	1,100	54,500
The period	1,100	1,100	1,100	122,000
1910				
August 12-31	1,750	850	1,310	52,000
September	1,750	1,050	1,360	80,900
The period	1,750	850	1,340	133,000
October	2,020	1,270	1,560	95,900
November 1-20	2,300	1,050	1,430	56,700
The period	2,300	1,050	1,500	153,000

[a] Estimated. [b] Mean for 26 days taken as mean for month.

Monthly discharge of Madison River near Three Forks, Mont., for the year 1895

[Location, at bridge of Northern Pacific Railway about half a mile east of railway station at Three Forks]

Month	Discharge in second-feet			Run-off in acre-feet
	Maximum	Minimum	Mean	
January			[a] 1,500	92,200
February			[a] 1,500	86,300
March			[a] 1,600	98,400
April	1,980	1,690	1,820	108,000
May	3,680	1,830	2,220	137,000
June	8,180	4,420	6,360	379,000
July	4,720	1,690	2,720	167,000
August	1,820	1,380	1,510	93,000
September	1,520	1,430	1,470	87,400
October	1,480	1,380	1,430	88,100
November			[a] 1,400	83,300
December			[a] 1,400	86,100

[a] Estimated.

Monthly discharge of Gibbon River near Yellowstone, Mont., for the years ending September 30, 1913–1916

[Location, at the Wylie Gibbon lunch station in Yellowstone National Park, about 2 miles below Gibbon Falls]

Month	Discharge in second-feet			Run-off in acre-feet
	Maximum	Minimum	Mean	
1913				
June 22–30	280	253	272	4,860
July	454	152	216	13,300
August	227	120	155	9,530
September			123	7,320
The period	454	120	177	35,000
1913–14				
October	148	101	128	7,870
November	132	101	115	6,840
December	112	87	95.3	5,860
January	92	90	91.8	5,640
February	91	84	86	4,780
March	113	87	91.8	5,640
April	219	116	159	9,460
June 15–30	250	162	188	5,970
July	162	101	135	8,300
August	148	66	86.2	5,300
September	175	84	111	6,600
1914–15				
October	175	101	125	7,690
November	107	84	88.2	5,250
December	123	71	86.1	5,290
January	108	71	81.5	5,010
February	80	68	73.4	4,080
March	92	62	68.5	4,210
April	175	92	146	8,690
May	204	92	143	8,790
June	234	92	138	8,210
July	101	71	88.7	5,450
August	112	71	83.2	5,120
September	92	77	86.2	5,130
The year	234	62	101	72,900
1915–16				
October	92	72	83.6	5,140
November	84	72	78.6	4,680
December	92	78	82.7	5,080
January	118	78	95.2	5,850
February	109	84	94.6	5,440
March	162	92	113	6,950
April	175	100	130	7,740
July	188	139	155	7,070
August	162	109	132	8,120
September	118	100	104	6,190

STORAGE

Storage in the Madison River basin is provided in the Hebgen and Madison reservoirs. The Hebgen reservoir was completed in 1915 by erecting a dam in unsurveyed T. 11 S., R. 3 E. Montana meridian, near the upper end of the upper canyon of the river. The area within the flow of the reservoir at high water is 13,400 acres, and the maximum storage capacity is 346,000 acre-feet. The dam is an earth-fill structure with a concrete core 87.5 feet in height above the original channel. The foundation of the core wall is on solid rock at a maximum depth of 35 feet below the original channel surface. The crest of the dam is 718 feet in length, and the structure contains 298,900 cubic yards of material. The altitude of the spillway is 6,491.5 feet, of the channel 6,418.5 feet, and of the crest of the dam 6,506 feet. The stored water is released through a 12-foot outlet pipe at a point 19 feet above the lowest point in the reservoir. The Madison reservoir is near the head of the lower canyon, in T. 4 S., R. 1 E., and was completed in 1905. This reservoir has a high-water flowage area of 4,000 acres and a capacity of 40,000 acre-feet; at the altitude of the spillway the area is 2,920 acres and the capacity 5,400 acre-feet. The dam is a rock-filled crib overflow structure 47 feet in height above its foundation and 31 feet above the original channel surface. The foundation of the dam rests on unconsolidated rock débris, which occupies the bottom of the canyon. These reservoirs are owned by the Montana Reservoir & Irrigation Co., a subsidiary of the Montana Power Co., and the data given here were obtained from the holding company.

The seepage loss from the Hebgen reservoir is insufficient to alter materially the regulation of Madison River obtainable from the reservoir, but evaporation reduces its effective storage capacity. No data on evaporation from the reservoir are available, and the only near-by points from which such data have been obtained are Bozeman, Mont., and Mud Lake, Idaho. The average evaporation at Bozeman for the seven months April to October during 1900 to 1912 was 24.08 inches. At Mud Lake, Idaho, where the meteorologic conditions that control evaporation are comparable to those at Bozeman, a mean annual loss of about 36 inches by evaporation from the lake occurred during 1921, 1922, and 1923. The Hebgen reservoir has a higher altitude and cooler climate than either Bozeman or Mud Lake; hence the rate of evaporation at that point should be materially lower. Probably a reasonable estimate for the annual evaporation from the Hebgen reservoir would be about 24 inches.

Records of stream flow obtained by the Montana Reservoir & Irrigation Co. during the low-water period from July 1, 1910, to April 30, 1912, together with due allowance for loss through evaporation, show that the maximum continuous flow obtainable with storage regulation at Hebgen is 1,100 second-feet. These records also indicate that during years of abnormally high run-off the same flow is maintained without storage regulation, and in actual practice the reservoir would provide sufficient regulation to maintain a higher usable flow, because there are fluctuations in demand. Estimates of potential power available in the upper canyon and middle valley sections based on a continuous flow of 1,100 second-feet are therefore conservative. During the same low-water period (July 1, 1910, to April 30, 1912) a continuous flow of 110,000 acre-feet per month, or about 1,830 second-feet, could have been maintained at the Madison reservoir outlet without altering the regulation at Hebgen. The Red Bluff and Norris records indicate that low-water periods may occur during which the regulated flow obtainable would be smaller than 1,830 second-feet, but it is not believed that the difference would materially reduce the output of power plants designed on the basis of this figure. The records on which this discussion is based indicate that the use of the Hebgen reservoir to maintain a continuous flow of 1,100 second-feet at its outlet results in nearly the same flow at the Madison reservoir as would result if Hebgen stored water were used only for regulation of flow at the Madison River dam, the difference being less than 3 per cent.

Summary of water-supply data for Madison River

	Drainage area [a] (square miles)	Flow obtainable for power (second-feet)		
		With existing storage	Without storage	
			90 per cent of the time	50 per cent of the time
Three Forks	2,590	([b])	([b])	([b])
Norris	2,380	1,830	1,200	1,500
Madison reservoir	2,170	1,830	1,095	1,370
Hebgen reservoir	911	1,100	825	1,020
Riverside	410	([c])	413	510

[a] Measured from Three Forks and Yellowstone Park topographic maps and Madison forest map.
[b] Run-off at Three Forks approximately the same as Norris.
[c] Above reservoirs.

WATER RIGHTS

The low-water flow of Madison River is controlled by power interests without interference with irrigation interests, and no cause has arisen for adjudication of the water rights of the main stream. Furthermore, there is no present prospect of any disturbance on account of irrigation development, because the diversions for irrigation are comparatively small and are made to a large extent during periods when the supply available is more than adequate for all needs. Probably this situation will not be materially altered by any future extension in irrigation development. All the tributaries of Madison River, however, in areas where irrigation is practiced are entirely appropriated during periods of normal flow.

The power interests are represented by the Montana Power Co., which owns the Hebgen and Madison reservoirs, the only storage sites on Madison River. These reservoirs are operated primarily for regulation on Missouri River and not in such a manner as to provide for complete development of the potential power resources on Madison River. The conflict which thus exists might be eliminated by developing storage on Bighole River, and it is believed that a project of that kind will be undertaken eventually, although probably not unless or until the demand for irrigation becomes sufficient to justify it. For the purpose of the present discussion, it will be assumed that the storage facilities on Madison River are to be used primarily to regulate Madison River and only incidentally to regulate Missouri River. Such an assumption permits a determination of the potential value of the water resources of the Madison River basin without regard to the economic value of the storage in connection with the development of Missouri River.

IRRIGATION

The location of the irrigated lands in the Madison River basin is shown on Figure 1. The principal crops produced on these lands at present are alfalfa, wheat, and oats, and the average yields per acre are 2½ tons, 20 to 25 bushels, and 40 to 50 bushels respectively. Some of the irrigated land is used to produce crops of native hay, of which the yield is about 1 ton to the acre. The total area irrigated is about 35,000 acres, most of it in the middle valley. In that section Indian, Bear, Cedar, and Jackass creeks, tributaries from the east, and Wigwam, Blaine Springs, and Meadow creeks, tributaries from the west, are the principal sources of water for irrigation, and practically all the normal flow available from these streams during the irrigation season is diverted. A comparatively small quantity of water is obtained by direct diversion from Madison River, chiefly for use on land in the flood plain. One bench-land area of 1,910 acres west of Ennis is irrigated from the river under a canal owned by the Madison Valley Irrigation District. According to the annual report of the Montana Irrigation Commission for 1920, this canal was completed and used in 1920 at a cost of approximately $18 an acre and may be extended later to include a total area of 3,200 acres.

A scheme has been proposed for irrigating an area of 5,000 to 7,000 acres of good land in the middle valley on Eightmile bench, south of the Madison Valley Irrigation District and west of Ennis, in T. 6 S., Rs. 1 and 2 W. Montana meridian. A canal 20 miles long, diverting from Madison River above the mouth of Ruby Creek in lot 5, sec. 13, T. 9 S., R. 1 W., would be required. A scheme called the Madison irrigation project was proposed several years ago to embrace an area of about 30,000 acres of smooth, gently sloping bench land on the east side of the middle valley. This scheme contemplates a 40-mile canal diverting from Madison River in sec. 3, T. 11 S., R. 1 E., and ending on Jack Creek in T. 5 S., R. 1 E. The approximate location of these canals is shown on Figure 1, and if constructed as proposed they will probably be capable of delivering water to all the nonirrigated arable land in the middle valley that may be susceptible of successful irrigation. The principal difficulty to be overcome in connection with these projects will be encountered in preventing excessive loss from seepage in a canal excavated through terrace gravel.

In the lower valley irrigation canals can be constructed with little difficulty, and several have been built on both sides of Madison River. The soil is good, but at present irrigation is limited mainly to land near the rim of the valley plain, where good natural drainage exists. Further development of irrigation in this section is believed to be in large measure dependent upon drainage and diking.

Investigations have been made by the United States Bureau of Reclamation [1] to determine the feasibility of diverting water from Madison River to bench lands between Madison and Jefferson rivers and west of Missouri River in Prickly Pear and Crow Creek valleys. A total area of 148,000 acres is physically irrigable by means of a canal diverting from Madison River in the lower canyon near the mouth of Hot Spring Creek. The construction work required consists of a 600,000-acre-foot reservoir created by enlarging the Madison reservoir, 16 miles of tunnel, 4 miles of siphon pressure pipe, 27¾ miles of concrete-lined canals, 99.5 miles of earth canal, and one drop of 70 feet and another of 260 feet. The scheme has been abandoned and is mentioned here merely as a matter of historical interest. The cost of an undertaking of this kind would be prohibitive for lands of the character susceptible of irrigation in this region, and probably there is not sufficient unappropriated water available for diversion from Madison River to irrigate 148,000 acres. A similar scheme proposed more recently contemplates the use of water from Jefferson River for irrigating the same areas, but it involves construction difficulties of nearly equal magnitude.

WATER POWER

GENERAL CONDITIONS

Water power is one of Montana's most valuable natural resources and contributes very largely to the welfare of the State. Statistics compiled by the Geological Survey in 1924 show that the power already developed amounts to a total capacity of 345,000 horsepower, which makes Montana sixth among the United States in installed water-power plant capacity. During 1923 the output of the Montana plants was 1,139,000,000 kilowatt-hours, of which 50,883,000 kilowatt-hours, or 4.5 per cent, was produced in the Madison River basin. It has been estimated by the Geological Survey that the potential water power in Montana amounts to 2,550,000 horsepower with the unregulated stream flow available 90 per cent of the

[1] U. S. Recl. Service Fifth Ann. Rept., p. 167, 1906.

time and 3,700,000 horsepower with the unregulated flow available 50 per cent of the time. The undeveloped power resources on Madison River amount to about 3.5 per cent of the estimated total potential power for the State.

Practically all the developed water power in the Madison River basin is generated at the Madison No. 2 plant of the Montana Power Co. and distributed over a system of transmission lines interconnected with other power plants of the company or associated concerns to supply the commercial market of central and western Montana. This market includes the mining operations of the Anaconda Copper Co. and others at Butte, the Anaconda smelter, and electrolytic and other plants at Great Falls, as well as street railways, municipal lighting, irrigation pumping, and the operation of the electrified portion of the Chicago, Milwaukee & St. Paul Railway. Although fluctuations in mining operations have affected the demand for power, there has been an increase in the power consumption in this region during the last decade, and it probably is safe to predict that a continued increase in the power demand will eventually lead to additional power development on Madison River.

DEVELOPED WATER POWER

The Madison No. 1 plant of the Montana Power Co. is in the lower canyon immediately below the Madison reservoir dam, in lot 5, sec. 20, T. 4 S., R. 1 E. This plant was completed in 1901 and remodeled in 1907. The installation consists of two horizontal-turbine water wheels having a total capacity of 3,000 horsepower supplied with water through a 10-foot wood-stave pipe. The electrical equipment includes two 3-phase 60-cycle 1,500-volt generators having a combined rated output of 2,000 kilowatts. During recent years this plant has been operated only occasionally, and in 1923 it was idle.

The Madison No. 2 plant of the Montana Power Co. is at a point in lot 5, sec. 17, T. 4 S., R. 1 E., 7,500 feet downstream from the Madison reservoir dam. This plant was completed in 1906. It is operated under a head of 110 feet with water conveyed through one 10-foot and one 12-foot wood-stave pipe, both of which terminate in a concrete pressure chamber whence the water is conducted through 9-foot steel penstocks to four horizontal-turbine water wheels having a rated capacity of 3,600 horsepower each at 300 revolutions a minute. The water wheels are direct-connected to four 4,000-volt 3-phase 60-cycle generators having a rated output of 2,250 kilowatts each. The plant contains eleven transformers, in three of which the current is stepped up to 102,000 volts and in the other eight to 46,200 volts.

A small plant installed at the outlet of the Hebgen dam on unsurveyed land in what will probably be sec. 23, T. 11 S., R. 3 E., affords power for the dam and appurtenances. Another plant, owned by the Economy Power Co., in sec. 18, T. 7 S., R. 1 W., generates current for municipal lighting in Virginia City. This plant, which has been in operation 14 years, obtains its water supply from Blaine Springs. The installation consists of one 450-kilowatt 2,200-volt 5-pole generator with four termini at 118 amperes each, operating at a speed of 600 revolutions a minute, generating 3-phase 60-cycle current, with three 150-kilowatt transformers which step the current up to 16,500 volts for transmission. The generator is direct-connected to a 600-horsepower horizontal Leffel turbine. The exciter unit consists of a 125-kilowatt 125-volt 100-ampere generator operated at 750 revolutions a minute by a 2-inch double-nozzle Pelton wheel. Water is delivered to the turbine through a 3-foot wood-stave pipe.

UNDEVELOPED WATER POWER

The potential power resources of the Madison River basin which may have commercial value lie along the main stream in the two canyon sections and the upper 27 miles of the middle valley. The fall in the upper canyon is estimated at 29 feet to the mile on the basis of data showing the altitude of the river channel at Hebgen as furnished by the Montana Reservoir & Irrigation Co. and the altitude at the mouth of the canyon as determined by the plane-table survey in the middle valley. The potential power in the canyon, therefore, at an over-all plant efficiency of 70 per cent, is 1,900 horsepower to the mile with the flow available 90 per cent of the time, 2,370 horsepower to the mile with the flow available 50 per cent of the time, and 2,550 horsepower to the mile with the available storage regulation. The total potential power in the canyon on the basis of these estimates would be 13,700 horsepower with 90 per cent flow 17,000 horsepower with 50 per cent flow, and 18,400 horsepower with storage regulation. The 27-mile power section of the middle valley extends from the mouth of the upper canyon, in sec. 35, T. 11 S., R. 2 E., down to a point in sec. 36, T. 8 S., R. 1 W. In this section Madison River is intrenched in a narrow trough between terraces and has a fall determined by plane-table survey ranging from 25 feet to nearly 40 feet to the mile and aggregating 800 feet. The total potential power for the 27 miles at a plant efficiency of 70 per cent is approximately 53,000 horsepower with 90 per cent flow, 65,000 horsepower with 50 per cent flow, and 70,000 horsepower with storage regulation. All these estimates are based on the flow of Madison River at Hebgen, with no allowance for additional flow from tributaries, which would add somewhat to the potential power.

The physical conditions in the upper canyon and the upper 27 miles of the middle valley (see p. 3) would permit the development of part of the fall in the river by means of dams of sufficient height to eliminate difficulties from frazil ice, but in addition conduits would be required. The available foundations, however, appear to be unsatisfactory for masonry dams. In the upper canyon rock-crib structures could be built, but the opportunities for dams in the middle valley are somewhat less favorable. The conduits would traverse talus slopes or pass through terrace gravel and would require lining to prevent excessive loss from seepage. The best opportunity for developing power in the sections under discussion involves the construction of a diversion dam about 1 mile above the mouth of the upper canyon and a 6-mile conduit extending down the right side of the canyon and across a middle-valley terrace to a point in the SE. ¼ sec. 24, T. 11 S., R. 1 E., where a static head of 310 feet can be obtained. The power output of such a development at a plant efficiency of 70 per cent would be 20,000 horsepower with 90 per cent flow, 25,000 horsepower with 50 per cent flow, and 27,000 horsepower with storage regulation.

Below the 27-mile section of the middle valley a 6-mile conduit could be constructed from a point on the right bank of Madison River in sec. 24 or 25, T. 8 S., R. 1 W., to a point on the upper edge of a middle-valley terrace where a static head of 120 feet would be available, which might be utilized for developing power. There is no dam site at the point of diversion, however, and the canal if constructed probably would be of greater value for irrigation than for power. The alinement of the canal required for this development is identical with that of the canal described on page 15, which has never been completed.

The upper canyon is practically devoid of any economic value other than its power resources. The Vigilante Trail to Yellowstone Park traverses the canyon but could be relocated at little expense. A right of way through the canyon was granted to the Montana Railway Co. in 1887, but the grant was declared forfeited in 1915 for nonuse, and there is no present prospect that a railroad will be built through the canyon. In the upper 27 miles of the middle valley there is some agricultural land along the river, but such land would offer no serious impediment to power development.

The undeveloped power of the lower canyon constitutes its principal economic value. A total fall of 220 feet occurs in the 10-mile section from the tail-water of Madison No. 2 power plant to the center of sec. 11, T. 3 S., R. 1 E. The potential power in this 10-mile section at a plant efficiency of 70 per cent is 21,000 horsepower with 90 per cent flow determined from the Red Bluff-Norris record, 26,400 horsepower with 50 per cent flow, and 32'000 horsepower with available storage regulation at the Hebgen and Madison reservoirs. The explorations of the Montana Power Co. for dam foundations in this canyon indicate that the depth to bedrock is too great to permit the economical development of power by a high dam resting on bedrock. Whether grouting of the rock débris that overlies the bedrock in the canyon would be practicable as a preliminary step to the building of a high dam has not been determined. If a high dam is impracticable, the only alternative method of development would be to construct two or more low diversion dams similar to that for the Madison reservoir, with conduits or tunnels. Development by this method would be expensive, for the conduits would in places have to be carried through solid rock. In the remainder of the lower canyon the total fall is 110 feet and the potential power at a plant efficiency of 70 per cent is 10,600 horsepower with 90 per cent flow, 13,200 horsepower with 50 per cent flow, and 16,000 horsepower with storage regulation. The field investigations indicated that the only opportunity for developing power in this lower end of the canyon is probably by diversion from the river in sec. 11, T. 3 S., R. 1 E., through a conduit extending to a power house on the left bank near sec. 30, T. 2 S., R. 2 E. A static head of about 80 feet could be obtained, and the estimated potential power is 7,680 horsepower with 90 per cent flow, 9,600 horsepower with 50 per cent flow, and 11,700 horsepower with available storage regulation. Difficult rock excavation would be encountered in the first 2 miles of the conduit, and one side stream would have to be crossed.

The total estimated undeveloped power on Madison River is 98,300 horsepower with 90 per cent flow, 121,600 horsepower with 50 per cent flow, and 136,400 horsepower with storage regulation. These estimates cover the main stream only. The region has a commercial market that is being abundantly supplied with water power from other sources at a lower cost than is possible by further power development on Madison River; hence the value of the undeveloped power of the stream at present is more theoretical than practical. Changes in this situation are certain to occur in the future, but the extent of such changes can not be foreseen. It is regarded as safe, however, to predict the development to some extent of the potential power resources of two sections, the 10-mile section in the lower canyon below the tailrace of Madison No. 2 plant and the section involving the dam and conduit at the lower end of the upper canyon and the upper end of the middle valley.

With the exception of streams in Yellowstone Park, the only tributary of Madison River known to be valuable for water power is Blaine Springs Creek, the potential power of which is being developed by the Economy Power Co. The potential power in Yellowstone Park is eliminated from consideration, because the scenic beauty of that part of the basin is a resource of value to the entire United States, and this beauty would be marred if not entirely destroyed by commercial development of the water power. Such development has therefore been prohibited by law.

CHEMICAL CHARACTER OF GROUND WATERS OF THE NORTHERN GREAT PLAINS

By H. B. Riffenburg

INTRODUCTION

The area discussed in this report forms the northern part of the Great Plains and extends from the eastern border of the Dakotas to the foothills of the Rocky Mountains and from the Canadian border into northern Wyoming and South Dakota. The section on geology is based on a number of published and unpublished reports on different parts of the area, and only enough description of each group or formation is given to show the relation of the ground water to the rock materials with which it comes into contact. The waters are discussed with reference to their chemical character and the alterations noted in the analyses of waters from different formations, of waters from the same formation in different localities, and of waters from different horizons in a formation.

Chemical and geologic results in published reports of numerous investigations of ground water in parts of Montana and the Dakotas, together with a large number of unpublished analyses made for individual reports, furnished the basis for a general study of the relation between the waters and the rocks of the northern Great Plains. About 400 of the unpublished analyses, made by Margaret D. Foster, C. S. Howard, and the writer, represent samples collected from the area by geologists of the United States Geological Survey and the North Dakota Geological Survey, and about 700 partial analyses were made in other laboratories for purposes that do not require analyses so complete as those made in the water-resources laboratory of the United States Geological Survey.

GEOLOGY

A review of the published reports on the geology of the northern Great Plains shows that the rocks above the granite are regarded as being almost entirely of sedimentary origin. These rocks range in thickness from about 1,000 feet[1] in the eastern part of the area to over 8,500 feet[2] in the western part. The sedimentary rocks consist of shale and sandstone[3] ranging in age from Paleozoic to Quaternary.[4] The present paper relates to the quality of water from the Quaternary, Tertiary, and Cretaceous formations, which are shown in the accompanying comparison of stratigraphic sections. The Fort Union and Lance formations are fresh-water deposits, except that in North and South Dakota the Cannonball member of the Lance is marine. Bowen[5] points out that the fossils indicate that the upper part of the Montana group changes from a fresh-water deposit in the western part of the area to a marine formation in the eastern part. All the formations below this are believed to be marine deposits.

In addition to the publications cited above, which deal with specific localities, a geologic report correlating the formations of the area[6] has been published, and four reports on areas in Montana and one on North Dakota are in preparation.

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[1] Barry, J. G., and Melsted, V. J., The geology of northeastern North Dakota: North Dakota Geol. Survey Fifth Bienn. Rept., p. 149, 1908.

[2] Thom, W. T., jr., Oil and gas prospects in and near the Crow Indian Reservation, Mont.: U. S. Geol., Survey Bull. 736, p. 36, 1922.

[3] Stone, R. W., and Calvert, W. R., Stratigraphic relations of the Livingston formation of Montana: Econ. Geology, vol. 5, p. 752, 1910. Clapp, C. H., Bevan, Arthur, and Lambert, G. S., Geology and gas prospects of central and eastern Montana: Montana Univ. Bull. 4, 1921. Calvert, W. R., and others, Geology of the Standing Rock and Cheyenne River Indian reservations, North and South Dakota: U. S. Geol. Survey Bull. 575, 1914. U. S. Geol. Survey Geol. Atlas, Folios 117, 127, 156, 168, 181, and 209.

[4] Leonard, A. G., North Dakota Geol. Survey Third Bienn. Rept., 1904. Todd, J. E., and Hall, C. M., Geology and water resources of part of the lower James River valley, S. Dak.: U. S. Geol. Survey Water-Supply Paper 90, 1904.

[5] Bowen, C. F., Gradations from continental to marine conditions of deposition in central Montana during the Eagle and Judith River epochs: U. S. Geol. Survey Prof. Paper 125, p. 11, 1920.

[6] Thom, W. T., jr., and Dobbin, C. E., Stratigraphy of the Cretaceous-Eocene transition beds in eastern Montana and the Dakotas: Geol. Soc. America Bull., vol. 35, pp. 481–505, 1924.

Comparison of stratigraphic divisions of Cenozoic and Mesozoic rocks in parts of Montana and the Dakotas

System	Series	Group	Eastern North Dakota	Northwestern South Dakota	Montana east of 106th meridian	Northern and central Montana
Quaternary.			Quaternary.	Quaternary.	Quaternary.	Quaternary.
Tertiary.	Miocene (?).			Arikaree (?) sandstone.	Arikaree (?) sandstone.[a]	
	Oligocene.			White River formation.	White River formation.[a]	
	Eocene.			Fort Union formation.	Fort Union formation (Lebo andesitic member at base).	Fort Union formation (Lebo shale member at base).
Tertiary (?).	Eocene (?).			Lance formation.	Lance formation.	Lance formation.
Cretaceous.	Upper Cretaceous.	Montana.		Fox Hills sandstone.	Fox Hills sandstone.	Lennep sandstone.[b]
			Pierre shale.	Pierre shale.	Pierre shale.	Bearpaw shale. Judith River formation. Claggett formation. Eagle sandstone.
		Colorado.	Niobrara shale.	Niobrara formation.	Niobrara shale.	Colorado shale.
			Benton shale.	Carlile shale. Greenhorn limestone. Graneros shale.	Benton shale.	
			Dakota sandstone.	Dakota sandstone.	Dakota sandstone.	(?)
	Lower Cretaceous.			Fuson formation.	Fuson formation.[c]	Kootenai formation.
				Minnewaste limestone.	(?)	
				Lakota sandstone.	Lakota sandstone.[c]	
Cretaceous (?).	Lower Cretaceous (?).			Morrison formation.	Morrison formation.	Morrison formation.
Jurassic.	Upper Jurassic.			Unkpapa sandstone.	(?)	Ellis formation.
				Sundance formation.	Sundance formation.	

[a] Known only in extreme eastern part of State.
[c] In Crazy Mountain region and probably represented in Bearpaw shale of some other areas.
[b] Southeastern part of State, near Black Hills.

PRECIPITATION

The precipitation in the northern Great Plains ranges from 10 to 30 inches a year, of which as much as 90 or 95 per cent may find its way into the ground. The portion that does not enter the ground may evaporate or run off. Only a small proportion of the precipitation is disposed of by run-off except where the slope is steep. The chief factors that regulate the absorption of water by the ground are surface slope, rate and seasonal distribution of precipitation, temperature of the air, texture of the soil, and vegetative cover. The soils of this area, except those overlying beds of shale, are relatively porous and readily absorb moisture. If, however, the rate of fall is very rapid, as it often is in the summer, or if the precipitation falls on saturated or frozen ground a large part of the water drains off before it can be absorbed.

COMPOSITION OF RAIN WATER

A study of about 200 articles on the composition of rain water in different parts of the world was made by the writer in 1923 and furnishes a basis for an estimate of the general composition of rain water. The following articles contain bibliographies, comprehensive summaries of results, or data of special significance:

Booth, W. M., Water problems: Jour. Ind. and Eng. Chemistry, vol. 2, p. 503, 1910.

Crowther, Charles, and Stewart, D. W., Distribution of atmospheric impurities in the neighborhood of an industrial city: Jour. Agr. Sci., vol. 5, pp. 390–408, 1912.

Dole, R. B., Chlorine content of rain water at Tortugas, Fla.: Washington Acad. Sci. Jour., vol. 4, pp. 3–4, 1914.

MacIntire, W. H., and Young, J. B., Sulphur, calcium, magnesium, and potassium content and reaction of rain water at different points in Tennessee: Soil Sci., vol. 15, p. 205, 1923. Give results of analyses of rain water collected at different points in Tennessee and a short bibliography.

Miller, N. H. J., The amounts of nitrogen as ammonia and as nitric acid and of chlorine in the rain water collected at Rothamsted: Jour. Agr. Sci., vol. 1, pp. 280–303, 1905. Give tables of analyses of rain water collected at Rothamsted and reviews the literature up to 1905.

Russell, E. J., and Richards, E. H., The amount and composition of rainfall at Rothamsted: Jour. Agr. Sci., vol. 9, pp. 309–337, 1919. Summarize analyses covering a period of 28 years, and give a list of references.

Wilson, B. D., Sulphur supplied to the soil in rain water: Am. Soc. Agron. Jour., vol. 13, pp. 226–229, 1921.

A comparison of the published analyses shows the following average amounts of impurities in rain water, in parts per million: Chloride (Cl), 3.0; nitrogen as NO_3, 0.2; nitrogen as NH_3, 0.4; sulphate (SO_4), 5.0. The amount of impurities occurring in rain water varies greatly with conditions and location. The smoke from cities and industrial centers may increase the sulphur and carbon dioxide content several hundred per cent over the amounts found in country districts. The quantities of chloride and of nitrogen do not vary widely. The hydrogen ion concentration (pH) was not given in any of the papers cited.

In connection with the study several samples of rain water collected in Washington, D. C., were analyzed. The maximum and minimum amounts of certain constituents in these waters are shown in the following table. The results are typical of the published analyses of rain waters collected in other cities. These waters probably contain a greater quantity of mineral constituents than rain which has fallen in the open country, as over the Great Plains.

TABLE 1.—*Range in certain constituents of 23 samples of rain water collected at Washington, D. C., 1923–1924, in parts per million*

	Sulphate radicle (SO_4)	Chloride radicle (Cl)	pH
Maximum	17.0	3.0	7.7
Minimum	1.0	Trace.	4.4

None of the samples contained the carbonate radicle (CO_3) or bicarbonate radicle (HCO_3).

GENERAL CHARACTER OF GROUND WATER

Ground waters are chiefly solutions of bicarbonates, sulphates, and chlorides of the alkaline earths and the alkalies. The amounts of these constituents that a water may contain depend on several factors, such as the origin of the water, the time it has been in contact with the rocks, the nature of the rocks, and the degree of concentration, if any, of the water.

Connate waters contain substances which they held in solution at the time of deposition of the beds that contain them, but the constituents of waters of meteoric origin are dissolved from the rock materials through which the waters pass. Meteoric waters entering the soil and rocks first take up soluble constituents from the soil, which always contains a quantity of decaying organic matter, humus, and some disintegrated rock particles. The water, after taking carbon dioxide from the air and from the organic matter and humus, acts vigorously on the rock particles—especially in areas like that here considered, where the amount of feldspar in the rocks is as much as 60 per cent—breaking them up and forming new compounds consisting of calcium, magnesium, and sodium bicarbonate, soluble silicates, free silicic acid, and hydrated aluminum silicate, an end product insoluble in water.[7] In this area, where there is only a moderate

[7] Buckman, H. O., The chemical and physical processes involved in the formation of residual clay: Am. Ceramic Soc. Trans., vol. 8, p. 336, 1911.

amount of precipitation, the products of decomposition of the rocks remain in the soil or are transported to low places, where great quantities of dissolved matter are deposited by evaporation of the water. This concentration furnishes the soluble constituents for the alkali waters, which may continue to seep downward, carrying the mineral matter with them. Headden,[8] Harris,[9] and others have found that the occurrence of alkali in the soils of the Great Plains is practically universal. As the soil becomes saturated the water with its dissolved matter seeps downward, but that remaining within several feet of the surface is brought back by capillary action when the surface becomes dry, and the salts are deposited as the water evaporates. The constituents generally found in the soils or in low places where the water has evaporated are sulphates of sodium, calcium, and magnesium with smaller amounts of bicarbonate. Almost everywhere in this area the shale contains sulphides as pyrites, which upon exposure to the air are oxidized to iron oxides and sulphuric acid. The sulphuric acid then unites with calcium, with sodium, and with magnesium to form sulphates and replace part of the bicarbonate of the waters. Where large quantities of soluble compounds of calcium and magnesium are formed from rocky decay the shallow waters are hard.

CHANGES IN GROUND WATER

The chemical and physical reactions that take place in a water as it percolates through the rocks may vary greatly. Ground waters of meteoric origin in this area may be altered through concentration by evaporation, base exchange, or adsorption of constituents without exchange, reduction of sulphate by carbonaceous solids or gases, concentration by evaporation with natural gas, or change in composition resulting from mixing with connate waters.

BASE EXCHANGE

It has been known since 1850 that clay, soil, and sandstone enter into chemical exchange with solutions, giving off some constituents and taking on others. The literature on base exchange has been reviewed by Sullivan[10] and more recently by Renick,[11] and the reactions were considered by Mills and Wells.[12] Instances of base

[8] Headden, W. P., Alkalies in Colorado: Colorado Agr. Exper. Sta. Bull. 239, 1918.

[9] Harris, F. S., Soil alkali, its origin, nature, and treatment, New York, John Wiley & Sons, 1919.

[10] Sullivan, E. C., The interaction between minerals and water solutions, with special reference to geologic phenomena: U. S. Geol. Survey Bull. 312, 1907.

[11] Renick, B. C., Base exchange in ground water by silicates as illustrated in Montana: U. S. Geol. Survey Water-Supply Paper 520, pp. 53–72, 1924.

[12] Mills, R. V. A., and Wells, R. C., The evaporation and concentration of waters associated with petroleum and natural gas: U. S. Geol. Survey Bull. 693, p. 75, 1919.

exchange in ground waters are noted in unpublished reports on waters in the Coastal Plain of Virginia (by H. B. Riffenburg, 1920), Mississippi (by C. S. Howard, 1921), and North Dakota (by H. B. Riffenburg, 1922). The commonly noted result of base exchange in ground water is softening by contact with rock materials that give up sodium in exchange for calcium and magnesium. The reverse reaction may take place, as pointed out by Mills and Wells, when strong solutions of sodium chloride come into contact with minerals that have previously abstracted calcium and magnesium from hard waters.

ADSORPTION OF BASE AND ACID

The amounts of the different acid ions that are adsorbed by clay, soil, and other rock materials can not be determined without considerable investigation; but apparently the least soluble compounds are lost from solution first and are followed by other compounds in the reverse order of their solubility, because the weak acids have the greater tendency to form insoluble compounds whose salts are hydrolyzed by water. A water that has been in contact with the soil and contains calcium carbonate or sodium and potassium carbonate is alkaline in reaction. A solution containing a salt made up of a strong base and a weak acid (such as the carbonates, silicates, and phosphates of the alkalies and alkaline earths) is hydrolyzed, with the resulting formation of free alkali, which is adsorbed directly without substitution, forming insoluble silicates or aluminum silicates. Where such a reaction takes place the acid radicle may increase in concentration or be adsorbed by the colloid.

Way [13] noted the fact that the weak acids are removed from solution by soils together with the bases.

Henneberg and Stohmann [14] described experiments confirming Way's results. They found that in nitrate, chloride, and sulphate the acid radicle showed little change in concentration but that the acid radicle was precipitated as well as the base from solutions of carbonates, phosphates, or silicates.

Liebig [15] showed that the acid radicle of sodium and potassium silicates was removed in part by soils. According to Kullenberg,[16] the phosphate radicle is taken up by soils from solution in greater

[13] Way, J. T., The power of soils to absorb manure: Roy. Agr. Soc. Jour., vol. 11, p. 359, 1850.

[14] Henneberg, W., and Stohmann, F., Über das Verhalten der Ackerkrume gegen Ammoniak und Ammoniaksalze: Annalen der Chemie, vol. 107, p. 152, 1858; Jour. Landw., vol. 3, p. 25, 1859.

[15] Liebig, Justus von, Über einige Eigenschafter der Ackerkrume: Annalen der Chemie, vol. 105, p. 109, 1858.

[16] Kullenberg, O., Über das Absorptionsvermögen des Erdbodens sind Untersuchungen: Jahrb. Fortschr. agr. Chemie, vol. 8, p. 15, 1865.

quantity the higher the atomic weight of the metal with which it is combined.

Peters[17] found that greater absorption occurs in alkaline solutions than in neutral solutions and that the phosphate ion is absorbed as well as the base.

Warrington[18] and others attribute the removal of weak acid ions from solution by soils chiefly to interaction with ferric and aluminum oxides, with the formation of insoluble compounds.

Van Bemmelen[19] showed that a soil, after extraction with hydrochloric acid, which dissolved the oxides of iron and aluminum and decomposed the silicates, would not precipitate the carbonate, phosphate, and borate radicles, though it had precipitated large amounts of them before extraction. However, if calcium carbonate is present it gives the solution an alkaline reaction, and free alkali unites with the silicic acid and is thus precipitated, while more calcium carbonate dissolves to replace the calcium hydroxide removed. Lemberg,[20] who had earlier brought out the same point, adds:

Consider a carnallite bed underlain by layers of clay, and suppose the clay to be transformed in places to some product rich in potassium, as a mica. Naturally the potassium content of the metamorphic product is attributed to the overlying carnallite. The altered portions contain calcium carbonate and the others do not. Calcium carbonate and sodium chloride acting on the clay form calcium chloride and also potassium carbonate, which, being alkaline, is capable of changing the clay into potassium silicate.

Liégeois and Parmentier[21] found appreciable quantities of calcium carbonate precipitated in sieved sand and sand washed with hydrochloric acid after the sand had been put in glass tubes and water containing bicarbonate percolated through it from six days to a year. They contend that the calcium bicarbonate is broken up, forming calcium carbonate, which is precipitated, and carbon dioxide, which passes off into the air.

REDUCTION OF SULPHATE

The reduction of sulphate in ground waters has been observed in the United States, Europe, and Asia. The reaction between sulphate

[17] Peters, E., Studien über den Boden, aus dem Laboratorium zu Tharend; Über die Absorption von Kali durch Ackererde: Landw. Vers.-Stat., vol. 2, p. 113, 1860.

[18] Warrington, Robert, jr., On the part taken by oxide of iron and alumina in the absorptive action of soils: Chem. Soc. London Jour., vol. 21, p. 1, 1868.

[19] Van Bemmelen, J. M., Das Absorptionsvermögen der Ackererde: Landw. Vers.-Stat., vol. 23, p. 267, 1879.

[20] Lemberg, J., Über Silicatumwandlungen: Deutsch. geol. Gesell. Zeitschr., vol. 28, pp. 593–594, 1876.

[21] Liégeois, P., and Parmentier, A., Expériences sur la circulation des eaux calcareuses dans les terrains poreux: Soc. géol. Belgique Annales, vol. 45, pp. B 147–151, 1922; vol. 46, pp. B 235–236, 1923.

and organic matter was suggested by Bischof [22] to explain the origin of certain sulphur deposits.

In 1882 Potilitzin [23] pointed out that the waters associated with oil in the Caucasian oil fields contained no sulphate.

Höfer [24] noted the widespread occurrence of oil-field waters low in sulphate and suggested that the sulphate is reduced to hydrogen sulphide, which passes off while an equivalent portion of the natural gas is oxidized to carbon dioxide and carbonate. His equation follows:

$$CaSO_4+CH_4=CaO+H_2S+CO_2+H_2O$$

or

$$CaSO_4+CH_4=CaS+CO_2+2H_2O=CaCO_3+H_2S+H_2O$$

Rogers,[25] Renick,[26] and others have referred to occurrences of waters that appear to have been altered by these reactions.

Meyer [27] and others have shown that microorganisms decompose sulphates. The sulphide-producing bacteria are anaerobic, but it is very doubtful if they can live under the conditions and at the depth of most ground waters that have undergone such alteration.

LABORATORY TESTS OF REACTIONS BETWEEN WATERS AND ROCK MATERIALS FROM MONTANA

Some of the reactions discussed in the preceding pages were obtained in the laboratory by allowing natural waters to come into contact with samples of sandstone and shale collected by B. C. Renick in Rosebud County and by G. M. Hall in Fergus County, Mont. The rock samples were probably somewhat weathered, and one of them apparently contained salts deposited by the evaporation of ground water, but the tests illustrate the kinds of exchange and absorption that must take place underground. The results of some of the tests are given in Table 2. For convenience of comparison the analytical results are given in milligram equivalents of the radicles per kilogram of water as well as in parts per million. The quantities of water and rock given are only approximate.

[22] Bischof, G., Chemische und physikalische Geologie, vol. 2, pp. 144–164, 1851.

[23] Potilitzin, A., Zusammensetzung des die Naphta begleitenden und aus Schlammvulkanen ausströmenden Wassers: Russ. phys.-chem. Gesell. Jour., vol. 1, p. 300, 1882; abstract in Deutsch. chem. Gesell. Ber., Band 15, p. 3099, 1882.

[24] Engler, C., and Höfer, H., Das Wasser in den Erdölgebieten: Das Erdöl, Band 2, p. 28, 1909.

[25] Rogers, G. S., Chemical relations of the oil-field waters in San Joaquin Valley, Calif.: U. S. Geol. Survey Bull. 653, 1917.

[26] Renick, B. C., Some geochemical relations of ground water and associated natural gas in the Lance formation of Montana: Jour. Geology, vol. 32, pp. 668–684, 1924.

[27] Meyer, Lothar, Chemische Untersuchung der Thermen zu Landeck in der Grafschaft Glatz: Jour. prakt. Chemie, Band 91, pp. 5–6, 1864.

TABLE 2.—*Partial analyses of water before and after treatment with rock materials*

No.[a]	Total hardness as $CaCO_3$ (calculated)		Bicarbonate radicle (HCO_3)		Sulphate radicle (SO_4)	
	Parts per million	Milligram equivalents per kilogram	Parts per million	Milligram equivalents per kilogram	Parts per million	Milligram equivalents per kilogram
1 A	497	9.94	634	10.39	909	18.93
B	314	6.28	318	5.21	-----	-----
2 A	497	9.94	1,044	17.11	909	18.93
B	391	7.82	986	16.16	-----	-----
3 A	497	9.94	1,044	17.11	909	18.93
B	264	5.38	795	13.03	1,000	20.82
4 A	226	6.10	368	6.03	100	2.08
B	0	.0	305	5.00	450	9.37
5 A	257	5.14	458	7.51	139	2.89
B	55	1.10	415	6.80	241	5.02
6 A	257	5.14	458	7.51	139	2.89
B	136	2.72	331	5.42	173	3.60
7 A	293	5.86	473	7.75	148	3.08
B	195	3.90	356	5.83	189	3.94
8 A	317	6.34	473	7.75	148	3.08
B	143	2.86	379	6.21	165	3.44
9 A	107	2.14	461	7.56	51	1.06
B	36	.72	-----	-----	69	1.44
10 A	794	15.89	681	11.16	681	14.18
B	600	12.28	610	10.00	938	19.53
11 A	107	2.14	-----	-----	-----	-----
B	183	3.66	-----	-----	-----	-----
12 A	107	2.14	-----	-----	-----	-----
B	137	2.74	-----	-----	-----	-----
13 A	107	2.14	-----	-----	-----	-----
B	55	1.10	-----	-----	-----	-----

[a] A, before treatment; B, after treatment.

1. 100 cubic centimeters of water percolated in 3 hours through 150 grams of Fort Union sandstone in a long glass tube.
2. 100 cubic centimeters of water percolated in 5 minutes through 400 grams of Fort Union sandstone in a small laboratory softener.
3. Same as test 2, except that the time of contact was 3 days.
4. 50 cubic centimeters of water in contact 2 months with 2 grams of Fort Union sandstone in a beaker.
5. 250 cubic centimeters of water in contact 16 hours with 300 grams of Fort Union sandstone in a beaker.
6. 250 cubic centimeters of water in contact 16 hours with sandstone used in test 2.
7. 500 cubic centimeters of water in contact 22 hours with 500 grams of Eagle sandstone in a small laboratory softener.
8. 250 cubic centimeters of water in contact 18 hours with the sandstone used in test 1.
9. 25 cubic centimeters of water in contact 40 hours with 2.5 grams of Lance sandstone.
10. 250 cubic centimeters of water in contact with 400 grams of Lance sandstone in a beaker.
11. 25 cubic centimeters of water in contact 40 hours with 2.5 grams of Lance shale.
12. 25 cubic centimeters of water in contact 40 hours with 2.5 grams of Lance shale in a beaker.
13. Same as test 12, except that the time of contact was 40 days.

In test 1 the bicarbonate lost through contact with the rock was more than equivalent to the reduction in hardness; in tests 3, 4, 5, 6, 8, and 10 the reduction in bicarbonate was less than the reduction in hardness. In tests 3, 6, and 8 the increase in sulphate is equivalent to less than half the decrease in bicarbonate; in tests 4, 5, and 10 it is three to seven times the decrease in bicarbonate. In test 7 the decrease in bicarbonate is almost exactly equivalent to the decrease in hardness, but at the same time the sulphate increased by an amount equivalent to about half the loss in bicarbonate or hardness.

Tests 2 and 3, which are typical, show that a certain amount of softening may take place almost instantly and that the softening action may continue for a considerable time. This water showed comparatively little increase in sulphate. The chloride content of the waters was practically unchanged in all the tests.

It is evident that the softening which takes place in these waters is due partly to direct adsorption of calcium and magnesium carbonates and partly to base exchange in which calcium and magnesium have been given up for sodium. Some of the reduction in bicarbonate may be due to an exchange with sulphate. However, the wide variation in amounts of sulphate taken up by the water with apparently no relation to the decrease in bicarbonate or the amount of softening makes it impossible to approximate the amount of exchange of acid radicles.

CHARACTER OF WATERS FROM INDIVIDUAL FORMATIONS

Although the waters in any geologic formation may vary widely in composition, there are nevertheless limits of concentration and general characteristics that can be given for the waters of each of the main formations in the area here considered. The analytical results represented by typical analyses and summary tables in the following discussions of the formations illustrate the changes that have been described above.

WATERS FROM THE SURFICIAL DEPOSITS

The surficial deposits of the northern Great Plains consist of clay, sand, and gravel which have been derived from the sedimentary rocks of the area and from many kinds of rocks brought in from different areas by ice, water, or wind. These deposits range in thickness from 1 foot to over 200 feet.

The waters contained in these deposits entered the surface as meteoric waters of about the composition shown in Table 1 (p. 35). The widely varying amounts of constituents which the waters dissolved from the rock materials with which they came into contact are shown in Table 3.

TABLE 3.—*Constituents of waters from surficial deposits in Montana and North Dakota*

[From 142 analyses made in the water-resources laboratory of the United States Geological Survey. Parts per million]

	Maximum	Minimum	Average
Calcium (Ca)	500	15	124
Magnesium (Mg)	201	9.0	53
Sodium and potassium (Na+K)	880	4.0	140
Bicarbonate radicle (HCO_3)	883	95	412
Sulphate radicle (SO_4)	1,600	12	382
Chloride radicle (Cl)	472	1.0	58
Total dissolved solids at 180° C	3,660	223	1,027
Total hardness as $CaCO_3$ (calculated)	1,972	88	574

The quantities of sulphate, chloride, and carbonate (calculated from bicarbonate) are plotted against the sum of the constituents for each of the 142 analyses of waters from the surficial deposits in the area, and the resulting curve is shown in Figure 3. A large number of the waters have less than 600 parts per million of mineral constituents in solution. Examination of the individual analyses shows that waters from these deposits may be divided into two types—those with calcium, magnesium, and carbonate predominating, of which A, Figure 4, is representative; and those with calcium, magnesium, and sulphate predominating, of which B, Figure 4, is representative. The increase in solids above 600 parts per million is generally due to the addition of sodium and sulphate, as represented by C, Figure 4. Figure 3 shows that after the concentration has reached about 700 parts per million sulphate increases in definite proportion to the total

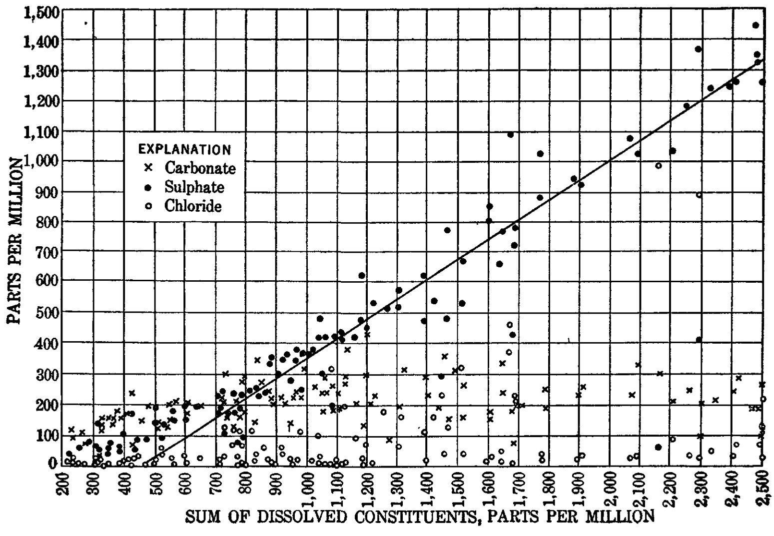


FIGURE 3.—Relation of carbonate, sulphate, and chloride to sum of dissolved constituents in waters from surficial deposits of northern Great Plains

dissolved solids but that bicarbonate and chloride have little relation to concentration. Individual analyses show that sodium is generally the added basic radicle when the concentration is high.

Table 3 shows that practically all the waters are hard. As previously explained this hardness is due to the solution of calcium and magnesium liberated by disintegration of the feldspars and other rock materials. The analyses of waters from the surficial deposits all show bicarbonate with no carbonate, because carbonates are changed to bicarbonates in the presence of air and carbon dioxide.

Many highly mineralized waters occur in surface deposits as a result of concentration by evaporation, which takes place in the waters of such deposits after they have accumulated from higher places either as run-off or as seepage water. After a dashing rain or rapidly melting snow the water drains off the higher slopes, carrying with it any soluble materials picked up from the surface, and accumulates in the lower places or valleys, which serve as a reservoir. Water that seeps into the ground may be carried to the lower places in the water table, where in dry spells it is brought to the surface again by capillary action. This water carries a variable amount of dissolved material, which is deposited upon evaporation. Any water in the low places that continues to seep into the ground contains great quantities of dissolved minerals, and if a well is driven where such water can enter it a highly mineralized water will be obtained.

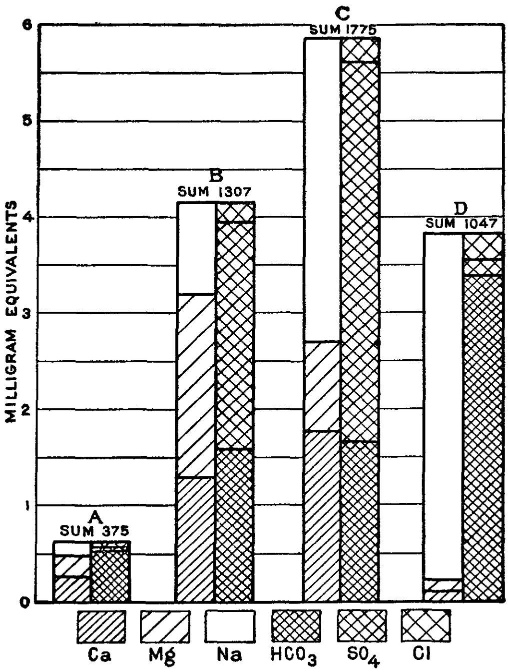


FIGURE 4.—Dissolved constituents in typical waters from northern Great Plains. (For explanation of diagram, see Collins, W. D., Graphic representation of water analyses: Ind. and Eng. Chemistry, vol. 15, No. 4, p. 394, 1923)

WATERS FROM THE FORT UNION AND LANCE FORMATIONS

The Fort Union and Lance formations are sedimentary deposits that were laid down in fresh water, except the Cannonball marine member of the Lance formation. The Fort Union consists of sandstone and soft shale, with persistent beds of lignite. It is underlain by the Lance formation, which is very similar in composition. The Fort Union is overlain in parts of the region by late Tertiary deposits, glacial drift, or other surficial deposits. Where it is eroded away the Lance is exposed. The maximum thickness of the two is about 2,000 feet. The waters in these formations are very similar and will be considered together.

Waters of meteoric origin reaching these formations have first percolated through the surficial deposits and dissolved a variable amount of mineral matter. Analyses show that the waters from surficial deposits overlying the Fort Union and Lance formations generally contain from 300 to 1,000 parts per million of total dissolved solids, of which calcium and magnesium are the principal basic radicles and make the waters hard. The changes in chemical character of the waters that have percolated into the Fort Union and Lance formations are shown by the analyses discussed below.

TABLE 4.—*Typical analyses of waters from Fort Union and Lance formations*

[Parts per million]

No.	Total dissolved solids at 180° C.	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Carbonate radicle (CO_3)	Bicarbonate radicle (HCO_3)	Sulphate radicle (SO_4)	Chloride radicle (Cl)	Nitrate radicle (NO_3)	Total hardness as $CaCO_3$ [a]	Analyst [b]
Fort Union													
1	2,345	15	0.75	16	4.8	882	29	2,152	31	110	Trace.	60	H. B. R.
2	1,294	8.6	.33	4.0	2.9	456	38	522	506	8.0	Trace.	22	H. B. R.
3	1,010	13	.40	5.2	1.8	{Na 401, K 12}	0	964	7.2	78	Trace.	20	H. B. R.
4	1,351	28	5.3	144	135	92	0	517	634	11	1.5	914	H. B. R.
Lance													
5	1,580	21	0.31	4.8	3.4	640	0	1,332	6.6	236	Trace.	26	H. B. R.
6	1,204	12	Trace.	5.2	2.3	488	43	932	3.3	166	1.5	22	H. B. R.
7	477	8.8	.40	12	6.1	155	0	381	66	3.0	Trace.	55	H. B. R.
8	640	10	.20	61	29	134	0	444	165	12	10	271	H. B. R.
9	1,328	10	.13	6.2	.8	467	36	473	518	32	1.6	19	C. S. H.
10	208	4.0	.12	30	17	[a]8.5	0	156	31	2.0	.38	145	C. S. H.

[a] Calculated.
[b] H. B. R., H. B. Riffenburg, U. S. Geol. Survey; C. S. H., C. S. Howard, U. S. Geol. Survey.

1. Well 175 feet deep in SE. ¼ sec. 21, T. 155 N., R. 85 W., Ward County, N. Dak. Collected July 5, 1921.
2. Well 300 feet deep in NE. ¼ sec. 27, T. 140 N., R. 102 W., Billings County, N. Dak. Collected July 20, 1921.
3. Well 178 feet deep in NE. ¼ sec. 3, T. 3 S., R. 44 E., Rosebud County, Mont. Collected July 24, 1923.
4. Well 48 feet deep in NW. ¼ sec. 6, T. 1 N., R. 40 E., Rosebud County, Mont. Collected July 30, 1923.
5. Well 2,100 feet deep in SW. ¼ sec. 29, T. 154 N., R. 100 W., Williams County, N. Dak. Collected June 22, 1921.
6. Well 365 feet deep in SW. ¼ sec. 22, T. 1 N., R. 44 E., Rosebud County, Mont. Collected July 23, 1923.
7. Well 19 feet deep in SE. ¼ sec. 23, T. 6 N., R. 39 E., Rosebud County, Mont. Collected August 20, 1923.
8. Well 53 feet deep in NE. ¼ NE. ¼ sec. 23, T. 10 N., R. 34 E., Rosebud County, Mont. Collected October 8, 1923.
9. Well 100 feet deep in SE. ¼ sec. 7, T. 3 N., R. 26 E., Yellowstone County, Mont. Collected October 27, 1921.
10. Spring in S. ½ sec. 9, T. 5 N., R. 36 E., Treasure County, Mont. Collected September 29, 1921.

Analyses of characteristic waters from the Fort Union and Lance formations are given in Table 4; maximum, minimum, and average amounts of constituents of 118 analyses of waters from these formations are shown in Table 5; the relation of quantities of certain constituents to the total is shown in Figure 5; and the relation of total hardness to depth of wells in the Fort Union and Lance formations is shown in Figure 6. The waters represented by analyses 4, 7, 8, and 10 in Table 4 came from shallow wells and with the exception of No. 7 are similar in character to those represented by A and B, Figure 4, which is typical of the shallow-well waters of these formations as well as the waters of the surficial deposits. Tables 4 and 5 and the individual analyses show that nearly all the waters from shallow wells in the Fort Union and Lance formations are hard and are similar in character to the waters from the surficial deposits.

TABLE 5.—*Constituents of waters from Fort Union and Lance formations*

[Based on 118 analyses made in water-resources laboratory of United States Geological Survey. Parts per million]

	Fort Union			Lance		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Calcium (Ca)	336	4.0	54	110	3.8	21
Magnesium (Mg)	215	1.0	41	71	.8	13
Sodium and potassium (Na+K)	920	8.0	286	957	8.0	470
Bicarbonate radicle (HCO_3)	2,152	63	666	1,674	155	789
Sulphate radicle (SO_4)	2,440	2.6	316	1,594	1.0	379
Chloride radicle (Cl)	306	1.0	33	533	2.0	72
Total dissolved solids at 180° C	3,735	274	1,080	2,911	170	1,381
Total hardness as $CaCO_3$ (calculated)	1,722	15	295	516	14	108

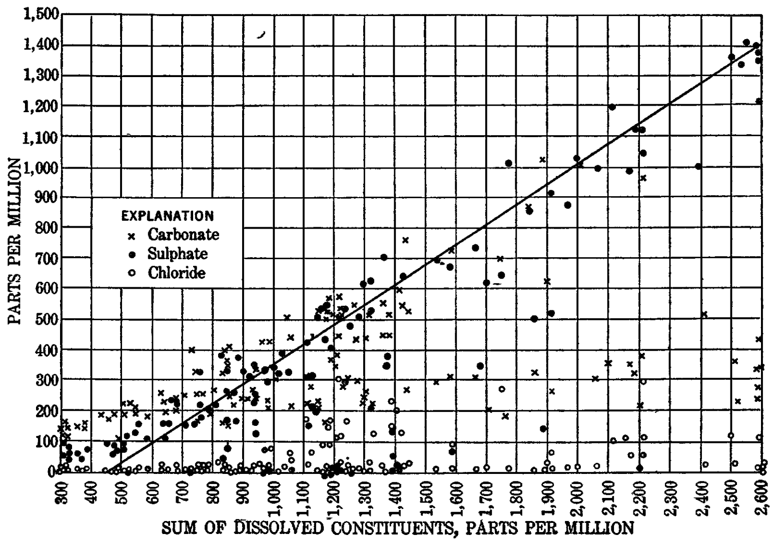


FIGURE 5.—Relation of carbonate, sulphate, and chloride to sum of dissolved constituents in waters from Fort Union and Lance formations

Analyses 1, 2, 3, 5, 6, and 9, Table. 4, represent deep-well waters, of which D, Figure 4, is typical, and show an entirely different character from that of the shallow-well waters in the Fort Union and Lance formations. The striking features of the deep-well waters are that they are all soft, that many of them contain carbonate as well as bicarbonate, and that although some of them contain large amounts of sulphate (analyses 2 and 9), others contain very little (analyses 1, 3, 5, and 6).

Figure 6 shows that a definite relation exists between hardness and depth of wells. The waters from wells 100 to 125 feet deep are generally soft, and all the waters below this depth are soft. A comparison of the analyses of the deep-well waters with those of waters from the shallow wells shows that a definite softening action has taken place in the deep waters. Renick[28] concludes from a microscopic examination of some of the rock materials from Rosebud County, Mont., that the softening action in these formations is due to leverrierite.

The analyses and the experiments discussed on page 39 suggest that some of the softening may be due to adsorption of calcium and magnesium carbonate. Analyses 1, 2, 6, and 9, like many other analyses of waters of these formations, show carbonate in variable

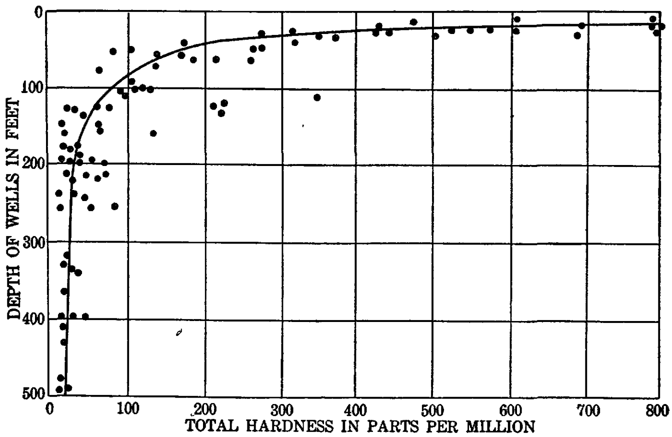


FIGURE 6.—Relation of total hardness to depth of wells in Fort Union and Lance formations

amounts, together with bicarbonate. Large quantities of calcium and magnesium can not remain in solution in the presence of carbonate, and these constituents may have been precipitated as the waters seeped through the rocks that contained carbonaceous materials.

From a comparison of Figures 3 and 5 it will be seen that in most waters in the surficial deposits carbonate equivalent to the bicarbonate is well under 300 parts per million, whereas in many waters from the Fort Union and Lance formations nearly twice as much is found, and a few contain bicarbonate equivalent to over 1,000 parts of carbonate. Figures 3 and 5 show that there is no noticeable difference in the amounts of chloride in waters from the two horizons. Individual analyses of waters from wells more than 100 feet deep in the Fort Union and Lance formations do not show

[28] Renick, B. C., Base exchange in ground water by silicates as illustrated in Montana: U. S. Geol. Survey Water-Supply Paper 520, pp. 53–72, 1924.

much variation in the amount of dissolved constituents as the depth of wells increase.

Figures 3 and 5 show sulphate to be the added basic radicle in the highly concentrated waters of the surficial deposits and of the Fort Union and Lance formations. Figure 5 shows that in many of the waters from the Fort Union and Lance formations the quantity of sulphate is very low and the bicarbonate high, a relation which is not shown in Figure 3 for waters of the surficial deposits. Examination of analyses of waters from the surficial deposits and from the Fort Union and Lance formations shows that the deep-well waters in the Fort Union and Lance formations are the only ones that contain small amounts of sulphate. Analyses 1, 3, 5, and 6 in Table 4, like many other analyses of waters from these formations, show that the waters deficient in sulphate contain unusually large amounts of bicarbonate. The relation of sulphate to bicarbonate in these waters and in the waters of shallow wells in these formations or in the surficial deposits may be explained as due either directly or indirectly to the action of the lignite, carbonaceous shale, or natural gas contained in the rocks of the Fort Union and Lance formations in the manner discussed by Höfer, referred to on page 39. It appears from examination of the analyses that the waters containing sulphate, such as those represented by A and B, Figure 4, have had their sulphate reduced on sinking to greater depths and at the same time have taken up large amounts of bicarbonate. (See analyses 1, 3, 5, and 6.) The waters showing such changes came from wells that draw on strata near lignite beds or beds containing considerable natural gas. According to the reaction described by Höfer an equivalent amount of bicarbonate is produced for the sulphate reduced. Many waters of the area appear to show this relation, but others may have been further altered later, so that the effect of this change is concealed.

Below is a comparison of the acid radicles shown by analyses of two waters from different depths in the same section in Rosebud County, Mont., that are typical of many waters throughout the area.

TABLE 6.—*Constituents of waters from shallow and deep wells in the same locality, Rosebud County, Mont.*

[Miligram equivalents per kilogram]

	Shallow well	Deep well
Carbonate radicle (CO_3)	0.00	1.20
Bicarbonate radicle (HCO_3)	8.47	12.00
Sulphate radicle (SO_4)	4.41	.06
Chloride radicle (Cl)	.20	.51
	13.08	13.77

WATERS FROM THE MONTANA GROUP

The Montana group occurs throughout most of the area considered. Its divisions vary with the locality, as shown in the geologic column (p. 33). The group is essentially a salt-water deposit.[29] The rocks consist of shale, except where they are interstratified with sandstone and sandy shale. Many of the sandstone beds are lenticular and not very thick. The group is not water-bearing throughout, though some of the larger sandstone beds, as the Judith River, the Fox Hills, and the Eagle, yield considerable water. The shales do not give up their water readily, and few wells sunk in them yield satisfactory supplies.

Table 7 gives the maximum, minimum, and average amount of constituents contained in the waters from this group.

TABLE 7.—*Constituents of waters from the Montana group*

[Based on 83 analyses made in the water-resources laboratory of the United States Geological Survey. Parts per million]

	Maximum	Minimum	Average
Calcium (Ca)	523	3.0	82
Magnesium (Mg)	285	1.7	54
Sodium and potassium (Na+K)	2,438	16	457
Bicarbonate radicle (HCO_3)	1,691	44	562
Sulphate radicle (SO_4)	5,609	5.9	676
Chloride radicle (Cl)	1,048	1.0	80
Total dissolved solids at 180° C	8,726	336	1,742
Total hardness as $CaCO_3$ (calculated)	1,907	18	460

Nearly all the waters analyzed came from shallow dug wells, many of which are in the soils and weathered portions of the rocks. These waters are similar in character to those of the surficial deposits. Probably the greatest variation is in concentration. Many of the waters resemble those represented by A, B, and C, Figure 4, and others resemble waters from the Lance and Fort Union formations. Bowen[30] reports that some of the sandstones of this group resemble those of the Lance formation in character and composition, from which it may be inferred that the water in these beds has been subjected to a softening action similar to that which has occurred in the Fort Union and Lance formations. However, only a very few waters with hardness less than 50 parts per million have been found in these beds. Perhaps if the sandstones were thicker and the wells deeper more soft waters would be found.

The chlorides are higher in many waters from the east end of the area than in those from the west end. Many of the high-chloride

[29] Stanton, T. W., and Hatcher, J. B., Geology and paleontology of the Judith River beds: U. S. Geol. Survey Bull. 257, 1905.

[30] Bowen, C. F., Gradations from continental to marine conditions of deposition in central Montana during the Eagle and Judith River epochs: U. S. Geol. Survey Prof. Paper 125, p. 11, 1920.

waters come from lenticular deposits of sandstone and have neither migrated far nor been replaced by meteoric waters, because the relatively impervious shale in which the sandstone lenses occur has held the waters of deposition within the sandstone. The sandstones in the west end of the area are partly fresh-water deposits, and they were laid down in larger areas and thus afford more favorable conditions for washing by the meteoric waters under static pressure toward the west.

Table 7 and the individual analyses show that some of these waters are higher in bicarbonate than those from the surficial deposits and that some of them contain very small amounts of sulphate. This condition is probably due to the formation of carbonates with the reduction of sulphate in the same manner as in waters in the Fort Union and Lance formations, described above.

Many of the waters from the Montana group appear not to have undergone extensive alteration but simply to have dissolved the soluble materials of the rocks. Others appear to have undergone alterations similar to those in the waters of the Fort Union and Lance formations. (See pp. 43–47.)

Waters containing much more than 1,000 parts per million of mineral matter generally have sodium and sulphate as the added constituents, but in a few calcium, magnesium, and sulphate are the constituents in excess of the quantities found in the less mineralized waters.

TABLE 8.—*Typical analyses of waters from the Dakota and Lower Cretaceous sandstones*

[Parts per million]

	1	2	3	4	5	6	7
Silica (SiO_2)	19	33	17	27	25	19	30
Iron (Fe)	2.0	3.2	2.3	.14	.48	Trace	.27
Calcium (Ca)	30	5.6	204	10	13	6.8	4.8
Magnesium (Mg)	13	2.4	64	1.7	5.8	2.0	1.6
Sodium and potassium (Na+K)	990	1,248	320	1,318	13	198	{Na 350 {K 5.6
Carbonate radicle (CO_3)	0	48	0	72	0	24	38
Bicarbonate radicle (HCO_3)	495	1,025	171	1,957	49	483	425
Sulphate radicle (SO_4)	236	764	1,200	7.9	6.1	12	329
Chloride radicle (Cl)	1,150	710	70	832	23	2.0	24
Nitrate radicle (NO_3)	Trace.	Trace.	Trace.	Trace.	6.0	Trace.	Trace.
Total dissolved solids at 180° C	2,700	3,400	2,079	3,398	174	505	995
Total hardness as $CaCO_3$ (calculated)	128	22	772	32	56	25	19
Date of collection	June 28, 1921.	June 12, 1921.	June 28, 1921.	Aug. 27, 1921.	Aug. 22, 1922.	Sept. 6, 1922.	Sept. 1, 1923.
Analyst [a]	H. B. R.	H. B. R.	H. B. R.	C. S. H.	H. B. R.	H. B. R.	H. B. R.

[a] H. B. R., H. B. Riffenburg, U. S. Geol. Survey; C. S. H., C. S. Howard, U. S. Geol. Survey.

1. Well 1,087 feet deep, SW. ¼ sec. 12, T. 129 N., R. 63 W., Dickey County, N. Dak.
2. Well 2,235 feet deep, SW. ¼ sec. 31, T. 150 N., R. 72 W., Wells County, N. Dak.
3. Well 1,385 feet deep, SW. ¼ sec. 12, T. 129 N., R. 63 W., Dickey County, N. Dak.
4. Well 2,235 feet deep, SE. ¼ sec. 7, T. 2 S., R. 24 E., Yellowstone County, Mont.
5. Well 60 feet deep, NW. ¼ sec. 7, T. 13 N., R. 24 E., Fergus County, Mont.
6. Well 417 feet deep, NE. ¼ sec. 5, T. 15 N., R. 18 E., Fergus County, Mont.
7. Well 1,860 feet deep, SE. ¼ sec. 1, T. 15 N., R. 28 E., Fergus County, Mont.

WATERS FROM THE COLORADO GROUP

The Colorado shales are of very fine grain and are poor water bearers. They are similar to the shales of the Montana group and in places yield small amounts of water similar in character to the water in the Montana group. Not enough samples from this group were analyzed to warrant a detailed study. In the area here discussed it is drawn upon for a water supply only to a minor extent in a small area in Montana, where it forms the bedrock. The waters are generally hard and highly mineralized and are unsatisfactory for domestic use.

WATERS FROM THE DAKOTA AND LOWER CRETACEOUS SANDSTONES

The Dakota sandstone consists of sandstone interstratified with shaly beds. It occurs throughout the area and is overlain by the Colorado group except in the Red River valley of North Dakota, where surficial deposits form the overlying beds, and in small areas in Montana, where the overlying beds have been eroded away. It has not been reached by drilling in the central part of the area, but farther east it is valued for the great quantity of water it yields by artesian flow. Of the Dakota waters analyzed many of those from the western part of the area came from deep wells being drilled for oil. Those from the eastern part came from the first, second, or third sand in the Dakota sandstone.

Table 8 gives representative analyses of waters from the Dakota sandstone, and Table 9 gives the maximum, minimum, and average quantities of dissolved constituents in the 57 waters analyzed.

TABLE 9.—*Constituents of waters from the Dakota and Lower Cretaceous sandstones*

[Based on 57 analyses made in the water-resources laboratory of the United States Geological Survey. Parts per million]

	Maximum	Minimum	Average
Calcium (Ca)	204	5.0	60
Magnesium (Mg)	72	1.2	16
Sodium and potassium (Na+K)	1,710	3.0	629
Bicarbonate radicle (HCO_3)	1,402	49	662
Sulphate radicle (SO_4)	1,989	2.0	542
Chloride radicle (Cl)	1,832	2.0	355
Total dissolved solids at 180° C	4,799	174	1,988
Total hardness as $CaCO_3$ (calculated)	772	17	150

The waters from different localities and horizons differs considerably in character. Shepard[31] found that the artesian waters from

[31] Shepard, J. H., The artesian waters of South Dakota: South Dakota Agr. College and Exper. Sta. Bull. 41, 1895.

the first sand are generally soft and high in chloride, but that waters from the lower sands are hard and generally contain relatively small amounts of chloride. Meinzer[32] noted similar conditions in the Cretaceous waters in southwestern Minnesota. Analyses 1 and 2, Table 8, represent waters from the first sand and analysis 3 a water from the second sand. These waters are representative of waters from North Dakota and of those from South Dakota cited by Shepard. They confirm the characteristics brought out by Shepard. Analyses 5, 6, and 7 are typical of the waters from the west end of the area, where no difference was noted in the character of waters from different horizons. These analyses show that the waters are soft, that some of them contain very small quantities of sulphate, that all are low in chloride content, and that none are highly mineralized. The waters of the west end are not so highly mineralized as those of the east end: they are, if anything, lower in chloride than waters from the second sand, and they are comparatively soft, like those from the first sand. Sulphate is high in all the waters from the second sand and in most of those from the first sand. No reduction of sulphate is apparent in these waters, but analyses of some of the waters in the west end of the area indicate that sulphate has been reduced, as in the waters of the Fort Union and Lance formations. Table 8 shows that waters from both ends of the area contain carbonate as well as bicarbonate. Analysis 3 shows a relatively small content of bicarbonate, which was noted in several of the waters from the east end. It has been suggested that the hardness of the waters from the second sand is due to the large amount of limestone lying at the base of the sandstone.

The water represented by analysis 4 is the only one in the whole western part of the area that shows either so high a concentration or so much chloride.

It appears that the waters in the first sand in the east end of the area have undergone only one characteristic alteration—namely, softening—though the sulphate in some of them may have been reduced. Although the analyses do not show a similarity to sea water, they indicate that connate waters still occur in the rocks and that such waters may have been greatly diluted with meteoric water. Analyses of waters from the western part of the area and from the deeper sands in the eastern part suggest that these waters are entirely of meteoric origin and have dissolved their load of mineral matter from the materials with which they have come into contact, unless the deposits were laid down in a fresh-water lake.

[32] Hall, C. W., Meinzer, O. E., and Fuller, M. L., Geology and underground waters of southern Minnesota: U. S. Geol. Survey Water-Supply Paper 256, pp. 54–78, 132, 210, 304, 1911.

SUMMARY

The relative proportions of the several constituents in the waters of the northern Great Plains, whether from the fresh-water deposits or from the rocks that were laid down in a salty sea, indicate that the ground waters are in general of meteoric origin and have replaced the waters of sedimentation, and this conclusion is supported by the fact that they contain only small quantities of chloride. The deep-seated waters in the east end of the area may be mixtures of connate and meteoric waters. Extensive migration and the partial expulsion of the included waters have been due to the consolidating processes that took place as deposition continued. The later tilting of the beds in the Rocky Mountains has caused more or less movement in the waters toward the east by hydrostatic pressure, and the exposure of the formations in the foothills affords an opening to the rocks to receive a continuous supply of rain and snow water. Cementation, heat, and the chemical and mineral changes within the rocks also assisted in the migration and expulsion of the interstitial waters.

Meteoric waters containing a small amount of mineral matter absorbed from the air have dissolved more material from the soil and rocks through which they percolated. The chemical character of these waters has been altered by reaction with the materials with which they have come into contact. The changes in the waters from the time they entered the soil as rain to the time that they were analyzed have resulted from the solution of such compounds as sulphates and carbonates of calcium, magnesium, and sodium; from the redeposition and exchange of part of the constituents; and from chemical reactions brought about by the oxidation of pyrite or by the reduction of sulphates, whether by bacteria or organic matter.

Some of the shallow waters have been concentrated by evaporation, but there is little evidence of such concentration of the deep-seated waters.

INDEX OF ANALYSES OF NATURAL WATERS IN THE UNITED STATES

By W. D. Collins and C. S. Howard

INTRODUCTION

Examinations of water by Federal, State, or municipal agencies have been made mainly for the solution of problems relating to health and sanitation, but many analyses have been made that show the chemical characteristics of waters and indicate their suitability for industrial use and for irrigation.

The water-supply papers and other publications of the United States Geological Survey contain more mineral analyses than any other series of publications. Several State laboratories have published collections of mineral analyses and either alone or in cooperation with the United States Geological Survey have made comprehensive surveys of the surface and ground waters within their respective States. For other States comparatively little has been published. The list of published collections of analyses given in this paper is intended to include all Federal and State reports of geological surveys, experiment stations, and health departments. In addition, references are given to journal articles that contain collections of analyses. The Geological Survey will welcome corrections or additions for revision or extension of the list.

ANALYSES FOR PRIVATE INTERESTS

As a general rule public funds are not available to pay for making water analyses for the benefit of private persons or corporations. It is evident, however, that many analyses which may have value to individuals ought to be made for the public welfare. This consideration applies particularly to examinations of the sanitary condition of bottled water or water from privately owned systems of public water supply.

In areas that are not fully developed the analysis of water for private interests may be a useful part of governmental aid in the settlement and development of the lands, to add to the wealth and income of a State. In the course of a systematic survey of water conditions in an area many analyses of waters controlled by private persons are likely to be made, but the samples are taken as representative of conditions in definite geologic formations or in certain significant localities.

ANALYSES FOR PUBLIC SURVEYS

The individual who wishes to know the chemical composition of water from a particular source can have an analysis made by a commercial laboratory as well as by a public laboratory. The one who wishes to know where water of a given composition can be obtained or the sections of the country where different kinds of water are to be found can hardly afford to send and get samples for all the analyses needed to answer his question, much less to pay for the analyses. An inventory of the natural waters available throughout a State, part of a State, or a larger unit is of value to many individuals and is evidently work that must be handled by some public agency if it is to be done without needless duplication of effort.

In a survey of water conditions such as is given in certain United States Geological Survey water-supply papers a moderate number of analyses are so used as to have the value of a much greater number. Study of the analyses in relation to geologic conditions makes possible prediction of the probable quality of water in a well not yet drilled. Reports of a general character may have more value to persons not living in the area than they do to those who use the waters for which analyses are given.

A published analysis of water from a given source may save not only the expense of collection and analysis of a sample but also the time required to make an analysis, which may be a few days or a few weeks.

PUBLISHED ANALYSES

The list of published collections of analyses on pages 56–85 is confined almost wholly to reports containing several or many complete mineral analyses. Under "General reports" are given those which contain analyses of waters from more than one State. Under each State reference is made to general reports that contain analyses for the State, and the individual reports for the State are listed. The number of analyses in each report is indicated, at least approximately, and the analyses are classified by types of analyses and types of sources. In the list of publications the term "analysis" without qualification is used for analyses that include determinations of the mineral constituents generally present in significant quantities in natural waters. These analyses may not show the quantities of potassium; but they give the quantities of calcium, magnesium, chloride, sulphate, and alkalinity. Silica and either iron or iron and aluminum oxides together are generally given. Sodium is given or can be calculated. Nitrate is nearly always given for waters containing more than a few tenths of a part per million.

Partial analyses generally include determinations of total dissolved solids and of several constituents, but not enough to make it possible to calculate the sodium. An assay usually includes determinations of the acid radicles and hardness. Sanitary analyses include determinations of nitrogen in various forms, chloride, total dissolved solids, and sometimes iron and total hardness.

Reports containing only sanitary analyses have not been listed unless they record investigations of special importance or relate to areas for which few mineral analyses are available.

The most comprehensive studies of surface waters are reported in United States Geological Survey Water-Supply Papers 236, 237, 239, 273, 274, 339, and 363 (general report 8, California 19, Illinois 13, Kansas 5, general report 10, Washington 4, Oregon 2). Most of the analyses in all these publications except Water-Supply Paper 274 are reprinted in Professional Paper 135 (general report 21). A number of the analyses of surface waters from these papers are also given in Bulletin 770 (general report 22).

Each of the water-supply papers mentioned above contains tables giving analyses of weekly composites or ten-day composites of daily samples of water taken over a period of a year. In addition a number of single analyses of surface waters are given in most of the reports.

Some of the reports containing analyses of mineral waters are listed below; for the larger reports the number of analyses is indicated in parentheses.

General reports: 1, 3, 4, 7, 11, 14, 22.
Alabama: 1.
Alaska: 1.
Arkansas: 1, 2, 3.
California: 6 (100), 14 (41), 22 (300).
Colorado: 1, 3, 4, 8, 14, 15, 20, 21, 25 (202), 26.
Georgia: 3 (170).
Indiana: 3 (80).
Kansas: 2 (129).
Kentucky: 2, 3, 4, 5, 6, 9, 10.
Maine: 2, 4, 7.
Missouri: 1, 2, 3 (180).
New Mexico: 8.
New York: 4, 5.
North Carolina: 2.

AVAILABILITY OF THE PUBLICATIONS LISTED

Most of the publications listed are available for consultation in the larger public and educational libraries. Many are out of print, some can be purchased, and others are still available for free distribution from the office of publication. The price is given for Geological Survey publications that are for sale. Geologic folios can be purchased only from the Director, United States Geological Survey, Washington, D. C.; all other Survey publications are sold by the Superintendent of Documents, Government Printing Office, Washington, D. C. Payment for publications is required in advance. Some of the Geological Survey publications are available for free distribution by the Survey during the first year after publication, but the supply available for free distribution is generally exhausted before the end of the year.

PUBLICATIONS CONTAINING COLLECTIONS OF MINERAL ANALYSES OF WATERS

[Figures in parentheses alone or followed by "s" indicate number of analyses. For example, "(14s, 22)" means that the report contains 14 series of analyses of surface waters covering a period of about a year for each place, and 22 single analyses of either surface or ground water.]

GENERAL REPORTS

1. Peale, A. C., Lists and analyses of the mineral springs of the United States: U. S. Geol. Survey Bull. 32, 1886 (out of print). More than 850 analyses of spring waters are quoted from many sources.
2. Darton, N. H., Artesian-well prospects in the Atlantic Coastal Plain region: U. S. Geol. Survey Bull. 138, 1896 (out of print). Analyses of water from wells in Coastal Plain of Georgia (1), New Jersey (9), Maryland (2), and South Carolina (9).
3. Crook, J. K., Mineral waters of the United States and their therapeutic uses, New York and Philadelphia, Lea Brothers & Co., 1899. More than 450 analyses of mineral waters made by many analysts. A number of the analyses are copied from advertising matter put out by the spring owners.
4. Fuller, M. L., Contributions to the hydrology of eastern United States: U. S. Geol. Survey Water-Supply Paper 102, 1904 (out of print). 111 sanitary analyses of waters from Vermont and 200 mineral analyses, of which 100 represent spring waters from Connecticut (38), Florida (17), Massachusetts (24), Michigan (26), Missouri (48), New Hampshire (20), New York (14), and other States (a few each).
5. Fuller, M. L., Contributions to the hydrology of eastern United States: U. S. Geol. Survey Water-Supply Paper 110, 1905 (out of print). Sanitary analyses of 40 samples from Watkins Glen quadrangle, New York, and 25 mineral analyses of samples from other States.
6. Jackson, D. D., The normal distribution of chlorine in the natural waters of New York and New England: U. S. Geol. Survey Water-Supply Paper 144, 1905 (10 cents). Determinations of chloride in unpolluted waters from Connecticut (1,200), Maine (120), Massachusetts (6), New Hampshire (150), New York (100), Rhode Island (13), Vermont (100).
7. Haywood, J. K., and Smith, B. H., Mineral waters of the United States: U. S. Dept. Agr. Bur. Chemistry Bull. 91, 1905 (out of print). Analyses (by the authors) of 41 samples of bottled mineral waters purchased on the open market and of 13 samples from Saratoga Springs, N. Y., collected for the report, with advertised analyses for comparison. The methods of analysis used are described. The classification and the medicinal value of mineral waters are discussed.

8. Dole, R. B., The quality of surface waters in the United States, Part I, Analyses of waters east of the one hundredth meridian: U. S. Geol. Survey Water-Supply Paper 236, 1909 (out of print). 71 tables of analyses (by chemists of the water-resources branch of the United States Geological Survey) of composites of samples of surface waters taken daily for a year or longer. The methods of analysis used are described and the accuracy of the results discussed. The tables of analyses are reprinted in general report 21.
9. Palmer, Chase, The geochemical interpretation of water analyses: U. S. Geol. Survey Bull. 479, 1911 (out of print). Averages of 31 sets of analyses of surface waters from general report 8 and a few analyses from other sources are classified and discussed in terms of the properties of reaction introduced by the author in this report. The method of recording and interpreting analyses first used in this paper has been followed in a number of later reports, particularly those relating to oil-field waters.
10. Stabler, Herman, Some stream waters of the western United States, with chapters on sediment carried by the Rio Grande and the industrial application of water analyses: U. S. Geol. Survey Water-Supply Paper 274, 1911 (out of print). Analyses of composites of daily samples of surface waters are given in 55 tables. Partial analyses (acid radicles and total dissolved solids) of weekly composites of daily samples of surface waters are given in 54 tables. The paper contains 80 analyses of single samples from streams and 120 analyses of samples from wells. The analyses were made by C. H. Stone and other chemists of the United States Reclamation Service. The section on the industrial application of water analyses gives Stabler's formulas and classification of waters for industrial use and for irrigation, which have been followed in many later publications.
11. Skinner, W. W., and Stiles G. W., jr., American mineral waters—the New England States: U. S. Dept. Agr. Bur. Chemistry Bull. 139, 1911 (out of print). Chemical and bacteriologic analyses of 38 spring waters from New England, made in the Bureau of Chemistry.
12. Emmons, W. H., The enrichment of sulphide ores: U. S. Geol. Survey Bull. 529, 1913 (out of print). 13 analyses of waters from copper mines and 19 analyses of waters from gold and silver mines. Most of these analyses are also given in general report 16.
13. Phalen, W. C., The occurrence of potash salts in the bitterns of the eastern United States: U. S. Geol. Survey Bull. 530, pp. 313–329, 1913 (out of print; also in Bull. 530–B, 5 cents). Analyses (from miscellaneous sources) of bitterns from Michigan (8), New York (6), Ohio (5), and West Virginia (2).
14 Clarke, F. W., Water analyses from the laboratory of the United States Geological Survey: U. S. Geol. Survey Water-Supply Paper 364, 1914 (5 cents). "203 analyses made in the chemical laboratory of the United States Geological Survey. Most of them have been published elsewhere, but many of the original documents are out of print and therefore obtainable with difficulty." Includes all analyses from Geological Survey Bulletins 9, 27, 42, 47, 60, 64, and 113.
15. Siebenthal, C. E., Origin of the zinc and lead deposits of the Joplin region, Missouri, Kansas, and Oklahoma: U. S. Geol. Survey Bull. 606, 1915 (out of print). 119 analyses (from miscellaneous sources) of zinc-bearing and related waters.

16. Emmons, W. H., The enrichment of ore deposits: U. S. Geol. Survey Bull. 625, 1917 (out of print). Analyses of 56 mine waters, of which 37 are published in general report 12. Graphs based on analyses of 117 waters from hot springs.
17. Phalen, W. C., Technology of salt making in the United States: U. S. Bur. Mines Bull. 146, 1917 (25 cents). 14 analyses of brines made by W. B. Hicks, of the United States Geological Survey, for this report, to supplement data in general report 18, and 21 other analyses of brines and bitterns.
18. Phalen, W. C., Salt resources of the United States: U. S. Geol. Survey Bull. 669, 1919 (35 cents). 254 analyses of natural and artificial brines and of bitterns from brines and from sea water. Most of the analyses were made by chemists of the United States Geological Survey and of the Bureau of Soils of the Department of Agriculture. Includes 175 analyses of brines published in Bur. Soils Bull. 94, 1913, The occurrence of potassium salts in the salines of the United States, by J. W. Turrentine and others. About 100 of the analyses are published in a series of articles entitled "Composition of the salines of the United States, by J. W. Turrentine, with analyses by A. R. Merz and R. F. Gardiner (pt. 1, Rock salt, artificial brines and mother liquors from artificial brines: Jour. Ind. and Eng. Chemistry, vol. 4, p. 828, 1912; pt. 2, Natural (subterranean) brines and mother liquors from natural brines: Idem, p. 885; pt, 3, Brines from the ocean and salt lakes: Idem, vol. 5, p. 19, 1913).
19. Mills, R. V. A., and Wells, R. C., The evaporation and concentration of waters associated with petroleum and natural gas: U. S. Geol. Survey Bull. 693, 1919 (20 cents). 39 analyses of brines from Appalachian oil and gas fields and 15 partial analyses of waters from shallow wells in the area. Some of the analyses were made in the United States Geological Survey.
20. Collins, W. D., The industrial utility of public water supplies in the United States: U. S. Geol. Survey Water-Supply Paper 496, 1923. (10 cents). Analyses (from miscellaneous sources) showing the chemical character of water from public supplies of 307 larger cities.
21. Clarke, F. W., The composition of the river and lake waters of the United States: U. S. Geol. Survey Prof. Paper 135, 1924 (50 cents). 193 tables of analyses of 10-day composites of daily samples for about a year, from Water-Supply Papers 236, 237, 239, 273, 339, 363 (general report 8, California 19, Illinois 13, Kansas 5, Oregon 2, Washington 4). Nearly 800 single analyses of surface waters from all parts of the United States. About one-third have not been published before.
22. Clarke, F. W., The data of geochemistry, 5th edition: U. S. Geol. Survey Bull. 770, 1925 ($1). Over 200 analyses of surface waters and over 100 analyses of waters from wells and springs. Many of the surface-water analyses are averages of series of analyses reprinted in general report 21. References are given to publications containing more extensive collections of analyses of certain types or from special places. The earlier editions of "The data of geochemistry" were U. S. Geological Survey Bulletins 330, 491, 616, 695. A few additions or omissions of water analyses were made at each revision, but the analyses are substantially the same in all the editions.

ALABAMA

General reports: 1 (19), 3 (9), 4 (2), 8 (3 s), 20 (5), 21 (3 s, 1), 22 (3).

1. Smith, E. W., The underground water resources of Alabama, Alabama Geol. Survey, 1907. 110 analyses (made for the report) of well and spring waters. The report deals mainly with mineral waters.

ALASKA

General reports: 21 (1 s, 31), 22 (8).

1. Waring, G. A., Mineral springs of Alaska, with a chapter on the chemical character of some surface waters of Alaska by R. B. Dole and A. A. Chambers: U. S. Geol. Survey Water-Supply Paper 418, 1917 (25 cents). Analyses of spring waters (29) and Yukon River (17) made by the United States Geological Survey. Analyses of streams in Yukon-Tanana region (11) and other surface waters (8) made for the report by S. C. Dinsmore.

ARIZONA

General reports: 1 (3), 3 (3), 10 (4 s), 20 (4), 21 (5), 22 (3).

1. Waters and water analyses: Arizona Agr. Exper. Sta. Bull. 4, 1891. Analyses (made at Experiment Station) of water from 3 wells and 13 surface supplies. Contains directions for sampling water for analysis.
2. Collingwood, C. B., Soils and waters: Arizona Agr. Exper. Sta. Bull. 6, 1892. Monthly analyses of the sediment from samples of Colorado River water taken daily for seven months.
3. McClatchie, A. J., and Forbes, R. H., Sugar-beet experiments during 1898: Arizona Agr. Exper. Sta. Bull. 30, 1899. Discussion of water supply for factory requirements. Analyses (made at Experiment Station) of 36 samples of well water from Salt River Valley, with a discussion of the suitability of their use in the manufacture of beet sugar.
4. Arizona Agr. Exper. Sta. Eleventh Ann. Rept., for year ending June 30, 1900 (report of the Dept. of Chemistry, pp. 180–184). Partial analyses (made at Experiment Station) of water from Colorado River at Yuma, Gila River at Florence, Salt River at Mesa City, and of samples from nine wells.
5. Forbes, R. H., The river irrigating waters of Arizona, their character and effects: Arizona Agr. Exper. Sta. Bull. 44, 1902. Analyses (made at Experiment Station) of irrigating waters of the Territory: Gila River (6), Salt River (7), Colorado (7), miscellaneous sources (16 partial).
6. Skinner, W. W., The underground waters of Arizona, their chemistry and uses: Arizona Agr. Exper. Sta. Bull. 46, 1903. 300 analyses (made at Experiment Station) of waters from various sources throughout the territory.
7. Lee, W. T., The underground waters of Gila Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 104, 1904 (10 cents). 23 analyses from miscellaneous sources.
8. Lee, W. T., Underground waters of Salt River valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 136, 1905 (25 cents). Analyses from Experiment Station Bulletins 30 (36), 44 (6), and 46 (125) (Arizona 3, 5, 6). 9 analyses of underflow of Salt and Gila rivers.
9. Arizona Agr. Exper. Sta. Twenty-third Ann. Rept., for year ending June 30, 1912, pp. 698–700. Observations of the close proximity of black alkaline and calcium sulphate waters. Partial analyses (made at Experiment Station) of 7 well waters and 1 surface water. Discussion of the neutralizing effect of black alkali and gypsum.

10. Meinzer, O. E., and Kelton, F. C., Geology and water resources of Sulphur Spring Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 320, 1913 (45 cents). 123 partial analyses (by W. H. Ross, Arizona Agr. Exper. Sta.) of ground water of the area.
11. Meinzer, O. E., and Ellis, A. J., Ground water in Paradise Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 375, pp. 51–75, 1916 (out of print). 10 assays of waters from wells, made for the report by A. E. Vinson, Arizona Agr. Exper. Sta.
12. Schwennesen, A. T., Ground water in San Simon Valley, Arizona and New Mexico: U. S. Geol. Survey Water-Supply Paper 425, pp. 1–35, 1919 (out of print). 14 analyses of waters from wells and springs, made by A. E. Vinson and D. W. Moore, Arizona Agr. Exper. Sta.
13. Arizona Agr. Exper. Sta. Ann. Rept. for 1919. 11 complete analyses of water from Salton Sea, made from 1907 to 1918. Each of the annual reports from 1908 to 1914 and 1916 contains the analyses completed when it was published.
14. Vinson, A. E., Catlin, C. N., and Griffin, S. W., Studies of irrigated soils and irrigation waters: Arizona Agr. Exper. Sta. Thirty-first Ann. Rept., for year ending June 30, 1920, pp. 436–439. Partial analyses (made at Experiment Station) of 5 monthly samples of water from the Tempe drainage ditch. Data on the character of the ground waters east of Agua Fria River.
15. Ross, C. P., The lower Gila region, Ariz: U. S. Geol. Survey Water-Supply Paper 498, 1923 (50 cents). 29 analyses (mostly by United States Geological Survey) of samples from watering places.
16. Bryan, Kirk, The Papago country, Ariz: U. S. Geol. Survey Water-Supply Paper 499 (in press; probably $1). 32 analyses by A. A. Chambers and C. H. Kidwell, of the United States Geological Survey.

ARKANSAS

General reports: 1 (5), 3 (3), 4 (3), 8 (2 s), 14 (5), 15 (2), 21 (1 s, 2), 22 (2).

1. Arkansas Geol. Survey, vol. 1, 1891, The mineral waters of Arkansas. 9 analyses of spring waters from Hot Springs and 60 analyses of other mineral waters of the State.
2. Haywood, J. K., and Weed, W. H., The Hot Springs of Arkansas: 57th Cong., 1st sess., S. Doc. 282, 1902 (out of print). 46 analyses (by J. K. Haywood, U. S. Dept. Agr. Bur. Chemistry), of the waters of Hot Springs. Analyses reprinted in Arkansas 3.
3. Weed, W. H., Notes on certain hot springs of the southern United States: U. S. Geol. Survey Water-Supply Paper 145, pp. 185–206, 1905 (out of print). Analyses from Arkansas 2.
4. Veatch, A. C., Geology and underground water resources of northern Louisiana and southern Arkansas: U. S. Geol. Survey Prof. Paper 46, 1906 (out of print). Analyses of water from wells of Arkansas (10), Louisiana (22), Mississippi (1), and Texas (2).
5. Stephenson, L. W., and Crider, A. F., Geology and ground waters of northeastern Arkansas, with a discussion of the chemical character of the waters by R. B. Dole: U. S. Geol. Survey Water-Supply Paper 399, 1916 (out of print). 47 analyses of ground water by J. R. Bailey, Univ. Texas; 52 field assays by Stephenson and Crider.

CALIFORNIA

General reports 1 (44), 3 (86), 7 (1), 10 (10 s), 12 (2), 14 (26), 18 (20), 20 (17), 21 (33s, 85), 22 (20).

1. Hilgard, E. W., Alkali lands, irrigation and drainage in their mutual relations: California Univ. Agr. Exper. Sta. Rept. for 1886, appendix 7. 55 analyses (made at Experiment Station) of water from springs and wells.
2. Hilgard, E. W., Report of examination of waters, water supply, and related subjects: Advance sheets from combined reports of California College Agr. Exper. Stas. for 1888 and 1889; pp. 13–32, quantities of total solids for 42 samples of ground and surface waters; pp. 44–57, lake waters of San Joaquin Valley (also in Exper. Sta. Bull. 82, 1889), a study of the change in composition of the waters of Kern, Tulare, and Buena Vista lakes due to decrease in supply and evaporation; pp. 51–56, salts of the alkaline earths and alkalies, mutual reactions, discussion of this subject with respect to the change in Lake Tulare water.
3. Hilgard, E. W., California Agr. Exper. Sta. Rept. for 1890, pp. 51–82. Analyses (made at Experiment Station) of surface waters (9), springs (12), common wells (11), artesian wells (11).
4. Foster, E. Le N., Production of carbonate of soda from the alkaline waters of Owens Lake: Colorado Sci. Soc. Proc., vol. 3, p. 245, 1890: 4 analyses (from miscellaneous sources) of water from soda lakes with a discussion of the production of sodium carbonate.
5. Hilgard, E. W., Report of the Agricultural Experiment Stations of the University of California for the year 1891–92, pp. 50–75. Analyses (made at Experiment Station) of surface waters (13), springs (9), common wells (24), artesian wells (6).
6. Anderson, Winslow, Mineral springs and health resorts of California, San Francisco, Bancroft & Co., 1892. Analyses (from miscellaneous sources) of about 100 California springs and about 200 other springs, American and foreign.
7. Hilgard, E. W., Report of the Agricultural Experiment Stations of the University of California for the year 1892–93 and part of 1894, pp. 157–184. Analyses (made at Experiment Stations) of surface waters (4), springs (10), common wells (32), artesian wells (9).
8. Lindgren, Waldemar, The gold-quartz veins of Nevada City and Grass Valley districts, Calif.; U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, p. 120, 1896 (out of print). 2 analyses of ground waters by W. F. Hillebrand.
9. Hilgard, E. W., Report of the Agricultural Experiment Stations of the University of California for the year 1897–98, pp. 118–130. Analyses (made at Experiment Stations) of surface waters (5), springs (16), common wells (38), artesian wells, reservoirs, and irrigation ditches (8).
10. Hilgard, E. W., Report of the Agricultural Experiment Stations of the University of California for the years 1898–1901, pt. 2, pp. 215–230. Analyses (made at Experiment Stations) of samples of surface waters (19), springs (67), common wells (155), artesian wells (19), reservoirs (24).
11. Lippincott, J. B., Development and application of water near San Bernardino, Colton, and Riverside, Calif.: U. S. Geol. Survey Water-Supply Paper 59, 1902 (out of print). Analyses of 1 surface water and 2 artesian wells.
12. Bailey, G. E., The saline deposits of California: California State Min. Bur. Bull. 24, 1902. About 15 analyses of brines of the State; most of them have been published elsewhere.

13. Hamlin, Homer, Water resources of the Salinas Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 89, 1904 (15 cents). Analysis of water from Arroyo Seco (1), San Lorenzo Creek in dry season (2) and in wet season (1). Made by Bureau of Soils, U. S. Dept. Agr.
14. Hilgard, E. W., Report of the Agricultural Experiment Station of the University of California for the year 1903-4, pp. 34-43. Analyses (made at Experiment Station) of water from streams (12), springs (41), common wells (82), artesian wells (9).
15. Lippincott, J. B., Water problems of Santa Barbara, Calif.: U. S. Geol. Survey Water-Supply Paper 116, 1905 (10 cents). Analyses (from miscellaneous sources) of water from Cold Spring Creek (1), Mission Creek (1), Mono Creek (8), Santa Ynez River (5), Santa Barbara City supply (1).
16. Mendenhall, W. C., The hydrology of San Bernardino Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 142, 1905 (25 cents). Analyses (from miscellaneous sources) of surface water (1), springs (3), wells (4).
17. Lee, W. T., Geology and water resources of Owens Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 181, 1906 (out of print). Four analyses of water of Owens Lake by Prof. Phillips, of England; Oscar Loew, of the Wheeler Survey; T. M. Chatard, of the U. S. Geological Survey; and C. H. Stone, of the U. S. Reclamation Service (1876-1905). Analysis of Mono Lake (1882) by T. M. Chatard.
18. Mitchell, J. P., A study of the normal constituents of the potable waters of the San Francisco Peninsula: Leland Stanford Junior Univ. Pub., Univ. Ser., Paper 1, 1910. Quantities of total solids, hardness, chloride, and nitrogen for about 240 ground and surface waters.
19. Van Winkle, Walton, and Eaton, F. M. The quality of the surface waters of California: U. S. Geol. Survey Water-Supply Paper 237, 1910 (20 cents). 35 series of analyses covering about a year for the more important rivers. 35 single analyses of surface waters. Practically all analyses were made by or under the direction of the authors.
20. Johnson, H. R., Water resources of Antelope Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 278, 1911 (out of print). 6 analyses of well and spring waters made by the United States Geological Survey.
21. Gale, H. S., Prospecting for potash in Death Valley, Calif.: U. S. Geol. Survey Bull. 540, pp. 407-415, 1914 (out of print). 14 partial and 4 complete analyses of brines from Death Valley made by the U. S. Geological Survey. Several potash determinations for waters of the area.
22. Hamilton, Fletcher, California State Mineralogist Fourteenth Bien. Rept. for 1913, California State Min. Bur., 1916. Analyses of spring water from Calaveras County (1), Humboldt County (2), Mendocino County (4), and foreign sources (3).
23. Waring, G. A., Springs of California: U. S. Geol. Survey Water-Supply Paper. 338, 1915 (60 cents). About 300 analyses of spring waters. Many of the analyses were taken from California 6. Some were made by Oscar Loew, of the Wheeler Survey.
24. Mendenhall, W. C., Dole, R. B., and Stabler, Herman, Ground water in San Joaquin Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 398, 1916 (25 cents). 400 field assays by R. B. Dole, U. S. Geological Survey, 50 analyses by F. M. Eaton, U. S. Geological Survey, and 65 analyses from miscellaneous sources.
25. Hamilton, Fletcher, California State Mineralogist Fifteenth Bienn. Rept., for 1915-16, California State Min. Bur., 1919. 41 analyses of spring and lake waters. Most of them are from California 23 or other U. S. Geological Survey reports.

26. McLaughlin, R. P., California State Oil and Gas Supervisor Second Ann. Rept. for 1916–1917: California State Min. Bur. Bull. 82, 1918. 10 analyses (from miscellaneous sources) of waters from the Casmalian field, p. 206. Total solids, total carbonate, total sulphate, and total chloride for waters from 13 wells of Petrol County, p. 335.
27. McLaughlin, R. P., California State Oil and Gas Supervisor Third Ann. Rept., for 1917–1918: California State Min. Bur. Bull. 84, 1918. 15 analyses of "top waters" and 11 analyses of probable "bottom waters," p. 368. 3 analyses of "bottom waters" and 3 analyses of water from "water zone," p. 383. Analyses from miscellaneous sources.
28. Hicks, W. B., Evaporation of brine from Searles Lake, Calif.: U. S. Geol. Survey Prof. Paper 98, pp. 1–8, 1916 (out of print). 3 analyses of brine from the lake.
29. Rogers, G. S., Chemical relations of the oil-field waters in San Joaquin, Valley, Calif., U. S. Geol. Survey Bull. 653, 1917 (10 cents). 88 analyses of oil-field waters; 30 of the analyses were made by or for the U. S. Geological Survey.
30. Rogers, G. S., The Sunset-Midway oil field, Calif., Part II, Geochemical relations of the oil, gas, and water: U. S. Geol. Survey Prof. Paper 117, 1919 (out of print). Analyses of waters of this area made by the U. S. Geological Survey (29), by the Standard Oil Co. and the Kern Trading and Oil Co. (27), and by industrial chemists (18).
31. Waring, G. A., Ground water in the San Jacinto and Temecula basins, Calif.: U. S. Geol. Survey Water-Supply Paper 429, 1919 (40 cents). Analyses (40) and assays (70) of water from wells and springs; 4 analyses of surface waters. All made by S. C. Dinsmore.
32. Ellis, A. J., and Lee, C. H., Geology and ground waters of the western part of San Diego County, Calif.: U. S. Geol. Survey Water-Supply Paper 446 1919 (out of print). 7 analyses of surface waters and 9 assays of ground water, made in the water resources laboratory of the U. S. Geological Survey. 50 analyses of ground water made by S. C. Dinsmore.
33. Thompson, D. G., Ground water in Lanfair Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 450, pp. 29–50, 1921 (40 cents). 4 analyses (3 made in water resources laboratory of U. S. Geological Survey).
34. Waring, G. A., Ground water in Pahrump, Mesquite, and Ivanpah valleys, Nev. and Calif.: U. S. Geol. Survey Water-Supply Paper 450, pp. 51–86, 1921 (Water-Supply Paper 450–C, 5 cents) (Nevada 11). Analyses (made for the report) of ground waters from California (12) and from Nevada (8).
35. Bryan, Kirk, Geology and ground water resources of Sacramento Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 495, 1923 (60 cents). 47 analyses of ground water made by S. C. Dinsmore and 23 assays made by G. H. P. Lichthardt.
36. Brown, J. S., The Salton Sea region, Calif.: U. S. Geol. Survey Water-Supply Paper 497, 1923 (50 cents). 53 analyses of water of the Salton Sea region; 7 analyses of well waters of the Holtville area, Imperial Valley. Most of the analyses were made in the water-resources laboratory of the U. S. Geological Survey.

COLORADO

General reports: 1 (38), 3 (16), 7 (1), 10 (4 s), 12 (5), 14 (21), 15 (11), 16 (5), 20 (3), 21 (16), 22 (8).

1. Smith, J. A., Report on the development of the mineral, metallurgical, agricultural, pastoral, and other resources of Colorado for the year 1881–82, Denver, Chain & Hardy, 1883. Analyses of waters from hot sulphur springs.

2. Chauvenet, Regis, Chemistry of the wells: Colorado Sci. Soc. Proc., vol. 1, sec. 3, 1884. 4 analyses of Denver artesian waters.
3. Chauvenet, Regis, Analyses of natural, thermal, and mineral waters of Colorado: Colorado School of Mines Bienn. Rept., p. 21, 1890. 15 analyses of waters from springs.
4. Lakes, Arthur, Hahns Peak: Colliery Eng. and Metal Miner, vol. 16, p. 147, 1895. Discusses the relation of mineral springs of Steamboat Springs to mineral deposits. Gives geology of the region and analyses of spring waters.
5. Emmons, S. F., Some mines of Rosita and Silver Cliff, Colo.: Am. Inst. Min. Eng. Trans., vol. 26, p. 773, 1896. 3 chemical analyses of waters from deep levels in Geyser mine; discussion of results.
6. Emmons, S. F., Cross, Whitman, and Eldridge, G. H., Geology of the Denver Basin in Colorado: U. S. Geol. Survey Mon. 27, 1896 ($1.50). 4 analyses of well waters from Denver, published in Colorado 2, made by Prof. Regis Chauvenet, Colorado School of Mines, assisted by C. A. Gehrmann.
7. Gilbert, G. K., The underground water of the Arkansas Valley in eastern Colorado: U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, pp. 551–601, 1896 (out of print). 8 analyses (from miscellaneous sources) of underground waters.
8. Colorado State Bur. Mines Rept. for 1897. About 50 analyses of mineral springs of the State. Some analyses made by the U. S. Geological Survey; others from miscellaneous sources. Practically the same analyses are given in report for years 1901–2.
9. Strong, W. C., The sanitary chemical character of some of the artesian waters of Denver: Colorado Sci. Soc. Proc., vol. 5, p. 17, 1898. Discusses geologic occurrence of the waters and gives analyses.
10. Jones, L. J. W., Ferric sulphate in mine waters, its action on metals: Colorado Sci. Soc. Proc., vol. 6, p. 46, 1902. Describes experimental work and gives analyses of waters from mineral springs.
11. Headden, W. P., The ground water: Colorado Agr. Exper. Sta. Bull. 72, pt. 4, 1902. 14 analyses (made at Experiment Station) of ground water, with a discussion of the origin and effect of constituents.
12. Headden, W. P., Colorado irrigation waters and their changes: Colorado Agr. Exper. Sta. Bull. 82, 1903. Discussion of the character, source, and conditions affecting the nature of irrigation waters of Colorado. 50 analyses (made at Experiment Station) of surface and ground waters of the State. Some of the ground-water samples were taken to show change after irrigation.
13. Darton, N. H., Preliminary report on the geology and underground water resources of the central Great Plains: U. S. Geol. Survey Prof. Paper 32, 1905 (out of print). Analyses (from miscellaneous sources) of well waters. Colorado (11), Kansas (1), South Dakota (1), Wyoming (1).
14. Headden, W. P., The Doughty Springs, a group of radium-bearing springs, Delta County, Colo.: Am. Jour. Sci., 4th ser., vol. 19, p. 297, 1905. Describes the springs and gives 3 analyses. (Abstract from Colorado 15.)
15. Headden, W. P., The Doughty Springs, a group of radium-bearing springs on the north fork of the Gunnison River, Delta County, Colo.: Colorado Sci. Soc. Proc., vol. 8, pp. 1–30, 1905. 4 analyses of water from the springs. Discussion of chemical composition of deposits found near the springs.
16. Fisher, C. A., U. S. Geol. Survey Geol. Atlas, Nepesta folio (No. 135), 1906 (out of print). Analyses of water from 2 wells at Pueblo and 1 spring near Fowler.

17. Darton, N. H., Geology and underground waters of the Arkansas Valley in eastern Colorado: U. S. Geol. Survey Prof. Paper 52, 1906 (out of print). Analyses (from miscellaneous sources) of well water from eastern Colorado (6), and from Dakota sandstone in southeastern Colorado (28).
18. Slichter, C. S., and Wolff, H. C., The underflow of the South Platte Valley: U. S. Geol. Survey Water-Supply Paper 184, 1906 (out of print). 52 analyses of water along the Union Pacific Railroad in western Nebraska and eastern Colorado, furnished by the railroad company.
19. Gale, H. S., Geology of the Rangely oil district, Rio Blanco County, Colo., with a section on the water supply: U. S. Geol. Survey Bull. 350, 1908 (out of print). Analysis (by R. B. Dole) of the water of White River near Rangely.
20. Headden, W. P., Notes on some mineral springs: Colorado Sci. Soc. Proc., vol. 9, p. 259, 1909. Analyses and descriptive notes of springs in Platte Canyon and in Delta County.
21. Lowther, W. H., and Knowles, R. R., The mineral waters of Steamboat Springs: Western Chemist and Metallurgist, vol. 6, p. 60, 1910. Analyses for 12 springs; rate of discharge and other data.
22. Siebenthal, C. E., Geology and water resources of the San Luis Valley, Colo.: U. S. Geol. Survey Water-Supply Paper 240, 1910 (25 cents). 17 analyses (from miscellaneous sources) of ground waters.
23. Sackett, W. G., A comparative bacteriological study of the water supply of city and county of Denver, Colo.: Colorado Agr. Exper. Sta. Bull. 225, pp. 3–14, 1917. Describes the water supply of the city and county.
24. Headden, W. P., The waters of the Rio Grande: Colorado Agr. Exper. Sta. Bull. 230, 1917. Analyses (made at Experiment Station) of water from surface sources (11) and wells (13); several analyses of alkali deposits; discussion of the irrigation problem.
25. George, R. D., Curtis, H. A., Lester, O. C., Crook, J. K., Yeo, J. B., and others, Mineral waters of Colorado: Colorado Geol. Survey Bull. 11, 1920 202 analyses (by H. A. Curtis) of mineral waters expressed in milligrams of radicle per liter, in hypothetical combinations, and in properties of reaction as proposed by Palmer (general report 9). Radioactivity determined by O. C. Lester.
26. Bastin, E. S., Silver enrichment in the San Juan Mountains, Colo.: U. S. Geol. Survey Bull. 735, pp. 65–129, 1923 (55 cents). Analyses (made by U. S. Geological Survey) of hot-spring waters from Ouray (4), mine waters from Genesee mine, Red Mountain (2), and mine waters from Dunton (3).
27. Bastin, E. S., Observations on the rich silver ores of Aspen, Colo.: U. S. Geol. Survey Bull. 750–C, 1924 (5 cents). Analyses (by Chase Palmer, U. S. Geological Survey) of 2 mine waters from Aspen, Colo.

CONNECTICUT

General reports: 1 (2), 3 (4), 4 (38), 6 (1,200 chloride determinations), 11 (5), 20 (7), 21 (7).

1. Connecticut State Board of Health reports. Most of the reports contain sanitary analyses of samples from several public supplies and from other sources.
2. Gregory, H. E., Underground water resources of Connecticut: U. S. Geol. Survey Water-Supply Paper 232, 1909 (out of print). 24 analyses from miscellaneous sources.

3. Gregory, H. E., and Ellis, A. J., Ground water in the Hartford, Stamford, Salisbury, Willimantic, and Saybrook areas, Conn.: U. S. Geol. Survey Water-Supply Paper 374, 1916 (30 cents). 21 analyses by R. B. Dole, U. S. Geological Survey.
4. Ellis, A. J., Ground water in the Waterbury area, Conn.: U. S. Geol. Survey Water-Supply Paper 397, 1916 (15 cents). 1 analysis and 3 assays by R. B. Dole, U. S. Geological Survey.
5. Waring, G. A., Ground water in the Meriden area, Conn.: U. S. Geol. Survey Water-Supply Paper 449, 1920 (25 cents). 24 analyses made for the report by S. C. Dinsmore.
6. Palmer, H. S., Ground water in the Norwalk, Suffield, and Glastonbury areas, Conn.: U. S. Geol. Survey Water-Supply Paper 470, 1920 (65 cents). 25 analyses and 42 assays made for the report in the water-resources laboratory of the U. S. Geological Survey.
7. Palmer, H. S., Ground water in the Southington-Granby area, Conn.: U. S. Geol. Survey Water-Supply Paper 466, 1921 (50 cents). 31 analyses and 50 assays made for the report by S. C. Dinsmore. 4 analyses made by A. A. Chambers, U. S. Geological Survey.
8. Brown, J. S., Coastal ground water, with special reference to Connecticut: U. S. Geol. Survey Water-Supply Paper 537, 1925 (20 cents). 16 analyses of well waters from the New Haven coast, with reference to probable contamination by sea water; several determinations of chloride showing contamination of well waters with sea water. Most of the analyses were made in the water-resources laboratory of the U. S. Geological Survey.

DELAWARE

General reports: 20 (2).

DISTRICT OF COLUMBIA

General reports: 14 (7), 20 (1 s), 21 (1 s).

FLORIDA

General reports 1 (4), 3 (1), 4 (17), 14 (3), 20 (4), 21 (7), 22 (1).

1. Florida Agr. Exper. Sta. Bull. 6, pp. 5–10, 1889. 10 analyses from miscellaneous sources.
2. Sellards, E. H., Occurrence and use of artesian and other underground water: Florida Agr. Exper. Sta. Bull. 89, pp. 85–113, 1907. 10 analyses made at Experiment Station.
3. Sellards, E. H., A preliminary report on the underground water supply of central Florida: Florida Geol. Survey Bull. 1, 1908. Analyses of 14 springs and 17 wells; 8 made by U. S. Geological Survey for other reports, some made by the State chemist.
4. Sellards, E. H., and Gunter, Herman, The artesian water supply of eastern Florida: Florida Geol. Survey Third Ann. Rept., pp. 77–195, 1910. 18 analyses of artesian water, many made by the State chemist.
5. Sellards, E. H., and Gunter, Herman, The underground water supply of west-central and west Florida: Florida Geol. Survey Fourth Ann. Rept., pp. 87–155, 1912. 16 analyses from miscellaneous sources.
6. Sellards, E. H., and Gunter, Herman, Artesian water supply of eastern and southern Florida: Florida Geol. Survey. Fifth Ann. Rept., pp. 103–290, 1913. Reprint from Florida 4, with additional report for southern Florida. 36 analyses from miscellaneous sources.

7. Rose, R. E., Water analyses: Florida Dept. Agr. Quart. Bull. 21, pp. 139–156, 1911. Complete analyses (13), quantities of total solids (20), quantities of solids, chloride, carbonate, and bicarbonates (37) for waters from different sources. Analyses made by State chemist.
8. Matson, G. C., and Sanford, Samuel, Geology and ground waters of Florida: U. S. Geol. Survey Water-Supply Paper 319, 1913 (out of print). 30 assays (by Samuel Sanford) of ground waters of southern Florida.

GEORGIA

General reports: 1 (21), 3 (10), 8 (6 s), 20 (5), 21 (6 s, 1), 22 (6).

1. Fuller, M. L., Peculiar mineral waters from crystalline rocks of Georgia: U. S. Geol. Survey Water-Supply Paper 160, pp. 86–91, 1906 (out of print). 5 analyses of water from wells and springs of Georgia, by Edgar Everhart, Georgia Geological Survey.
2. McCallie, S.W., A preliminary report on the underground waters of Georgia: Georgia Geol. Survey Bull. 15, 1908. 130 analyses made by Edgar Everhart and others. Some of these were used in Georgia 4.
3. McCallie, S. W., A preliminary report on the mineral springs of Georgia: Georgia Geol. Survey Bull. 20, 1913. 170 analyses by Edgar Everhart and others.
4. Stephenson, L. W., and Veatch, J. O., Underground waters of the Coastal Plain of Georgia and a discussion of the quality of the waters by R. B. Dole: U. S. Geol. Survey Water-Supply Paper 341, 1915 (50 cents). 170 analyses, mostly by Edgar Everhart; 6 tables of analyses of surface waters of Georgia from general report 8.

IDAHO

General reports: 1 (2), 3 (1), 10 (2 s) , 20 (2), 21 (1 s), 22 (1).

1. McCurdy, C. W., Water and water analyses: Idaho Agr. Exper. Sta. Bull. 8, 1894. A general discussion of water and water supply, with partial analyses (made at Experiment Station) of 27 samples of water.
2. Avery, S., Report of the department of chemistry: Idaho Agr. Exper. Sta. Bull. 29, pp. 12–14, 1901. 6 sanitary analyses made at Experiment Station.
3. Kemmerer, George, Bovard, J. F., and Boorman, W. R., Northwestern lakes of the United States: U. S. Dept. Commerce Bur. Fisheries Bull. 39, pp. 51–140, 1923. Complete analyses of waters from 4 lakes in Idaho and 1 in Washington.
4. Piper, A. M., Geology and water resources of the Goose Creek basin, Cassia County, Idaho: Idaho Bur. Mines and Geology Bull. 6, 1923. 7 analyses of ground waters made by Margaret D. Foster, U. S. Geological Survey.

ILLINOIS

General reports: 1 (14), 3 (6), 14 (3), 20 (10), 21 (23 s, 11), 22 (7).

1. Leverett, Frank, The water resources of Illinois: U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, pp. 695–849, 1896 (out of print). 53 analyses (by State Board of Health) of water from wells.
2. Palmer, A. W., Chemical survey of the water supply of Illinois: Illinois Univ. Prel. Rept., 1897. 1,800 sanitary analyses of surface and ground waters of the State, made in the Water Survey laboratory.

3. Alden, W. C., U. S. Geol. Survey Geol. Atlas, Chicago folio (No. 81), 1902 (out of print). Analyses of 4 wells near Chicago.
4. Palmer, A. W., Chemical survey of the waters of Illinois: Illinois Univ. Rept., 1897-1902. About 3,000 sanitary analyses (residue, chloride, and nitrogen) made by the State Water Survey.
5. Leighton, M. O., Pollution of Illinois and Mississippi rivers by Chicago sewage, a digest of the testimony taken in the case of the State of Missouri vs. the State of Illinois and the Sanitary District of Chicago: U. S. Geol. Survey Water- Supply Paper 194, 1907 (out of print). Several hundred sanitary analyses.
6. Bowman, Isaiah, and Reeds, C. A., Water resources of the East St. Louis district: Illinois Geol. Survey Bull. 5, 1907. 61 analyses made by the State Water Survey.
7. Udden, J. A., Artesian wells in Peoria and vicinity: Illinois Geol. Survey Bull. 8, 1907. 8 analyses made at the University of Illinois.
8. Bartow, Edward, Municipal water supplies of Illinois: Illinois Univ. Bull., Water Survey Ser. 5, 1907. Analyses (by State Water Survey) of water from 60 ground-water sources and 12 surface-water supplies; many sanitary analyses. Data on the source of supply and quality of water for cities with population of more than 1,000 (1900 census).
9. Bartow, Edward, The mineral content of Illinois waters: Illinois Univ. Bull., Water Survey Ser. 4, 1908. Same as Bull. 10, State Geol. Survey (Illinois 11, below). 500 analyses of well waters and 30 analyses of surface waters made in Water Survey laboratory.
10. Bartow, Edward, Chemical and biological survey of the waters of Illinois: Illinois Univ. Bull., Water Survey Ser. 6, 1908, pp. 33–52, with J. M. Lindgren, Laboratory experiments in water treatment. 3 analyses of ground water. (Also in Am. Chem. Soc. Jour., vol. 29, pp. 1293–1304, 1904; and Am. Waterworks Assoc. Proc., vol. 27, pp. 505–527, 1907.) Pp. 53–58, Normal waters of Illinois. 4 average analyses from Illinois 13.
11. Bartow, Edward, Udden, J. A., Parr, S. W., and Palmer, G. T., The mineral content of Illinois waters: Illinois Geol. Survey Bull. 10, 1909. 530 analyses by the State Water Survey (also published in Illinois 9).
12. Bartow, Edward, Chemical and biological survey of waters of Illinois: Illinois Univ. Bull., Water Survey Ser. 7, 1909. Pp. 98–104, The hardness of Illinois municipal water supplies (also in Illinois Soc. Engineers and Surveyors Twenty-fourth Ann. Rept., pp. 213–219, 1909). Pp. 78–97, Farm water supplies.
13. Collins, W. D., The quality of the surface waters of Illinois: U. S. Geol. Survey Water-Supply Paper 239, 1910 (10 cents). 27 series of analyses (by W. D. Collins and C. K. Calvert) covering a period of a year for the more important rivers of the area.
14. Bartow, Edward, Sanitary survey of the Vermilion River: Illinois Univ. Bull., Water Survey Ser. 9, pp. 136-146, 1912. 7 analyses of deep-well waters and 1 of Vermilion River at Streator.
15. Udden, J. A., Geology and mineral resources of the Peoria quadrangle, Ill.: U. S. Geol. Survey Bull. 506, 1912 (25 cents). 8 analyses of ground waters made at the University of Illinois.
16. Udden, J. A., and Shaw, E. W., U. S. Geol. Survey Geol. Atlas, Belleville-Breese folio (No. 195), 1915 (25 cents). Analyses of waters from 6 wells and springs, taken from Illinois 9, above.

17. Shaw, E. W., and Trowbridge, A. C., U. S. Geol. Survey Geol. Atlas, Galena-Elizabeth folio (No. 200), 1916 (25 cents). Analyses for deep wells in Illinois (4 from Illinois 9) and in Iowa (1 from Iowa 3).
18. Cady, G. H., Geology and mineral resources of the Hennepin and La Salle quadrangles: Illinois Geol. Survey Bull. 37, 1919. 10 analyses of artesian water.
19. Anderson, C. B., The artesian waters of northeastern Illinois: Illinois Geol. Survey Bull. 34, 1919. 78 mineral analyses of underground waters of the area. 270 boiler analyses of underground waters (magnesium, iron, nitrate, chloride, sulphate, residue, alkalinity, and hardness). Most of the analyses were made by the State Water Survey.
20. Hinds, Henry, U. S. Geol. Survey Geol. Atlas, Colchester-Macomb folio (No. 208), 1919 (25 cents). Analyses of 6 well waters at Macomb, from Illinois 9.
21. Shaw, E. W., U. S. Geol. Survey Geol. Atlas, New Athens-Okawville folio (No. 213), 1922 (25 cents). Analysis of public supply at Mascoutah, of well water from Okawville, and 2 analyses of surface waters.
22. Savage, T. E., and Udden, J. A., The geology and mineral resources of the Edginton and Milan quadrangles: Extract from Illinois Geol. Survey Bull. 38, 1921. 8 analyses of ground and surface waters, 22 sanitary analyses of Mississippi River at Moline.
23. Savage, T. E., and Nevel, M. L., Geology and mineral resources of the La Harpe and Good Hope quadrangles, Ill.: Illinois Geol. Survey Bull. 43, 1923. 9 analyses (from miscellaneous sources) of well waters.

INDIANA

General reports: 1 (29), 3 (7), 7 (1), 8 (4 s), 20 (13), 21 (4 s, 25) 22 (5).

1. Cox, E. T., Indiana Geol. Survey Second Rept., p. 106, 1871. Chapter headed "Martin County" has section on mineral waters. 5 analyses from miscellaneous sources.
2. Leverett, Frank, The water resources of Indiana and Ohio: U. S. Geol. Survey Eighteenth Ann. Rept. pt. 4, pp. 419–560, 1897 ($1.75). 32 analyses from miscellaneous sources.
3. Blatchley, W. S., The mineral waters of Indiana: Indiana Dept. Geology and Nat. Res. Twenty-sixth Ann. Rept., pp. 11–158, 1903. (This annual report gives on pp. 159–226 an article by Robert Hessler on the medicinal properties and use of Indiana waters). 80 analyses from miscellaneous sources.
4. Capps, S. R., The underground waters of north-central Indiana, with a chapter on the chemical character of the waters by R. B. Dole: U. S. Geol. Survey Water-Supply Paper 254, 1910 (40 cents). 320 analyses of ground water and 13 analyses of surface water, made in laboratories of U. S. Geological Survey and State Board of Health.

IOWA

General reports: 1 (14), 3 (5), 8 (4 s), 14 (2), 20 (12), 21 (3 s, 33), 22 (3).

1. Norton, W. H., Report on lead, zinc, artesian wells in Iowa: Iowa Geol. Survey, vol. 6, 1897. Analyses (from miscellaneous sources) of waters from rivers (20), artesian wells (50), shallow wells (33), wells in drift (11). Contains a bibliography on waters from artesian wells.

2. Grant, U. S., and Burchard, E. F., U. S. Geol. Survey Geol. Atlas, Lancaster-Mineral Point folio (No. 145), 1907 (5 cents). Analyses (from Iowa 1) of water from 2 artesian wells near Dubuque.
3. Norton, W. H., Hendrixson, W. S., Simpson, H. E., Meinzer, O. E., and others, Underground water resources of Iowa: U. S. Geol. Survey Water-Supply Paper 293, 1912 (70 cents). 400 analyses of ground waters. Nearly one-half were made by W. S. Hendrixson in the chemical laboratory of Grinnell College; 45 were taken from Iowa 1; the rest were obtained from railroads and other sources.
4. Norton W. H., and others, Underground water resources of Iowa: Iowa Geol. Survey, vol. 21, pp. 29–1186, 1912. 400 analyses of well waters, which are given in Iowa 3.
5. Gabriel, G. A., River waters in Iowa—a preliminary report: Iowa Geol. Survey, vol. 26, pp. 29–48, 1917. 9 tables of analyses of waters of Cedar, Des Moines, and Iowa rivers.
6. Knight, Nicholas, Some Iowa waters: Iowa Acad. Sci. Proc., vol. 15, pp. 109–110, 1908. 5 analyses including public supplies of Springville and Lisbon.

KANSAS

General reports: 1 (24), 3 (13), 15 (8), 18 (14), 20 (3), 21 (24s, 116), 22 (17).

1. Bailey, E. H. S., and Franklin, E. C., A chemical examination of the waters of the Kaw River and its tributaries: Kansas Univ. Quart., vol. 3, p. 91, 1895. 9 analyses of surface waters made at the University. The methods used are described.
2. Bailey E. H. S., Special report on mineral waters: Kansas Univ. Geol. Survey, vol. 7, 1902. 129 analyses of mineral waters made by the author.
3. Slichter, C. S., The underflow in Arkansas Valley in western Kansas: U. S. Geol. Survey Water-Supply Paper 153, 1906 (out of print). 70 assays of ground waters made in the field.
4. Wolff, H. C., The utilization of the underflow near St. Francis, Kans.: U. S. Geol. Survey Water-Supply Paper 258, pp. 98–119, 1911 (out of print). Field assays of 19 well waters made by the author.
5. Parker, H. N., Quality of the water supplies of Kansas, with a preliminary report on stream pollution by mine waters in southeastern Kansas by E. H. S. Bailey: U. S. Geol. Survey Water-Supply Paper 273, 1911 (30 cents). 25 tables of series of analyses of composites of daily samples of surface waters; 150 single analyses and 250 assays. 500 analyses and 500 assays of ground water. Most of the analyses were made under the direction of E. H. S. Bailey at the University of Kansas. Most of the field assays were made by H. N. Parker. A number of analyses were obtained from testing laboratories of railroads.
6. Haskins, C. A., and Young, C. C., Water supplies of Kansas: Kansas Univ. Bull., vol. 16., No. 10, 1915. 150 analyses (made at the University) of water from public supplies.
7. Meinzer, O. E., Preliminary report on ground water for irrigation in the vicinity of Wichita, Kans.: U. S. Geol. Survey Water-Supply Paper 345, pp. 1–9, 1915 (30 cents). Determinations of total solids, bicarbonate, sulphate, and chloride for 37 ground waters.
8. Darton, N. H., U. S. Geol. Survey Geol. Atlas, Syracuse-Lakin folio (No. 212), 1920 (25 cents). Analyses (by Atchison, Topeka & Santa Fe Railway) of 20 well waters.

KENTUCKY

General reports: 1 (80), 3 (15), 4 (2), 7 (1), 8 (3 s), 14 (1), 15 (12), 20 (3), 21 (3 s, 2), 22 (6).

1. Kentucky Agr. Exper. Sta. Ann. Repts. Reports for each year from 1894 to 1917 contain from 1 to 10 complete analyses and from 1 to 60 partial analyses, all made at the Experiment Station. Many of the partial analyses give only the total solids.
2. Peter, Robert, Chemical report: Kentucky Geol. Survey Rept. 3, pt. 2, 1857. 13 analyses (by the Survey) of mineral waters.
3. Peter, Robert, First, second, and third chemical reports; Kentucky Geol. Survey, 1884. Analyses (by author) of mineral waters, from 1875 report (20), 1877 report (17), 1878 report (16).
4. Peter, Robert, and Peter, A. M., Fourth, fifth, and sixth chemical reports: Kentucky Geol. Survey Chem. Analyses A 2, 1885. Analyses (by authors) of mineral waters from 1879 report (2), 1883 report (20), 1884 report (6).
5. Peter, Robert, and Peter, A. M., Chemical reports: Kentucky Geol. Survey Chemical Analyses A 3, 1888. 8 analyses (by authors) of mineral waters.
6. Foerste, A. F., The Silurian, Devonian, and Irvine formations of east-central Kentucky: Kentucky Geol. Survey Bull. 7, 1906. 30 analyses (by the Survey) of mineral springs.
7. Glenn, L. C., Underground waters of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois (Tennesee 1, below): U. S. Geol. Survey Water-Supply Paper 164, 1906 (25 cents). Analyses of water from wells at Wickliffe (2) and McGee Spring, Ballard County (1). 12 analyses of waters from Tennessee.
8. Matson, G. C., Water resources of the Blue Grass region, Ky., with a chapter on the quality of the waters, by Chase Palmer: U. S. Geol. Survey Water-Supply Paper 233, 1909 (20 cents). 74 analyses (by Chase Palmer) of ground waters, 20 analyses from miscellaneous sources of spring waters, 60 field assays by Palmer.
9. Crider, A. F., Geology of the Dawson Springs quadrangle: Kentucky Geol. Survey, ser. 4, vol. 2, pt. 1, 1914. 11 analyses (by Survey) of mineral waters.
10. Shaw, E. W., The Irvine oil field, Estill County, Ky.: U. S. Geol. Survey Bull. 661, pp. 141–192, 1918 (Bull. 661–D, 15 cents). 4 analyses of water from Estill Springs.
11. McHargue, J. S., and Peter, A. M., The removal of mineral plant-food by natural waters: Kentucky Agr. Exper. Sta. Bull. 237, 1921. Analyses (made at Experiment Station) of ground and surface waters from Fayette and Woodford counties (17), waters from Mississippi and Pennsylvania areas (11), Mississippi River system (16), other river waters (8).

LOUISIANA

General reports: 8 (2 s), 20 (4), 21 (2 s, 1), 22 (3).

1. Veatch, A. C., The salines of north Louisiana: Geology and agriculture of Louisiana, pt. 6, pp. 47–100, Louisiana State Exper. Sta. 1902. Analyses (from miscellaneous sources) of brines of Louisiana (10) and of other parts of the country (46). 18 partial analyses of artesian waters.
2. Stubbs, W. C., Dodson, W. R., and Brown, C. A., Rice: Louisiana Agr. Exper. Sta. Bull. 77, 2d ser., pp. 382–385, 1904. 22 partial analyses (made at Experiment Station) of waters used in the irrigation of rice fields; 18 of these are from Louisiana 1.

3. Harris, G. D., Underground waters of southern Louisiana, with discussions of their uses for water supplies and for rice irrigation by M. L. Fuller U. S. Geol. Survey Water-Supply Paper 101, 1904 (20 cents). 18 analyses of water from artesian wells taken from Louisiana 1.
4. Harris, G. D., Veatch, A. C., and others, Underground waters of southern Louisiana: Louisiana Geol. Survey Bull. 1, pp. 1–77, 1905. Analyses of water from the public supply at Baton Rouge and from 2 other sources. 18 partial analyses from Louisiana 1.
5. Veatch, A. C., Geology and underground water resources of northern Louisiana and southern Arkansas: U. S. Geol. Survey Prof. Paper 46, 1906 (out of print). Analyses (from miscellaneous sources) of water from wells of Louisiana (22), Arkansas (10), Mississippi (1), Texas (2).
6. Veatch, A. C., Geology and underground water resources of northern Louisiana: Louisiana Geol. Survey Bull. 4, 1906. Excerpts from Louisiana 5. Analyses of ground waters (13) and brines (10). Some of the brine analyses are from Louisiana 1.

MAINE

General reports: 1 (22), 3 (8), 4 (6), 6 (120 chloride determinations), 7 (1), 8 (1 s), 11 (8), 20 (2), 21 (2 s, 12), 22 (4).

1. Maine State Board of Health Ann. Repts. Most of the reports contain sanitary analyses of samples from public supplies and other sources.
2. Bayley, W. S., Occurrence of underground waters of Maine: U. S. Geol. Survey Water-Supply Paper 114, 1905 (out of print). 22 analyses (from miscellaneous sources) of spring waters.
3. Barrows, H. K., Water resources of the Kennebec River basin, Maine, with a section on the quality of the Kennebec River water, by G. C. Whipple: U. S. Geol. Survey Water-Supply Paper 198, 1907 (30 cents). 20 sanitary analyses of the river water.
4. Clapp, F. G., Underground waters of southern Maine, with records of deep wells by W. S. Bayley: U. S. Geol. Survey Water-Supply Paper 223, 1909 (55 cents). 9 analyses of spring waters by W. W. Skinner. Analyses and assays (from miscellaneous sources) of spring waters (88), and well waters (202).
5. Clapp, F. G., Occurrence and composition of well waters in the slates of Maine: U. S. Geol. Survey Water-Supply Paper 258, pp. 32–39, 1911 (out of print). 13 analyses by F. C. Robinson.
6. Clapp, F. G., Occurrence and composition of well waters in the granites of New England: U. S. Geol. Survey Water-Supply Paper 258, pp. 40–47, 1911 (out of print). 7 analyses by F. C. Robinson.
7. Clapp, F. G., Composition of mineral springs in Maine: U. S. Geol. Survey Water-Supply Paper 258, pp. 66–74, 1911 (out of print). 11 analyses from miscellaneous sources.

MARYLAND

General reports: 1 (4), 2 (2), 3 (5), 7 (3), 8 (1 s), 20 (2), 21 (1 s, 17), 22 (2).

1. Clark, W. B., Mathews, E. B., and Berry, E. W., The surface and underground water resources of Maryland, including Delaware and the District of Columbia: Maryland Geol. Survey, vol. 10, 1918. 95 analyses of ground waters by Penniman & Browne and others. 150 sanitary analyses made by the State Board of Health. Descriptions of public water supplies with analyses.

MASSACHUSETTS

General reports: 1 (8), 3 (5), 4 (24), 5 (2), 6 (60 chloride determinations), 11 (13) 20 (2), 21 (3).

1. Massachusetts Agr. Exper. Sta. Ann. Repts. (Pub. Doc. 33). Reports for each year from 1888 to 1894 contain from 65 to 200 sanitary analyses made at the Experiment Station.
2. Massachusetts State Dept. Public Health Ann. Repts. Most of these reports contain sanitary analyses of samples from all the public supplies of the State and from some miscellaneous sources.

MICHIGAN

General reports: 1 (29), 3 (28), 4 (26), 7 (1), 8 (5 s), 13 (8), 14 (1), 16 (5), 17 (9), 18 (36), 20 (13), 21 (6 s, 26), 22 (9).

1. Houghton, Douglass, Report of the State Geologist in relation to the improvement of the State salt springs: Michigan House of Representatives Doc. 2, 1839. 12 analyses of the New York brines (by Professor Goesman, of Syracuse), and discussion of the Michigan brines.
2. Lane, A. C., Lower Michigan mineral waters, a study into the connection between their chemical composition and mode of occurrence: U. S. Geol. Survey Water-Supply Paper 31, 1899 (10 cents). Over 300 analyses (from miscellaneous sources) of surface and ground waters.
3. Leverett, Frank, and others, Flowing wells and municipal water supplies in the southern portion of the southern peninsula of Michigan: U. S. Geol. Survey Water-Supply Paper 182, 1906 (50 cents). 20 complete and 80 partial analyses, from miscellaneous sources.
4. Leverett, Frank, and others, Flowing wells and municipal water supplies in the middle and northern portions of the southern peninsula of Michigan: U. S. Geol. Survey Water-Supply Paper 183, 1907 (50 cents). 12 analyses of well and spring waters and 50 partial and field analyses, from miscellaneous sources.
5. Russell, I. C., and Leverett, Frank, U. S. Geol. Survey Geol. Atlas, Ann Arbor folio (No. 155), 1908 (5 cents). Analyses of 5 mineral waters.
6. Lane, A. C., The Keweenaw series of Michigan: Michigan Geol. and Biol. Survey Pub. 6, Geol. Ser. 4, 1911. 50 analyses (from miscellaneous sources) of mine waters.
7. Cook, C. W., The brine and salt deposits of Michigan: Michigan Geol. and Biol. Survey Pub. 15, Geol. Ser. 12, 1914. 90 analyses of brines and bitterns of the State. Most of these have been published before. In some analyses the units are not given and therefore the concentration is not shown.
8. Sherzer, W. H., U. S. Geol. Survey Geol. Atlas, Detroit folio (No. 205), 1917 (50 cents). Analyses (from other publications) of brines (11), surface waters (2), salt mine and well (3).

MINNESOTA

General reports: 1 (7), 4 (1), 8 (2 s), 20 (5), 21 (2 s, 45), 22 (10).

1. Upham, Warren, The glacial Lake Agassiz: U. S. Geol. Survey Mon. 25, 1896 ($1.70). Analyses (from miscellaneous sources) of water from Minnesota (10), Manitoba (1), North Dakota (1).
2. Dole, R. B., and Wesbrook, F. F., The quality of surface waters in Minnesota: U. S. Geol. Survey Water-Supply Paper 193, 1907 (25 cents). Over 500 partial analyses made by R. B. Dole and others.

3. Hall, C. W., Meinzer, O. E., and Fuller, M. L., Geology and underground waters of southern Minnesota: U. S. Geol. Survey Water-Supply Paper 256, 1911 (60 cents). 400 analyses obtained from testing laboratories of railroads and from other sources.
4. Sardeson, F. W., U. S. Geol. Survey Geol. Atlas, Minneapolis-St. Paul folio (No. 201), 1916 (25 cents). 10 analyses of ground waters from Minnesota 3, and 2 of surface waters from general report 8.

MISSISSIPPI

General reports: 1 (4), 3 (8), 8 (1 s), 14 (1), 20 (2), 21 (1 s), 22 (1).
1. Mississippi Agr. Exper. Sta. Twelfth Ann. Rept., p. 41, 1899. 6 analyses of artesian waters made at the Experiment Station.
2. Logan, W. N., and Perkins, W. R., Underground waters of Mississippi: Mississippi Agr. Exper. Sta. Bull. 89, 1905. 75 analyses made at the Experiment Station.
3. Crider, A. F., and Johnson, L. C., Summary of the underground-water resources of Mississippi: U. S. Geol. Survey Water-Supply Paper 159, 1906 (20 cents). 99 analyses of ground water; 67 are from Mississippi 2.

MISSOURI

General reports: 1 (28), 3 (8), 4 (48), 8 (2 s), 14 (9), 15 (29), 16 (7), 20 (4), 21 (1 s, 17), 22 (11).
1. Woodward, A. E., The mineral waters of Saline County: Missouri Geol. Survey Bull. 1, p. 45, 1890. 11 analyses of Missouri waters and 7 others.
2. Woodward, A. E., The mineral water of Henry, St. Clair, Johnson, and Benton counties: Missouri Geol. Survey Bull. 3, p. 85, 1890. 12 analyses of Missouri waters and 6 others.
3. Schweitzer, Paul, Report on the mineral waters of Missouri: Missouri Geol. Survey, vol. 3, 1892. 83 analyses made for the report by A. E. Woodward and Paul Schweitzer, 15 analyses of foreign mineral waters, about 100 additional analyses of mineral waters of the State from miscellaneous sources. A bibliography of about 200 titles of publications on mineral waters from 1500 to 1883.
4. Gallaher, J. A., Preliminary report on the structural and economic geology of Missouri: Missouri Bur. Geology and Mines, vol. 13, 1900. 41 analyses of mineral waters taken from Missouri 3.
5. Smith, W. S. T., Water resources of the Joplin district, Mo.-Kans.; U. S. Geol. Survey Water-Supply Paper 145, pp. 74–83, 1905 (out of print). Analyses (from miscellaneous sources) of waters from springs (6) and from deep wells (6).
6. Shepard, E. M., Underground waters of Missouri, their geology and utilization; U. S. Geol. Survey Water-Supply Paper 195, 1907 (30 cents). Analyses (from miscellaneous sources) of waters from city supplies (24) and from wells and springs (60).
7. Buckley, E. R., Geology of the disseminated lead deposits of St. Francois and Washington counties; Missouri Bur. Geology and Mines, vol. 9, pt. 1, 1909. Analyses (from miscellaneous sources) of 11 mine waters.
8. McCourt, W. E., The geology of Jackson County; Missouri Bur. Geology and Mines, vol. 14, 2d ser., 1917. Analyses (from miscellaneous sources) of waters from rivers (2), wells and springs (8).

MONTANA

General reports: 1 (8), 3 (3), 10 (4 s), 12 (7), 14 (13), 15 (2), 16 (6), 20 (2), 21 (4), 22 (1).

1. Fisher, C. A., Geology and water resources of the Great Falls region, Mont.: U. S. Geol. Survey Water-Supply Paper 221, 1909 (20 cents). 80 assays from miscellaneous sources.
2. Meinzer, O. E., The water resources of Butte, Mont.: U. S. Geol. Survey Water-Supply Paper 345, pp. 79–105, 1915 (30 cents). 8 analyses made for the report by S. C. Dinsmore, 13 from railroad laboratories, 7 analyses of mine waters given in general report 14.
3. Meinzer, O. E., Artesian water for irrigation in Little Bitterroot Valley, Mont.: U. S. Geol. Survey Water-Supply Paper 400, pp. 9–37, 1917 (15 cents). 14 analyses of ground waters made by S. C. Dinsmore, Carl Gottschalk, and W. M. Cobleigh, for the U. S. Geological Survey.
4. Ellis, A. J., and Meinzer, O. E., Ground water in Musselshell and Golden Valley counties, Mont.: U. S. Geol. Survey Water-Supply Paper 518, 1924 (20 cents). Analyses (from miscellaneous sources) of water from Musselshell River (10) and from wells and springs (51).
5. Pardee, J. T., Geology and ground-water resources of Townsend Valley, Mont.: U. S. Geol. Survey Water-Supply Paper 539, 1925 (15 cents). 12 analyses by C. S. Howard, U. S. Geological Survey.
6. Reeves, Frank, Geology and possible oil and gas resources of the faulted area south of the Bearpaw Mountains, Mont.: U. S. Geol. Survey Bull. 751, pp. 71–114, 1924 (Bull. 751–C, 15 cents). Analyses (by C. S. Howard) of water from sands at 2,855 and 3,177 feet in a test well near Winifred.

NEBRASKA

General reports: 3 (1), 8 (4 s), 20 (2), 21 (4 s, 14), 22 (3).

1. Slichter, C. S., and Wolff, H. C., The underflow of the South Platte Valley: U. S. Geol. Survey Water-Supply Paper 184, 1906 (out of print). 52 analyses of water along the Union Pacific Railroad in western Nebraska and eastern Colorado, made in the railroad testing laboratory; 30 field assays.
2. Condra, G. E., Geology and water resources of a portion of the Missouri River valley in northeastern Nebraska; U. S. Geol. Survey Water-Supply Paper 215, 1908 (40 cents). 3 analyses of artesian waters.
3. Meinzer, O. E., Ground water for irrigation in Lodgepole Valley, Wyo. and Nebr.: U. S. Geol. Survey Water-Supply Paper 425, pp. 37–69, 1919 (out of print) (Wyoming 9). 10 analyses of waters from Nebraska and 12 from Wyoming made by S. C. Dinsmore and others.

NEVADA

General Reports: 1 (6), 3 (1), 10 (2 s), 12 (8), 14 (18), 16 (9), 20 (2), 21 (12), 22 (10).

1. Wilson, N. E., Drinking water: Nevada Agr. Exper. Sta. Bull. 34, 1896. 79 sanitary analyses made at the Experiment Station.
2. Nevada Agr. Exper. Sta. Bull. 72, pp. 40–44, 1909. Analyses (made at Experiment Station) of water from public supplies of Dixie, Elko City, Mazuma, Rawhide, Reno, and Yerrington.
3. Hance, J. H., Potash in western saline deposits: U. S. Geol. Survey Bull. 540, pp. 457–469, 1914 (out of print). Quantities of soluble material and potash for about 100 samples of residues and brines, total solids for 31 spring and well waters. Analyses made for the report by A. R. Merz.

4. Dole, R. B., Exploration of salines in Silver Peak Marsh, Nev.: U. S. Geol. Survey Bull. 530, pp. 330–345, 1913 (out of print). 12 analyses of waters by Walton Van Winkle (also given in Nevada 7). 13 partial analyses of brines by Van Winkle, 13 determinations of total solids and potassium in brines by A. R. Merz.
5. Carpenter, Everett, Ground water in southeastern Nevada: U. S. Geol. Survey Water-Supply Paper 365, 1915 (out of print). 42 analyses of ground and surface waters made by S. C. Dinsmore.
6. Hicks, W. B., The composition of muds from Columbus Marsh, Nev.: U. S. Geol. Survey Prof. Paper 95, pp. 1–11, 1916 (20 cents). 9 partial analyses (by author) of waters from a test well.
7. Meinzer, O. E., Geology and water resources of Big Smoky, Clayton, and Alkali Spring valleys, Nev.: U. S. Geol. Survey Water-Supply Paper 423, 1917 (30 cents). 60 analyses of ground water, most of them by S. C. Dinsmore (12 are from Nevada 4).
8. Bastin, E. S., and Laney, F. B., The genesis of the ores at Tonopah, Nev.: U. S. Geol. Survey Prof. Paper 104, 1918 (15 cents). 3 analyses of mine waters by Chase Palmer and R. C. Wells, U. S. Geological Survey.
9. Waring, G. A., Ground water in Reese River basin and adjacent parts of Humboldt River basin, Nev.: U. S. Geol. Survey Water-Supply Paper 425, pp. 95–129, 1919 (out of print). 37 analyses made for the report by S. C. Dinsmore.
10. Clark, W. O., and Riddell, C. W., Exploratory drilling for water and use of ground water for irrigation in Steptoe Valley, Nev.: U. S. Geol. Survey Water-Supply Paper 467, 1920 (out of print). 16 analyses and 10 assays of well and spring waters, 7 analyses and 3 assays of water from test wells, made for this report in the water-resources laboratory, U. S. Geological Survey.
11. Waring, G. A., Ground water in Pahrump, Mesquite, and Ivanpah valleys, Nev. and Calif.: U. S. Geol. Survey Water-Supply Paper 450, pp. 51–86, 1921 (Water-Supply Paper 450–C, 5 cents) (California 34). Analyses (made for the report) of ground waters from Nevada (8) and California (12).
12. Bastin, E. S., Bonanza ores of the Comstock lode, Virginia City, Nev.: U. S. Geol. Survey Bull. 735, pp. 41–63, 1923 (Bull. 735–C, 5 cents). 2 analyses of mine waters by N. E. Wilson, University of Nevada; 1 by Chase Palmer, U. S. Geological Survey.

NEW HAMPSHIRE

General reports: 1 (8), 3 (2), 4 (20), 6 (150 chloride determinations), 7 (1), 11 (6), 21 (8), 22 (1).

1. New Hampshire State Board of Health Repts. Most of the reports contain sanitary analyses (residue is not given) of samples of public supplies and other waters.

NEW JERSEY

General reports: 1 (8), 2 (9), 3 (3), 8 (2 s), 20 (9), 21 (2 s, 1), 22 (2).

1. New Jersey State Dept. Health Repts. Many of the reports contain partial analyses of samples from public supplies of the State.
2. Cook, G. H., State Geologist, Ann. Rept. 1868, pp. 701–708. 12 analyses from miscellaneous sources.
3. Cook, G. H., State Geologist, Ann. Rept. 1876. 23 partial analyses from miscellaneous sources.

4. Cook, G. H., State Geologist, Ann. Rept. 1879, pp. 123–150. 4 analyses from miscellaneous sources.
5. Cook, G. H., State Geologist, Ann. Rept. 1884, pp. 121–150. 7 analyses from miscellaneous sources.
6. Vermeule, C. C., Report on water supply: State Geologist Final Report. vol. 3, 1894. 40 more or less complete analyses from miscellaneous sources.

NEW MEXICO

General reports: 1 (12), 3 (3), 10 (8 s), 14 (3), 20 (2), 21 (4), 22 (4).

1. Goss, Arthur, and Holt, A. M., New Mexico sugar beets: New Mexico Agr. Exper. Sta. Bull. 29, pp. 197–203, 1899. 12 analyses of samples from the Rio Grande, collected monthly from June, 1893, to June 1894. 9 analyses of other waters, all made at the Experiment Station.
2. Goss, Arthur, Principles of water analysis as applied to New Mexico waters: New Mexico Agr. Exper. Sta. Bull. 34, 1900. Sanitary and mineral analyses of 148 samples of stream, spring, and well waters, made at Experiment Station in previous 8 years.
3. Fisher, C. A., Preliminary report on the geology and underground waters of the Roswell artesian area, N. Mex.: U. S. Geol. Survey Water-Supply Paper 158, 1906 (out of print). Analyses of 20 spring waters by E. M. Skeetz. Analyses (from miscellaneous sources) of 12 artesian waters and 2 river waters.
4. Lee, W. T., Water resources of the Rio Grande Valley in New Mexico and their development: U. S. Geol. Survey Water-Supply Paper 188, 1907 (out of print). 35 analyses of ground water, made by R. F. Hare, of the New Mexico Experiment Station, and by other analysts. 12 analyses from New Mexico 2 above.
5. Meinzer, O. E., Preliminary report on the ground waters of Estancia Valley, N. Mex.: U. S. Geol. Survey Water-Supply Paper 260, 1910 (out of print). 84 field assays of ground waters (also in New Mexico 6).
6. Meinzer, O. E., Geology and water resources of Estancia Valley, N. Mex., with notes on ground-water conditions in adjacent parts of central New Mexico: U. S. Geol. Survey Water-Supply Paper 275, 1911 (out of print). 84 field assays of ground waters (also given in New Mexico 5).
7. Hare, R. F., and Mitchell, S. R., Composition of some New Mexico waters, with discussion of their fitness for irrigation and domestic purposes: New Mexico Agr. Exper. Sta. Bull. 83, 1912. About 350 analyses of surface and ground waters, one-half complete, the others sanitary or partial. Made at Experiment Station in the previous 10 years.
8. Kelly, C., and Anspach, E. V., A preliminary study of the waters of the Jemez Plateau, N. Mex.: New Mexico Univ. Bull. 71, 1913. 11 analyses (by the authors) of water from springs.
9. Meinzer, O. E., and Hare, R. F., Geology and water resources of Tularosa Basin, N. Mex.: U. S. Geol. Survey Water-Supply Paper 343, 1915 (out of print). About 170 analyses of ground waters and 10 surface waters, mostly made at the New Mexico Agricultural Experiment Station under the supervision of R. F. Hare.
10. Darton, N. H., Geology and underground water of Luna County, N. Mex.: U. S. Geol. Survey Bull. 618, 1916 (20 cents). 9 analyses made in railroad laboratories.
11. Darton, N. H., U. S. Geol. Survey Geol. Atlas, Deming folio (No. 207), 1917 (25 cents). Analyses for 2 wells near Deming.

12. Schwennesen, A. T., Ground water in the Animas, Playas, Hachita, and San Luis basins, N. Mex., with analyses of water and soil by R. F. Hare: U. S. Geol. Survey Water-Supply Paper 422, 1918 (20 cents). 60 analyses of well and spring waters made by R. F. Hare, New Mexico Experiment Station.
13. Schwennesen, A. T., Ground water in the San Simon Valley, Ariz. and N. Mex.: U. S. Geol. Survey Water-Supply Paper 425, pp. 1–35, 1919 (out of print). 14 analyses of well and spring waters made by A. E. Vinson and D. W. Moore, Arizona Agricultural Experiment Station.

NEW YORK

General reports: 1 (93), 3 (61), 4 (14), 6 (100 chloride determinations), 7 (20) 8 (4 s), 13 (6), 18 (39), 20 (12), 21 (3 s, 12), 22 (13).

1. New York State Dept. Health Repts. Most of the reports contain data on several public supplies of the State; some sanitary analyses are also reported.
2. Leighton, M. O., Quality of water in the Susquehanna River drainage basin: U. S. Geol. Survey Water-Supply Paper 108, 1904 (out of print) (Pennsylvania 1). Total solids, incrustants, nonincrustants, and chloride for about 200 surface and ground waters of the area; nitrogen, chloride, total residue, and iron for about 100 surface waters. Most of the area covered by this report is in Pennsylvania.
3. Veatch, A. C., Slichter, C. S., Bowman, Isaiah, Crosby, W. O., and Horton, R. E., Underground water resources of Long Island, N. Y.: U. S. Geol. Survey Prof. Paper 44, 1906 (out of print). 25 analyses from miscellaneous sources.
4. Kemp, J. F., The mineral springs of Saratoga: New York State Mus. Bull. 159, 1912. 110 analyses (from miscellaneous sources) of the waters of Saratoga Springs, covering many years.
5. Milford, L. R., Analyses of the Saratoga mineral waters: Jour. Ind. and Eng. Chemistry, vol. 4, p. 593, 1912; vol. 5. pp. 24, 557, 1913; vol. 6, p. 207, 1914. Analyses (by the author) of the important Saratoga waters.

NORTH CAROLINA

General reports: 1 (20), 3 (7), 7 (1), 8 (3 s), 14 (1), 15 (2), 20 (2), 21 (3 s), 22 (4).

1. Blair, A. W., Drinking water, city, town, and rural supplies: North Carolina Agr. Exper. Sta. Bull. 161, 1899. Total solids, chloride, hardness, and ammonia for 88 samples of water determined at the Experiment Station.
2. Pratt, J. H., The mining industry in North Carolina during 1907, with a special report on the mineral waters: North Carolina Geol. and Econ. Survey Econ. Paper. 15, p. 74, 1908. 80 analyses of mineral waters made at the State University.
3. Clark, W. B., Miller, B. L., Stephenson, L. W., Johnson, B. L., and Parker, H. N., The Coastal Plain of North Carolina: North Carolina Geol. and Econ. Survey, vol. 3, pp. 333–502, 1912. 45 partial analyses from miscellaneous sources. 188 assays made for the report.

NORTH DAKOTA

General reports: 1 (6), 20 (3), 21 (22), 22 (1).

1. Darton, N. H., Preliminary report on artesian waters of a portion of the Dakotas: U. S. Geol. Survey, Seventeenth Ann. Rept., pt. 2, pp. 603–694, 1896 (out of print). 23 analyses from miscellaneous sources.

2. Ladd, E. F., Drinking water: North Dakota Agr. Exper. Sta. Bull. 32, pp. 267–270, 1898. Quantities of total solids and sodium chloride for 20 samples of artesian water, with complete analyses of 3 samples, made at the Experiment Station.
3. Jensen, C. A., and Neill, N. P., Soil survey of the Grand Forks area, N. Dak.: North Dakota Agr. Coll. Survey, Second Bienn. Rept., pp. 35–58, 1904 (reprint from Field Operations, U. S. Bur. Soils, 1902). 37 partial analyses from miscellaneous sources.
4. Ladd, E. F., Waters of North Dakota: North Dakota Agr. Exper. Sta. Bull. 66, pp. 559–571, 1905. Tests of 160 samples of waters made at the Experiment Station.
5. Ladd, E. F., Special food bulletin: North Dakota Agr. Exper. Sta., Food Dept., vol. 1, pp. 166–167, 1910. Tests of 35 samples of drinking water made at the Experiment Station.
6. Ladd, E. F., North Dakota waters: North Dakota Agr. Exper. Sta. Twenty-third Ann. Rept., pt. 3, pp. 449–483, 1912. Total solids and chloride are reported for 725 waters tested at the Experiment Station.

OHIO

General reports: 1 (15), 3 (8), 8 (3 s), 13 (5), 17 (6), 18 (32), 19 (21), 20 (13). 21 (3 s, 31), 22 (5).

1. Leverett, Frank, The water resources of Indiana and Ohio: U. S. Geol. Survey Eighteenth Ann. Rept., pt. 4, p. 495, 1897 ($1.75). 31 analyses (from miscellaneous sources) of waters from Ohio.
2. Orton, Edward, The rock waters of Ohio: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 4, pp. 633–717, 1899 ($1.85). 24 analyses from miscellaneous sources.
3. Fuller, M. L., and Clapp, F. G., The underground waters of southwestern Ohio, with a discussion of the chemical character of the waters by R. B. Dole: U. S. Geol. Survey Water-Supply Paper 259, 1912 (35 cents). 200 analyses and field assays of ground waters by R. B. Dole and others, 40 analyses (from miscellaneous sources) of surface waters.
4. Hubbard, G. D., Stauffer, C. R., Bownocker, J. A., Prosser, C. S., and Cumings, E. R., U. S. Geol. Survey Geol. Atlas, Columbus folio (No. 197), 1915 (25 cents). Partial analyses for 8 wells near Columbus; averages of partial analyses for Scioto River at Columbus.

OKLAHOMA

General reports: 10 (4 s), 14 (3), 15 (12), 20 (3), 21 (1).

1. Holter, G. L., and Fields, John, A study of waters for irrigation: Oklahoma Agr. Exper. Sta. Bull. 29, pp. 3–14, 1897. Analyses (made at the Experiment Station) of surface waters (14), ground waters (12), and 12 sanitary analyses. Oklahoma Agr. Exper. Sta. Bull. 38, pp. 3–7, has most of the data in Bulletin 29 and a few more analyses.
2. Oklahoma Agr. Exper. Sta. Rept., 1900, pp. 73–75. 18 analyses made at the Experiment Station.
3. Ford, A. G., Miscellaneous water analyses: Oklahoma Agr. Exper. Sta. Bull. 67, 1905. 125 analyses made at the Experiment Station, most of which represent ground water. About half are complete analyses.
4. Gould, C. N., Geology and water resources of Oklahoma: U. S. Geol. Survey Water-Supply Paper 148, 1905 (out of print). Analyses of waters from streams (50), springs (15), wells (85), ponds (3), made by Edwin DeBarr at the University of Oklahoma.

5. Schwennesen, A. T., Ground water for irrigation in the valley of North Fork of Canadian River near Oklahoma City, Okla.: U. S. Geol. Survey Water-Supply Paper 345, pp. 41–51, 1915 (30 cents). 7 partial analyses of water from alluvium.
6. Thompson, D. G., Ground water for irrigation near Gage, Ellis County, Okla.: U. S. Geol. Survey Water-Supply Paper 500, pp. 33–53, 1922 (Water-Supply Paper 500–B, 5 cents). 4 assays of ground water made for the report in the water-resources laboratory of the U. S. Geological Survey.
7. Renick, B. C., Additional ground-water supplies for the city of Enid, Okla.: U. S. Geol. Survey Water-Supply Paper 520-B, 1924 (5 cents). 5 analyses made by C. S. Howard, U. S. Geological Survey.

OREGON

General reports: 1 (8), 3 (4), 10 (2 s), 14 (2), 21 (23 s, 41), 22 (24).

1. Waring G. A., Geology and water resources of a portion of south-central Oregon: U. S. Geol. Survey Water-Supply Paper 220, 1908 (20 cents). 6 analyses made by W. H. Heileman, Berkeley, Calif.
2. Van Winkle, Walton, Quality of the surface waters of Oregon: U. S. Geol. Survey Water-Supply Paper 363, 1914 (20 cents). 26 tables containing series of analyses covering a period of about a year, 50 single analyses of surface waters. Most of the analyses were made by the author.

PENNSYLVANIA

General reports: 1 (33), 3 (19), 5 (3), 7 (1), 8 (7 s), 14 (1), 18 (6), 19 (21), 20 (16), 21 (7 s, 18), 22 (5).

1. Leighton, M. O., Quality of water in the Susquehanna River drainage basin: U. S. Geol. Survey Water-Supply Paper 108, 1904 (out of print) (New York 2). Total solids, incrustants, nonincrustants, and chloride for about 200 surface and ground waters of the area; nitrogen, chloride, total residue, and iron for about 100 surface waters. Part of the area covered by this report is in New York.
2. Lewis, S. J., Quality of water in the upper Ohio River basin and at Erie, Pa.: U. S. Geol. Survey Water-Supply Paper 161, 1906 (out of print). Field assays of waters from streams (100), springs (30), and wells (70).

RHODE ISLAND

General reports: 1 (2), 3 (2), 4 (6), 6 (13 chloride determinations), 11 (3).

1. Rhode Island State Board of Health Repts. Most of these reports contain sanitary analyses of samples from public supplies and other sources.

SOUTH CAROLINA

General reports: 1 (6), 2 (9), 3 (6), 8 (2 s), 14 (2), 20 (2), 21 (2 s, 1), 22 (2).

1. South Carolina State Board of Health Repts. Most of the reports contain sanitary analyses of samples from public supplies of the State.
2. South Carolina Agr. Exper. Sta. Fifth Ann. Rept., pp. 21–24, 1893. 22 analyses made at the Experiment Station.
3. South Carolina Agr. Exper. Sta. Seventh Ann. Rept., pp. 16–22, 1895. 28 analyses made at the Experiment Station.
4. South Carolina Agr. Exper. Sta. Eighth Ann. Rept., pp. 58–61, 1896. 15 complete and 35 partial analyses made at the Experiment Station.

5. Stephenson, L. W., A deep well at Charleston, S. C., with a report on the mineralogy of the water by Chase Palmer: U. S. Geol. Survey Prof. Paper 90, pp. 69–94, 1915 (out of print). 2 average analyses from general report 8 and 3 analyses of artesian water.

SOUTH DAKOTA

General reports: 3 (3), 10 (1 s), 20 (1), 21 (13).

1. Shepard, J. H., The artesian waters of South Dakota: South Dakota Agr. Exper. Sta. Bull. 41, 1895. 20 analyses made at the Experiment Station, Bulletin 49, 1896, of the Experiment Station is a continuation of Bulletin 41 and has 11 additional analyses. Bulletin 81, 1903, is substantially a reprint of Bulletins 41 and 49.
2. Darton, N. H., Preliminary report on artesian waters of a portion of the Dakotas: U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, pp. 603–694. 1896 (out of print). 22 analyses from miscellaneous sources.
3. Darton, N. H., New developments in well boring and irrigation in eastern South Dakota: U. S. Geol. Survey Eighteenth Ann. Rept., pt. 4 pp. 561–616, 1898 ($1.75). 4 analyses (from miscellaneous sources) of waters from South Dakota, 3 from Montana.
4. Todd, J. E., Mineral resources of South Dakota: South Dakota Geol. Survey Bull. 3, pp. 121–129, 1902. 36 analyses (from miscellaneous sources) of spring and well waters.
5. Darton, N. H., and Smith, W. S. T., U. S. Geol. Survey Geol. Atlas, Edgemont folio (No. 108), 1904 (5 cents). 2 analyses obtained from railroad laboratories.
6. Darton, N. H., and O'Harra, C. C., U. S. Geol. Survey Geol. Atlas, Belle Fourche folio (No. 164), 1909 (5 cents). Analyses of water from 3 wells near Orman.
7. Todd, J. E., U. S. Geol. Survey Atlas, Aberdeen-Redfield folio (No. 165), 1909 (out of print). 8 analyses of artesian water from Aberdeen (6 from South Dakota 1).
8. Darton, N. H., Geology and underground waters of South Dakota: U. S. Geol. Survey Water-Supply Paper 227, 1909 (out of print). 7 railroad analyses.
9. Larsen, C., and others, Effects of alkali water on dairy products: South Dakota Agr. Exper. Sta. Bull. 132, pp. 220–254, 1912. Analyses (made at the Experiment Station) of alkali water from 14 different wells, with a discussion of the effects on butter and milk.
10. Darton, N. H., Artesian waters in the vicinity of the Black Hills, S. Dak.: U. S. Geol. Survey Water-Supply Paper 428, 1918 (15 cents). 4 railroad analyses.
11. Sharwood, W. J., Analyses of some rocks and minerals from the Homestake mine, Lead, S. Dak.: Econ. Geology, vol. 6, pp. 729–789, 1911. Analyses (by the author) of waters from the mines (6) and from two creeks (5). Also published in U. S. Geol. Survey Bull. 765, p. 24, 1924.

TENNESSEE

General reports: 1 (25), 3 (11), 7 (1), 8 (3 s), 12 (6), 14 (8), 16 (6), 20 (6), 21 (3 s), 22 (2).

1. Glenn, L. C., Underground waters of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois: U. S. Geol. Survey Water-Supply Paper 164, 1906 (25 cents). 7 analyses and 5 assays obtained from miscellaneous sources. 3 analyses of waters from Kentucky.

2. Miser, H. D., Mineral resources of the Waynesboro quadrangle, Tenn.: Tennessee Geol. Survey Bull. 26, 1921. 6 analyses made by Margaret D. Foster, U. S. Geological Survey.

TEXAS

General reports: 1 (13), 3 (6), 8 (3 s), 10 (1 s), 14 (3), 20 (12), 21 (3 s, 18), 22 (3).

1. Adriance, Duncan, Tilsen, P. S., and Harrington, H. H., Miscellaneous analyses: Texas Agr. Exper. Sta. Bull. 35, pp. 595–599, 1895. 22 analyses made at the Experiment Station.
2. Hill, R. T., and Vaughan, T. W., Geology of the Edwards Plateau and Rio Grande Plain adjacent to Austin and San Antonio, Tex., with reference to the occurrence of underground waters: U. S. Geol. Survey Eighteenth Ann. Rept., pt. 2, pp. 193–322, 1898 (out of print). 14 analyses from miscellaneous sources.
3. Hill, R. T., Geography and geology of the Black and Grand prairies, Tex., with detailed descriptions of the Cretaceous formations and special reference to artesian waters: U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, 1901 (out of print). 28 analyses (from miscellaneous sources) of artesian waters.
4. Richardson, G. B., Report of a reconnaissance in trans-Pecos Texas, north of Texas & Pacific Railroad: Texas Univ. Min. Survey Bull. 9, 1904. 25 analyses (from miscellaneous sources) of mine waters.
5. Slichter, C. S., Observations on the ground waters of Rio Grande valley: U. S. Geol. Survey Water-Supply Paper 141, 1905 (out of print). 10 analyses furnished by A. Courchesne, of El Paso.
6. Taylor, T. U., Underground waters of the Coastal Plain of Texas: U. S. Geol. Survey Water-Supply Paper 190, 1907 (out of print). 16 analyses from miscellaneous sources.
7. Richardson, G. B., U. S. Geol. Survey Geol. Atlas, El Paso folio (No. 166), 1909 (out of print). Analyses of 7 well waters near El Paso by Arthur Goss, New Mexico College of Agriculture, and others.
8. Fraps, G. S., Irrigation waters and alkali soil of Texas: Texas Agr. Exper. Sta. Bull. 130, 1910. 24 analyses (made at the Experiment Station) of surface and ground waters of Pecos Valley. Analyses showing alkali content of about 45 waters.
9. Gordon, C. H., Geology and underground waters of northeastern Texas: U. S. Geol. Survey Water-Supply Paper 276, 1911 (out of print). 29 analyses, 13 made by the U. S. Geological Survey.
10. Gordon, C. H., Geology and underground waters of the Wichita region, north-central Texas: U. S. Geol. Survey Water-Supply Paper 317, 1913 (out of print). 36 analyses, some made by the U. S. Geological Survey.
11. Richardson, G. B., U. S. Geol. Survey Geol. Atlas, Van Horn folio (No. 194), 1914 (25 cents). Analyses for 2 wells near Van Horn, made by the U. S. Geological Survey.
12. Deussen, Alexander, Geology and underground waters of the southeastern part of the Texas Coastal Plain: U. S. Geol. Survey Water-Supply Paper 335, 1914 (out of print). 80 analyses from miscellaneous sources, 30 from previous publications.
13. Baker, C. L., Geology and underground waters of the northern Llano Estacado: Texas Bur. Econ. Geology and Technology Bull. 57, 1915. 29 analyses of well waters of Hale County, made at the laboratory of the Bureau of Economic Geology; 12 analyses of well waters from miscellaneous sources, 98 analyses furnished by the Atchison, Topeka & Santa Fe Railway.

14. Deussen, Alexander, and Dole, R. B., Ground water in La Salle and McMullen counties Tex.: U. S. Geol. Survey Water-Supply Paper 375, pp. 141–177, 1915 (out of print). 22 analyses and 90 assays of ground waters of the area by W. T. Read, University of Texas.
15. Matson, G. C., and Hopkins, O. B., The Corsicana oil and gas field, Tex.: U. S. Geol. Survey Bull. 661, pp. 211–252, 1918 (out of print). 2 analyses of water from near Corsicana.
16. Schoch, E. P., Chemical analyses of Texas rocks and minerals: Texas Univ. Bull. 1814, 1918. 850 analyses of waters grouped as well waters, surface waters, unclassified waters. A collection of all available analyses for the State. Many of the analyses are from earlier publications.

UTAH

General reports: 1 (9), 3 (5), 10 (1 s), 14 (8), 17 (9), 20 (6), 21 (23), 22 (13).

1. Cutter, W. P., Value of natural water for crop growth: Utah Agr. Exper. Sta. Bull. 22, 1893. 7 analyses made at the Experiment Station.
2. Utah Agr. Exper. Sta. Eighth Ann. Rept., pp. 30–31, 1897. 5 analyses of water from Logan River made at the Experiment Station.
3. Richardson, G. B., Underground water in the valleys of Utah Lake and Jordan River, Utah: U. S. Geol. Survey Water-Supply Paper 157, 1906 (20 cents). Analyses of water from streams, springs, and lakes (21), wells (10), Great Salt Lake (6). Most of these analyses are published elsewhere.
4. Richardson, G. B., Underground water in Sanpete and central Sevier valleys, Utah: U. S. Geol. Survey Water-Supply Paper 199, 1907 (25 cents). 30 field assays made by the author, 1 analysis from Cooper Hot Springs.
5. Lee, W. T., Water resources of Beaver Valley, Utah: U. S. Geol. Survey Water-Supply Paper 217, 1908 (10 cents). 15 analyses, assays of waters from streams (15), springs (16), wells (110).
6. Meinzer, O. E., Ground water in Juab, Millard, and Iron counties, Utah: U. S. Geol. Survey Water-Supply Paper 277, 1911 (25 cents). 19 analyses (from miscellaneous sources) of ground water, 2 of surface water.
7. Carpenter, Everett, Ground water in Boxelder and Tooele counties, Utah: U. S. Geol. Survey Water-Supply Paper 333, 1913 (10 cents). Analyses of water from streams (3), springs (3), Great Salt Lake (8), published in general report 22; field assays (130).
8. Stewart, Robert, and Hirst, C. T., The alkali content of irrigation waters: Utah Agr. Exper. Sta. Bull. 147, 1916. 30 analyses.
9. Groves, J. E., and Hirst, C. T., Composition of the irrigation waters of Utah: Utah Agr. Exper. Sta. Bull. 163, 1918. Analyses (made at the Experiment Station) of waters from streams and lakes (58), springs (8), wells (32), reservoirs (5), drains (8).

VERMONT

General reports: 1 (10), 3 (8), 4 (111 sanitary analyses), 6 (100 chloride determinations), 7 (1), 11 (3), 20 (2), 21 (3).

1. Vermont State Board of Health Repts. Most of the reports contain sanitary analyses of samples from public supplies of the State.
2. Vermont Agr. Exper. Sta. Ann. Repts. Reports from 1889 to 1899 each contain from 13 to 59 partial analyses made at the Experiment Station.

3. Leighton, M. O., Preliminary report on the pollution of Lake Champlain: U. S. Geol. Survey Water-supply Paper 121, 1905 (20 cents). Analyses of water from Lake Champlain (6), Ticonderoga Creek (2), a number of sanitary analyses.

VIRGINIA

General reports: 1 (87), 3 (38), 7 (16), 8 (3 s), 14 (11), 15 (5), 20 (6), 21 (3 s, 6), 22 (6).

1. Darton, N. H., U. S. Geol. Survey Geol. Atlas, Norfolk folio (No. 80) 1902 (out of print). Analyses for 2 wells near Norfolk.
2. Sanford, Samuel, Underground water resources of Coastal Plain province: Virginia Geol. Survey Bull. 5, 1913. 275 analyses and field assays (160 assays made by the author).

WASHINGTON

General reports: 1 (1), 3 (1), 10 (2 s), 14 (2), 20 (2), 21 (16 s, 9), 22 (10).

1. Russell, I. C., A geological reconnaissance in central Washington: U. S. Geol. Survey Bull. 108, 1893 (out of print). 12 analyses of water from lakes of the arid region; some of these have been published elsewhere.
2. Byers, H. E., Water resources of Washington: Washington Geol. Survey Ann. Rept., vol. 1, pt. 5, 1901. 42 sanitary analyses of public water supplies, 5 analyses of spring and lake waters.
3. Landes, Henry, Preliminary report on the underground waters of Washington: U. S. Geol. Survey Water-Supply Paper 111, 1905 (10 cents). 12 analyses from miscellaneous sources.
4. VanWinkle, Walton, Quality of the surface waters of Washington; U. S. Geol. Survey Water-Supply Paper 339, 1914 (15 cents). 18 tables containing series of analyses by the author covering periods of about one year for the important rivers of the State.

WEST VIRGINIA

General reports: 1 (22), 3 (11), 7 (1), 8 (1 s), 13 (2), 14 (1), 17 (3), 18 (17), 19 (11), 20 (2), 21 (1 s, 20), 22 (1).

WISCONSIN

General reports: 1 (58), 3 (18), 7 (3), 8 (2 s), 20 (6), 21 (2 s, 76), 22 (2).

1. Alden, W. C., U. S. Geol. Survey Geol. Atlas, Milwaukee special folio (No. 140), 1906 (out of print). 9 analyses from miscellaneous sources.
2. Birge, E. A., and Juday, Chancey, The inland lakes of Wisconsin; the dissolved gases of the waters and their biological significance: Wisconsin Geol. and Nat. History Survey Bull. 27, 1914. 25 analyses of water of 19 lakes.
3. Weidman, Samuel, and Schultz, A. R., The undergound and surface water supplies of Wisconsin: Wisconsin Geol. and Nat. History Survey Bull. 35, 1915. 600 analyses of well and spring waters and over 200 analyses of river and lake waters. None of the analyses were made for the report, but they were obtained from various sources—400 from Chicago, Milwaukee & St. Paul Railway, 200 from Chicago & Northwestern Railway, 40 from Dearborn Drug & Chemical Co., some from water-supply papers of the U. S. Geological Survey.

WYOMING

General reports: 1 (7), 3 (2), 10 (4 s), 14 (46), 20 (2), 21 (17), 22 (17).

1. Gooch, F. A., and Whitfield, J. E., Analyses of the waters of the Yellowstone National Park, with an account of the methods of analysis employed: U. S. Geol. Survey Bull. 47, 1888 (out of print). 44 analyses by the authors. All but 6 of these analyses are in general report 14.
2. Weed, W. H., Formation of travertine and siliceous sinter by the vegetation of hot springs: U. S. Geol. Survey Ninth Ann. Rept., pp. 613–676, 1889 ($2). Analyses of several of the waters of Yellowstone Park, many of which are in Wyoming 1.
3. Slosson, E. E., Water analyses: Wyoming Agr. Exper. Sta. Bull. 24, 1895. 35 analyses of samples of spring, well, and irrigation waters made at the Experiment Station.
4. Knight, W. C., A preliminary report on the artesian basins of Wyoming: Wyoming Agr. Exper. Sta. Bull. 45, 1900. 24 analyses made by E. E. Slosson (nearly all in Wyoming 3).
5. Knight, W. C., and Slosson, E. E., Alkali lakes and deposits: Wyoming Agr. Exper. Sta. Bull. 49, 1901. Discussion of some of the alkali waters, with analyses made at the Experiment Station.
6. Fisher, C. A., Mineral resources of the Bighorn Basin: U. S. Geol. Survey Bull. 285, pp. 311–315, 1906 (out of print). Analysis (by E. E. Slosson. University of Wyoming) of water from Thermopolis hot springs.
7. Darton, N. H., and Siebenthal, C. E., Geology and mineral resources of the Laramie Basin, Wyo.: U. S. Geol. Survey Bull. 364, 1909 (out of print), 6 analyses by E. E. Slosson, from Wyoming 3, 4. Several analyses of waters and deposits of soda lakes.
8. Darton, N. H., Blackwelder, Eliot, and Siebenthal, C. E., U. S. Geol. Survey Geol. Atlas, Laramie-Sherman folio (No. 173) 1910 (out of print). 3 analyses (from miscellaneous sources) of water from the Union Pacific Soda Lakes, 6 analyses of waters from the Laramie Basin (from Wyoming 3, 4).
9. Meinzer, O. E., Ground water for irrigation in Lodgepole Valley, Wyo. and Nebr.: U. S. Geol. Survey Water-Supply Paper 425, pp. 37–69, 1919 (out of print) (Nebraska 3). 12 analyses of water from Wyoming and 10 from Nebraska, made by S. C. Dinsmore and others.

PRELIMINARY REPORT ON THE GEOLOGY AND WATER RESOURCES OF THE MUD LAKE BASIN, IDAHO

By H. T. STEARNS and L. L. BRYAN

INTRODUCTION

LOCATION AND EXTENT OF THE REGION INVESTIGATED

The region covered by this report lies some distance north of Idaho Falls, Idaho. It is approximately bounded on the east and southeast by Henrys Fork and Snake River; on the west by Birch Creek; on the north by the crest of the Rocky Mountains, which form the Continental Divide and the north boundary of this part of the State; and on the south by rolling lava plains that terminate the Mud Lake drainage basin. (See Pl. I.) This region is about 80 miles long from east to west, has a maximum width of about 60 miles, and covers approximately 4,000 square miles. It is crossed by the 112th meridian and the 44th parallel and includes all of Clark County and parts of Fremont, Jefferson, Butte, and Lemhi counties. It includes approximately that part of Idaho north of T. 4 N. and between Rs. 30 and 42 E. Boise meridian. Its altitude ranges from about 4,740 feet above sea level along Snake River in the southeast corner of the region to more than 10,000 feet in some of the peaks of the Continental Divide on the north. The altitude of Mud Lake is about 4,780 feet.

The region investigated covers the drainage basin of Mud Lake and such adjacent tracts as were suspected of influencing the surface-water or ground-water supply of this basin.

HISTORY OF THE WATER SUPPLY OF THE REGION

Irrigation was first practiced in this region in the early eighties, when a few scattered hay ranches were being developed along Camas, Beaver, and Medicine Lodge creeks. At that time, according to early inhabitants, Mud Lake was merely a more or less intermittent pond, never covering more than a few hundred acres, whereas Sand Hole Lake, from all known records, never went dry. As early as 1870 a stage station on the route from Salt Lake City to Butte was situated on Sand Hole Lake. About 1895 irrigation began on the terrace southwest of St. Anthony known as Egin

Bench. About 1900, according to F. J. Hagenbarth, of Spencer, Idaho, J. L. Hoffman, of Camas, Idaho, and Frank Reno, of Reno, Idaho, water began to be noticed standing in pools just east of the railroad about 1 mile north of the present site of Hamer.

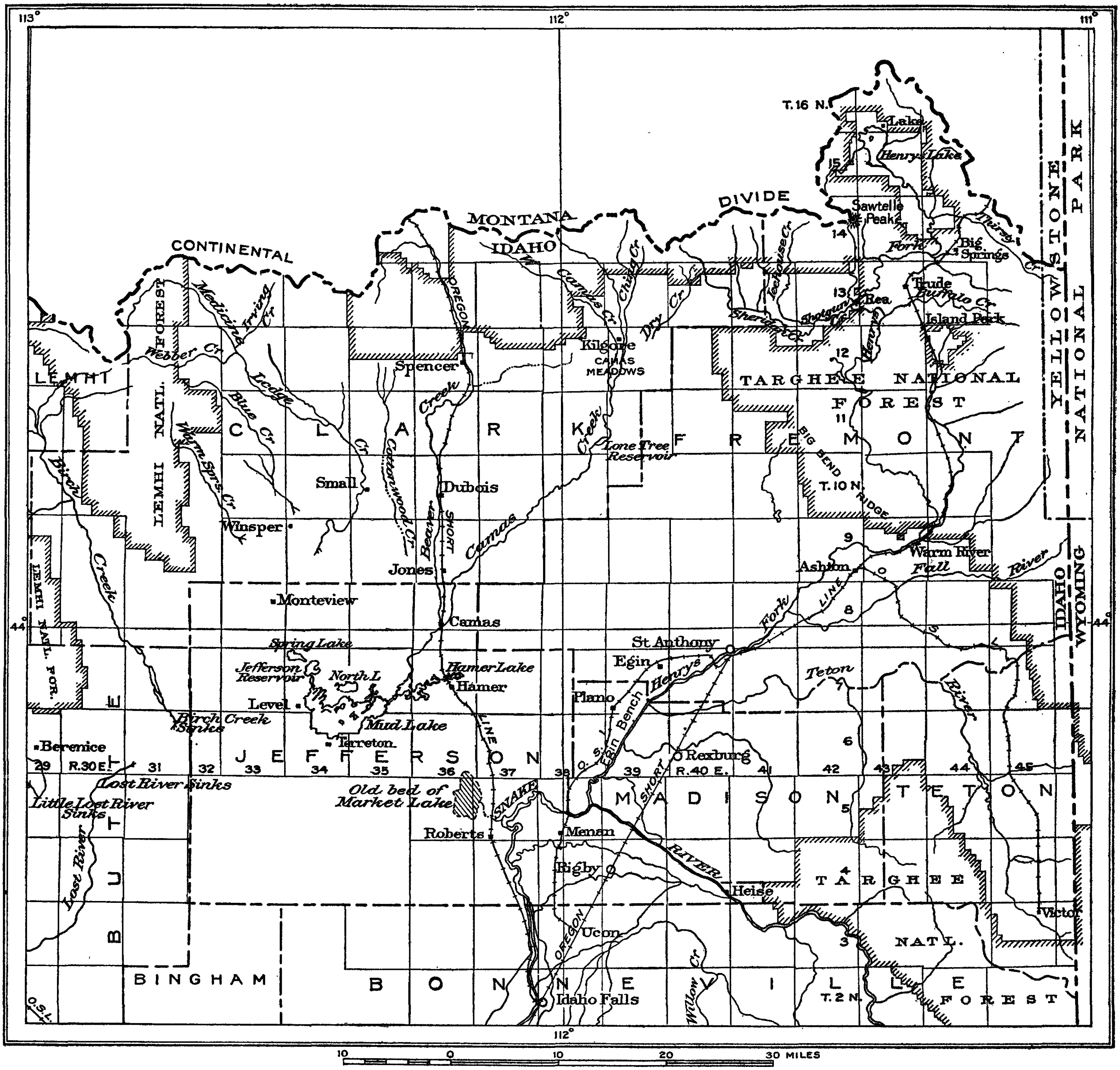
In May and June, 1899, a meander of Mud Lake by the United States General Land Office indicated a water surface of 2,460 acres and dry lake beds to the south and west of Mud Lake occupying approximately 3,000 acres. From 1899 to 1908 the lake rose very little, if at all. In 1908 a survey of the lake made by O. E. Peterson showed practically the same area covered by water as was shown by the survey made by the United States General Land Office in 1899. Mr. Peterson found all except one of the original Land Office monuments around the lake. From 1908 to 1914 the lake rose about 5 feet, as indicated by a survey made by D. P. Olson in 1914, which showed a water surface of approximately 14,200 acres. This is the latest survey of any consequence until the present investigation was commenced. Unfortunately, no gage readings were made prior to 1921 to show the rise and fall of Mud Lake.

In 1908 the first water filing was made on Mud Lake for irrigation, and in 1921 more than 150,000 acres was included in several projects for which it was planned to obtain water from Mud Lake and near-by lakes and sloughs. This acreage was divided among two large Carey Act projects aggregating approximately 30,000 acres and numerous private irrigation enterprises.

PURPOSE AND HISTORY OF THE INVESTIGATION

No thorough investigation of the water supply of the region has hitherto been made. Moreover, in view of the changing conditions caused by the relatively recent rise of the lake and of the surrounding water table, some of the studies and reports that have been made are likely to be misleading. Urgent need for a comprehensive and detailed investigation of the water supply of Mud Lake and the adjacent tracts of small lakes and shallow ground water has been felt for some time to afford a basis for intelligent decision by State and Federal authorities regarding numerous land and water filings that have been made by private and Carey Act irrigation enterprises proposing to obtain their water supplies from Mud Lake or from adjoining water bodies.

To protect investors and settlers it is necessary to know approximately the annual water supply and to limit the amount of land brought under irrigation from this supply. Otherwise there will be overdevelopment, and the water that accumulates in the lake each year will all be diverted before the need for irrigation is over. Thus those holding early rights will be deprived of their legitimate



INDEX MAP SHOWING LOCATION OF MUD LAKE BASIN, IDAHO

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supply, and the owners of later rights who may likewise have attempted in good faith to reclaim land will also suffer. Estimation of the available annual supply of Mud Lake is peculiarly difficult because of the large amount of ground water which it receives through seepage and because of variations in seepage accretions and evaporation losses with fluctuating levels of the lake and of the ground water. The problem is made more complex by the outstanding fact that within the last 25 years the water supply has notably increased.

On account of these conditions a thorough investigation, including an inventory of the water supply, was necessary in order to appraise the possibilities for reclamation and to take definite and proper action upon the pending questions regarding desert-entry applications and the sale of water rights for the Carey Act lands. This investigation should serve a twofold purpose—it should result in full development of the available water resources and it should protect prospective investors and settlers from financial loss by showing the futility of development where no water supply is available.

Financial support was given to the investigation by the Idaho Department of Reclamation, the United States General Land Office, the Idaho Bureau of Mines and Geology, and the United States Geological Survey. The investigation was conducted under the technical supervision of C. G. Paulsen, district engineer, and O. E. Meinzer, geologist in charge of the ground-water division, both of the Geological Survey. The geologic work was assigned to H. T. Stearns and the hydraulic engineering to L. L. Bryan.

Field work was begun in March, 1921. Systematic records were obtained of precipitation, temperature, wind movement, stream flow, seepage losses and gains, pumpage from the lake, evaporation from land and lake pans, evaporation and transpiration from a tule pan, water levels in Mud Lake and several of the smaller lakes, and water levels in about 400 wells. A plane-table traverse was made of Mud Lake and adjoining lakes, sloughs, and swampy areas, and soundings were made to determine the capacity of the lake at different stages. A detailed geologic map of most of the Mud Lake basin and a reconnaissance geologic map of the rest of the region were made. Many miles of levels were run, and contour maps of the land and of the water table were constructed. With these data the source, movement, and disposal of the ground water were largely determined, and inventories were made of the total water supply of the basin.

In June, 1922, a preliminary report on the region covering the period from April 1, 1921, to March 31, 1922, was made public in mimeographed form. Field work was continued during the summer of 1922, and records of precipitation, evaporation, stream flow, pumpage from the lake, and water levels in wells are still being obtained. A final report on the geology and water supply of the Mud Lake basin is in preparation. The present report is a brief description of the geology and hydrology of the basin, with inventories of its water supply for the years ending March 31, 1922, and March 31, 1923.

ACKNOWLEDGMENTS

Special acknowledgments are due to the Idaho Department of Reclamation for the free use of its reports, maps, and instruments and for assistance rendered in preparing the report. Acknowledgments are also due to the canal companies and individual water users in the vicinity of Mud Lake for their active cooperation in reading gages and furnishing records of their pumping operations.

Valuable information was furnished by W. R. Armstrong, assistant chief engineer of the Oregon Short Line Railroad, who permitted the use of alignment maps and contributed data on railroad wells. Records of the United States Weather Bureau and maps and records of the United States Forest Service were used throughout the report. The residents of the region gave hearty support to the investigation, and valuable data were furnished by drillers in regard to wells and by several old settlers in regard to the history of the region.

TOPOGRAPHY

The northern part of the region is occupied by the Rocky Mountains. Farther west are the Lemhi and other ranges, forming an extensive mountainous country. South of the mountains lie the Snake River Plains, which are underlain for the most part by great deposits of basalt that has been poured out at different times from many widely distributed craters. These erratic lava flows have piled up the basalt to higher levels at some distance from the mountains than in the vicinity of the mountains and have thus produced a large but shallow, undrained depression. Into this depression the streams from the mountains discharge, and if their waters are not entirely absorbed or diverted on the way they come to rest in the lowest parts of the depression. Thus, in flood stages, Camas Creek discharges into Mud Lake, whereas Birch Creek, Little Lost River, and Big Lost River discharge into "sinks" farther west, which are at nearly the same level as Mud Lake and are separated from it by only an imperceptible divide.

The Mud Lake basin is regarded as including the drainage areas of Camas Creek and of all other streams that are tributary or potentially tributary to the lake. Thus, it includes the drainage area of Medicine Lodge Creek, which flows toward the lake but in all seasons dries up before it reaches the lake, but not that of Birch Creek, whose flood waters come to rest in another "sink." The investigation, however, was carried east to Henrys Fork and west to Birch Creek in order to determine whether the adjacent tracts contribute in any way to the water supply of this basin. In this report the term "Mud Lake region" is used in a general sense to include the Mud Lake basin and adjacent areas.

The Rocky Mountains form a rugged belt 20 to 30 miles wide, with peaks rising to about 10,500 feet above sea level. The lowest pass through the mountains is at the point where they are crossed by the Oregon Short Line, at an altitude of 6,700 feet.

Big Bend Ridge is approximately 8 miles wide and extends north from Henrys Fork near St. Anthony for 18 miles. It reaches a maximum altitude of about 7,500 feet. The ridge is separated from the Rocky Mountains to the north by the wide valley of Sheridan Creek, which is tributary to Henrys Fork.

From the edge of the mountains a smooth alluvial slope, built up of gravelly débris deposited by streams, extends down to the lower parts of the basin with constantly decreasing gradient. The lowest part of the basin, lying farthest from the mountains, is, however, nearly level, and south of Mud Lake it has a very gentle northward gradient. This exceedingly flat plain adjacent to Mud Lake extends southwestward from the lake fully 30 miles with very little change in altitude. It is apparently the bed of an ancient lake.

The alluvial slope and low, flat plain are in many places interrupted by lava buttes and undulating lava plains. Some of these are older than the slope and plain and stood too high to be covered with the sediments deposited by the streams and lake. Others are younger and are composed of lava that was extruded through the sediments and poured out over them. The part of the region lying east of the railroad that passes through Hamer consists largely of undulating lava plains with numerous lava buttes. Thus Camas Creek has practically no alluvial slope.

About 6 miles west of St. Anthony are the Juniper Buttes, a small group of lava and sand hills that are nestled together more or less in the form of a circle with a depression in the center. Sandhill Mountain is one of these hills whose rock core is almost buried by migrating dunes. North of Mud Lake is an extensive lava plain with fantastic buttes. Southwest of Mud Lake are Antelope and Circular buttes, two volcanic cones that project above the low plain. South of the low plain the lava fields of the Snake River Plains extend indefinitely, forming the south rim of the Mud Lake basin.

Mud Lake and the "sinks" farther west occupy shallow but definite depressions in the low plain which were formed, at least in part, by wind erosion. Some of the numerous small lakes, ponds, and sloughs north and east of Mud Lake occupy depressions made by the wind, and others occupy depressions in the lava. The depression occupied by the main body of water of Mud Lake owes its origin to a recent fault that forms a part of its north boundary.

Stretching southwestward from St. Anthony, on the left bank of Henrys Fork, is a river terrace known as Egin Bench. It is approximately 14 miles long and 4 miles wide. It is underlain by gravel and sand, and, although it appears flat, it has an average gradient of about 10 feet to the mile. It lies outside of the Mud Lake basin but within the region covered in this investigation.

GEOLOGY

Archean system.—The oldest rocks that crop out in the region are of Archean age. They are exposed in the region of Sawtelle Peak southwest of Henrys Lake and consist of marble and quartzite.

Carboniferous system.—Between the headwaters of Sheridan Creek and Sawtelle Peak thick beds of Carboniferous age crop out along the Continental Divide. Fossils collected on the divide were identified by G. H. Girty as belonging to the Madison limestone (lower Mississippian). The Phosphoria formation (Permian) also crops out in this region. Thick deposits of Carboniferous rocks are exposed in the Rocky Mountains from Medicine Lodge Creek westward. Approximately 2,000 feet of Carboniferous strata are exposed in the canyon of this creek. Throughout the region the Carboniferous beds have a general dip to the east. They consist of bluish-gray sandy fine-grained limestone. A few fossils were collected in this region which Mr. Girty identified as belonging to Mississippian and Permian deposits. He provisionally referred the Permian fossils to the Phosphoria formation. Thus there is in this region a series of beds that correspond probably to the phosphate beds at the headwaters of Shotgun Creek, and this suggests the possibility that economic phosphate deposits will be discovered in the future in this region. The Carboniferous rocks in an adjacent area have been described by Umpleby [1] and bear an important relation to the drainage of the region, for it was the deformation of these strata, together with subsequent erosion, that determined the valleys of Birch and Medicine Lodge creeks.

Triassic system.—In the course of the field work a series of thick-bedded red sandstone and conglomerate with thin beds of fossiliferous limestone was discovered at the headwaters of Irving Creek, a tributary to Medicine Lodge Creek. Fossils collected at this

[1] Umpleby, J. B., Geology and ore deposits of the Mackay region, Idaho: U. S. Geol. Survey Prof. Paper 97, p. 29, 1917.

locality were identified by G. H. Girty as coming from the Thaynes limestone, of Lower Triassic age. The Triassic deposits are several thousand feet thick and form the crest of the Rocky Mountains for a number of miles. The beds in general dip to the northeast.

Cretaceous system.—Overlying the Triassic beds and extending eastward beyond the limits of the region investigated are light-yellow clay and sandstone, believed to be of Cretaceous age. They are extensively exposed in the mountains along Beaver Creek. Along the Continental Divide north of Camas Creek the Cretaceous rocks contain a bed of bituminous coal 32 inches thick. The abandoned Scott & Bucy mine is located on an outcrop of this coal bed.[2]

Tertiary and Quaternary systems.—The Paleozoic and Cretaceous formations are largely covered by Tertiary and Quaternary volcanic and sedimentary deposits. The volcanic rocks consist of rhyolite, obsidian, tuff, andesite, and basalt; the later eruptions are almost entirely basalt. Rhyolite, obsidian, and tuff are found chiefly in the mountains, but they also form the Juniper Buttes, which are outliers of the Yellowstone plateau. Basaltic lavas erupted from vents in the mountains flowed down the principal stream valleys. Later the beds of basalt were eroded by the streams, which cut narrow gorges in the black rock. Great quantities of basalt have been erupted from about 150 craters and fissures throughout the Mud Lake basin from the Pliocene epoch of the Tertiary period almost to the present time.

During the Miocene epoch, before most of the lava was poured out, a huge lake existed in southern Idaho and adjacent areas, as is shown by numerous outcrops of a thick series of strata of sand, clay, and gravel. This ancient lake is called Lake Payette, and the lake deposits are called the Payette formation.[3] How far these lake beds extend toward the northeast beneath the thick deposits of lava has presented a problem for many years. Umpleby[4] found Miocene lake beds of sand and clay extensively exposed in Lemhi Valley and believes that these beds extend southward under the Birch Creek valley and belong to the Payette formation. According to Frank Reno, the well at the Reno ranch penetrated 160 feet of sandstone below 380 feet of gravel. This record tends to confirm Umpleby's conclusion and to suggest that the Payette beds extend beneath the Mud Lake basin, although they are not known to crop out anywhere in this region.

[2] Mansfield, G. R., Coal in eastern Idaho: U. S. Geol. Survey Bull. 716, pp. 123–153, 1921.

[3] Lindgren, Waldemar, U. S. Geol. Survey Geol. Atlas, Boise folio (No. 45), 1898.

[4] Umpleby, J. B., Geology and ore deposits of the Mackay region, Idaho: U. S. Geol. Survey Prof. Paper 97, p. 20, 1917.

Beneath the alluvial slope and the low plain of the Mud Lake basin lie deposits of gravel, sand, silt, and clay that have been penetrated by many wells. Near the mountains these deposits consist chiefly of coarse gravel. Down the alluvial slope the gravel gradually becomes finer and eventually gives way largely to sand. Beneath the low plain the sand, for the most part, gives way to silt and clay. The clay beds underlying the low plain are consistently fine textured and indicate deposition in the quiet waters of a lake. They range in thickness from a few feet east of Hamer to at least 180 feet south of Mud Lake. Their southerly extent is unknown at present because of vast unexplored lava fields extending in that direction. It is not known whether these beds were laid down after the present depression came into existence, and are therefore terminated by the lava on the south side, or whether they continue southward and pass under the upper beds of lava.

Fragments of fossil bones were found at two localities in the gravelly deposits of Medicine Lodge Creek (NW. ¼ sec. 15, T. 7 N., R. 33 E., and SW. ¼ sec. 28, T. 8 N., R. 33 E.) and in volcanic ash at a point northwest of Dubois (NW. ¼ sec. 9, T. 11 N., R. 35 E.). These bones were identified by J. W. Gidley, of the United States National Museum, as belonging to species of camels and elephants of probable Pliocene or early Pleistocene age. The silt and clay beds underlying the low plain are apparently of about the same age as the deposits in which the fossil bones were found and are therefore distinctly younger than the Payette formation.

The large numbers of volcanic cones in the region probably range in age from early Pliocene nearly to the present. Their differences in size and shape are due to many causes. Such low cones as Circular and Antelope buttes, southwest of Mud Lake, are relatively very old and have been greatly weathered and partly buried by clay deposits of later origin. The Mud Lake craters, which in perfect symmetry rise so abruptly north of the lake, show by their degree of preservation that they are much more recent. Moreover, in the walls of some of these craters are found large chunks of baked clay and sandstone brought up from the sediments through which the lava came. They are evidently younger than some of the sedimentary deposits underlying the Mud Lake basin.

As volcanic eruptions have occurred at many different times, now in one part of the region and then in another, the lava has become interbedded with the deposits of gravel, sand, and clay in a very intricate and irregular manner. The structural relations between the lava and the gravel, sand, and clay have to some extent been deciphered through the study of well logs, but they are far too complicated to be completely determined. The investigation has shown clearly that these structural relations absolutely control the occurrence and head of the ground water and the available supply of both ground water and surface water in the Mud Lake basin.

SOIL

In the mountains of this region there is very little agriculture because of the high altitude and the lack of soil, but in the main valleys agriculture is successful because of protection from severe storms, plenty of water, and good soil.

Wherever fresh lava does not lie at the surface the Snake River Plains are generally covered with a clayey soil, most of which is deposited from dust-laden winds sweeping across the desert. Wherever it is irrigated this soil produces excellent crops. It is also a good soil for dry farming. Where it is not cultivated, it produces native grass and sagebrush in abundance. If it were not for this loess-like soil, tens of thousands of acres of rather recent lava which are now so valuable for sheep grazing would be barren and worthless. Here truly, "it is an ill wind that blows nobody good."

The soil south and west of Mud Lake is a clayey loam, which is very productive when irrigated. It is remarkably free of any coarse material and does not vary notably in texture except where the clayey material is covered by wind-blown sand. In the region north of New Monteview the soil is clayey loam with a few streaks of pea-sized gravel.

The Mud Lake basin as a whole is remarkably free from alkali. Except in the vicinity of Spring Lake and along the sloughs in other localities, alkali has not been brought to the surface in such quantities as to be detrimental.

The Juniper Buttes are largely covered with a heavy loam that in some years yields cereal crops without irrigation. Thousands of acres in the vicinity of the Juniper Buttes are, however, covered with migrating sand dunes of the cusp type, some of which reach heights of 200 feet.

The upper part of Egin Bench consists of loam underlain by gravel, but this soil changes progressively to a sandy loam and to a black sand toward the south and west. On account of the great permeability of the soil and subsoil Egin Bench requires an excessive use of water for successful cultivation. The entire bench is subirrigated by building up the water table.

VEGETATION

As can be seen from the records of precipitation, the Mud Lake basin is an arid region. Sagebrush is the most abundant native plant, growing luxuriantly almost everywhere except in the swampy tracts, where it has been killed by the rise of the water table. White or sweet sage, rabbit brush, and Russian thistle are also common throughout the region. Above altitudes of 4,500 feet buck brush and chaparral are found.

Around Mud Lake and the sloughs near by are luxuriant growths of marsh grass and tules. Where the sagebrush has been killed by the rise of the water table, greasewood, wild rye, and squirrel tail have grown up in its place.

The mountain areas support good stands of Douglas fir and lodgepole pine.

CROPS

Dry farming, or farming without irrigation, has been tried in several parts of the region. It has been partly successful on the high slopes north of Dubois between Medicine Lodge and Camas creeks and in the vicinity of the Juniper Buttes. In the country adjacent to Mud Lake dry farming has been a complete failure.

Average yields of irrigated crops per acre in the vicinity of Mud Lake are as follows: Alfalfa, 3 to 4 tons; wheat, 30 to 40 bushels; oats, 50 to 60 bushels; potatoes, 100 sacks. In the Camas Meadows the main crop is hay.

CLIMATE

Precipitation.—Precipitation records covering a number of years have been obtained by the United States Weather Bureau at several points in or near the Mud Lake region. In connection with the present investigation records have been obtained since the early part of 1921 at the First Owsley pumping plant and at Camas, Monteview, and Magill's ranch, near the West Hamer bridge. (For locations of rain gages see Pl. II; for precipitation data see pp. 101–102.) The First Owsley pumping plant is about 1 mile east of Terreton and about 1 mile south of Mud Lake. At this plant, which is in what is probably the driest part of the region under investigation, only 8.29 inches of precipitation was recorded for the year ending March 31, 1922, and 8.20 inches for the year ending March 31, 1923. At Camas a five-year record (1908–1912) shows a mean annual precipitation of 10.85 inches. At higher altitudes the precipitation is somewhat greater. Thus at Spencer, about 1,000 feet higher than Mud Lake, the mean annual precipitation (1915–1921) is 17.22 inches, and at Kilgore, which is at nearly the same altitude as Spencer, the mean (1912–1916) is 22.32 inches. At Arco, on the plain 40 miles west of Mud Lake, the mean (1901–1921) is only 9.61 inches. At Idaho Falls, 40 miles southwest of Mud Lake and slightly lower, the mean (1880–1921) is 14.22 inches. At Sugar City, 33 miles directly east of Mud Lake, the mean (1907–1921) is 12.26 inches.

Temperature.—The mean temperature during the year ending March 31, 1922, was 38° at Mud Lake (First Owsley pumping plant), 42.8° at Idaho Falls, 36.2° at Lake, and 40.9° at Lost River. During the same period the mean was 47.6° at Pocatello and 50.6° at Boise. The mean temperature at Mud Lake for January, 1922, was 3°, which, according to the United States Weather Bureau, was a lower mean for the same month than at any other station in Idaho. During the year ending March 31, 1922, the minimum temperature at Mud Lake was 36° below zero, on January 19, 1922, and the maximum was 96° above zero, on July 9 and 21, 1921.

Wind movement.—Records obtained from April 1, 1921, to March 31, 1922, from the anemometer installed at the First Owsley pumping plant in connection with the evaporation pan at that place, which is about 3 feet above the ground surface, showed the mean wind movement to be 4.7 miles an hour. The prevailing direction of the wind was from the southwest. During the spring the wind velocity was usually high. The mean monthly velocity ranged from 7.3 miles an hour in May, 1921, to only 2.7 miles an hour in January, 1922. The mean hourly wind movement during 1921 was 5.3 miles at Boise, 8.97 miles at Pocatello, and 8.24 miles at Yellowstone.

Evaporation and transpiration.—It was necessary to determine as closely as possible the heavy losses due to evaporation and transpiration from Mud Lake and from the large adjoining water-covered and marshy areas. A land evaporation pan was installed at the First Owsley pumping plant, in connection with other Weather Bureau instruments, on April 27, 1921. (See Pl. II.) The pan is 6 feet in diameter and 30 inches high, is made of galvanized iron, painted black on the outside, and has a covered 2-inch stilling well on the outside of the pan. It rests on 1-inch planks laid flat on the ground. It was kept filled with water within 2 or 3 inches of the top. The height of water in the pan was read daily at 7 a. m. by Paul D. Bonnel. Readings were obtained to thousandths of an inch by means of a micrometer.

A floating evaporation pan was installed on August 3, 1921, near the mouth of Camas Creek, in the backwater of Mud Lake, at Magill's ranch, about 2 miles southwest of the West Hamer bridge, 5 miles west of Hamer, and 5 miles northeast of the land evaporation pan. (See Pl. II.) The pan is made of galvanized sheet iron, 4 feet in diameter and 3 feet deep, with covered stilling well 2 inches in diameter outside the pan. The pan was floated on a raft made of 2 by 12 inch timbers. The top or rim was about 2 inches above the water surface. A platform from the bank to the pan was constructed on piles. The water level in the pan was read daily to sixteenths of an inch by C. O. Magill. A standard rain gage was installed 300 feet east of the pan, and rainfall records were obtained while the pan was in operation.

The tule-covered parts of the lakes and the adjoining marsh lands together occupy about three times as much area as the tracts of open water (where there is no vegetation), and they undoubtedly discharge vast quantities of water by transpiration. To aid in determining this loss a pan in which tules were grown was installed on June 13, 1921, in a marsh 1 mile north of the land evaporation pan. (See Pl. II.) This pan is made of heavy galvanized sheet iron, is 4 feet in diameter and 4 feet deep, and has a covered stilling well 2 inches in diameter inside the pan. The pan was sunk in the mud so that the rim was only about 4 inches above the ground surface and was filled with earth and water to a level 6 inches below the outside ground surface. Clumps of tules in about the same density as in the surrounding area were transplanted into the pan, care being taken to damage the roots as little as possible. The pan was next filled with water and allowed to stand a day before readings were commenced. Daily readings were not obtained on account of the isolated location of the pan, but readings were made weekly, and at those times the pan was refilled within 3 inches of the rim. The tules in the pan showed the same growth as the plants in the adjoining marsh.

The results of the observations on the three pans are shown graphically in Figure 7. Monthly summaries and means are shown in the table on pages 101–102. The following conclusions have been reached from a study of the data:

1. Evaporation from the land pan varied directly with the temperature and also showed considerable variation due to the strong winds that intermittently swept the region in the spring.

2. Evaporation from the floating pan was only about 75 per cent as great as evaporation from the land pan. The difference is explained partly by the fact that the temperature of the water was considerably higher in the land pan than in the floating pan and partly by the fact that the sides of the land pan were warmer than the sides of the floating pan, causing a larger loss from the land pan. Moreover, the floating pan is east of the lake, on the leeward of the prevailing southwest winds, and is therefore in the belt of comparatively high humidity, whereas the land pan is on the south side of the lake and receives the dry southwest winds before they have touched the lake.

3. The evaporation from the lake surface is believed to be even less than that from the floating pan, because the humidity is greater over the body of the lake than at the shore, thereby tending to lessen evaporation, and the loss from wave action on the inside of the

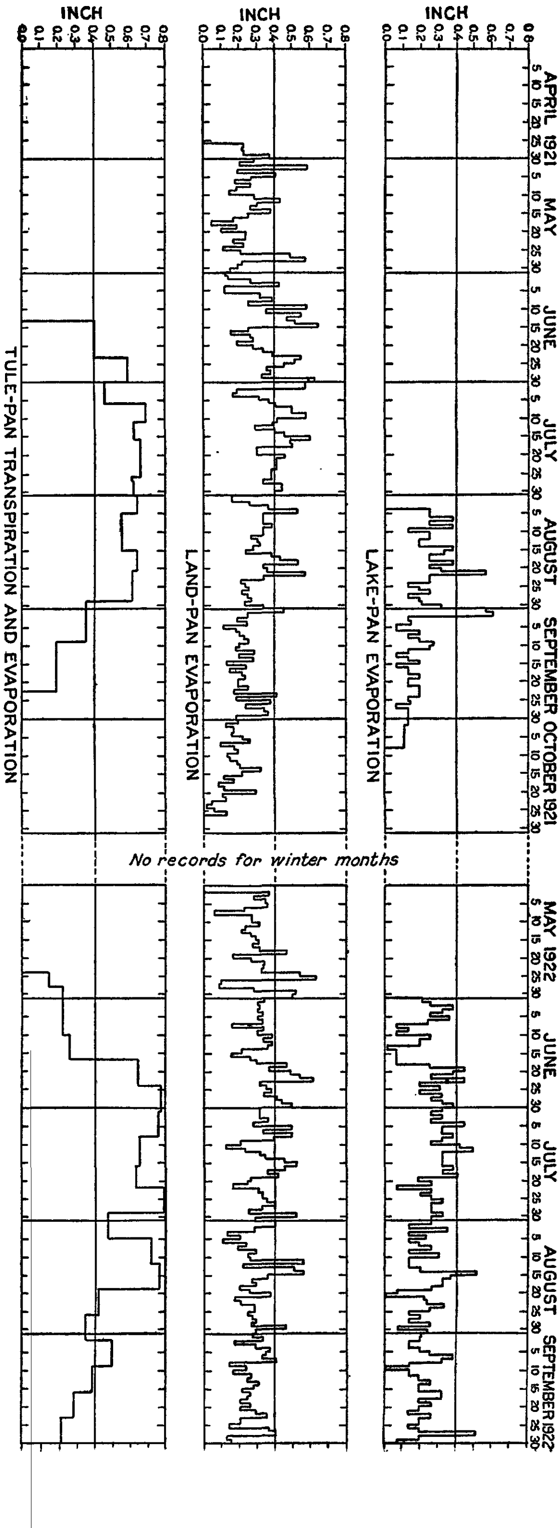


FIGURE 7.—Graphs showing evaporation from land pan, lake pan, and tule pan, Mud Lake, Idaho

rim of the floating pan tends to make the evaporation from it greater. The effect of the wind on the lake surface in increasing evaporation is not believed to be large enough to balance the conditions that favor more rapid evaporation from the floating pan. The ratio of the evaporation from open water to the evaporation from a 4-foot floating pan is estimated by Mead [5] to be 0.83. To reduce the land-pan records to evaporation from the lake surface it would accordingly be necessary to apply a coefficient of 0.83×0.75, or 0.62. A coefficient of 0.65 was somewhat arbitrarily adopted and was applied to the land-pan records in determining the loss from the open-water areas throughout the region under investigation—that is, the water areas without tules or other vegetation.

4. The evaporation from the land pan from April 1 to November 30, 1921, was 4.94 feet (including estimates for April 1–23 and October 28 to November 30, when records were not obtained). If the coefficient 0.65 is applied to this figure, the loss by evaporation from the open water of Mud Lake during the same period is found to have been 3.21 feet. The evaporation from the land pan from April 1 to November 30, 1922, was 4.83 feet (including estimates for April 1 to May 2 and November 1–30, when records were not obtained). Applying the coefficient 0.65 shows that the loss from the open water of Mud Lake during the same period was 3.13 feet.

5. During the season of plant growth the total losses by evaporation and transpiration from the marsh and tule-covered water areas are considerably larger than the loss by evaporation from open-water surfaces. Thus in July the loss was about 12.6 inches from the land pan and 19 inches from the tule pan, and in August it was about 9.8 inches from the land pan and 18 inches from the tule pan. From June 13 to September 23, 1921, the loss was about 34.2 inches from the land pan and 51.4 inches from the tule pan.

[5] Mead, D. W., Hydrology, p. 151, New York, McGraw-Hill Pub. Co., 1919.

Summary of meteorologic data at Mud Lake, Idaho

Month	Air temperature (° F.)			Precipitation (inches)	Evaporation (inches)				Transpiration and evaporation from tule pan (inches)		Wind movement (miles)	
					Land pan		Lake pan					
	Mean maximum	Mean minimum	Mean		Total	Daily mean	Total	Daily mean	Total	Daily mean	Total	Mean per hour
1921												
April	[a] 50.5	[a] 23.7	[a] 37.1	[a] 0.05	[b] 1.05	[b] 0.26					[a] 1,226	[a] 7.3
May	66.1	41.3	53.7	2.24	7.94	.26					5,409	7.3
June	78.6	49.5	64.0	.36	10.49	.35			[c] 8.85	[c] 0.49	4,040	5.6
July	87.0	50.0	68.5	.62	12.56	.40			18.98	.61	3,640	4.9
August	84.8	47.5	66.2	.23	9.78	.32	[d] 7.14	[d] 0.26	17.98	.58	3,020	4.1
September	69.9	32.8	51.4	.42	7.06	.24	5.06	.17	[e] 5.54	[e] .24	4,020	5.6
October	67.1	26.5	46.8	.16	[f] 4.23	[f] .16	[g] .87	[g] .11			2,439	3.3
November	49.0	18.3	33.6	.08	[h] 2.40	.08					3,076	4.3
December	32.5	8.7	20.6	1.95	[i] 1.60	.05					2,473	3.3
Total or average				6.11	57.11	.23	13.07	.18	51.35		29,343	5.1
1922												
January [j]	15.7	−9.6	3.0	.79							1,990	2.7
February [k]	26.2	−4.4	10.9	.39							3,204	4.8
March	[l] 34.8	[l] 5.6	[l] 20.1	1.00							2,603	3.5
April	[m] 50.6	[m] 24.6	[m] 37.5	.68	[h] 4.00	.13					4,237	5.9
May	66.7	37.2	51.6	1.18	[n] 9.48	.31			[o] .94	.13	5,600	7.5
June	81.9	45.3	63.6	.62	10.47	.35	6.79	.23	13.47	.45	3,485	4.8
July	85.8	49.2	67.5	.63	10.41	.34	9.16	.30	21.42	.69	3,160	4.2
August	84.4	40.9	62.6	2.02	8.99	.29	6.40	.21	17.33	.56	2,865	3.8
September	80.0	[p] 43.4	[p] 61.7	.00	7.65	.26	6.01	.20	10.26	.34	2,660	3.7
October	64.1	[p] 33.5	[p] 48.8	.35	4.83	.16					2,730	3.7
November	[p] 40.4	[p] 16.4	[p] 28.4	[q] .55	[h] 2.00	.07					[r] 2,940	4.1
December	30.4	8.4	19.4	.75							2,740	3.7
Total or average	55.1	24.2	39.6	8.96	57.83	.24			63.42	.49	38,214	4.4
1923												
January	30.0	6.1	18.0	[p] .82							2,430	
February	[p] 26.7	[p] 2.1	[p] 14.4	.45							2,180	3.3
March	[v] 33.4	[v] 12.8	[v] 18.1	[t] .15							Incomplete.	3.2
April	[w] 57.7	[w] 28.4	[w] 43.0	.95	[h] 3.00	.10	[x] 1.99	.12			4,540	6.3
May	[y] 67.2	[y] 38.8	[y] 53.0	1.59	7.14	.23	4.62	.15			4,460	6.0
June	[y] 71.0	[y] 43.0	[y] 57.0	1.80	7.61	.25	7.36	.25	[z] 5.79	.31	4,060	5.6
July	[aa] 87.5	[aa] 53.1	[aa] 70.3	1.40	11.42	0.37	9.43	0.30	11.70	0.38	3,590	4.8
August	[aa] 83.3	[aa] 47.3	[aa] 65.3	1.05	9.19	.30	8.17	.26	13.38	.43	[bb] 4140	[bb] 5.6
September	[cc] 76.9	[cc] 39.8	[cc] 58.4	.50	7.20	.24	6.31	.21	11.06	.37	4,275	5.9
October	[cc] 56.2	[cc] 27.2	[cc] 41.7	1.40	[dd] 3.02	.10			[ee] .97	.06	2,955	4.0
November	[aa] 48.7	[aa] 15.7	[aa] 32.2	.00	[h] 1.92	.06					1,580	2.2
December	[ff] 31.0	[ff] 2.6	[ff] 16.8	.00							Incomplete.	[ff] 2.3
Total or average	55.8	26.4	41.1	10.11	50.50	.21		([gg])				

[a] April 24–30.
[b] April 27–30.
[c] June 13–30.
[d] 27.5 days, Aug. 3–31.
[e] Sept. 1–23.
[f] Oct. 1–27; pan froze Oct. 27.
[g] Oct. 1–8.
[h] Estimated.
[i] Estimated. Lake ice-covered Dec. 20–31.
[j] Lake ice-covered. Minimum temperature, 36°, Jan. 19.
[k] Lake ice-covered.
[l] 17 days.
[m] 29 days.
[n] Estimated May 1–2.
[o] May 24–30.
[p] Dubois record used.
[q] Monteview record used Nov. 18–30.
[r] Estimated Nov. 18–30.
[s] Corrected by Dubois record.
[t] Monteview record used.
[u] Estimated Dec. 1–4.
[v] Dubois record Mar. 1–28.
[w] 7 days from Idaho Falls record.
[x] Apr. 15–30.
[y] 28 days.
[z] June 12–30.
[aa] 26 days.
[bb] Uncertain.
[cc] 24 days.
[dd] Estimated Oct. 7–13, 18–31.
[ee] Oct. 1–16.
[ff] 22 days.
[gg] Tule-pan record lower for 1923 than for 1921 and 1922 because plant growth in pan was not normal.

Summary of meteorologic data at Mud Lake, Idaho—Continued

Month	Air temperature (° F.)			Precipitation (inches)	Evaporation (inches)				Transpiration and evaporation from tule pan (inches)		Wind movement (miles)	
					Land pan		Lake pan					
	Mean maximum	Mean minimum	Mean		Total	Daily mean	Total	Daily mean	Total	Daily mean	Total	Mean per hour
1924												
January	[hh]26.1	[hh]−7.8	[hh]9.2	[t].18							1,460	2.0
February	[y]39.1	[y]16.1	[y]27.6	.35							1,860	2.7
March	[m]40.8	[m]15.3	[m]28.0	[t].45							4,140	5.6
April	[cc]57.0	[cc]25.6	[cc]41.3	[t].11							4,065	5.7
May	[aa]74.5	[aa]39.2	[aa]56.8	[t].17							4,855	6.5
June	[ii]79.2	[ii]41.6	[ii]60.4	[t].10							5,000	7.0
July	[y]90.5	[y]43.3	[y]66.9	[t]1.14							3,900	5.2
August	[m]88.1	[m]41.6	[m]64.8	[t]Trace.							3,660	4.9
September	[aa]75.3	[aa]34.7	[aa]55.0	.80							3,150	4.4
October	[y]63.5	[y]29.0	[y]46.2	.95							2,850	3.8
November	[aa]44.7	[aa]11.7	[aa]28.2	[t].19							3,340	4.6
December				[t].72							1,820	2.5
Total or average				5.16							40,100	4.6

[m] 29 days.
[t] Monteview record used.
[y] 28 days.
[aa] 26 days.
[cc] 24 days.
[ii] Based on 23 days' record.
[hh] Based on 30 days' record.

STREAMS

The streams that are contributors to the water supply of the Mud Lake basin are Camas, Beaver, Dry, Cottonwood, and Medicine Lodge creeks. Beaver Creek is a tributary of Camas Creek. Camas Creek is the only stream that discharges surface water into Mud Lake or into the adjoining lakes and sloughs. In addition to these Blue, Warm, Crooked, and Birch creeks were investigated.

CAMAS CREEK

Camas Creek heads in several branches that rise in high and heavily timbered parts of the Rocky Mountains and flow into the high basin known as the Camas Meadows (Pl. I). In this basin there are numerous springs and the water table is very close to the surface, as is shown by natural meadow lands and shallow wells. At a point about 5 miles south of Idmon the basin narrows, forming a lava canyon, above which all the branches unite to form Camas Creek. This canyon extends to a point a few miles above Camas. Below the canyon the creek flows over sand and gravel to Rays Lake, where lava crops out in some places. From Rays Lake it flows to Mud Lake over sand and clay.

Continuous records were obtained at two gaging stations on the creek. The Camas Mutual Irrigation District, which proposes to impound water in a reservoir in the upper reaches of the creek for irrigation in the vicinity of Camas, had previously installed a gaging station from which partial records during the flood periods of 1919 and 1920 were obtained. On April 16, 1921, this station was taken over by the United States Geological Survey, and a Stevens continuous recording gage was installed. The station is in the NE. 1/4 SE. 1/4 sec. 13, T. 11 N., R. 38 E., 2 miles above the Lone Tree reservoir, 7 1/2 miles south of Kilgore, and 19 miles northwest of Dubois. The drainage area above this point is 216 square miles. Another station, consisting of a staff gage, was installed April 2, 1921, in the NE. 1/4 sec. 34, T. 9 N., R. 36 E., a quarter of a mile south of C. J. Thompson's ranch and 5 miles northeast of Camas, or about 23 miles below the upper station. Late in the fall of 1921 an eight-day Stevens recording gage was installed.

The discharge from April 1, 1921, to March 31, 1922, was about 92,600 acre-feet at the upper station and 35,300 acre-feet at the lower station. Thus the difference in flow at the two stations during the year amounted to about 57,300 acre-feet. Approximately 5,730 acre-feet was diverted for irrigation and watering stock between the two stations during 1921. Deducting this amount from 57,300 acre-feet leaves a balance of 51,570 acre-feet, which was evidently contributed to the ground-water supply. Doubtless some of the diverted water also percolated down to the water table. The discharge from April 1, 1922, to March 31, 1923, was about 77,700 acre-feet at the upper station and 28,160 acre-feet at the lower station.

A considerable part of the water lost from Camas Creek went through Lone Tree reservoir, about 2 miles below the upper gaging station. This reservoir, which has a maximum capacity of approximately 3,000 acre-feet, was constructed by the Wood Live Stock Co. Recently it was bought, together with certain water rights, by the Camas Mutual Irrigation District.

The miscellaneous measurements tabulated on page 104 indicate that most of the water disappearing in Camas Creek sinks in the Lone Tree reservoir. There was no gage installed in the reservoir at the time these measurements were made, but as no changes in the outlet gates had been made prior to those dates it can be assumed that the normal flow of Camas Creek was passing through the reservoir.

Approximately 15,000 acres in the Camas Meadows, above the upper gaging station, is under cultivation, including the hay land. This land is watered largely by subirrigation. As the ground water is near the surface throughout this section, it evidently does not have free escape toward the south. Nevertheless a substantial amount of ground water may find its way to the lower lands adjacent to Mud Lake or to other regions. Two large stock-watering ditches diverted approximately 8,670 acre-feet during the year from points above the upper station and carried this water several miles out into the lavas, where some of the water doubtless percolated down to the water table.

Losses in Camas Creek from gaging station 2 miles above Lone Tree reservoir to Jacoby's ranch, about 6 miles below the reservoir, 1923–1924

Date	Measurements (second-feet)								Total flow		Loss	
	Made by—	1	2	3	4	5	6	7	In	Out	Sec.-feet	Per cent
May 20, 1923	A. G. Fielder	423	0.0	7.36	------	------	------	108	------	115	308	72.8
June 8, 1923	do	297	[a]3.0	3.76	------	------	------	98.1	------	105	192	64.6
July 5, 1923	do	88.2	.0	.00	------	------	------	[b]93.0	------	[b]93.0	------	------
Sept. 5, 1923	B. Johnson	43.5	.0	.00	------	------	------	39.8	------	39.8	3.7	8.5
May 30, 1924	F. M. Veatch and B. Johnson.	13.6	[a].35	1.58	[a]0.40	1.04	------	7.31	13.6	10.7	2.9	21.3
July 4, 1924	F. M. Veatch	13.0	.0	.00	[a].40	1.86	------	5.74	13.0	8.0	5.0	38.5
Sept. 7, 1924	do	18.1	.0	.00	[a].40	3.33	[a]0.20	8.56	18.3	12.3	6.0	32.8

[a] Estimated.
[b] The fact that stored water was being released from Lone Tree reservoir at the time these measurements were made accounts for the gain as shown.

1. Camas Creek near Dubois, 2 miles above Lone Tree reservoir, in sec. 13, T. 11 N., R. 38 E.
2. Wood's Live Stock ditch No. 1, about sec. 30, T. 11 N., R. 39 E. (diverts water ½ mile above Lone Tree reservoir).
3. Woodie ditch No. 2, sec. 26, T. 11 N., R. 38 E. (diverts water from Lone Tree reservoir).
4. Hoop ditch, about sec. 10, T. 10 N., R. 38 E. (diverts water about 3½ miles below Lone Tree reservoir).
5. Jacoby ditch, sec. 17, T. 10 N., R. 38 E. (diverts water 6 miles below Lone Tree reservoir).
6. Return flow from Jacoby ditch.
7. Camas Creek at Jacoby's ranch, sec. 20, T. 10 N., R. 38 E., 6 miles below reservoir.

The Frazier reservoir, on West Camas Creek, stores between 2,000 and 3,000 acre-feet for watering stock of the Wood Live Stock Co. This small reservoir and the Lone Tree reservoir are the only existing storage units on the creek above Mud Lake.

The water master reports that between the lower gaging station and Mud Lake 870 acres are irrigated from Camas Creek, of which about 500 acres are partly watered by subirrigation. The water table is 25 feet below the surface at the lower gaging station and comes progressively nearer the surface downstream until it forms sloughs in the vicinity of Hamer. The water lost in Camas Creek below the lower gaging station is doubtless chiefly contributed to Mud Lake or evaporated from the wet lands that lie northeast of the lake.

BEAVER CREEK

Beaver Creek heads in the high peaks along the Continental Divide and flows in a canyon to a point some distance below Spencer and thence in a lava gorge about 50 feet deep to Dubois, where the stream commences to lose its water rapidly in coarse gravel. During the flood period, which usually lasts about two months, the water flows across the porous gravel from Dubois to Camas, where it joins Camas Creek and contributes to the supply of Mud Lake. During the remainder of the year the creek loses all of its flow before it reaches a point 3 miles south of Dubois.

Two gaging stations were established on the creek in April, 1921. The upper station is in the NW. ¼ sec. 21, T. 10 N., R. 36 E., at E. F. Palmer's ranch, half a mile north of Dubois. The drainage area above this point is 220 square miles. The discharge at this station for the year ending March 31, 1922, was about 48,000 acre-feet and for the year ending March 31, 1923, 39,180 acre-feet. The lower station is in sec. 21, T. 8 N., R. 36 E., about three-eighths of a mile above its confluence with Camas Creek at Camas and below all diversions. As mentioned before, there is no flow past this station except during flood periods. The discharge during the flood periods of 1921 and 1922 was 11,400 acre-feet and 10,000 acre-feet, respectively.

In 1920 the water master reported that approximately 3,000 acres was being irrigated above Dubois, largely by water diverted from Beaver Creek above the upper gaging station but in part by water from small tributaries of Beaver Creek. Below Dubois about 1,500 acres was irrigated by water diverted below the upper gaging station.

As about 48,000 acre-feet was discharged past the upper station and 11,400 acre-feet past the lower station in 1921, the total loss of water for that year, including diversions between the two stations, was about 36,600 acre-feet. If 4,500 acre-feet was diverted for irrigation below Dubois (an estimate based on a duty of 3 acre-feet during the season for 1,500 acres) about 32,100 acre-feet was contributed to the ground-water supply as a result of losses in the channel below Dubois. About 11,400 acre-feet was contributed to the lake as surface water during 1921 and 10,000 acre-feet in 1922.

Miscellaneous measurements made during 1922 and 1923 indicate a loss of about 1.5 per cent to the mile in the 14-mile section of Beaver Creek between Spencer and Dubois during the spring floods and less than 0.5 per cent to the mile during low water. The loss occurring in this stretch of the stream is an additional contribution to the ground-water supply.

MEDICINE LODGE CREEK

Medicine Lodge Creek rises in the high mountains and owes considerable of its flow to springs. A number of small perennial streams enter from each side of the creek as it wends a southeasterly course. None, however, enter below the gaging station, which is at the mouth of the canyon. This station was installed April 19, 1921, and consists of a staff gage in sec. 25, T. 11 N., R. 34 E., at the H. W. Small ranch, about 3 miles northwest of Small and 12 miles west of Dubois. The drainage area above this station is 270 square miles.

The discharge at the gaging station for the year ending March 31, 1922, was 51,500 acre-feet, and for the year ending March 31, 1923, 50,200 acre-feet. No stream-flow records prior to these are available.

Between 5,000 and 6,000 acres is irrigated below the gaging station, and after the flood season the entire flow is diverted. A very small amount of water is diverted for irrigation in the narrow valleys above the canyon. The creek commences to lose water through its porous channel below the gaging station and sinks entirely, even in the flood season, about 6 miles northwest of the Jefferson reservoir. If during the year ending March 31, 1922, 3 feet of water was lost by evaporation and transpiration on 6,000 acres of irrigated land, a total of 18,000 acre-feet, a balance of 33,500 acre-feet must have been lost by percolation. Thus the contribution to the ground-water supply from water that passed the gaging station was probably not less than 33,500 acre-feet in 1921–22 and 32,200 acre-feet in 1922–23.

BIRCH CREEK

Birch Creek has its origin in a series of springs a few miles upstream from the ranch of the Wood Live Stock Co. The flow of the stream is practically constant throughout the year. During the summer the entire flow is diverted for irrigation, but during the rest of the year the stream flows in a southeasterly direction and gradually loses its water through its porous channel until at a point about 20 miles from its source the water completely disappears in what is known as the Birch Creek Sinks.

A gaging station that had been in operation from September 5, 1910, to June 30, 1912, was reestablished on April 6, 1921. It consisted of a staff gage installed in sec. 13, T. 10 N., R. 29 E. Boise meridian, about 6 miles northwest of Reno, above practically all diversions.

The records show that for the year ending March 31, 1922, a discharge of 59,900 acre-feet passed the station. Previous published records[6] show that during the year ending September 30, 1911, a flow of 65,100 acre-feet passed the station, and for the period October 1, 1911, to June 30, 1912, 52,100 acre-feet. Though the records show that the discharge was slightly less during the year ending March 31, 1922, than during the corresponding period in 1911–12, yet the annual yield from this particular drainage basin has not changed materially during the last 12 years.

About 1,200 acres is being irrigated from this creek. An application has been filed on a reservoir site in the canyon a short distance above the gaging station, where the Birch Creek Irrigation District proposes to store about 40,000 acre-feet to irrigate land at the lower end of the valley.

The ground-water contours, as shown on the map of this region (Pl. II), demonstrate conclusively that no water from Birch

[6] U. S. Geol. Survey Water-Supply Papers 312 and 332.

Creek or from Lost or Little Lost rivers contributes to the ground-water supply in the vicinity of Mud Lake.

INTERMITTENT STREAMS

Of the small intermittent streams that have their sources in the region north of Mud Lake the principal ones are Dry, Cottonwood, Blue, Warm, and Crooked creeks. Each of these has a comparatively large flood run-off of short duration. All these streams lose water rapidly after leaving the foothills, for the flow of each rarely exceeds 2 second-feet a short distance from the hills. They doubtless all contribute to the ground-water supply, but a study of the water table indicates that only the ground water contributed by Dry and Cottonwood creeks has any chance of reaching the vicinity of Mud Lake. A measurement obtained on Dry Creek May 9, 1921, indicated a flow of 91 second-feet at a point about 6 miles northeast of Kilgore. At that time it was noted that the entire flow disappeared in lava beds about 4 miles below the point of measurement. A number of large springs, however, were noticed about a mile west of this sink, in the eastern edge of the Camas Meadows, where a large portion of the water lost probably reappears and flows into Camas Creek. The entire normal flow and about half of the flood flow of Dry Creek is diverted into the reservoir of the Wood Live Stock Co. on Sheridan Creek, which flows into Shotgun Creek and thence into Henrys Fork. The point of diversion in Dry Creek is about 2 miles above the point where the measurement was made.

WATER TABLES

METHODS OF INVESTIGATION

The water table, or upper surface of the zone of saturation, is almost nowhere a level surface but has irregularities which can be shown on a map by means of contour lines, just as the irregularities of land surfaces are shown on topographic maps. A contour map of the water table of a region generally throws much light on the source, movement, and disposal of the ground water and may also give important information as to the quantity of ground water and the influence of geologic structure upon its occurrence. The water table is generally highest in areas of intake and lowest in areas of discharge of ground water. As ground water, like surface water, tends to move down grade, it generally moves in the direction that the water table slopes, about at right angles to the water-table contours.

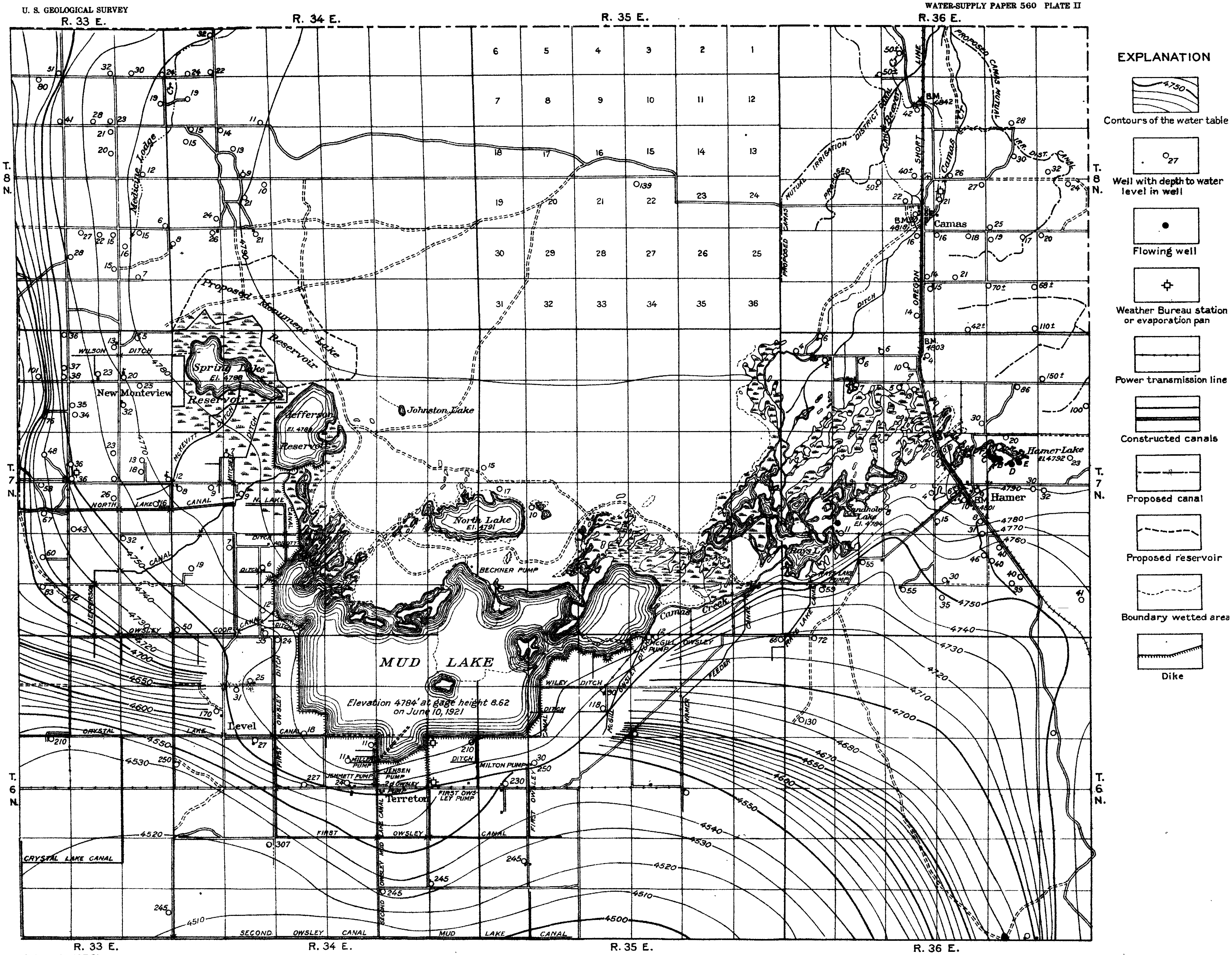
As the water supply of the Mud Lake basin was known to be derived largely from ground water, it was evident that the investigation must include the preparation of an accurate contour map of the water table. In order to prepare such a map records were obtained of about 400 wells, including nearly all the wells in the region. Measurements were made of the depth to the water level in practically all the open wells, but for the depth to water in most of the drilled wells it was necessary to take the owners' statements, many of which were verified by the drillers. All measurements were made from definite bench marks, which were installed in order that continued observations could be referred to the same datum plane. The altitudes of most of the wells were tied in by levels in order that the measurements to the water table in the different wells could be referred to the same datum. All sloughs and other outcrops of the water table were mapped.

In order to ascertain the fluctuations of the water table, monthly measurements were made in nearly all the open wells. The reported rise of the water table near Mud Lake during the last 20 years was verified by mapping the areas of dead sagebrush, for it has been found that if the water table rises high enough to wet the roots of sagebrush continually the sagebrush soon dies. Areas of greasewood were also mapped, because greasewood is known to depend upon the ground water for existence, and the invasion of a new area by this brush would indicate that the water table had risen. In June, 1922, a well was drilled in sec. 16, T. 7 N., R. 38 E., to ascertain the exact depth to water and the fluctuation of the water table between Egin Bench and Hamer.

As the structure of the basalt varies widely from place to place and as the basalt is intricately related to interbedded and overlying layers of impervious clay, the water table was found to be very capricious and to have peculiar features not commonly found in other regions.

PERCHED CONDITION OF MUD LAKE AND CONTIGUOUS GROUND WATER

One of the most striking and significant facts disclosed by this investigation is that Mud Lake and the water found in the shallow wells in the vicinity of the lake form a perched body of water that lies a few hundred feet above the water table of a deeper body of ground water. The shallow wells on all sides of Mud Lake have water levels that are more or less concordant with the water level of the lake, but deep wells drilled south of the lake pass through the deposit of clay and find water in the basalt, generally 250 to 275 feet below the lake level. The deep water does not rise perceptibly in the wells. It forms a true water table that is far below the lake level and that doubtless extends beneath the lake, as shown in Plate II. From all indications, Mud Lake lies upon the thick clay



Culture by H.T. Stearns
Drainage by L.L. Bryan
Surveyed in May and June, 1921

DETAILED MAP OF MUD LAKE AND VICINITY, JEFFERSON COUNTY, IDAHO

Showing wells and contours of the water table

0 1 2 3 4 5 Miles

Wells and contours of the water table by H. T. Stearns

strata, which are mainly the cause of its perched situation. The perched water table in the clay beds southwest of Mud Lake is due in part to irrigation and in part to water seeping away from Mud Lake. In time, with continued irrigation, this water table will be extended farther from the lake. The lower water table south of Mud Lake is continuous with the water table west of Roberts and has a general slope to the southwest.

WATER TABLE NORTH OF MUD LAKE

There seems to be a sort of cascade of the ground water after it reaches the lava plains at the foot of the mountains and south of the Camas Meadows. A short distance from the mountains the water table assumes a more gentle gradient and slopes in general toward the southwest until it comes to an end or descends abruptly.

To this water table percolates the water that is lost from Camas, Beaver, and Medicine Lodge creeks and a few smaller streams and also an undetermined part of the water that falls as rain or snow in the Mud Lake basin but does not reach these streams. The disposal of this ground water depends chiefly on the slope of the water table at the edges of the basin and on the relation of this ground water to the deep ground water south and west of Mud Lake.

The flatness of the water table north and east of Hamer indicates that the ground water in that area is in pervious strata of lava. Whether the water table extends across the large lava field north of Mud Lake is uncertain. Much of this lava is, in all probability, porous enough to allow water to percolate through it, although the volcanic necks below the craters may be impervious. It seems unlikely that there are two distinct water tables north of Mud Lake, as there are south of it. There may, however, be sufficient leaks in the formations to allow water to escape to the deep water table south of the lake and to cause funnel-shaped depressions in the water table in the lava field north of the lake. The craters north of Mud Lake are younger than any of the water-bearing formations near by, and the lava extruded from them must have come up through all underlying formations.

The water-table contours indicate that the water lost from Camas and Beaver creeks reappears, for the most part, as ground water in the swampy area northeast of Mud Lake, where it is disposed of mainly by evaporation and transpiration or by percolating to the surface and draining into Mud Lake. A part of the ground water derived from these creeks probably percolates westward into the lava that lies north of Mud Lake, whence it may pass farther westward to the wet areas of the vicinity of the Jefferson reservoir and Spring Lake or may escape from the basin by deep percolation.

A part of the water from these creeks may also escape from the basin by percolating southward in the vicinity of Hamer, where the water table drops off rapidly toward the south.

The water lost by Medicine Lodge Creek sinks to this water table and doubtless furnishes the principal supply encountered by numerous wells near Winsper, Old Monteview, and New Monteview. Some of the water from this creek may reach Spring Lake and the wet tracts farther south, but the map shows that the water table in this part of the basin slopes steeply toward the west, proving that most of the supply from this creek percolates westward to great depths and is lost to the Mud Lake basin. The only means of recovering most of this water before it escapes from the Mud Lake basin is by pumping it from wells.

In the vicinity of Spring Lake and the Jefferson reservoir there is a large tract of swampy land that is apparently supplied by seepage from the lava that lies to the east. This swampy tract has been produced largely by a rise in the water table similar to the rise farther east. Apparently this rise has had a tendency to elevate the water table farther north, below the fan of Medicine Lodge Creek. A part of the water that comes to the surface in the vicinity of Spring Lake and the Jefferson reservoir is used for irrigation, and a part is lost by evaporation and transpiration. A part also doubtless percolates westward and is lost to the Mud Lake basin except as it is pumped from wells in the belt to the west, where the depth to water is only moderate.

EGIN BENCH IN RELATION TO THE WATER SUPPLY OF THE MUD LAKE BASIN

The great and progressive increases in the visible supply of water in the Mud Lake basin during the last 25 years has attracted wide attention. This increase has long been attributed by the inhabitants of the region to percolation of water used in irrigation on Egin Bench. (See Pl. I.) In this investigation an effort has been made to determine conclusively whether water percolates from Egin Bench to the Mud Lake basin, and, if so, in what quantities.

The problem can be approached in two different ways—(1) by establishing the fact that there has been an increase in water supply and then attempting to eliminate all other possible causes, or (2) by determining the geologic structure, the slope of the water table, and the movement of ground water between Egin Bench and the swampy tracts in the Mud Lake basin. Both these methods of investigation were pursued so far as was feasible.

That there has been a large increase in the size of Mud Lake and a substantial rise in the water table has been definitely proved by the testimony of many trustworthy persons and by abundant physical evidence, such as the existence of dead sagebrush in the west areas and of submerged houses and wells.

There is also evidence that the increase in water supply is not due to a succession of wet years. The available records of precipitation do not indicate any change in climate competent to produce so great an increase in water supply. However, very long records are not available, and even if they were, weather cycles might be hard to detect. Evidence was found that no comparable increase in water supply has occurred in other basins in the same part of the State, such as those of Birch Creek, Little Lost River, Big Lost River, and Pahsimeroi River. Records of the flow of Birch Creek in the year ended March 31, 1922, and in previous years indicate that there has been no increase in that creek. (See under "Streams.") The conclusion therefore appears unavoidable that the increase of water supply in the Mud Lake basin is not due to climatic change but to some natural or artificial change that has specifically affected this basin.

A natural change may have taken place, such as the closing of channels in the lava through which water may have been escaping or the opening of new channels for ground-water inflow by earthquake or other agency. Such a natural change is very improbable, though unfortunately its occurrence can not well be either proved or disproved.

A careful study was made of the areas adjacent to the Mud Lake basin in order to discover any artificial change that should be taken into account. None was found except the irrigation development on Egin Bench. Hence, though this method of approaching the problem does not lead to any positive conclusion, it establishes a strong a priori assumption that the increase in the water supply of the Mud Lake basin is due to irrigation on Egin Bench.

It has been assumed by some persons that the water from Egin Bench percolates to the swampy tracts of the Mud Lake basin through intervening surface deposits of sand. This investigation has shown, however, that the sand deposits lie largely above the water table, and that any water that percolates from Egin Bench to the swampy tracts of the Mud Lake basin must pass through lava or through deposits of sand or gravel interbedded with lava.

In June, 1922, a test well was drilled by the Geological Survey in the NE. ¼ sec. 16, T. 7 N., R. 38 E., to explore the water table. Later in the year several other wells were drilled by local people between Hamer and the test well. The form of the water table as determined by these wells indicates that the ground water moves largely in a southwesterly direction toward the deep-water region south of Hamer. It is therefore improbable that Mud Lake receives any large supplies of ground water from the lower part of Egin Bench by way of Hamer.

During the later part of 1922 a careful survey was made of all the deep wells north of Egin Bench. A water-table map constructed from the data obtained indicates that on the north side of Egin Bench there is a ground-water cascade which causes large quantities of the water used for irrigation on the bench to flow northward. The map also indicates that after the ground water has moved northward some distance it turns westward and later rises in the bed of Camas Creek and adjacent depressions south of the town of Camas, eventually finding its way into Mud Lake. The fact that the rise of the water table was first observed in the wells near Camas also supports this evidence.

Owing to the method of subirrigating on Egin Bench, large quantities of water are used. During the winter the water table sinks to levels 10 to 25 feet below the surface, but in the spring it is built up by seepage from the canals, and during the summer it is usually held up by the same method within 3 to 5 feet of the surface. The water is diverted from Henrys Fork through six large canals.

Monthly discharge, in second-feet, of canals diverting water on Egin Bench, for the year ending March 31, 1922

Canal	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Total
Dewey	-------	[a] 300	604	630	560	302	0	0	0	0	0	0	-------
Last Chance	-------	[a] 1,000	2,206	1,804	1,614	982	0	0	0	0	0	0	-------
St. Anthony Union	-------	12,631	12,433	12,514	9,300	5,117	3,680	950	3,930	1,824	1,671	2,389	-------
Egin	-------	9,109	7,467	8,714	6,519	3,016	3,376	1,960	548	[b] 0	[b] 0	543	-------
St. Anthony Union Feeder	-------	2,630	1,948	1,593	1,525	593	1,408	966	49	0	0	0	-------
Independent	-------	9,171	7,416	6,543	4,806	3,605	6,352	4,080	882	0	0	0	-------
Total:													
Second-feet	[a] 10,000	34,841	32,074	31,798	24,324	13,615	14,816	7,956	5,409	1,824	1,671	2,932	181,260
Acre-feet	19,800	66,600	63,700	63,300	48,200	27,900	29,400	15,800	10,400	3,620	3,320	5,820	357,860

[a] Estimated. [b] Reported practically dry.

The foregoing table gives results derived from records obtained by G. C. Baldwin, district engineer of the United States Geological Survey at Idaho Falls, in connection with the distribution of water on Henrys Fork. Ordinarily records of these diversions are procured only during the irrigation season, but to assist in this investigation arrangements were made whereby records were obtained throughout the winter of 1921–22. However, the diversions of all canals in April, 1921, and of two canals in May, 1921, were estimated because of lack of records. The records and estimates indicate that a total of 357,860 acre-feet was diverted upon Egin Bench in the year ending March 31, 1922.

Diversions and return flow of Henrys Fork between St. Anthony and Rexburg gaging stations and approximate losses on Egin Bench, 1919–1921

	June	July	Aug.	Sept.	Total
1919					
Total diversions on Egin Bench .... second-feet	32,808	25,724	22,561	15,721	96,814
Other diversions between St. Anthony and Rexburg .... do	20,093	5,783	7,673	8,255	-------
Total diversions between St. Anthony and Rexburg .... do	52,901	31,507	30,234	23,976	-------
Gain between St. Anthony and Rexburg .... do	14,040	9,110	7,940	7,990	-------
Gain between St. Anthony and Rexburg .... per cent	26	29	26	33	-------
Probable return flow from Egin Bench .... second-feet	8,500	7,470	5,860	5,200	-------
Approximate losses due to evaporation and vegetation on Egin Bench, based on cultivated area of 30,000 acres .... second-feet	[a]8,520	[a]10,200	[a]7,950	[a]5,740	-------
Approximate total losses on Egin Bench .... do	17,020	17,670	12,810	10,940	-------
Approximate permanent contribution to ground water table on Egin Bench .... second-feet	15,788	8,054	9,751	4,781	38,374
Approximate permanent contribution to ground water table on Egin Bench .... acre-feet	31,300	16,000	19,400	9,460	76,160
1920					
Total diversions on Egin Bench .... second-feet	39,780	31,259	24,128	6,343	101,510
Other diversions between St. Anthony and Rexburg .... do	22,125	17,406	11,836	3,076	-------
Total diversions between St. Anthony and Rexburg .... do	61,905	48,665	35,964	9,419	-------
Gain between St. Anthony and Rexburg .... do	8,341	17,714	12,487	6,682	-------
Gain between St. Anthony and Rexburg .... per cent	13½	36	35	71	-------
Probable return flow from Egin Bench .... second-feet	5,370	11,200	8,450	4,500	-------
Approximate losses due to evaporation and vegetation on Egin Bench, based on cultivated area of 30,000 acres .... second-feet	[a]8,520	[a]10,200	[a]7,950	[a]2,870	-------
Approximate total losses on Egin Bench .... do	13,890	21,400	16,400	7,370	-------
Approximate permanent contribution to ground water table on Egin Bench .... second-feet	25,890	9,859	7,728	0	43,477
Approximate permanent contribution to ground water table on Egin Bench .... acre-feet	51,400	19,600	15,300	0	86,300
1921					
Total diversions on Egin Bench .... second-feet	32,074	31,798	24,324	13,015	101,811
Other diversions between St. Anthony and Rexburg .... do	54,396	50,447	35,053	19,819	-------
Total diversions between St. Anthony and Rexburg .... do	86,470	92,245	59,377	33,434	-------
Gain between St. Anthony and Rexburg .... do	12,827	17,875	16,162	10,383	-------
Gain between St. Anthony and Rexburg .... per cent	15	19	27	31	-------
Probable return flow from Egin Bench .... second-feet	4,810	6,040	6,570	4,220	-------
Approximate losses due to evaporation and vegetation on Egin Bench, based on cultivated area of 30,000 acres .... second-feet	[a]8,520	[a]10,200	[a]7,950	[a]5,740	-------
Approximate total losses on Egin Bench .... do	13,330	16,240	14,520	9,960	-------
Approximate permanent contribution to ground water table on Egin Bench .... second-feet	18,744	15,558	9,804	3,655	47,761
Approximate permanent contribution to ground water table on Egin Bench .... acre-feet	37,200	30,900	19,400	7,260	94,760

[a] Determined on evaporation loss of 6.816 inches during June, 8.166 inches during July, 6.360 inches during August, 4.592 inches during September, based on land-pan evaporation records corrected by 65 per cent. (Land-pan records obtained at Mud Lake.) Probable additional loss due to transpiration assumed to be offset or compensated by probable decrease in cultivated and evaporated area as the irrigation season advanced.

The foregoing table gives some idea of the quantity of irrigation water that may percolate from Egin Bench toward the west and northwest. It was prepared from records obtained by Mr. Baldwin in connection with the distribution of water from Henrys Fork during the irrigation seasons of 1919, 1920, and 1921. It shows the diversions upon Egin Bench and the return flow into Henrys Fork between the St. Anthony and Rexburg gaging stations during these three seasons. As a basis for computing the part of the return flow that probably comes from Egin Bench it was assumed that the return on the opposite sides of Henrys Fork is in proportion to the diversions. Probably, however, the return flow from Egin Bench is much greater, owing to the porous character of its formation and its higher altitude with respect to the river.

The losses due to evaporation and transpiration were estimated to be 65 per cent of the recorded losses during 1921 from the land evaporation pan at Mud Lake, applied to a cultivated area of 30,000 acres, which includes the entire area of the Egin bench after deducting 10 per cent for houses, roads, etc. The table shows that the losses by return flow, evaporation, and transpiration amount to about 60 per cent of the water annually diverted upon Egin Bench, leaving about 40 per cent that may flow toward the west and northwest into the lavas. Forty per cent of the total diversion during the year ending March 31, 1922, which was probably a normal year, is about 140,000 acre-feet. A part of this water reaches Mud Lake basin in the way already described.

INVENTORY OF WATER SUPPLY

The units of storage in the Mud Lake basin are Hamer Lake, Mud Lake (including Rays and Sandhole lakes), the Jefferson reservoir, the Jefferson reservoir addition, Spring Lake, and North Lake. (See Pl. II.)

MUD LAKE

In this discussion Rays Lake, Sandhole Lake, and all other ponds and sloughs that are directly tributary to Mud Lake and were affected by backwater of the lake during the high stage in June, 1921, are included and considered a part of Mud Lake, and all deductions and conclusions are based on this definition of area. Hamer Lake, the Jefferson reservoir, the Jefferson reservoir addition, and Spring Lake are not included. North Lake was not tributary to Mud Lake during 1921. During the spring of 1922, however, North Lake spilled over into Mud Lake. Its area, capacity, and supply is considered a separate unit from Mud Lake in this report for the sake of convenience and because it was physically connected with Mud Lake only during 1922.

AREA AND CAPACITY

Plane-table surveys outlining the areas covered by the high and low stages of Mud Lake in 1921 were made during the season. (See Pl. II.) From these surveys and from soundings obtained through ice cover in January, 1922, area and capacity curves were constructed (fig. 8). Daily gage heights were obtained from a gage at the First Owsley intake, and these were supplemented by occasional readings from the Beckner gage, on the north shore of the lake, during periods when operation of the pumps at the First Owsley station caused erratic fluctuations in the intake. By means of these data the following table was prepared:

Gage height and contents of Mud Lake, April 1, 1921, to March 31, 1923

Date	Gage height (feet)	Contents (acre-feet)	Increase or decrease in storage during month (acre-feet)
Mar. 31, 1921		[a] 42,490	
Apr. 30, 1921	7.95	46,440	+3,950
May 31, 1921	8.49	53,020	+6,580
June 30, 1921	7.69	43,470	−9,550
July 31, 1921	5.79	26,840	−16,630
Aug. 31, 1921	4.11	17,030	−9,810
Sept. 30, 1921	3.95	16,220	−810
Oct. 31, 1921	4.72	20,280	+4,060
Nov. 30, 1921	5.50	24,930	+4,650
Dec. 31, 1921	6.38	31,250	+6,320
Jan. 31, 1922	7.07	37,170	+5,920
Feb. 28, 1922	7.54	41,850	+4,680
Mar. 31, 1922	8.02	47,260	+5,410
Net increase in storage during year			4,770

Date	Gage height (feet)	Contents (acre-feet)	Increase or decrease in storage during month (acre-feet)
Apr. 30, 1922	8.53	53,520	+6,260
May 31, 1922	8.90	58,240	+4,720
June 30, 1922	8.00	47,020	−11,220
July 31, 1922	6.60	33,040	−13,980
Aug. 31, 1922	5.68	26,100	−6,940
Sept. 30, 1922	5.23	23,250	−2,850
Oct. 31, 1922	5.79	26,840	+3,590
Nov. 30, 1922	([b])	32,470	+5,630
Dec. 31, 1922	7.14	37,770	+5,300
Jan. 31, 1923	7.67	43,110	+5,340
Feb. 28, 1923	8.18	48,970	+5,860
Mar. 31, 1923	8.58	53,820	+4,850
Net increase in storage during year			6,560

[a] Estimated. [b] Interpolated.

It is reported that 160 acres has been diked off since the capacity of Mud Lake was calculated. The total increase in storage from April 1, 1921, to March 31, 1923, was 11,330 acre-feet.

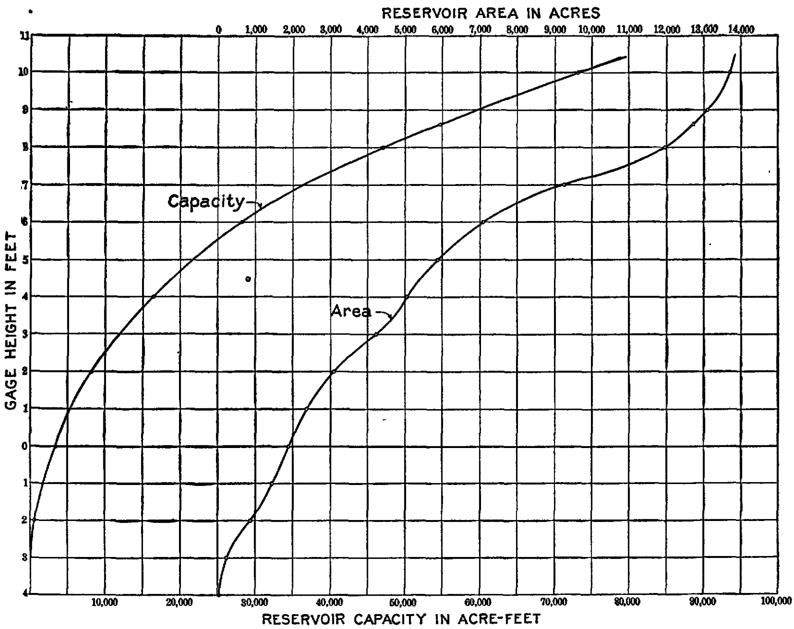


FIGURE 8.—Area and capacity curves for Mud Lake, Idaho, 1921–22

The maximum stage recorded during the year 1921 was at a gage height of 8.65 feet on June 7 to 9. This area of the water surface at this stage was 12,670 acres and the corresponding contents of the lake 55,040 acre-feet. The minimum stage was at a gage height of 3.94 feet on September 14 to 19. The area at this stage was 5,000 acres and the corresponding contents 16,160 acre-feet. Investigation of the dikes on the east, south, and west sides of the lake indicates that the lake could rise 1.5 feet above the highest level reached in 1921 without causing damage to surrounding territory. This would correspond to a capacity of 73,000 acre-feet, which is probably the maximum quantity of water that the lake with its present diking system could safely hold. Zero on the gage is 4,775.33 feet above sea level.

DIVERSIONS

On account of the levelness of the land surrounding Mud Lake most of the diversion canals are built in fills, and the water from the lake is pumped into them by means of electrically driven centrifugal pumps. Fifteen pumping plants have been installed around the lake, with maximum lifts ranging from about 2 feet at the Owsley Cooperative pumps to about 11 feet at the First Owsley pumps. The size of the units varies with the acreage under the several projects. The Second Owsley Co. has three pumps with a total capacity of 240 cubic feet a second, the Mud Lake project has two pumps with a total capacity of 160 cubic feet a second, and the First Owsley Canal Co. has three pumps with a total capacity of about 180 cubic feet a second. Power was supplied to each pumping unit by the Ashton-St. Anthony Power Co. at a flat seasonal rate. Most of these plants are designed and installed to pump water from a level corresponding to the deepest part of Mud Lake.

Eleven gravity ditches were used for diverting water for irrigation during 1921. Four of these, the Wiley, Melton, Welchman, and Owsley Cooperative, were used as intakes for their respective pumping plants later in the season when the lowering of the lake made pumping necessary.

A total of 40,690 acre-feet was diverted from the lake during the irrigation season of 1921 and 37,430 acre-feet during the season of 1922. These results were obtained from records that each operator kept indicating the number of hours each pump was in operation and the amounts pumped. These records were checked frequently by current-meter measurements. Estimates of the flow in gravity ditches, the amount of which is small compared with the total diversions, were based largely upon the capacities of the canals and the number of acres irrigated.

No shortage of water was experienced for irrigating the land under cultivation during 1921 or 1922. Several thousand acres of new land was put into cultivation during these years.

The facts in regard to diversions, irrigation, and storage can be summarized as follows:

1. During the irrigation season of 1921 a total of approximately 11,050 acres was irrigated with water from Mud Lake.
2. During the same season 40,690 acre-feet was diverted from the lake for irrigation, indicating a use of approximately 3.7 acre-feet to the acre.
3. At the end of the irrigation season 16,000 acre-feet remained in the lake.
4. There was 4,770 acre-feet more water in the lake on April 1, 1922, than on the same date the year before. (See table on p. 115.)
5. During the irrigation season of 1922 a total of approximately 11,218 acres was irrigated with water from Mud Lake.
6. During the same season 37,430 acre-feet was diverted from the lake for irrigation, indicating a use of approximately 3.3 acre-feet to the acre. The smaller use per acre in 1922 was probably due to favorable weather conditions, as there was more rain in August, 1922, than in August, 1921.
7. On October 1, 1922, at the end of the irrigation season, the gage height of Mud Lake was 5.24 feet, corresponding to 23,310 acre-feet of water, which was left in the lake.
8. There was an increase in storage from April 1, 1922, to March 31, 1923, of 6,560 acre-feet, making the total increase in storage from April 1, 1921, to March 31, 1923, 11,330 acre-feet.

LOSSES

Estimates of the losses due to evaporation and transpiration from the area occupied by the lake at its highest stage in 1921 are based on records obtained at the Mud Lake stations. (See "Climate" and table on pp. 101–102.) The evaporation from the open-water surface of the lake was taken to be 65 per cent of the evaporation from the land pan. The reasons for using the coefficient 0.65 have been discussed under "Climate." Of the total area of about 12,600 acres occupied by the lake at its highest stage, about 6,600 acres was covered with a rank growth of tules or other marsh plants and therefore lost heavily by transpiration. The records given on pages 101–102 show that this area lost water more rapidly than the open water of the lake. The additional loss from the submerged part of the 6,600 acres was computed for each month by multiplying the average area of this part by the difference between the loss from the land pan and the loss from the tule pan. The loss from the unsubmerged part of the 6,600 acres was computed by multiplying the average area by the loss from the tule pan. However, the figures for evaporation and transpiration are unavoidably less accurate than the other figures that are given in the inventory.

As the lake is underlain by nearly impervious clay, the loss due to seepage out of the lake is believed to be small.

WATER SUPPLY

Mud Lake receives most of its supply from Camas Creek, which flows into the lake about at the West Hamer bridge. The surface flow at this point, however, includes considerable ground water that is picked up from the near-by sloughs and flows into the creek above the bridge. In addition some surface inflow is derived from sloughs fed by ground water immediately west of the West Hamer bridge.

The following table gives a summary of the water supply of Mud Lake for the years ending March 31, 1922, and March 31, 1923, taking into account the measured surface inflow, precipitation upon the 12,600 acres of lake bed, losses due to evaporation and transpiration from the same area of 12,600 acres, diversions for irrigation, and storage in the lake.

Summary of the water supply of Mud Lake, years ending March 31, 1922 and 1923, in acre-feet

	1922	1923
Visible supply:		
Flow under West Hamer bridge	64,700	74,600
Other surface inflow	12,400	12,200
Total observed surface flow into the lake	77,100	86,800
Precipitation	8,700	8,600
	85,800	95,400
Withdrawals and storage:		
Water stored in Mud Lake at end of year	47,300	53,800
Water stored in Mud Lake at beginning of year	42,500	47,300
Increase in storage	4,800	6,500
Evaporation and transpiration	49,600	55,700
Diversions for irrigation	40,700	37,400
	95,100	99,600
Difference between total withdrawals and storage and total visible supply	9,300	4,200

The table summarizes the water supply of the lake in two different ways, which in a measure afford a check on the results obtained. The total visible supply takes into account all the measurable intake. On account of severe backwater conditions in Camas Creek at the West Hamer bridge the flow at that point was determined by means of miscellaneous measurements and careful graphic comparison with the flow at Wood's ranch and at Camas. These results, however, are believed to be fairly reliable, because at Camas the flow of the creeks was accurately measured and below Camas the inflow by seepage was very uniform. The flow into Mud Lake from sloughs west of the West Hamer bridge was also summarized by means of miscellaneous measurements, and as this flow was likewise very uniform the determination should be fairly reliable. If all the figures are accurate, about 9,300 acre-feet of water entered the lake during the year ending March 31, 1921, and 4,200 acre-feet during the year ending March 31, 1922, either through its bed or from other unseen sources. While soundings of the lake were being made through the ice in January, 1922, two distinct springs in the center of the lake were noticed to be discharging water under some pressure. The flow from these springs could easily amount to 4,200 to 9,300 acre-feet a year.

The following table shows approximately the part of the water supply of Mud Lake that came from underground sources:

Summary of contributions of ground water to Mud Lake, years ending March 31, 1922 and 1923, in acre-feet

	1922	1923
Total surface flow into the lake	77,100	86,800
Total flow of surface water (in Camas and Beaver creeks) near Camas	46,700	38,200
Surface inflow derived from ground water	30,400	48,600
Ground water discharged directly into the lake	9,300	4,200
Total quantity of ground water contributed to the lake	39,700	52,900

It must, of course, be borne in mind that the figures obtained as summarized in these tables are not absolutely correct. Many of the data could not be obtained by definite measurements, owing to the peculiar conditions that were involved, and it is therefore reasonable to expect some error in the results.

The table indicates a smaller flow of Camas and Beaver creeks into Mud Lake during the year ending March 31, 1923, than in the preceding year. To judge from records of precipitation and run-off in adjoining drainage areas, the run-off during 1921 was probably somewhat above the normal, yet during the year ending March 31, 1923, when the run-off was lower than in 1921, there was an increase in the visible supply, indicating definitely that there was a larger contribution of ground water. The difference is 13,200 acre-feet, which suggests that Mud Lake has not yet reached an equilibrium. This is also indicated by the steadily increasing stage of the lake.

ESTIMATE OF SUPPLY OF WATER AVAILABLE FOR IRRIGATION

By J. F. Deeds

Records obtained during the years 1921, 1922, 1923, and 1924 have been used in preparing the following tabulation of the water supply available for diversion from Mud Lake. The tabulation is made on the assumption of a yearly irrigation demand of 60,000 acre-feet, distributed through the irrigation season substantially in accordance with records showing the demand heretofore made on the Mud Lake and Minidoka pumping projects—that is, 13 per cent in May, 26 per cent in June, 26 per cent in July, 22 per cent in August, and 13 per cent in September. It is assumed also that if the lake is about empty on October 1, it will contain 35,000 acre-feet of water by the following April 1. The basis for this assumption is the fact that in one such period (October 1, 1921, to April 1, 1922) the lake, while receiving a measured surface inflow of 35,370 acre-feet, had its contents increased from 16,220 to 47,260 acre-feet, a gain of 31,040 acre-feet; and that in the following period (October 1, 1922, to April 1, 1923) the lake, while receiving a measured surface inflow of 41,940 acre-feet, had its contents increased from 23,310 to 53,840 acre-feet, a gain of 30,510 acre-feet. During the corresponding period of the next year (October 1, 1923, to April 1, 1924), the measured surface inflow amounted to about 44,790 acre-feet and the lake contents increased from 23,100 acre-feet to 55,400 acre-feet, a gain of 32,300 acre-feet. In each period the gain exceeded 30,000 acre-feet and was larger in proportion to the inflow while the lake was maintained at the lower level. The inference is strong that there would be an even greater gain, assumed at 35,000 acre-feet, if the lake were maintained at lower levels in accordance with the assumptions stated. The table shows records of rainfall and of evaporation and transpiration and quantities derived from these records as applied to the area of the lake surface corresponding to the contents at the beginning of each month. Transpiration is tabulated as directly affecting the water supply only during June, July, August, and September, the months of appreciable growth of aquatic vegetation, and then only on areas of lake surface in excess of 6,000 acres, as there is little or no vegetation in the central part of the lake that has this area.

The water-supply tabulation indicates shortages of 8,060, 1,340, and 11,880 acre-feet late in the irrigation seasons of 1921, 1922, and 1924, respectively, and a surplus of 3,580 acre-feet in 1923. The deficiencies would be at least partly absorbed by the unmeasured ground-water inflow during the irrigation season, for which no allowance was made in the tabulation. It appears, therefore, that approximately 60,000 acre-feet, distributed as needed for irrigation, could have been supplied from Mud Lake in each of the years 1921, 1922, 1923, and 1924, except for part of the 1924 shortage, which probably was abnormally great owing to the unusual low-water conditions that prevailed during the year in Idaho.

Estimated supply of water that would have been available for diversion from Mud Lake in 1921, 1922, 1923, and 1924, if there had been complete utilization

[Based on records of surface inflow and rainfall, taking into account observed losses through evaporation and transpiration, and assuming an annual irrigation demand of 60,000 acre-feet]

Month	Irrigation demand		Losses			Condition of lake on first day of month		Rainfall on lake		Flow of surface water into lake (acre-feet)	Surplus or shortage at end of irrigation season (acre-feet)
	Per cent	Acre-feet	Evaporation from free water surface (feet)	Evaporation and transpiration from water with tules (feet)	Total (acre-feet)	Contents (acre-feet)	Area (acres)	Feet	Acre-feet		
1921											
April	0	0	0.239	-------	2,120	35,000	8,850	0.004	35	6,125	-------
May	13	7,800	.431	-------	4,350	39,040	10,100	.190	1,920	20,430	-------
June	26	15,600	.568	0.737	8,030	49,240	12,270	.030	368	9,570	-------
July	26	15,600	.682	1.58	8,830	35,550	9,000	.052	468	1,430	-------
August	22	13,200	.530	1.5	2,340	13,020	4,420	.020	88	1,200	−1,230
September	13	7,800	.382	.462	0	0	0	.035	-------	970	−6,830
1922											
April	0	0	.217	-------	1,920	35,000	8,850	.057	504	5,060	-------
May	13	7,800	.513	-------	5,280	40,560	10,290	.098	1,010	16,900	-------
June	26	15,600	.568	1.12	9,590	45,390	11,520	.052	600	10,400	-------
July	26	15,600	.563	1.78	6,670	31,200	7,850	.052	410	4,900	-------
August	22	13,200	.486	1.44	2,250	14,240	4,630	.170	790	3,800	-------
September	13	7,800	.414	.85	780	3,380	1,880	.000	0	3,860	−1,340
1923											
April	0	0	.162	-------	1,430	35,000	8,850	.080	710	6,870	-------
May	13	7,800	.387	-------	4,040	41,150	10,440	.132	1,380	8,200	-------
June	26	15,600	.413	.48	4,330	38,890	9,860	.150	1,480	8,900	-------
July	26	15,600	.619	.97	5,030	29,340	7,360	.120	880	6,070	-------
August	22	13,200	.497	1.12	2,430	15,660	4,880	.090	440	5,670	-------
September	13	7,800	.392	.92	990	6,140	2,520	.042	105	6,130	+3,580
1924											
April	0	0	[a].200	-------	1,770	35,000	8,850	.009	80	10,180	-------
May	13	7,800	[a].440	-------	4,860	43,500	11,040	.014	155	7,150	-------
June	26	15,600	[a].520	[a].80	6,705	38,145	9,665	.008	77	3,100	-------
July	26	15,600	[a].620	[a]1.60	3,360	19,020	5,425	.095	515	2,770	-------
August	22	13,200	[a].510	[a]1.35	964	3,340	1,890	.006	11	3,310	−7,500
September	13	7,800	[a].396	[a].75	-------	0	0	.051	-------	3,420	−4,380

[a] Evaporation and transpiration losses estimated during 1924.

MINOR LAKES

HAMER LAKE

Hamer Lake is a natural reservoir supplied entirely by seepage of ground water, supplemented during the irrigation season of 1921 by a flow of approximately 6 cubic feet a second from the six artesian wells of the Hamer Canal Co. A ditch has been dug from Hamer Lake northwestward through several ponds and sloughs and drains water from them into Hamer Lake during the irrigation season, when the lake is low. A plane-table survey of Hamer Lake, made in 1921, showed a high-water area of 184 acres. At the high stage, about June 1, 1921, the lake had an average depth of 3 feet and a content of 550 acre-feet. Early in July, 1921, the lake was practically pumped dry by the pumps of the Hamer Canal Co. The artesian wells were then uncapped and used to supplement the seepage from the shores and bed of the lake.

Records of pumping operations by the Hamer Canal Co. show that 2,370 acre-feet was diverted during 1921 to irrigate between 450 and 500 acres. Because the surrounding water table was at approximately the same altitude as the surface of the lake there were apparently no seepage losses. The total loss from evaporation during the year was about 590 acre-feet as calculated from an estimated loss of 3.2 feet over an area of 184 acres. On March 10, 1922, the gage in Hamer Lake read 2.90; on June 16, 1921, it read 2.16. The total quantity of water taken from the lake from April 1, 1921, to March 31, 1922, by diversions and by loss due to evaporation was about 2,960 acre-feet. In addition some water flowed from this lake into Mud Lake and has been reckoned with the supply of Mud Lake.

NORTH LAKE

As North Lake has no surface inlet, it receives its entire supply from ground water. It had no surface outlet in 1921, but in 1922 it spilled over into Mud Lake for a few weeks during a period of high water. Because it was not tributary to Mud Lake in 1921 it was not considered in the measurements of area or capacity of Mud Lake, and its area and capacity were not included in 1922 because the calculations for the two years would not be comparable. The altitude of the lake on June 20, 1921, was 4,792.35 feet above mean sea level, or 7.35 feet above Mud Lake on that date. The lake fell during the summer and rose again in the fall. A staff gage was installed June 25 on the south side of North Lake, on a fence post on the line between sec. 25, T. 7 N., R. 34 E., and sec. 30, T. 7 N., R. 35 E. At that time the gage read 6.92, and on October 10 it read 4.92. A plane-table survey of the lake, made in June, 1921, indicated a high-water area of 1,180 acres. The evaporation and transpiration from this area during the year ended March 31, 1922, was estimated to be 3.4 feet instead of 3.21 feet (the figure obtained for Mud Lake, as explained on p. 100), because of the small additional loss by transpiration on the marshy area. According to this estimate, the total loss through evaporation and transpiration for the year was 4,010 acre-feet.

There are at present no diversions from the lake for irrigation. Hence 4,010 acre-feet can be assumed as the approximate annual supply. No soundings were made of the lake, but from careful observations around the shores it was estimated that at high water the depth averaged 3.5 feet. This indicates a maximum content at the high stage in 1921 of 4,100 acre-feet. A survey by O. S. Anderson, of Menan, Idaho, in April and May, 1920, showed the area of the lake to be 1,200 acres and the content 5,000 acre-feet.

JEFFERSON RESERVOIR

The Jefferson reservoir receives its supply entirely from ground water. Formerly it was a series of springs and ponds that made their appearance about the time that ground water appeared at Hamer Lake and North Lake. It is now diked on the south and west sides and is used as a storage unit. No accurate data are available, however, to show that the flow from the Jefferson reservoir formerly entered Mud Lake. Reports of residents in the vicinity of the reservoir are conflicting. From available topographic data and a study of the situation in the field the following tentative deductions were made:

1. Before the present dikes and canals were built, water from the Jefferson reservoir probably wasted out over the level country to the southwest, as is indicated by the appearance of the soil, dead sagebrush, and relatively recent growth of greasewood. Very little water probably reached Mud Lake before these dikes were constructed. However, if the dikes separating the Jefferson reservoir from the swamp area due south of it were removed and the remainder of the diking system were unmolested, water would flow from the reservoir toward Mud Lake.

2. During the winter the Jefferson reservoir fills up, and water either wastes through the canal upon the lands of the reservoir project or flows over the spillway into the Jefferson reservoir addition to the south.

3. As shown by the map (Pl. II), the Jefferson reservoir addition is formed by a dike on its south and west sides, and were it not for the dike on the south, water would flow from it directly into Mud Lake. If the dike on the west were also removed, the prevailing direction of flow might possibly be toward the southwest, as from the Jefferson reservoir, for Mud Lake at extremely high stages discharges over its dikes in that direction.

The area of the Jefferson reservoir at its high stage, on June 21, 1921, was 1,104 acres. On the same date the altitude, at a gage height of 3.09, was 4,788.80 feet above sea level, or 5.12 feet higher than Mud Lake. No soundings of the reservoir were made. A survey made by O. S. Anderson in March, 1920, showed an area of 1,140 acres and a maximum content of 4,560 acre-feet. From observations made during the investigation it is believed that the average depth of the reservoir at the high stage is not more than 3 feet, which gives a maximum content of about 3,310 acre-feet.

Water was diverted for irrigating 862 acres through the main canal of the Jefferson Reservoir Irrigation Co. during the irrigation season of 1921. Daily readings of the depth of water over the two rectangular gates in the diversion dam were made by W. H. Abbott. From occasional discharge measurements of the flow through the canal and daily readings it has been calculated that about 3,930 acre-feet was diverted from April 1 to September 30, 1921.

On the basis of 3.4 feet of evaporation and transpiration over an area of 1,104 acres, a loss of 3,760 acre-feet was sustained during 1921. This is believed to be a conservative estimate of the loss, because about 40 per cent of the reservoir consists of tule marsh, in which the loss by transpiration is doubtless high.

The above data show a total supply throughout the year, including diversions, evaporation, and transpiration, of about 7,690 acre-feet. This, however, is probably a very moderate estimate, because the reservoir, usually fills early in the winter and considerable water wastes through the canal before irrigation begins.

JEFFERSON RESERVOIR ADDITION

Between the Jefferson reservoir and Mud Lake is the Jefferson reservoir addition. A dike about 200 feet long prevents the flow from the sloughs and any waste water from the Jefferson reservoir from entering Mud Lake. The area of the water surface at the high stage in June, 1921, was 250 acres. Two diversions for irrigation were noted—the Hansen ditch and the Abbott ditch. Approximately 200 acres was irrigated in 1921 with water diverted through these two ditches. This reservoir is believed to have an average depth of about 1 foot at the high stage. The constant flow from the springs on the east side is not enough to offset losses through evaporation and transpiration and diversions for irrigation during the summer, and hence the reservoir practically dries up before the end of the irrigation season.

An annual evaporation and transpiration loss of 4 feet has been assumed, as approximately 75 per cent of the reservoir contains tules or other marsh vegetation. This factor applied to 250 acres gives a loss of 1,000 acre-feet. On the assumption that diversions during the irrigation season amount to about 500 acre-feet, the total supply for 1921 is estimated at 1,500 acre-feet.

SPRING LAKE

No gage-height records were obtained on Spring Lake, and no soundings were made. The supply comes from a series of springs in the center and northeastern part of the lake. A rough plane-table survey made in July and October, 1921, shows a wetted area of 2,200 acres. Prior to the time that the dikes were constructed on the west and southwest sides of the lake the flow of the springs was used for irrigation, and during the remainder of the year this water wasted out over the nearly level country to the southwest. About 700 acres was irrigated from Spring Lake in 1921. The McKevitt, Mitchell, and Wilson ditches can divert water from the lake, but the Wilson ditch was not used in 1921. A shortage of water was experienced in July and August of that year. The lands were irrigated in the spring and again in the fall, but on account of the shortage reported it is believed that 2 acre-feet to the acre is a fair estimate of the amount used on the 700 acres. This gives 1,400 acre-feet used for irrigation. The loss from evaporation and transpiration is probably high, as about 60 per cent of the reservoir is marsh. If it was 4 feet over the entire wetted area of 2,200 acres, it amounted to 8,800 acre-feet. The total annual supply is therefore estimated at 10,200 acre-feet. In addition there were seepage losses toward the west from the lake. At the high stage the reservoir is estimated to have an average depth of 1.5 feet and a capacity of 3,300 acre-feet.

A study of the meager data available leads to the conclusion that the present irrigated area is sufficient to utilize the entire available flow of the springs rising in this reservoir.

GROUND-WATER SUPPLY

A rough analysis of the probable total quantity of ground water that feeds into the lakes and reservoirs in the Mud Lake basin or is discharged by evaporation and transpiration on the marshy lands without reaching any of the lakes is given below.

The water supplies of the minor lakes (diversions for irrigation plus losses by evaporation and transpiration) as determined during 1921 are about as follows: Hamer Lake, 2,960 acre-feet; North Lake, 4,010 acre-feet; Jefferson reservoir, 7,690 acre-feet; Jefferson reservoir addition, 1,500 acre-feet; Spring Lake, 10,200 acre-feet; total, 26,360 acre-feet. Practically all of this water is derived from springs and seepage except that which falls on the lakes as rain or snow. The areas of these lakes used in the preceding calculations are as follows: Hamer Lake, 184 acres; North Lake, 1,180 acres; Jefferson reservoir, 1,104 acres; Jefferson reservoir addition, 250 acres; Spring Lake, 2,200 acres; total, 4,918 acres. If the precipitation during 1921 was 8.29 inches, the total amount of water that fell on the lake areas as rain or snow was 3,390 acre-feet. Deducting 3,390 acre-feet from the total supply of 26,360 acre-feet leaves 22,970 acre-feet, which was derived from ground water during the year ending March 31, 1922.

The total area covered by lakes, reservoirs, and marshy lands where the water table is not more than 5 feet below the surface is approximately 27,670 acres, as determined by planimeter measurements on maps that were carefully made in the field with a plane table. The area of Mud Lake used in the preceding calculations is 12,600 acres, and the aggregate area of the minor lakes about 4,920 acres, making a total of 17,520 acres. Deducting 17,520 acres from 27,670 acres leaves 10,150 acres of wetted area which has not been taken into consideration but which was subjected to losses by evaporation and transpiration of ground water. Ground water that stands within a few feet of the surface will suffer loss by capillary raise and evaporation and by absorption and transpiration of plants. The depths from which ground water is discharged by these processes depends on the character of the soil and the kind of plants.

About 75 per cent of the 10,150 acres is subject to heavy transpiration on account of the prolific growth of marsh vegetation. The evaporation from the open water of Mud Lake during the year was determined to be 3.21 feet, the evaporation and transpiration from the tule pan from June 13 to September 23 was 4.28 feet, and the evaporation and transpiration from a submerged tule-covered area during the year, if computed by the difference method previously described, amounted to 4.62 feet. Therefore a loss of 4 feet was arbitrarily assumed for the 10,150 acres not previously considered. On this basis about 40,600 acre-feet was lost by evaporation and transpiration from the area in 1921. The precipitation upon the area, reckoned at 8.29 inches, amounted to 7,000 acre-feet. Deducting 7,000 acre-feet from 40,600 acre-feet leaves 33,600 acre-feet, which was derived from ground water.

On the basis of the foregoing calculations the quantity of ground water that appeared at the surface in the lakes and marshes of the Mud Lake basin during the year ending March 31, 1922, was as follows:

Ground-water supply of the Mud Lake basin during the year ending March 13, 1921, in acre-feet

Mud Lake	39,700
Five minor lakes	22,970
Marshes not included with lakes	33,600
	96,270

The ground-water supply of the Mud Lake basin for the year ending March 31, 1923, was probably somewhat higher, for, as shown on page 119, 13,200 acre-feet more of ground water was contributed to Mud Lake in that year than in the previous year. Moreover, the fact that North Lake spilled over for a short time during the high water of 1922 indicates that there was an increase in the amount of ground water entering the basin. The total amount for the year ending March 31, 1923, was probably about 120,000 acre-feet.

ARTESIAN CONDITIONS

Conditions in lava.—Some of the lava is very permeable and yields large supplies of water with but little drawdown. As a rule, it is too permeable to confine the water under artesian pressure. During the geologic development of the Mud Lake region a period of sedimentation was often interrupted by volcanism. Thus lava sometimes flowed out upon impervious clays and, with the renewal of deposition, was some times buried by more clay beds. Such a condition produced the artesian basin that underlies Hamer. Here the water has found its way into permeable lava and has become confined between two nearly impervious beds of clay. Thus the formations in the Mud Lake basin produce only local artesian conditions. The impervious clay beds between successive lava beds are of much more practical value in preventing the water from sinking than in holding it under artesian pressure.

Seven flowing wells have been obtained in the vicinity of Hamer. Six of these (wells A to F, Pl. II) belong to the Hamer Canal Co., and one, in the SW. ¼ SW. ¼ sec. 20, T. 7 N., R. 36 E., belongs to Robert Clinton. All are 8 inches in diameter except wells A and B, which are 6 inches in diameter, and well F, which is 10 inches in diameter. These wells penetrate the upper clay bed, which ranges in thickness from 17 to 70 feet, and end in the vesicular, water-bearing lava of Monument Butte, where they obtain large quantities of water. The water in the lava is here confined under sufficient head to cause it to rise to an altitude of 4,792 feet above sea level, or slightly above the surface. The water from the wells of the Hamer Canal Co. is raised 17 feet by pumps into the main canal.

The following data were obtained regarding the flowing wells of the Hamer Canal Co.:

Yield and head of flowing wells of the Hamer Canal Co.

	Depth (feet)	Yield		Head [a] (feet)	Specific capacity (gallons a minute for each foot of draw-down)
		Second-feet	Gallons a minute		
A	96	1.11	498		
B	120	1.11	498		
C	100	.95	427	[b] 2.75	155
D	60	1.35	605	1.18	512
E	60	1.24	556	1.25	445
F	100	2.23	[c] 1,003		

[a] Based on difference between water level in extension casing and water level in canal when well is flowing.
[b] Reported.
[c] Casing has since been cut lower so that flow is larger.

The table shows that the specific capacities of the wells are very large, especially those of wells D and E. Because of their large specific capacities, wells A and B, which are in the sump, could be made to yield more water by cutting off several feet of the casing. This would increase their flow when the water level in the sump is low during the irrigation season. If the head of any of these wells decreases only slightly, they will cease flowing, but they can still be made to yield large supplies by pumping.

Conditions in deposits of gravel and sand.—Some areas in the Mud Lake region are underlain by great deposits of sand and gravel with intervening beds of clay, but no artesian water has been found in these deposits. However, few wells have gone very deep below the water table. It is possible that flowing wells may yet be obtained from deeper parts of these deposits, but the great depth to the water table to the south and west is distinctly unfavorable.

QUALITY OF WATER

Analyses of 17 samples of water from the Mud Lake basin are given in the following table. Samples were taken from a few wells reported to have a high alkali content and from surface sources representing the entire supply of irrigation water diverted from Mud Lake and near-by sloughs. The water throughout the region is rather good for an arid basin where there is no outlet for the surface water. The good quality of water in the deposits of sand and gravel indicates that alkali and salts are being carried from the region by ground water. The water in the basalt contains comparatively small quantities of dissolved solids and generally is not hard. Spring Lake water proved to be the only irrigation water that contains enough alkali to be troublesome. Otherwise the irrigation water of the Mud Lake basin is to be considered good.

Analyses of water from Mud Lake region, Idaho

[Analyzed by Margaret D. Foster. Parts per million]

Owner or name	Location	Source	Depth of well (feet)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate radicle (HCO_3)	Sulphate radicle (SO_4)	Chloride radicle (Cl)	Nitrate radicle (NO_3)	Total dissolved solids at 180° C.	Total hardness as $CaCO_3$ (calculated)	Temperature when collected (° F.)	Material in which the water occurs
O. C. Brown	Northeast corner SE. ¼ sec. 14, T. 10 N., R. 35 E.	Drilled well	376	28	0.10	91	40	21	143	54	177	15	520	392	48	Basalt.
Hamer Canal Co.	NE. ¼ SW. ¼ sec. 14, T. 7 N., R. 36 E.	do	60	44	.08	27	10	13	131	11	6.2	2.2	169	108		Do.
Chas. Rising	NW. ¼ NE. ¼ sec. 29, T. 8 N., R. 34 E.	do	40	32	.19	31	13	20	158	14	16	1.4	204	131	55	Do.
C. A. Olson	Southeast corner SW. ¼ sec. 18, T. 6 N., R. 35 E.	do	262	33	.09	36	12	16	153	12	2.2	3.2	213	139	54	Do.
Luxton Market	1½ miles north of Idaho Falls.	do	190	23	.15	69	19	20	257	45	20	5.9	334	250		Do.
J. R. Raumaker	Northwest corner SW. ¼ sec. 5, T. 7 N., R. 37 E.	do	135	43	.08	27	9.4	15	[a] 140	7	6.4	2.9	178	106		Do.
J. Hendrickson	NW. ¼ SE. ¼ sec. 21, T. 8 N., R. 36 E.	Dug well	22	28	.16	52	11	6.6	206	6.2	4.6	6.7	216	175	54	Gravel.
C. S. Sharp	Northeast corner sec. 22, T. 8 N., R. 36 E.	do	28	25	.32	216	42	82	144	118	431	38	1,032	712	55	Do.
W. Czarvecki	SE. ¼ NE. ¼ sec. 23, T. 7 N., R. 33 E.	do	34	32	.09	104	32	45	193	55	205	Trace.	633	391	54	Do.
T. D. Scody	NW. ¼ SW. ¼ sec. 18, T. 7 N., R. 35 E.	do	17	15	.10	233	103	377	247	303	890	27	2,158	1,000	49	Sand.
G. Welchman	SE. ¼ SE. ¼ sec. 32, T. 7 N., R. 34 E.	do	50	9.2	.65	412	98	134	110	349	821	77	2,029	1,430	58	Do.
Alec Mitchell	Northwest corner NE. ¼ sec. 19, T. 7 N., R. 34 E.	Driven well	50	36	.24	49	15	17	162	30	34	1.4	274	184	62	Do.
Lidy Hot Springs	Sec. 2, T. 9 N., R. 33 E.	Hot springs		37	.17	80	17	34	164	176	8.7	Trace.	447	270	115	
North Lake	Sec. 19, T. 7 N., R. 35 E.			22	.37	56	16	68	314	21	49	Trace.	396	206	32.5	
Spring Lake	SE. ¼ sec. 5, T. 7 N., R. 34 E.			27	.22	71	70	415	[a] 675	356	313	Trace.	1,638	464	36	
Jefferson Lake	T. 7 N., R. 34 E.			24	.13	38	19	70	296	34	35	Trace.	367	173	36.5	
Mud Lake	First Owsley pumping plant.			27	.27	38	14	34	209	15	24	.50	268	152	60	

[a] Includes carbonate radicle less than 10 parts per million.

RECOVERY OF GROUND WATER

Some of the lava is compact and dense and therefore not adapted for yielding water, but much of it is vesicular or jointed and yields water very abundantly. The yield of the Hamer flowing wells is typical. Two drilled wells, 1 mile north of Spring Lake, end in lava at depths of 44 and 40 feet and supply enough water for irrigation. Each of these wells is reported to have yielded over 70 miner's inches (1.4 cubic feet a second) with little drawdown during a test of one hour in July, 1921.

The recognized methods of developing irrigation wells in sand and gravel deposits are the result of a vast amount of costly experience by innumerable drillers, and those who wish to develop such wells should use these recognized methods and should preferably have the work done by drillers who are experienced in well work of this kind. There are different types of successful irrigation wells in sand and gravel, but the most generally successful type consists of double stovepipe casing that is inserted as the hole is made and that is later perforated at all satisfactory water-bearing beds as determined by a carefully kept log of the well.[7] The perforations are generally rather large—perhaps a quarter of an inch across—and the well is pumped hard and long to remove the fine sand and leave a natural strainer of coarse material around the intake of the well. If no coarse material is penetrated in the well it is sometimes practicable to shut out the sand and increase the yield by inserting gravel according to one of several methods.[8] However, this process of developing a well by inserting gravel is likely to be difficult and uncertain. If the sand is very fine and incoherent and there is no coarse material mixed or interbedded with it, successful irrigation wells may be impossible. It is not necessary to obtain all the water that is required for a farm from one well. It may be entirely feasible to get the required yield by sinking two or more wells and pumping them by suction, the suction pipes all being connected at about the water level with a single centrifugal pump. Caisson wells, such as have been dug on several farms in this area, have also been successful in some places where the water-bearing bed occurs near the surface, but they have not come into such general use as the stovepipe wells, which are very extensively used in California for irrigation.[9] If it is found that in this area water-bearing beds of sand and gravel occur only near the surface or that the water in the

[7] See U. S. Geol. Survey Water-Supply Papers 110, 140, 257, and 375; also 467, which describes a model irrigation well drilled by the Geological Survey.

[8] Meinzer, O. E., and Hare, R. F., Geology and water resources of Tularosa Basin, N. Mex.: U. S. Geol. Survey Water-Supply Paper 343, pp. 120–122, 1915.

[9] See U. S. Geol. Survey Water-Supply Paper 375, pp. 1–49, 1916. Experiments with caisson wells have been made by the Arizona Agricultural Experiment Station. See Smith, G. E. P., A concrete caisson well: Cement Age, vol. 7, pp. 304–308, 1908.

deeper beds has too low a head to be available for pumping for irrigation, the caisson wells may prove best adapted to the local conditions. However, an adequate test should, if possible, be made with a properly constructed stovepipe well that is carried to considerable depth.

CONCLUSIONS

The data given in this report indicate that the total supply of water which appeared at the surface in Mud Lake and vicinity from April 1, 1921, to March 31, 1922, amounted to about 162,000 acre-feet, of which 95,000 acre-feet appeared in Mud Lake, 26,000 acre-feet appeared in five smaller lakes or reservoirs, and 41,000 acre-feet was discharged by evaporation and plant growth without reaching any of these lakes or reservoirs. Of the total that appeared at the surface about 96,000 acre-feet or a little more came from underground sources, 47,000 acre-feet or nearly that amount flowed into Mud Lake from Camas Creek without having passed underground, and 19,000 acre-feet fell upon the wetted area as rain or snow. In addition to the 162,000 acre-feet that appeared at the surface an unknown but probably considerable quantity of water escaped from the basin by percolation toward the south and west.

The aggregate flow of Camas and Beaver creeks at the upper gaging stations amounted during the year ending March 31, 1922, to 143,000 acre-feet. A large part of this water doubtless reappeared at the surface in Mud Lake and vicinity. The data given in the preceding paragraph indicate that 143,000 acre-feet appeared in Mud Lake and vicinity exclusive of the rain and snow that fell upon the wetted area. The exact agreement of these two quantities is, of course, accidental. Other possible sources of ground water are losses of Camas and Beaver creeks above the upper gaging stations, losses from Medicine Lodge Creek, losses from several smaller creeks in the same region, percolation of water from rain and snow that did not reach any of these creeks but sank in certain areas of permeable gravel or lava, and water that percolated westward from the irrigated district of Egin Bench.

The results given on page 118 show that the supply of Mud Lake for the year ending March 31, 1923, was greater than that for the previous year, indicating that the supply of Mud Lake is still increasing.

Of the total of 162,000 acre-feet that appeared at the surface in Mud Lake and vicinity in the year ending March 31, 1922, 4,800 acre-feet was stored in Mud Lake, about 49,000 acre-feet was used for the irrigation of about 13,300 acres, and about 108,000 acre-feet was discharged by evaporation or by transpiration from tules and other native plants of small economic value. These data show that the natural losses were very large in proportiton to the quantity used for irrigation. They at once raise the question whether the supply for irrigation can be increased by reducing the natural losses.

The question arises whether the natural losses can be diminished by further diking the lakes so as to decrease their areas. This question can not be definitely answered in the present stage of the investigation, but the conditions do not appear to be promising for improvement by such means. A restriction of the area of the lakes would result in a rise in the water level, and this rise would tend to extend the swampy areas and to increase percolation out of the basin. It is therefore not evident that further diking would increase the supply available for irrigation. The natural losses will, however, be diminished by more nearly complete utilization of the water, as is explained by Mr. Deeds on pages 119–121.

Another promising possibility is to reduce the losses through evaporation and transpiration, and also the losses through percolation, by pumping from wells where the ground water is nearly at the surface and where the water-bearing lavas are very permeable, as at the artesian wells of the Hamer Canal Co. The pumped water could be led into Mud Lake or into the other storage units at their low stages or directly upon land to be irrigated. If the pumped water is used on land lying within certain limits the percolation losses in irrigation will be recovered; if it is used south or west of those limits, the water that percolates beyond the reach of the roots of the irrigated crops will be permanently lost to this region. If it proves feasible to pump water from wells for irrigation in the belt west and northwest of the swampy tract of Spring Lake, where the water table slopes toward the west, the water recovered will be largely or wholly water that would otherwise be lost to the region.

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