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1923-1924

NATHAN C. GROVER, Chief Hydraulic Engineer

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CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES, 1923-24.

NATHAN C. GROVER, *Chief Hydraulic Engineer.*

VARIATION IN ANNUAL RUN-OFF IN THE ROCKY MOUNTAIN REGION.

By ROBERT FOLLANSBEE.

SUMMARY.

Records of run-off in the Rocky Mountain States since the nineties and for a few stations since the eighties afford a means of studying the variation in the annual run-off in this region. The data presented in this report show that the variation in annual run-off differs in different areas in the Rocky Mountain region, owing to the differences in the sources of the precipitation on these areas. Except in the drainage basins of streams in northern Montana the year of lowest run-off shown by the records was 1902, when the run-off at one station was only 36 per cent of the mean run-off for the periods covered by the several records available. The percentage variation of run-off for streams in different parts of Colorado is less for any one year than that for streams in the mountain region as a whole, and for streams in the same major drainage basin the annual variation is markedly similar. The influence of topography upon variation in annual run-off for streams in Colorado is marked, the streams that rise in the central mountain region having a smaller range in variation than the streams that rise on the eastern or western edges of the central mountain mass. The streams that rise on the plains just east of the mountains have a greater variation than those of any of the mountain groups.

The ratio of any 10-year mean to the mean for the entire period covered by the records ranges from 72 to 133 per cent. For the South Platte, Arkansas, and Rio Grande the run-off during the nineties was below the normal, but since about 1903 it has been above the normal. For the Cache la Poudre low-water periods occurred during the eighties and from 1905 to 1922, but during the nineties the run-off was above the normal.

MEASUREMENT OF NORMAL RUN-OFF.

To determine the ratio of the median run-off (or run-off for the middle year when the annual records are arranged in order of magnitude) to the mean run-off a study was made of 20 records, which ranged in length from 14 to 38 years and covered streams rising in the Rocky Mountains between northern Montana and southern Colorado.

Median and mean run-off for streams in Montana, Wyoming, and Colorado.

Station.	Drainage area (square miles).	Length of record (years).	Median (acre-feet).	Mean (acre-feet).	Ratio of median to mean (per cent).
St. Mary River near Babb, Mont.	177	14	407,000	401,000	101
Marias River near Shelby, Mont.	2,610	17	722,000	718,000	101
Beaverhead River near Barratts, Mont.	2,820	15	398,000	380,000	105
Big Horn River at Thermopolis, Wyo.	8 080	21	1,660,000	1,550,000	107
Green River at Green River, Wyo.	7,670	19	1,490,000	1,500,000	99
North Platte River at Saratoga, Wyo.	2,880	19	998,000	1,030,000	97
Laramie River near Woods, Wyo.	409	19	164,000	175,000	94
White River at Meeker, Colo.	634	17	475,000	478,000	99
Cache la Poudre River at mouth of canyon, Colo.	1,060	38	300,000	313,000	96
St. Vrain Creek at Lyons, Colo.	209	18	106,000	98,400	108
Clear Creek near Golden, Colo.	380	23	183,000	184,000	99
South Platte River at South Platte, Colo.	2,610	29	258,000	278,000	93
Arkansas River at Canon City, Colo.	3,060	35	571,000	557,000	103
Colorado River at Glenwood Springs, Colo.	4,520	23	2,180,000	2,280,000	96
Williams Fork near Parshall, Colo.	185	18	122,000	121 000	101
Rio Grande at Del Norte, Colo.	1 400	33	766 000	716,000	109
Conejos River near Mogote, Colo.	282	16	263,000	286,000	92
Gunnison River near Gunnison, Colo.	1,010	15	664,000	631,000	105
Gunnison River near Grand Junction, Colo.	7,920	14	2,300,000	2,230,000	103
Animas River at Durango, Colo.	694	24	707,000	693,000	102

The table shows that for 9 stations the median run-off is less than the mean, and for the remaining 11 stations it is larger. This indicates that during the period of record the run-off at the stations in the latter group has been in some years unusually low rather than unusually high. This is shown strikingly by the record of Big Horn River at Thermopolis (p. 3), where the maximum annual run-off exceeded the mean by only 23 per cent, and the minimum run-off was only 46 per cent of the mean.

As one unit of normal run-off appears to give nearly as accurate results as the other, and as the mean is the unit in most common use, it is taken in this paper to measure the normal run-off.

VARIATION IN ANNUAL RUN-OFF.

Streams in Montana, Wyoming, and Colorado.—The records obtained at the 20 gaging stations listed in the preceding table have been used to determine the variation in annual run-off in the Rocky Mountain region. In the following table the total run-off for each year at each station is expressed as a percentage of the mean run-off for all the years covered by each record:

Annual run-off of streams in the Rocky Mountain region.

Montana.

Year ending Sept. 30.	St. Mary River at Babb.		Marias River near Shelby.		Beaverhead River near Barratts.	
	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.
1902	478,000	119	960,000	134		
1903	539,000	134	1,000,000	139		
1904	377,000	94	750,000	104		
1905	310,000	77	441,000	61		
1906	379,000	95	526,000	73		
1907	496,000	124				
1908	505,000	126			487,000	128
1909	425,000	106			414,000	109
1910	371,000	93			398,000	105
1911	361,000	90	811,000	113	260,000	68
1912	306,000	76	693,000	97	419,000	110
1913	407,000	101	807,000	112	528,000	139
1914	336,000	84	497,000	69	370,000	97
1915	324,000	81	458,000	64	403,000	106
1916			1,030,000	143	401,000	105
1917			1,080,000	150	484,000	128
1918			722,000	101	318,000	84
1919			418,000	58	224,000	59
1920			787,000	110	245,000	64
1921			660,000	92	381,000	100
1922			565,000	79	390,000	103
Mean	401,000		718,000		380,000	

Wyoming.

Year ending Sept. 30.	Big Horn River at Thermopolis.[a]		North Platte River at Saratoga.[b]		Laramie River near Woods.[c]		Green River at Green River.	
	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.
1891					208,000	119		
1895							1,300,000	87
1896					126,000	72	1,420,000	95
1897					164,000	94	1,650,000	110
1898					140,000	80	1,580,000	105
1899					385,000	220	2,500,000	167
1900					164,000	94		
1901							1,300,000	87
1902	1,090,000	70					1,040,000	69
1903	1,840,000	119					1,310,000	87
1904	1,850,000	119	998,000	97			1,870,000	125
1905	1,160,000	75	910,000	88	160,000	91	1,010,000	67
1906	1,520,000	98	1,020,000	99			1,490,000	99
1907	1,860,000	120	1,310,000	127				
1908	1,710,000	110	663,000	64				
1909	1,870,000	121	1,760,000	171				
1910	1,210 000	78	623,000	60				
1911	1,420,000	92	885,000	86	140,000	80		
1912	1,780,000	115	1,220,000	118	212,000	121		
1913	1,770,000	114	871,000	85	112,000	64		
1914	1,360,000	88	1,210,000	117	191,000	109		
1915	1,340,000	87	617,000	60	91,500	52	834,000	56
1916	1,490,000	96	887,000	86	147,000	84	1,750,000	117
1917	1,910,000	123	1,600,000	155	282,000	161	2,080,000	139
1918	1,630,000	105	1,090,000	106	190,000	109	1,750,000	117
1919	713,000	46	612,000	59	84,300	48	685,000	46
1920	1,710,000	110	1,250,000	121	214,000	122	1,480,000	99
1921	1,730,000	112	1,350,000	131	207,000	118	1,770,000	118
1922	1,660,000	107	760,000	74	107,000	61	1,750,000	117
Mean	1,550,000		1,030,000		175,000		1,500,000	

[a] Records for 1904 and 1906–1910 taken as 43.5 per cent of records at Hardin, Mont.
[b] Records for 1907, 1908, and 1910 taken as 73 per cent of records at Pathfinder.
[c] Records for 1891–1911 based on records at Jelm and Woods Landing, an allowance is made for increased run-off between.

Annual run-off of streams in the Rocky Mountain region—Continued.

Colorado.

Year ending Sept. 30.	Cache la Poudre River at mouth of canyon.		St. Vrain Creek at Lyons.		Clear Creek near Golden.[d]		South Platte River at South Platte[e].		Arkansas River at Canon City.	
	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.
1884	679,000	217								
1885	483,000	154								
1886	312,000	100								
1887										
1888	176,000	56					188,000	68	627,000	112
1889	209,000	67					147,000	53	352,000	63
1890	244,000	78					173,000	62	587,000	105
1891	276,000	88					285,000	103	707,000	127
1892	224,000	72							649,000	117
1893	235,000	75							632,000	113
1894	323,000	103							634,000	114
1895	373,000	119							569,000	102
1896	277,000	89					170,000	61	415,000	75
1897	349,000	112					268,000	97	488,000	88
1898	196,000	63							483,000	87
1899	390,000	125					323,000	116	666,000	120
1900	454,000	145			204,000	111			604,000	109
1901	350,000	112	94,100	96	177,000	96	216,000	78	460,000	83
1902	137,000	44	48,800	49	98,800	54	112,000	40	252,000	45
1903	361,000	116	107,000	109	150,000	82	151,000	54	504,000	91
1904	306,000	98			224,000	122	215,000	77	384,000	69
1905	381,000	122			205,000	111	312,000	112	613,000	110
1906	294,000	94			199,000	108	244,000	88	565,000	101
1907	404,000	129			211,000	115	362,000	130	729,000	131
1908	270,000	86	62,300	63	105,000	57	113,000	41	373,000	67
1909	501,000	160	130,000	132	247,000	134	387,000	139	623,000	112
1910	178,000	57	52,500	53	132,000	72	251,000	90	536,000	96
1911	224,000	72	125,000	127	144,000	78	180,000	65	562,000	101
1912	312,000	100	124,000	126	225,000	122	333,000	120	684,000	123
1913	231,000	74	72,300	74	160,000	87	258,000	93	420,000	75
1914	300,000	96	145,000	148	306,000	166	663,000	239	648,000	116
1915	236,000	75	111,000	113	183,000	99	336,000	121	499,000	90
1916	269,000	86	93,700	95	145,000	79	237,000	85	608,000	109
1917	516,000	165	129,000	131	178,000	97	321,000	115	646,000	116
1918	300,000	96	100,000	102	197,000	107	319,000	115	571,000	103
1919	151,000	48	66,600	68	147,000	80	302,000	109	571,000	103
1920	378,000	121	106,000	108	184,000	100	339,000	122	630,000	113
1921	406,000	130	145,000	147	279,000	152	599,000	216	662,000	119
1922	175,000	56	58,200	59	125,000	68	253,000	91	537,000	97
Mean	313,000		98,400		184,000		278,000		557,000	

[d] Records for 1900–1908 and 1910–1911 taken as 110 per cent of records at Forkscreek.
[e] Corrected for storage. Records for 1888–1891, 1896, 1897, and 1899 taken at Platte Canyon.

Annual run-off of streams in the Rocky Mountain region—Continued.

Colorado—Continued.

Year ending Sept. 30.	Colorado River at Glenwood Springs.		Williams Fork near Parshall.		Gunnison River near Gunnison.[f]		Gunnison River near Grand Junction.[g]	
	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.
1897	....	....	....	....	....	....	2,850,000	128
1898	....	....	....	....	....	....	1,590,000	71
1899	....	....	....	....	....	....	2,220,000	100
1900	2,180,000	96	....	....	464,000	74		
1901	2,200,000	96	....	....	543,000	86	....	....
1902	1,510,000	66	....	....	304,000	48	1,120,000	50
1903	1,970,000	86	....	....	586,000	93	2,040,000	92
1904	2,140,000	94	....	....	....	....	1,290,000	58
1905	2,120,000	93	99,300	79	....	....	2,550,000	114
1906	2,620,000	115	1,220,000	97	....	....	2,930,000	131
1907	3,010,000	132	141,000	112	....	....	....	....
1908	1,610,000	71	88,300	70	....	....	....	....
1909	2,860,000	125	144,000	114	....	....	....	....
1910	1,720,000	75	96,300	76	....	....	....	....
1911	2,090,000	92	101,000	80	691,000	109	....	....
1912	2,890,000	127	163,000	129	759,000	120	....	....
1913	1,720,000	75	109,000	86	495,000	78	....	....
1914	3,000,000	132	167,000	123	846,000	134	....	....
1915	1,730,000	76	122,000	97	....	....	....	....
1916	2,210,000	97	117,000	93	717,000	114	....	....
1917	2,940,000	129	156,000	124	731,000	116	2,850,000	128
1918	2,780,000	122	169,000	134	822,000	130	2,020,000	90
1919	1,600,000	70	96,100	76	418,000	66	1,680,000	75
1920	2,710,000	119	126,000	100	848,000	134	3,020,000	135
1921	2,880,000	126	156,000	124	664,000	105	2,760,000	124
1922	1,970,000	86	99,000	79	583,000	92	2,300,000	103
Mean	2,280,000	....	126,000	....	631,000	....	2,230,000	....

Year ending Sept. 30.	Animas River at Durango.[h]		Rio Grande at Del Norte.[i]		Conejos River near Mogote.		White River at Meeker.	
	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.
1890	....	....	804,000	112	....	....	....	....
1891	....	....	834,000	117	....	....	....	....
1892	....	....	585,000	82	....	....	....	....
1893	....	....	392,000	55	....	....	....	....
1894	....	....	413,000	58	....	....	....	....
1895	628,000	91	638,000	89	....	....	....	....
1896	418,000	60	492,000	69	....	....	....	....
1897	958,000	138	729,000	102	....	....	....	....
1898	588,000	85	912,000	128	....	....	....	....
1899	401,000	58	368,000	51	....	....	....	....
1900	369,000	53	524,000	73	....	....	....	....
1901	469,000	68	492,000	69	....	....	....	....
1902	280,000	40	255,000	36	....	....	369,000	77
1903	856,000	124	767,000	107	....	....	426,000	89
1904	382,000	55	347,000	49	....	....	466,000	97
1905	1,010,000	146	901,000	126	....	....	475,000	99
1906	....	....	900,000	126	....	....	542,000	113
1907	....	....	1,110,000	155	364,000	127	....	....
1908	....	....	578,000	81	199,000	70	....	....
1909	....	....	870,000	122	332,000	116	....	....
1910	551,000	80	691,000	97	199,000	70	....	....
1911	1,130,000	163	922,000	129	363,000	127	428,000	90
1912	746,000	108	970,000	136	309,000	108	579,000	121
1913	503,000	72	549,000	77	155,000	54	366,000	76
1914	845,000	122	785,000	110	253,000	88	465,000	97
1915	663,000	96	687,000	95	238,000	83	338,000	71
1916	981,000	142	824,000	115	367,000	129	483,000	101
1917	878,000	127	1,010,000	141	318,000	111	587,000	123
1918	545,000	79	527,000	74	226,000	79	478,000	100
1919	707,000	102	766,000	107	242,000	85	368,000	77
1920	1,030,000	149	996,000	139	430,000	150	572,000	120
1921	897,000	129	1,020,000	143	263,000	92	707,000	148
1922	808,000	117	984,000	138	311,000	109	485,000	101
Mean	693,000	....	716,000	....	286,000	....	478,000	....

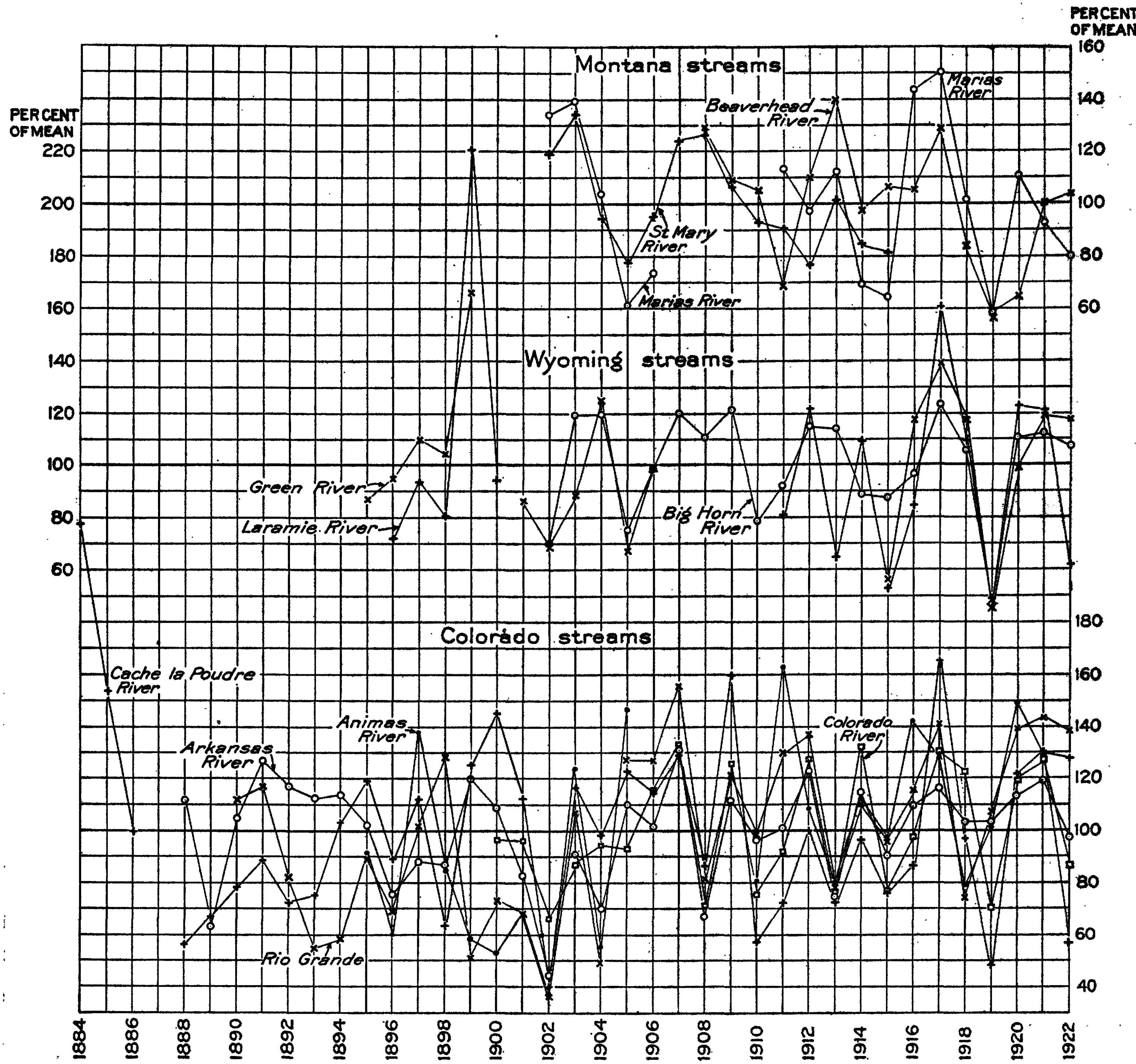
[f] Records for 1900–1903, taken as 80 per cent of records at Iola.
[g] Records for 1902–1906 taken at Whitewater.
[h] Calendar year. Records for 1895–1905 taken below Lightner Creek; 25,000 acre-feet subtracted to refer records to station above Lightner Creek.
[i] Record for 1907 estimated by State engineer's office.

The yearly percentages for stations in Montana and Wyoming and a few of the longer records for stations in Colorado are given in Plate I. These graphs show that the variation in run-off from year to year is not similar in all parts of the Rocky Mountain region. The most notable discrepancy occurred in 1902, in which the run-off was high for streams in Montana, fairly low for streams in Wyoming, and the lowest recorded for streams in Colorado. Another marked difference occurred in 1905, which was a year of low run-off for streams in Montana and Wyoming, but above the normal for streams in Colorado. For the years 1917 and 1919, however, the variation was similar in all the States; 1917 was a year of very high run-off, and 1919 was one of very low run-off for most of the streams. It is therefore evident that the variations in precipitation that cause variations in run-off are not always similar throughout the Rocky Mountain region but may differ widely in different areas. This is due to the fact that the precipitation comes from different sources. In general the areas of low atmospheric pressure, which cause precipitation, travel along three well-defined paths—from the north Pacific coast eastward along the Canadian boundary, from the north Pacific coast southeastward to the Gulf of Mexico, and from the plateau region in Arizona northeastward to the Great Lakes.

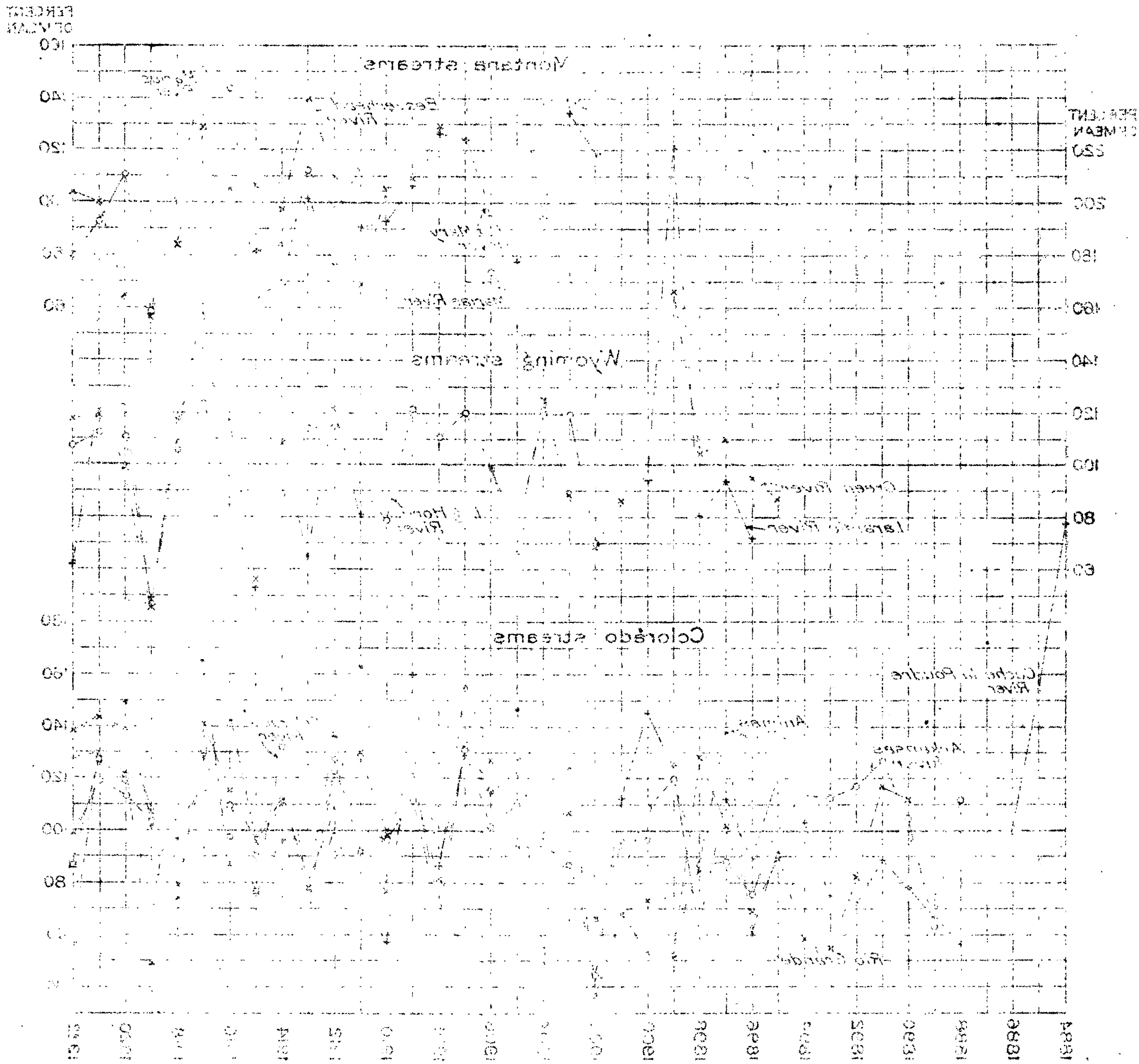
The precipitation in any part of the mountain region depends upon the point at which the area of low pressure crosses the mountains. On the eastern slope of the mountains the precipitation occurs north of the point of crossing, the moisture coming chiefly from the Gulf of Mexico and the Great Lakes; but on the western slope it occurs south of the point of crossing, the moisture coming from the Pacific Ocean. As each of the three general paths has rather wide limits, there are great variations in precipitation and resulting run-off throughout the mountain region in any one year.

Streams in different drainage basins in Colorado.—The variation in annual run-off for the drainage basins in Colorado (see Pl. I) is more uniform than for basins in Montana and Wyoming, which are widely scattered, though the great diversity in the topography of Colorado and its marked influence upon precipitation prevents the variation from being more than approximately uniform. During some years the variations in the different basins are markedly dissimilar, as was especially evident in the period from 1888 to 1901. Subsequent to that time, however, the variation has been fairly uniform. All the records except one show that 1902 was the year of lowest recorded run-off.

Streams within the same drainage basin.—The variation in the annual run-off is much more uniform for different parts of the same drainage basin than for different drainage basins, as may be shown for the records for streams in the upper parts of the Green, Arkansas,



YEARLY PERCENTAGE OF MEAN RUN-OFF FOR STREAMS IN ROCKY MOUNTAIN REGION.


PERCENT OF MEAN
Montana streams
Wyoming streams
Colorado streams
Green River
Laramie River
Cache la Poudre River
Animas
Arkansas River
Rio Grande

and Colorado river basins and adjacent streams in the Big Horn River basin.

Annual run-off of streams in Rocky Mountain region.

Big Horn River basin, Wyo.

Year ending Sept. 30.	Tensleep Creek near Tensleep (drainage area, 228 square miles).		Paintrock Creek near Bonanza (drainage area, 398 square miles).		Shell Creek at Shell (drainage area, 256 square miles).	
	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.
1911	87,100	73	78,900	69	....	....
1912	145,000	122	143,000	125	....	....
1913	....	....	152,000	133	140,000	132
1914	....	....	....	....	129,000	122
1915	140,000	118	125,000	110	104,000	98
1916	142,000	120	116,000	102	100,000	94
1917	142,000	120	136,000	119	105,000	99
1918	123,000	103	139,000	122	130,000	123
1919	78,800	66	64,400	56	74,000	70
1920	137,000	115	119,000	104	110,000	104
1921	98,000	82	95,100	84	85,100	80
1922	101,000	85	96,000	84	85,000	80
Mean	119,000	....	114,000	....	106,000	....

Upper Green River basin, Wyo.

Year ending Sept. 30.	New Fork near Boulder (drainage area, 578 square miles).		East Fork at Newfork (drainage area, 348 square miles).		Pine Creek at Pinedale (drainage area, 128 square miles).		Boulder Creek near Boulder (drainage area, 112 square miles).	
	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.
1915	200,000	63	80,000	60	72,000	60	70,000	57
1916	372,000	117	164,000	122	148,000	122	146,000	119
1917	377,000	118	186,000	139	157,000	130	163,000	134
1918	442,000	139	150,000	112	151,000	125	135,000	111
1919	151,000	47	62,000	46	57,200	47	56,200	46
1920	339,000	107	131,000	98	123,000	102	125,000	102
1921	336,000	106	151,000	113	124,000	102	135,000	111
1922	325,000	102	148,000	110	136,000	112	145,000	119
Mean	318,000	....	134,000	....	121,000	....	122,000	....

Upper Arkansas River basin, Colo.

Year ending Sept. 30.	Arkansas River at Salida (drainage area, 460 square miles).		East Fork of Arkansas River near Leadville (drainage area, 52 square miles).		Tennessee Fork near Leadville (drainage area, 45 square miles).		Cottonwood Creek near Buena Vista. (drainage area, 69 square miles).	
	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.
1910	435,000	89	....	....	....	....	....	....
1911	498,000	102	19,200	66	22,600	82	57,400	123
1912	506,000	103	32,800	113	40,500	146	57,500	123
1913	394,000	81	19,700	68	19,100	69	36,900	79
1914	550,000	112	34,800	120	39,600	143	59,200	127
1915	377,000	77	23,500	81	17,000	61	45,300	97
1916	563,000	115	36,100	124	27,700	100	48,000	102
1917	559,000	114	30,200	104	22,200	80	48,500	103
1918	523,000	107	36,600	126	35,700	129	39,800	85
1919	436,000	89	21,700	75	19,500	70	36,300	77
1920	549,000	112	29,500	101	31,300	113	44,600	95
1921	473,000	97	36,100	124	32,100	116	51,900	111
1922	505,000	103	38,500	98	25,500	92	36,900	79
Mean	490,000	....	29,100	....	27,700	....	46,900	....

Annual run-off of streams in Rocky Mountain region—Continued.

Upper Colorado River basin, Colo.

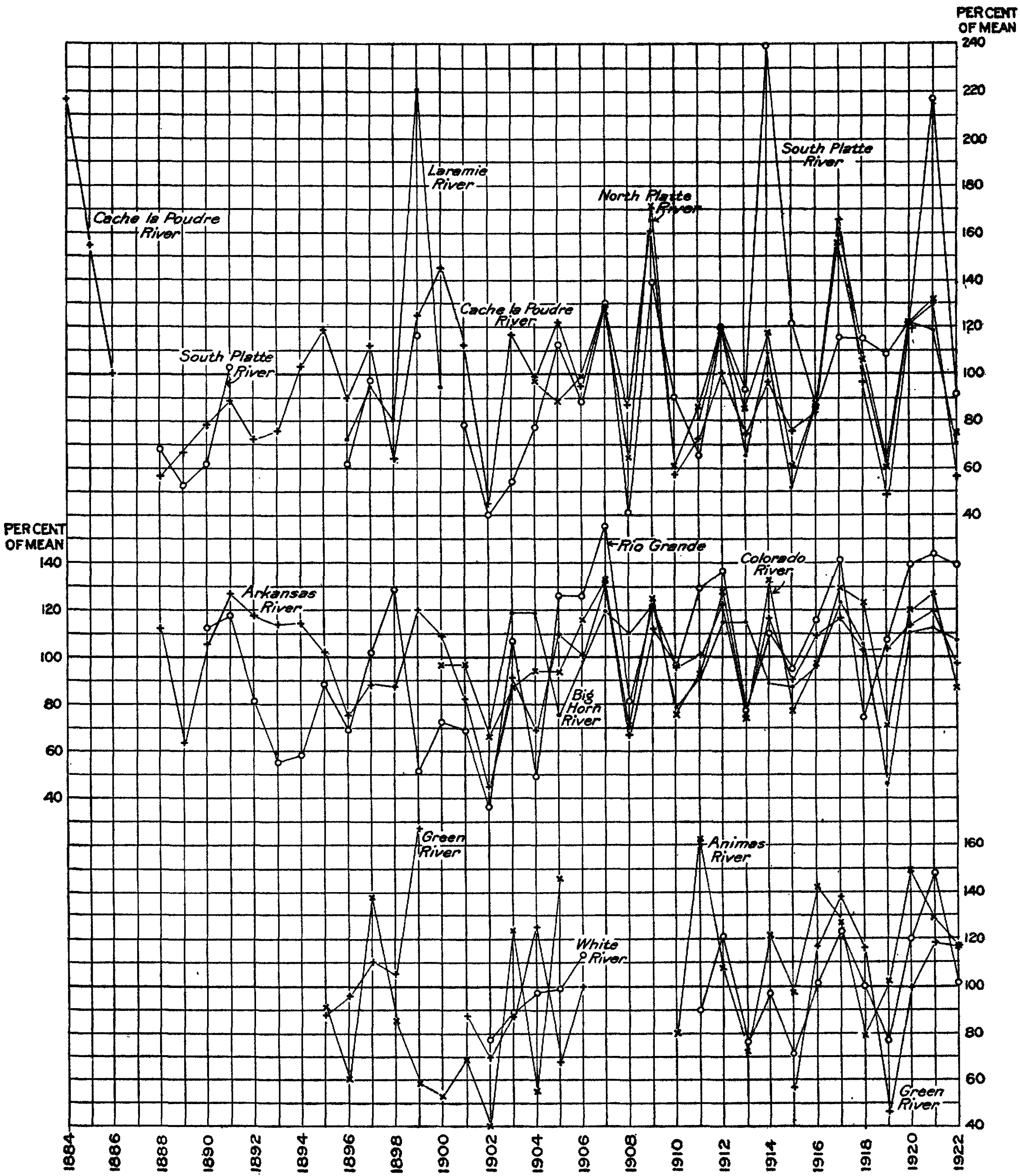
Year ending Sept. 30.	Colorado River at Hot Sulphur Springs (drainage area, 946 square miles).		Fraser River near Arrow (drainage area, 29 square miles).		Williams Fork near Parshall (drainage area, 185 square miles).		Blue River at Dillon (drainage area, 110 square miles).	
	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.
1911	497,000	84	31,200	92	101,000	76	82,700	85
1912	672,000	114	40,200	119	163,000	123	116,000	120
1913	407,000	69	25,100	74	109,000	83	87,000	90
1914	1,150,000	195	44,200	131	167,000	126	135,000	139
1915	423,000	72	40,200	119	122,000	92	83,200	86
1916	469,000	80	30,800	91	117,000	89	85,900	89
1917	675,000	114	31,500	93	156,000	118	107,000	110
1918	639,000	108	43,400	129	169,000	128	112,000	116
1919	360,000	61	23,800	70	96,100	73	69,600	72
1920	689,000	117	30,300	90	126,000	95	88,000	91
1921	697,000	118	39,400	116	156,000	118	124,000	128
1922	376,000	64	25,200	75	99,000	75	72,800	75
Mean	590,000	....	33,800	....	132,000	....	96,900	....

The graphs representing the percentage of annual run-off for each station are grouped by basins in Figure 1 and show the fairly uniform variation in annual run-off for stations in adjacent sections of the same drainage basin.

INFLUENCE OF TOPOGRAPHY UPON VARIATION IN ANNUAL RUN-OFF.

The influence of topography upon variation in annual precipitation and run-off is shown by the graphs in Plate II, which are divided into three groups. The upper group represents streams that drain either the eastern slope of the main mountain range or a region just west of the main range in North Park. The middle group represents streams that rise in the central part of the mountain region on both east and west sides. The lower group represents three streams that rise on the western edge of the mountains. A comparison of these groups shows that the streams that rise on the eastern and western slopes of the main mountain masses have a greater variation in annual run-off than those that rise near the center. The difference between the streams on the western slope and those in the central region is less marked than that between those on the eastern slopes and those in the central region.

Few records on streams that rise in the plains east of the mountains are available, and the only ones covering several consecutive years are those of Belle Fourche River near Belle Fourche, S. Dak. (1913 to 1921), and Cheyenne River near Hot Springs, S. Dak. (1915 to 1920). Both these streams rise in the northeastern part of Wyoming and drain adjacent areas.



INFLUENCE OF TOPOGRAPHY UPON VARIATION IN ANNUAL RUN-OFF OF STREAMS IN ROCKY MOUNTAIN REGION.

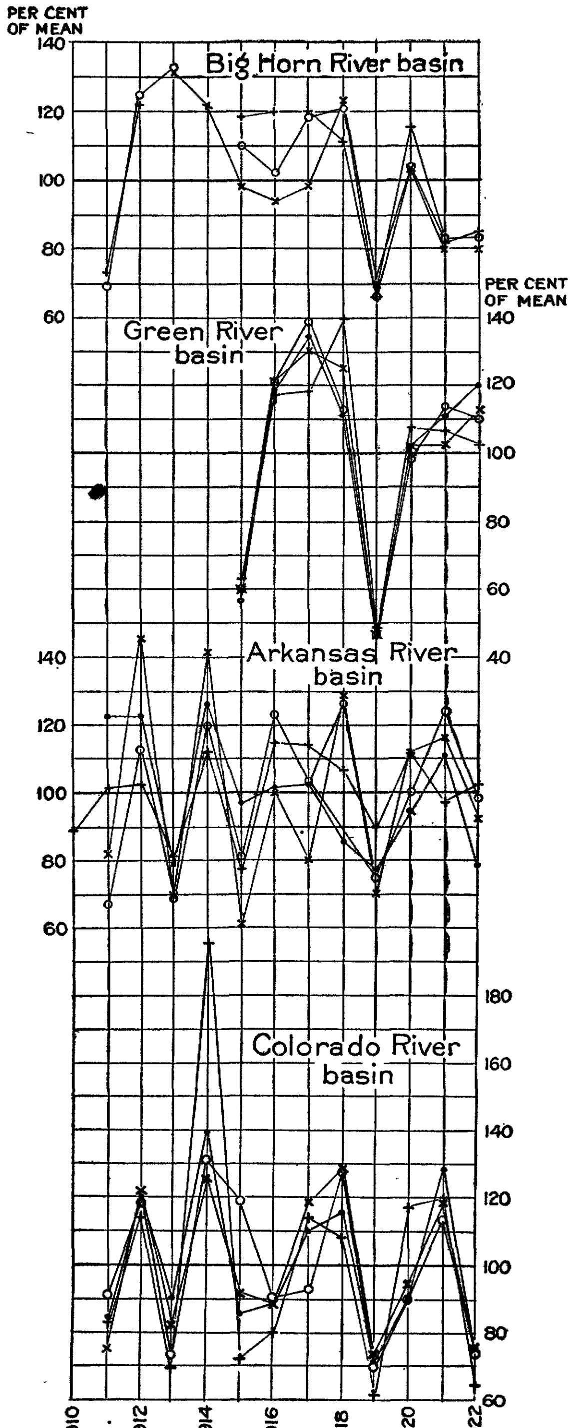


Figure 1.—Yearly percentage of mean run-off for streams in same drainage basin in Rocky Mountain region.

Annual run-off of plains streams.

Year ending Sept. 30.	Belle Fourche River near Belle Fourche, S. Dak.		Cheyenne River near Hot Springs, S. Dak.	
	Acre-feet.	Per cent of mean.	Acre-feet.	Per cent of mean.
1913	324,000	104		
1914	236,000	76		
1915	528,000	170	1,010,000	198
1916	406,000	130	237,000	47
1917	238,000	76	276,000	54
1918	245,000	79	307,000	60
1919	140,000	45	165,000	32
1920	514,000	165	1,050,000	206
1921	181,000	58		
Mean	312,000		508,000	

The annual run-off for the plains streams varies greatly, the range being from 45 to 170 per cent of the mean for the Belle Fourche and from 32 to 206 per cent for the Cheyenne. The run-off of Cheyenne River during one day in 1920 was 244,000 acre-feet, which was greater than the total run-off for either 1916 or 1919 and nearly equal to the total run-off for 1917. In two out of six consecutive years the run-off of Cheyenne River was double the mean annual run-off, a variation much greater than that recorded for any mountain streams.

Although records for other plains streams are not available, there is evidence to show that their variation in annual run-off is greater than that for the mountain streams studied and probably approaches or even exceeds the variation for Belle Fourche and Cheyenne rivers. This evidence is obtained by a comparison of precipitation and run-off in plains areas as shown by the records of Belle Fourche and Cheyenne rivers.

Comparison between precipitation and run-off in Cheyenne and Belle Fourche River basins, 1915–1920.

Cheyenne River near Hot Springs, S. Dak.

	1915	1916	1917	1918	1919	1920
Precipitation......inches..	27.67	13.56	13.50	19.94	14.23	17.62
Run-off......do....	2.17	.52	.60	.65	.39	2.26
Ratio	.078	.038	.044	.033	.027	.128

Belle Fourche River near Belle Fourche, S. Dak.

	1915	1916	1917	1918	1919	1920
Precipitation......inches..	22.15	16.02	12.18	20.89	13.98	20.87
Run-off......do....	2.28	.73	1.05	1.08	.63	1.66
Ratio	.103	.045	.086	.052	.045	.080

During the six years for which comparisons have been made the ratio of run-off to precipitation ranged from 0.033 to 0.128 for Cheyenne River, a difference of nearly 400 per cent, and from 0.045 to 0.103 for Belle Fourche River, a difference of 230 per cent. As the table shows, there is no definite relation between this ratio and the total precipitation. Run-off, especially in plains streams, is governed not so much by total rainfall as by its intensity; a hard rain of short duration furnishes a much larger percentage of run-off than a longer, less intense rain of greater total amount. Another factor that precludes any well-defined relation between precipitation and run-off is the amount of water used in transpiration by vegetation, evaporation from the soil, and percolation of water that does not reenter a stream. According to Gannett[1] the water required annually for transpiration, evaporation, and percolation is roughly 20 inches, and the annual run-off of a drainage basin is therefore about 20 inches less than the precipitation over the drainage basin. Studies by the United States Forest Service at Wagonwheel Gap experiment station, Colo., show the difference between precipitation and run-off to be 15 inches in the mountains. If 15 to 20 inches of water is required annually for transpiration, evaporation, and percolation, it is evident that where the total precipitation is less than about 20 inches, as it is generally in the plains areas east of the mountains, the run-off is very uncertain, depending almost entirely upon the intensity of rainfall, and hence must vary greatly.

RELATION OF 10-YEAR MEAN TO MEAN FOR ENTIRE PERIOD.

Records covering a period of 10 years are available for many streams in the Rocky Mountain region, and there is a rather prevalent idea among users of these records that the mean for that number of years agrees closely with the mean run-off to be expected in the future. To determine the truth or falsity of this idea, progressive 10-year means for stations having the longest records have been computed and compared with the mean for the total period covered by each record. As the records at some of the stations have not been continuous, some of the 10-year means given in the following tables do not represent 10 consecutive years.

Comparison between progressive 10-year means and mean for entire period of record.

Big Horn River at Thermopolis, Wyo.			North Platte River at Saratoga, Wyo.			Laramie River near Woods, Wyo.		
Period.	Mean run-off.		Period.	Mean run-off.		Period.	Mean run-off.	
	Acre-feet.	Per cent of total mean.		Acre-feet.	Per cent of total mean.		Acre-feet.	Per cent of total mean.
1902–1911	1,550,000	100	1904–1913	1,030,000	100	1891–1913	181,000	104
1903–1912	1,620,000	104	1905–1914	1,050,000	103	1896–1914	179,000	102
1904–1913	1,620,000	104	1906–1915	1,020,000	99	1897–1915	176,000	101
1905–1914	1,570,000	101	1907–1916	1,000,000	97	1898–1916	174,000	100
1906–1915	1,580,000	102	1908–1917	1,030,000	100	1899–1917	188,000	107
1907–1916	1,580,000	102	1909–1918	1,080,000	105	1900–1918	169,000	97
1908–1917	1,590,000	103	1910–1919	962,000	93	1905–1919	161,000	92
1909–1918	1,580,000	102	1911–1920	1,020,000	99	1911–1920	166,000	95
1910–1919	1,460,000	94	1912–1921	1,070,000	103	1912–1921	173,000	99
1911–1920	1,510,000	97	1913–1922	1,020,000	99	1913–1922	163,000	93
1912–1921	1,540,000	99						
1913–1922	1,530,000	99						

[1] Gannett, Henry, unpublished report on precipitation and run-off, U. S. Geol. Survey.

Comparison between progressive 10-year means and mean for entire period of record—Continued.

Green River at Green River, Wyo.

Period.	Mean run-off. Acre-feet.	Mean run-off. Per cent of total mean.
1895–1905	1,500,000	100
1896–1906	1,520,000	101
1897–1915	1,460,000	97
1898–1916	1,470,000	98
1899–1917	1,520,000	101
1901–1918	1,440,000	96
1902–1919	1,380,000	92
1903–1920	1,430,000	95
1904–1921	1,470,000	98
1905–1922	1,460,000	97

Rio Grande at Del Norte, Colo.

Period.	Mean run-off. Acre-feet.	Mean run-off. Per cent of total mean.
1890–1899	617,000	86
1891–1900	589,000	82
1892–1901	554,000	77
1893–1902	522,000	72
1894–1903	559,000	78
1895–1904	552,000	77
1896–1905	579,000	80
1897–1906	620,000	86
1898–1907	677,000	94
1899–1908	643,000	89
1900–1909	693,000	96
1901–1910	710,000	98
1902–1911	753,000	104
1903–1912	825,000	114
1904–1913	803,000	111
1905–1914	847,000	117
1906–1915	825,000	114
1907–1916	818,000	113
1908–1917	789,000	109
1909–1918	784,000	109
1910–1919	773,000	107
1911–1920	804,000	111
1912–1921	813,000	113
1913–1922	815,000	113

Colorado River at Glenwood Springs, Colo.

Period.	Mean run-off. Acre-feet.	Mean run-off. Per cent of total mean.
1900–1909	2,200,000	97
1901–1910	2,180,000	96
1902–1911	2,160,000	95
1903–1912	2,300,000	101
1904–1913	2,280,000	100
1905–1914	2,360,000	104
1906–1915	2,320,000	102
1907–1916	2,280,000	100
1908–1917	2,280,000	100
1909–1918	2,390,000	105
1910–1919	2,270,000	100
1911–1920	2,370,000	104
1912–1921	2,450,000	108
1913–1922	2,350,000	103

Cache la Poudre River at mouth of canyon, Colo.

Period.	Mean run-off. Acre-feet.	Mean run-off. Per cent of total mean.
1884–1894	316,000	101
1885–1895	286,000	91
1886–1896	265,000	85
1888–1897	269,000	86
1889–1898	271,000	87
1890–1899	289,000	92
1891–1900	310,000	99
1892–1901	317,000	101
1893–1902	308,000	99
1894–1903	321,000	103
1895–1904	319,000	102
1896–1905	320,000	102
1897–1906	322,000	103
1898–1907	327,000	104
1899–1908	335,000	107
1900–1909	346,000	110
1901–1910	318,000	101
1902–1911	306,000	98
1903–1912	323,000	103
1904–1913	310,000	99
1905–1914	310,000	99
1906–1915	295,000	94
1907–1916	292,000	93
1908–1917	304,000	97
1909–1918	307,000	98
1910–1919	272,000	87
1911–1920	292,000	93
1912–1921	310,000	99
1913–1922	296,000	94

South Platte River at South Platte, Colo.

Period.	Mean run-off. Acre-feet.	Mean run-off. Per cent of total mean.
1888–1903	203,000	73
1889–1904	206,000	74
1890–1905	222,000	80
1891–1906	230,000	83
1896–1907	237,000	85
1897–1908	232,000	83
1899–1909	244,000	88
1901–1910	236,000	85
1902–1911	233,000	84
1903–1912	255,000	92
1904–1913	266,000	96
1905–1914	310,000	112
1906–1915	313,000	113
1907–1916	312,000	112
1908–1917	308,000	111
1909–1918	328,000	118
1910–1919	320,000	115
1911–1920	329,000	118
1912–1921	371,000	133
1913–1922	363,000	131

Clear Creek near Golden, Colo.

Period.	Mean run-off. Acre-feet.	Mean run-off. Per cent of total mean.
1900–1909	182,000	99
1901–1910	175,000	95
1902–1911	172,000	93
1903–1912	184,000	100
1904–1913	185,000	100
1905–1914	193,000	105
1906–1915	191,000	104
1907–1916	186,000	101
1908–1917	182,000	99
1909–1918	192,000	104
1910–1919	182,000	99
1911–1920	187,000	102
1912–1921	200,000	109
1913–1922	190,000	103

Comparison between progressive 10-year means and mean for entire period of record—Continued.

Animas River at Durango, Colo.			White River at Meeker, Colo.			Arkansas River at Canon City, Colo.		
Period.	Mean run-off.		Period.	Mean run-off.		Period.	Mean run-off.	
	Acre-feet.	Per cent of total mean.		Acre-feet.	Per cent of total mean.		Acre-feet.	Per cent of total mean.
1895–1904	535,000	77	1902–1915	445,000	93	1888–1897	566,000	101
1896–1905	573,000	83	1903–1916	457,000	95	1889–1898	552,000	99
1897–1910	586,000	85	1904–1917	473,000	99	1890–1899	583,000	105
1898–1911	604,000	87	1905–1918	474,000	99	1891–1900	585,000	105
1899–1912	619,000	89	1906–1919	463,000	97	1892–1901	560,000	101
1900–1913	630,000	91	1911–1920	466,000	97	1893–1902	520,000	93
1901–1914	677,000	98	1912–1921	494,000	103	1894–1903	508,000	91
1902–1915	697,000	101	1913–1922	485,000	101	1895–1904	482,000	87
1903–1916	767,000	111				1896–1905	487,000	87
1904–1917	769,000	111				1897–1906	502,000	90
1905–1918	785,000	113				1898–1907	526,000	94
1910–1919	755,000	109				1899–1908	515,000	92
1911–1920	803,000	116				1900–1909	511,000	92
1912–1921	780,000	113				1901–1910	504,000	91
1913–1922	786,000	113				1902–1911	514,000	92
						1903–1912	557,000	100
						1904–1913	549,000	99
						1905–1914	575,000	103
						1906–1915	564,000	101
						1907–1916	568,000	102
						1908–1917	560,000	101
						1909–1918	580,000	104
						1910–1919	574,000	103
						1911–1920	584,000	105
						1912–1921	594,000	107
						1913–1922	579,000	104

The percentages of the total mean represented by the progressive 10-year means are shown by the graphs in Figure 2. The graphs for the South Platte, Arkansas, and Rio Grande show that during the nineties the mean discharge for each 10-year period represented was considerably below the normal but that since about 1903 the 10-year means have all been considerably above the normal. Of course, during the low-water period the discharge for individual years was above the normal, just as during the high-water period the discharge for individual years was below the normal. On the Cache la Poudre low-water periods occurred during the eighties and from 1905 to date, but during the nineties the discharge was above the normal.

Although any 10-year mean for the stations at which the records began subsequent to 1900 agrees closely with the mean for the entire period covered, it is possible that had these records included the eighties and nineties they would have shown variations similar to those exhibited by the longer records. It appears that for most of the streams in Colorado, with the notable exception of the Cache la Poudre, any 10-year mean since about 1903 is probably somewhat greater than the mean flow of the stream when the low flow during the nineties and the first years in the present century is considered.

It is impossible to state whether the same thing is true of streams in Wyoming, as the only record covering even a part of the earlier years for a Wyoming stream is that on Green River at Green River, which covers the years 1895 to 1906, and the progressive 10-year

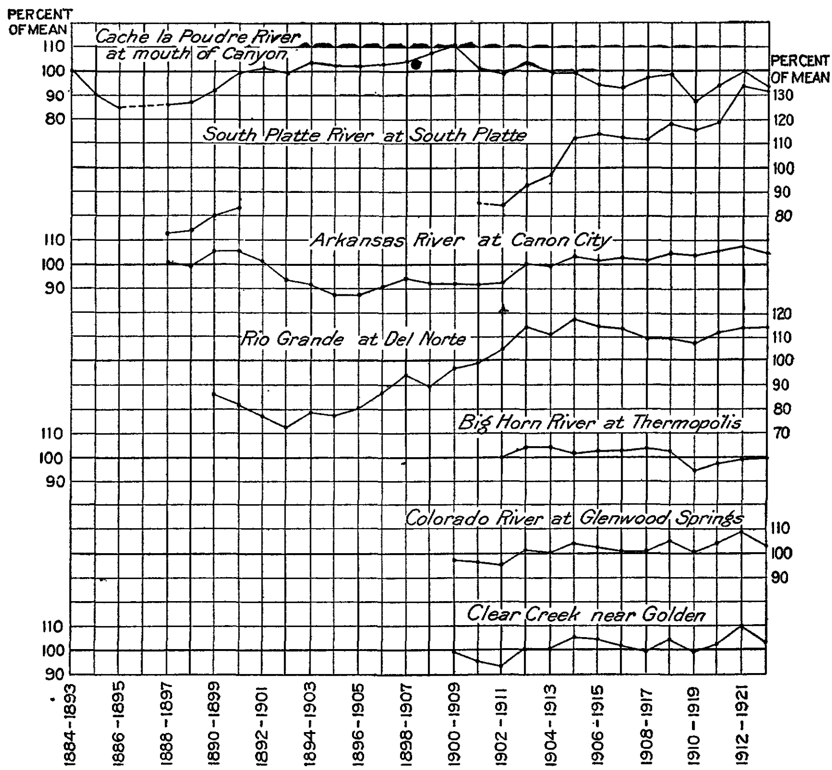


FIGURE 2.—Comparison between progressive 10-year means of run-off and mean for entire period of record on streams in Rocky Mountain region.

means during that period indicate practically a normal discharge. As shown in Figure 1, however, the variation in annual discharge is not the same in different basins in Wyoming, and the variation for streams on the eastern slope of the mountains may agree with the variation for the streams in Colorado.

ADDITIONAL GROUND-WATER SUPPLIES FOR THE CITY OF ENID, OKLAHOMA.

By B. Coleman Renick.

INTRODUCTION.

In 1914 the United States Geological Survey published a brief report on ground water for irrigation in the vicinity of Enid, Okla., based on a rapid examination of the area by A. T. Schwennesen.[1] The present report is published in response to a request for a short ground-water survey for the city. The commissioner and the superintendent of the waterworks reported a shortage of water during the summer, especially in July and August. This survey was desired to furnish information bearing on a proposed increase in the city water supply. The writer was engaged from November 14 to 20, 1923, inclusive, in a field examination of the country about Enid and the region west of Ringwood. The manuscript report was transmitted to the mayor of Enid on December 8, 1923. In order to make close estimates of the quantity of water available it would, however, be necessary to study the region in detail for a period of at least several months. It is not within the scope of this investigation to make estimates of the costs of installation.

ACKNOWLEDGMENTS.

The writer wishes to express his appreciation of the hearty cooperation of the city commissioners; Mr. F. C. Magruder, city engineer; Mr. Cecil Harrison, superintendent of the city waterworks; and Mr. J. D. Bomford, consulting engineer. Mr. Harrison rendered valuable assistance by conducting the writer over the field, supplying information pertaining to the present waterworks, and furnishing data concerning test holes bored under his direction. Mr. Bomford supplied the base map from which the accompanying ground-water map (fig. 3) has been prepared. The hearty cooperation of the well drillers and other citizens greatly facilitated the work. An unpub-

[1] Schwennesen, A. T., Ground water for irrigation in the vicinity of Enid, Okla.: U. S. Geol. Survey Water-Supply Paper 345, pp. 11–23, 1914.

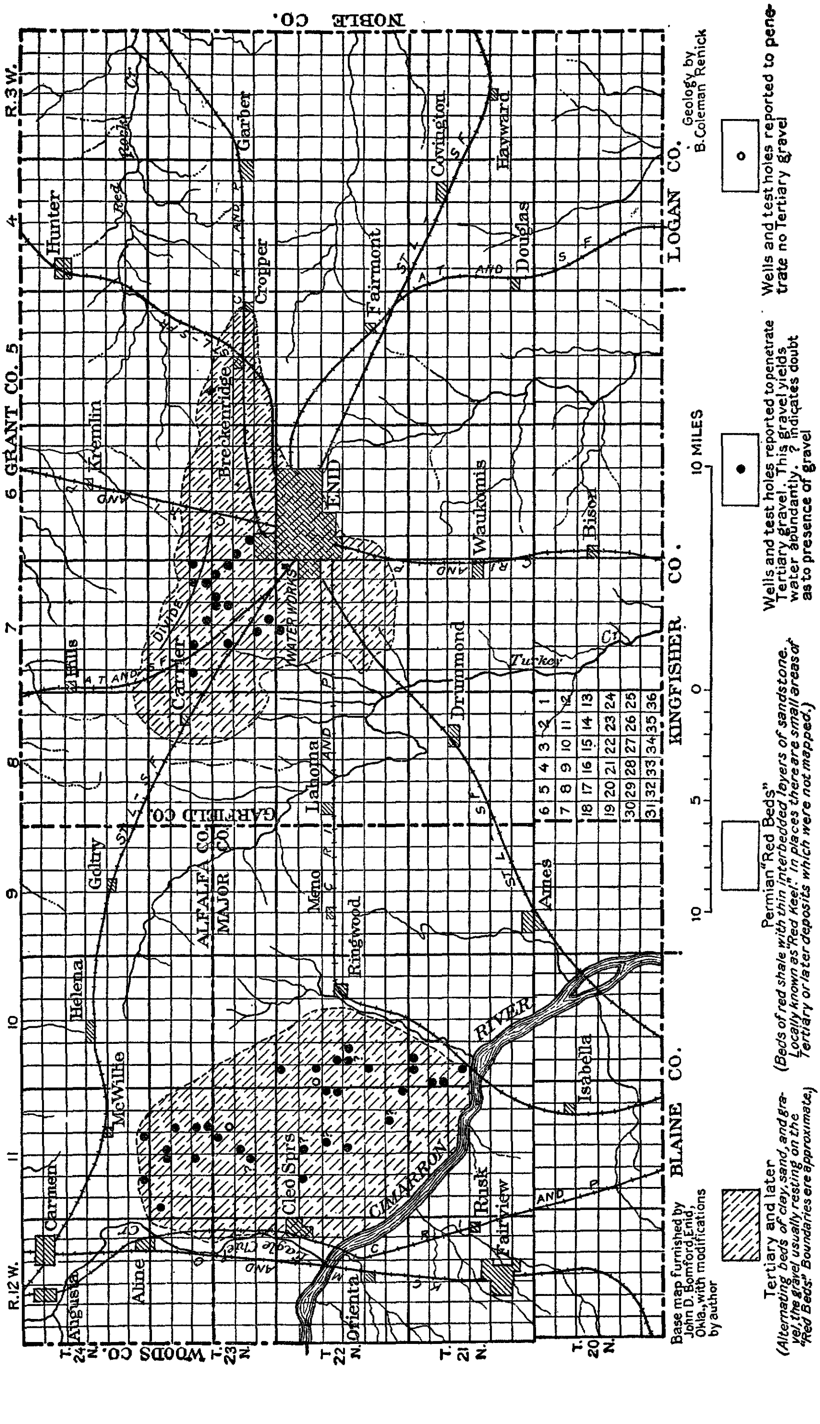


FIGURE 3.—Map of an area in the vicinity of Enid and Ringwood, Okla., showing distribution of water-bearing Tertiary and later deposits.

lished report on the water supply of Enid, prepared by Messrs. Black & Veatch, consulting engineers, and a short unpublished report prepared in October, 1923, by Messrs. Bomford and Magruder, were available for consultation.

The present report was carefully reviewed by O. E. Meinzer, geologist in charge of the division of ground water. The chemical analyses of five samples of water were made in the water-resources laboratory of the United States Geological Survey in Washington by C. S. Howard. The section of this report relating to the quality of water was prepared by W. D. Collins, chief of the division of quality of water. Several forms of showing diagrammatically the results of analyses of waters have been proposed. The form used in Figure 5, suggested by Collins,[2] has here been adopted.

GEOLOGY.

Permian rocks.—The oldest rocks exposed in the region are of Permian age and consist of red shale and some thin lenticular beds of sandstone. The rocks are commonly referred to as the "Red Beds," and are locally known as "red keel."

Drilling operations have shown that the "Red Beds" (Permian and probably some underlying Pennsylvanian strata) are at least 3,300 feet thick.[3] In many places it is difficult to determine the structure of these beds from their outcrops, and some oil companies have resorted to core drilling in order to work out the structural relations.

Tertiary and later deposits.—Resting unconformably on the "Red Beds" are much younger deposits, the oldest presumably Tertiary. These younger deposits consist of gravel, sand, and clay. At most places the gravel rests on the "Red Beds." The pebbles of the gravel are almost entirely quartz and the matrix is quartz sand and clay. The larger particles of the gravel so far as observed, did not exceed three-eighths of an inch in diameter except where they consist of fragments of "Red Beds." The gravel occurs in extremely lenticular beds and does not, as is commonly supposed, form a continuous sheet of uniform thickness. It has a maximum thickness of about 25 feet, but at many places in the areas of Tertiary deposits it is absent or is only a few inches thick. Sand of varying texture is encountered between the gravel and the surficial soil. Very commonly a layer of red or gray clay is interbedded in the sand that lies above the gravel. The maximum observed thickness of these deposits was 75 feet and the average thickness is 50 feet. (See fig. 4.) These beds are of terrestrial origin and are water-laid, with the

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[2] Collins, W. D., Graphic representation of water analyses: Ind. and Eng. Chemistry, vol. 15, No. 4, p. 394, April, 1923.

[3] Schwennesen, A. T., op. cit., pp. 11–23.

exception of some of the surficial sand, which has been rehandled by the wind since its deposition and is therefore of eolian origin. There are two large areas of these Tertiary deposits, one in the vicinity of Enid, covering an area of about 110 square miles, and another west of Ringwood, covering an area of about 120 square miles. (See map, fig. 3.)

WATER IN THE PERMIAN ROCKS.

Although there are noteworthy exceptions, the "Red Beds" will at most places yield water in sufficient quantity for ordinary farm use, especially where the well encounters a lens of sandstone in the "Red Beds." The chemical character of the water in a well can not be predicted before drilling, as the water from wells on adjoining quarter sections may differ considerably in its content of dissolved salts. In general, however, the water from the "Red Beds" is more highly mineralized than that from the Tertiary deposits.

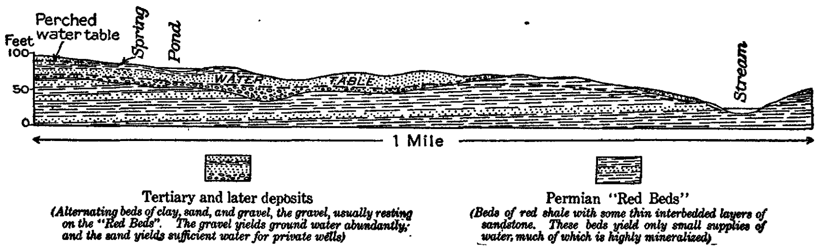

FIGURE 4.—Generalized diagrammatic section of rocks near Enid and west of Ringwood, Okla., showing ground-water conditions.

WATER IN THE TERTIARY AND LATER DEPOSITS.

The largest supplies of ground water are obtained from the deposits of Tertiary and later age. The quantity of water yielded by any water-bearing bed depends to a great extent upon the texture of the material; the best water-bearers are the coarsest, cleanest, and least compacted gravels. The coarse sands yield enough water for small farm plants but are not sufficiently permeable to supply city wells. At some places the interbedded clay acts as an impervious layer separating two sandy water-bearing beds and produces a "perched water table."[4] Such a table is common in the southern part of the Ringwood area, where one of these clay beds is especially persistent. (See fig. 4.)

SOURCE OF GROUND WATER.

The water found in wells in the "Red Beds" is derived in part from water that slowly migrates underground from more or less

[4] Meinzer, O. E., Outline of ground-water hydrology: U. S. Geol. Survey Water-Supply Paper 494, p. 41, 1923.

remote areas and in part from the water that is precipitated as rain and snow in the immediate vicinity. The water in the Tertiary deposits is derived entirely from precipitation within a few miles of the wells from which it is pumped and not from a remote source, as some have supposed.

RELATION OF GROUND WATER TO TOPOGRAPHY, SOIL, AND VEGETATION.

In a country that is underlain by porous and permeable materials, that is relatively flat and has few drainage lines, and that contains some undrained depressions, a considerable part of the water precipitated as rain and snow sinks into the soil and percolates downward to the water table. A porous and permeable material, such as sand, permits rapid migration of water downward and thus is favorable to a minimum evaporation. By evaporation from their leaves plants dissipate water which otherwise would percolate down to the water table and become available for pumping from wells. In the areas of Tertiary deposits west of Ringwood and northwest of Enid the conditions are favorable for replenishing the ground-water supply because the country is relatively flat and contains undrained depressions, the soil is very permeable, and the vegetation is scanty.

The Ringwood area of Tertiary deposits is not dissected by streams and therefore has less loss of ground water from seepage than the Enid area, where in places the Tertiary beds are dissected and the "Red Beds" are exposed.

PRESENT WATERWORKS OF ENID.

Main plant.—The plant of the city pumping waterworks, which is in the SE. ¼ sec. 1, T. 22 N., R. 7 W., was installed in 1911. It originally consisted of a central pump pit about 30 feet deep and two tunnels, one of which extends toward the northwest and the other toward the east. Each tunnel contained 16 wells drilled about 27 feet apart. These wells are 6 inches in diameter and are connected to a suction main. A valve at each well regulates the quantity of water pumped. In 1918 the tunnels were lengthened and 16 wells of similar type and spacing were drilled in each tunnel. The average depth of all these wells is about 50 feet. Since this last extension was made three wells of larger diameter have been dug. These wells extend in a general northerly and northwesterly direction from 600 to 1,800 feet from the present plant. Two of them have pits 6 feet in diameter that extend to the water level, and below that galvanized casings, 30 inches in diameter, extending 14 and 17 feet, respectively, into water-bearing gravel. The third well, 20 feet in diameter, has a brick curbing and is 47 feet deep.

Mr. Harrison, the superintendent of the waterworks, who kindly furnished the history of the plant, reported that this system will now yield an average of 900,000 gallons in 24 hours of pumping.

Wells on the King tract.—In 1919 the city of Enid extended its water system by installing 10 wells on the so-called King tract, in the SW. ¼ sec. 11, T. 22 N., R. 7 W. In each well a pit 6 feet in diameter extends to the water-bearing gravel and below this a 26-inch perforated casing penetrates the gravel and rests on the "Red Beds." At each well a layer of coarse gravel has been placed around the perforated casing. The average depth of these wells is about 45 feet. An electric motor furnishes power for an individual pump at each well.

CONSUMPTION OF WATER BY CITY OF ENID.

Mr. Harrison reported that the average daily capacity of the main pumping plant is 900,000 gallons, and he estimated that the wells on the King tract also contribute about 900,000 gallons, or that the total capacity of the wells that supply the city waterworks is about 1,800,000 gallons daily, and that during a considerable portion of the year the city consumes the entire 1,800,000 gallons each day.

QUANTITY OF GROUND WATER.

The average annual precipitation in the vicinity of Enid has been about 30.5 inches during the period of 25 years for which records have been obtained by the United States Weather Bureau. If the average annual precipitation is 30 inches, about 520,600,000 gallons of water will fall on each section of land. If in the area of gravel one-third becomes ground water (the other two-thirds either running off or evaporating or being consumed by plants), about 173,870,000 gallons will be contributed annually to the ground water on each section of land, or a daily average of about 470,000 gallons. If one-half of this amount can be recovered by pumping from wells, about 235,000 gallons daily is available from 1 square mile.

If these estimates are approximately correct it will require somewhat less than four sections to supply the 900,000 gallons a day that is pumped by the main plant and a similar area to supply the 900,000 gallons a day supplied by the wells on the King tract. The water utilized by the city does not, however, all come from an area of 8 square miles adjacent to the two pumping plants, for undoubtedly some of it finds its way to the pumps by slow underground flow from sections several miles away from the plants.

QUALITY OF WATER.

The analyses of samples of water from the Tertiary areas of Enid and Ringwood (see p. 22) may be divided into two groups. The two samples from Enid are similar in composition. The samples from Ringwood are like one another but differ noticeably from those from Enid. (See fig. 5.)

The water at Enid is slightly hard and contains little dissolved mineral matter. It is not very different in composition from that of the public supply of Chicago. It can be used for most domestic purposes without great trouble from hardness. For use in large boiler plants or in commercial laundries, it should be softened. It

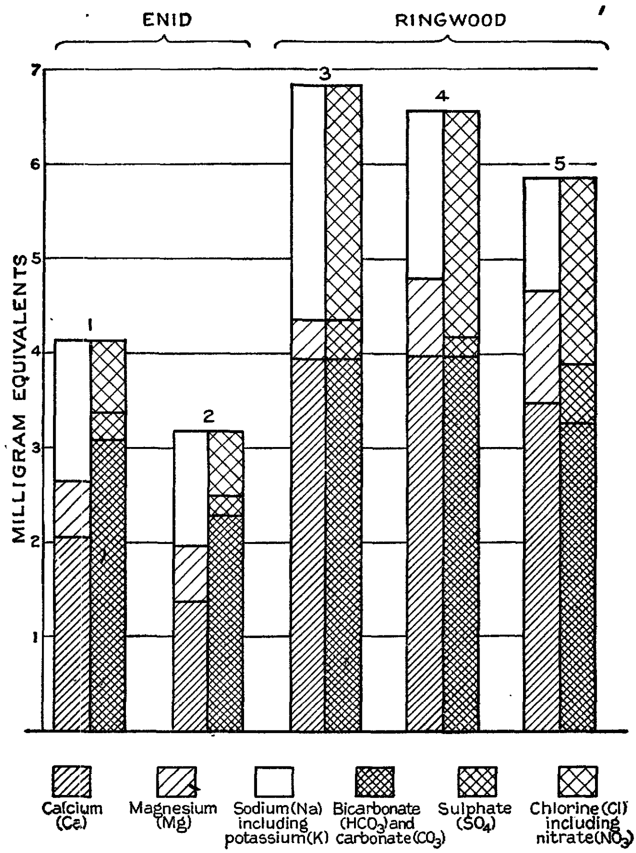

FIGURE 5.—Graphic representation of analyses of waters from Tertiary deposits near Enid and Ringwood, Okla. (See table, p. 22.)

should be satisfactory for use in boilers except that it may form a slight amount of soft scale.

The water from Ringwood is decidedly hard. Such water could profitably be softened for domestic use and for any industrial use in which hardness is detrimental. These waters may prove corrosive in steam boilers. In general the water at Ringwood has about the same composition as that at Enid but contains nearly twice the quantity of dissolved mineral matter.

Analyses of water from Tertiary deposits at Enid and near Ringwood, Okla.

[Analyst, C. S. Howard. Parts per million.]

	1	2	3	4	5
Silica (SiO_2)	....	26	....	26	....
Iron (Fe)	Trace.	.12	1.6	.12	.55
Calcium (Ca)	42	29	79	78	70
Magnesium (Mg)	7.8	7.5	5.7	9.6	15
Sodium and potassium (Na+K)	39	30	59	42	27
Bicarbonate radicle (HCO_3)	182	145	238	244	200
Sulphate radicle (SO_4)	15	9.1	21	12	30
Chloride radicle (Cl)	26	21	84	91	69
Nitrate radicle (NO_3)	6.2	1.0	2.2	Trace.	2.4
Total dissolved solids at 180° C	....	199	....	425	....
Total hardness as $CaCO_3$ (calculated)	137	103	221	234	236
Date of collection	Nov. 20, 1923.	Nov. 19, 1923.	Nov. 15, 1923.	Nov. 16, 1923.	Nov. 15, 1923.

1. Drilled well 50± feet deep; SE. ¼ sec. 1, T. 22 N., R. 7 W., Enid. Owned by city.
2. Bored well 47 feet deep; SE. ¼ NE. ¼ sec. 24, T. 23 N., R. 7 W., Enid. Owned by P. W. Dickman.
3. Drilled well 57.5 feet deep; NE. ¼ sec. 20, T. 22 N., R. 10 E., Ringwood. Owned by A. K. Manning.
4. Drilled well 82 feet deep; SE. ¼ sec. 12, T. 22 N., R. 12 W., Ringwood. Owned by Arnold Spenner.
5. Spring, SW. ¼ SW. ¼ sec. 22, T. 22 N., R. 10 E., Ringwood.

PROSPECTING FOR WATER-BEARING GRAVEL.

Some cities set about to develop a ground-water supply before testing the proposed well site thoroughly by drilling. At Enid there is a direct relation between the quantity of water that can be obtained and the thickness of the gravel that yields the water. The thickness of the gravel should therefore be determined before wells are drilled and a pumping system is installed. In areas where the gravel is thin or absent only small supplies can be expected.

In drilling test holes it is necessary to keep an accurate log of the hole, to collect samples for mechanical analyses at each change in the beds, and to collect samples of water for chemical analyses from certain holes, the number of samples collected depending on the number of holes drilled. Certain of the holes drilled should be tested by pumping and the drawdown measured. It should be remembered, too, that a well will yield water at a more rapid rate if it is pumped alone than if it is pumped simultaneously with other wells nearby. Moreover, a well will yield at a more rapid rate in a pumping test of only a few hours or a few days than during a longer period, and estimates of yield based on pumping for a short period should therefore be reduced accordingly.

The total available supply of ground water and the extent of its depletion by pumping may be determined at relatively small cost by carefully observing the water level in a number of properly distributed wells sunk for this purpose into the saturated gravels. At Enid a few such observation wells should be maintained near the pumping plants; a few should be maintained in the area 3 miles north of Enid that is recommended for new development; and a few should be maintained at intermediate points and at places still farther from Enid. The elevations of definite reference points in these wells should be established by instrumental leveling. The depth to the water level from the reference point in each well should be measured from time to time, preferably about once a month. The measurements on all the wells should, if possible, be made on the same day. The data obtained by these observations will show the shape and the fluctuations of the water table in relation to rainfall and pumpage and will soon give a reliable means of estimating the supplies available and of determining future developments.

Obviously any new pumping system that might be installed should be located at a place where the gravel is reasonably thick over a considerable area, and where pumping will not withdraw any great quantity of ground water that would otherwise be recovered at one of the present plants.

It would be inadvisable to expand either the main plant or the plant on the King tract by drilling new wells, because the new wells would merely withdraw water that would otherwise be available to the present wells.

Fortunately there is at least one and possibly more than one locality near Enid and the large area west of Ringwood at which additional supplies may be obtained for the city. Each of these areas is discussed below.

ENID AREA.

Conditions are favorable to the accumulation of ground water in secs. 15, 22, 23, 24, the southern part of secs. 13 and 14, the northern part of secs. 25, 26, and 27, T. 23 N., R. 7 W., and in secs. 19 and 30, T. 23 N., R. 6 W. (See fig. 3.) The area included in these sections is undissected by drainage lines and has many undrained depressions and a sandy, porous soil that is favorable to the seepage of water into the ground, and, according to well drillers and farmers, much of it is underlain by water-bearing gravel. Mr. P. W. Dickman, a well driller, gave from memory the following instructive information relating to the gravel, though the thicknesses given are only approximate:

Water-bearing materials reported in wells in an area north of Enid.

[All thicknesses are approximate.]

T. N.	R. W.	Section.	Quarter.	Water-bearing material.
23	7	13	NE.	7 feet gravel and sand.
23	7	13	SE.	15 feet gravel.
23	7	14	NE.	3 feet gravel.
23	7	14	SE.	1.5 feet gravel.
23	7	15	SW.	20± feet gravel.
23	7	21	SW.	22± feet sand and gravel.
23	7	22	SE.	30± feet sand and gravel, lower part coarse.
23	7	22	NE.	4 feet sand, fine.
23	7	22	SW.	About same as SE. ¼ sec. 22.
23	7	23	NW.	12± feet sand and gravel.
23	7	23	NE.	4 feet sand.
23	7	24	NW.	8 feet gravel.
23	7	25	NE.	20 feet gravel.
23	6	18	NW.	17 feet gravel and sand.
23	6	30	SE.	11 feet gravel and sand.
23	6	30	NW.	20 feet gravel and sand.

Secs. 23 and 24, T. 23 N., R. 7 W., should be carefully prospected to determine the thickness and depth of the gravel and adequate pumping tests should be made. Observations and calculations indicate that wells drilled in secs. 22, 23, and 24, T. 23 N., R. 7 W. would add considerably to the total water supply, though they would doubtless eventually cause some decrease of the supply at the main plant.

A well system installed about 3 miles northwest of the city of Enid will probably not greatly affect the water supply at the city plants, for wells in that area have suffered no appreciable drawdown since the main plant was installed at Enid, and the relative thinness of the saturated belt in the lower part of the Tertiary deposits precludes the possibility that the hydraulic gradient between the proposed area and the existing city plant will be much increased through the lowering of the water table by pumping at Enid. Hence, the movement of ground water from the area northwest of the city toward the existing pumping plants must remain very slow, despite the depletion of the supply in the vicinity of these plants. Furthermore, the lack of continuity of the gravel between these two areas indicates that the ground-water reserves of these two areas may be somewhat isolated from each other.

The sample of water (No. 2 in table on p. 22 and in fig. 5) from Mr. Dickman's well in the NE. ¼ sec. 24, T. 23 N., R. 7 W., is better than that of the present supply of Enid (No. 1, p. 22 and fig. 5) and is much better than the three samples taken from wells in the Ringwood area (Nos. 3, 4, 5, p. 22 and fig. 5).

No large supply of ground water can be obtained north of the divide, which is about 5 miles north of the court house at Enid (see map, fig. 3), because little gravel is found north of this divide. No undissected gravel-bearing tract that is of sufficiently large size to warrant development lies southwest of the city. Secs. 17 and 20, T. 22 N., R. 7 W., and all gravel-bearing sections to the west are dissected by streams that expose the "Red Beds," and break the continuity of the water-bearing gravel beds. South of the east-west half-section line in secs. 21, 22, 23, and 24, T. 22 N., R. 7 W., the country is dissected by streams and the "Red Beds" are exposed at many places. Therefore only secs. 9, 10, 11, 12, 13, 14, 15, 16, and the northern part of secs. 21, 22, and 23, T. 22 N., R. 7 W., are favorable, and the wells on the King tract, in the SW. ¼ sec. 11, undoubtedly exert considerable influence on the water table in the northeastern part of this area.

Before it is assumed that the city is obtaining all the ground water that it can procure near by, several test holes should be drilled northeast of the city, near the center of the area embracing secs. 19 to 34, inclusive, T. 23 N., R. 6 W. The opinion prevails that the gravel is thin or absent over much of this area, and a few test holes would either substantiate or disprove this opinion.

The broad plain east of Carrier, embracing secs. 12 and 13, T. 23 N., R. 8 W., and secs. 7, 8, 18, 19, and the western parts of secs. 17 and 20, T. 23 N., R. 7 W., is not a favorable area for obtaining additional water on account of its remoteness from Enid and the scarcity of gravel.

RINGWOOD AREA.

West of Ringwood, extending from Indian Creek on the east at least to Eagle Creek on the west, and from Cimarron River and Indian Creek on the south approximately to the north line of T. 23 N. on the north (see fig. 3), is an area which, considered as to its lack of drainage lines, its abundance of undrained depressions, its high soil porosity, and the presence of underlying gravel, is favorable to the accumulation of ground water. Springs having a considerable flow of water were observed where the gravel is exposed along Indian Creek southwest of Ringwood and at Cleo along Eagle Creek. These gravel deposits, like those near Enid, are of Tertiary or later age. The eastern margin of this area is about 21 miles from the courthouse at Enid.

The Ringwood area is on the whole more favorable to the accumulation of ground water than the Enid area and is considerably larger. The water-bearing gravel overlies the "Red Beds" in most of this area but is not present everywhere, so that it will be necessary to prospect any proposed well field in order to determine the presence and the thickness of the gravel.

The surface of the Ringwood area slopes south-southeast, toward Cimarron River and Indian Creek, and undoubtedly the water-bearing gravel slopes in the same direction. Aneroid measurements, which were checked several times, show that the surface at Cimarron River stands less than 1,200 feet above sea level, and that the northern part of the gravel-covered area, about 15 miles away, at the northern border of T. 23 N., stands more than 1,400 feet above sea level, giving a southward slope of about 15 feet to the mile.

When it is deemed necessary to utilize the Ringwood area, test holes should be drilled to test the thickness of the gravel in secs. 13 and 14, T. 22 N., R. 11 W., and sec. 18 and the W. ½ sec. 17, T. 22 N., R. 10 W., preferably in the southern parts of these sections. The altitude of the surface here is somewhat higher than at Enid and no static head would have to be overcome; but the friction head of the pipes for over 20 miles would prevent a sufficiently rapid gravity flow into Enid. The gravel probably rests on the "Red Beds" in the sections named. Wells drilled in these sections would intercept the southeastward-moving ground water. There is an adequate collecting area for ground water north of this prospective well field. The location of wells must depend upon the thickness of the gravel and the type of wells desired. Any well system developed in secs. 17 and 18, T. 22 N., R. 10 W., or in secs. 13 and 14, T. 22 N.,

R. 11 W., or both, might be extended toward the west into secs. 15, 16, and 17, T. 22 N., R. 11 W., and obtain additional supplies of water without interfering greatly with any existing system to the east, in secs. 13 and 14.

Until the maximum quantity of ground water available is obtained in the sections referred to above and to the north, developments should not be made southwest of Ringwood, near the junction of Indian Creek and Cimarron River, as has been suggested. Should the population of Enid become large enough to warrant the complete development of the Ringwood area test holes should be sunk in secs. 10, 11, and 12, T. 21 N., R. 11 W., and sec. 7, T. 21 N., R. 10 W. If these test holes penetrate gravel this locality would be favorable because wells at such a location would intercept the southeastward flowing ground water that would seep into the gravel south of the area recommended for first development, 5 or 6 miles to the north.

PROPOSED EXTENSION.

In order to increase the water supply at Enid the city must choose between two alternatives. Additional wells and a pumping system may be installed about 3 miles northwest of the main plant at relatively small cost or wells and a pumping system may be installed in the area west of Ringwood at much greater cost and the water piped to the city. With a proper installation at the locality about 3 miles north of Enid the city supply could probably be increased a net amount of 1,500,000 gallons a day. By completely utilizing the Ringwood area the supply could be increased several million gallons a day.

In 1910 the population of Enid was 13,799, and in 1920 it was 16,576—an increase of 2,777 in 10 years. Since 1920 the city has grown steadily. According to Mr. Harrison's estimate the present city water supply is about 1,800,000 gallons a day. If by fully developing the locality north of Enid the supply can be increased 1,500,000 gallons a day the aggregate supply would be 3,300,000 gallons a day. A supply of 3,300,000 gallons a day would provide for a daily per capita consumption of 110 gallons to a population of 30,000 people, which should be adequate. If the present population of Enid is 18,000 and the water supply is 1,800,000 gallons a day, the present average daily supply is 100 gallons per capita; if the present population is 23,000 the present supply is 78 gallons per capita.

If the city considers it desirable to develop the area west of Ringwood to the extent of 4,000,000 gallons a day it will have a per capita supply of 172 gallons a day for 23,000 people, or 133 gallons for 30,000 people.

POWER RESOURCES OF SNAKE RIVER BETWEEN HUNTINGTON, OREGON, AND LEWISTON, IDAHO.

By WILLIAM GLENN HOYT.

INTRODUCTION.

Thousands of people are familiar with that part of Snake River where it flows for more than 300 miles in a general westward course across the plains of southern Idaho, but few have traversed the river where it flows northward and for 200 miles forms the boundary between Idaho and Oregon and for 30 miles the boundary between Idaho and Washington. Below the mining town of Homestead, Oreg., which is the end of a branch line of the Oregon Short Line Railroad, Snake River finds its way through the mountain ranges that seem to block its way to Columbia River in a canyon which, though not so well known, so majestic, nor so kaleidoscopic in color, is in some respects worthy of comparison with the Grand Canyon of the Colorado, for at some places it is deeper and narrower than the Grand Canyon at El Tovar. The Snake, unlike the Colorado, can be reached at many points through the valleys of tributary streams, and the early prospectors no doubt thoroughly explored all parts of the canyon. To traverse the river between Homestead, Oreg., and Lewiston, Idaho, is, however, a difficult undertaking, and there are only a few records of boat journeys through the entire stretch.

It has long been known that this portion of Snake River contains large potential water powers, but until recently no detailed surveys or examinations covering the entire stretch of the river had been made to determine their location or extent. A railroad has been proposed between Homestead and Lewiston which would provide a direct connection between the railroad systems of northern and southern Idaho.

One function of the Geological Survey is to determine the possible interference between transportation routes on land and potential water-power development, and the information set forth in this paper has a bearing on that problem.

In 1920 the topographic branch of the Geological Survey made a map of the river between Huntington, Oreg., and Lewiston, Idaho. The writer was detailed to accompany the party and to report on the power and other features. The party left Huntington August 3 and arrived at Lewiston November 3. A plane-table survey was made of 187 miles of the river on a scale of 2 inches to the mile. Five dam sites were surveyed in detail, and a contour map on a scale of 2 inches to the mile was made of an area of about 30 square miles constituting the divide between Snake and Salmon rivers in T. 26 N., R. 1 E. and R. 1 W. Boise meridian, Idaho.

Maps in three colors showing the results of these surveys have recently been published by the Geological Survey. The complete set of 17 sheets (A to Q), each about 19 by 20 inches, entitled "Plan and profile of Snake River, Lewiston, Idaho, to Huntington, Oregon," may be purchased for $1.70 from the Director of the Geological Survey, Washington, D. C. Although these maps are complete in themselves, the published information relative to the area covered by the maps is so scanty that it has been thought desirable to prepare this brief summary of the power possibilities and other features of the area. This text should be read in connection with the river survey maps described above, without which a thorough understanding of this part of Snake River can not be had. Those desiring a more complete description of the power possibilities of the lower Snake may consult copies of an illustrated manuscript report, from which this text has been compiled, on file in the district offices of the Geological Survey at 615 Idaho Building, Boise, Idaho; 406 Federal Building, Tacoma, Wash., and 606 Post Office Building, Portland, Oreg.; also at 3244 Interior Department Building, Washington, D. C.

ACKNOWLEDGMENTS.

The writer is indebted to a number of colleagues in the Geological Survey, especially to J. T. Pardee and A. C. Spencer, geologists, for valuable notes on the geology of the river with special reference to dam and tunnel sites, compiled from various sources; to F. F. Henshaw, district engineer, Portland, Oreg., for data relative to surveys by the State engineer of Oregon; and to C. G. Paulsen, district engineer, Boise, Idaho, for valuable stream-flow and other data. The survey party which the writer accompanied was composed of W. R. Chenoweth, topographer and chief of party; Leigh Lint and Perry Crawford, rodmen; George Lee, boatman; and John Clagston, cook.

PHYSICAL FEATURES.[1]

Though the greater part of the Snake River drainage basin lies in Idaho, the outer edge drains parts of Washington, Oregon, Nevada, Utah, and Wyoming. The river rises near the Continental Divide in the southern part of Yellowstone National Park and flows generally south through Jackson Lake, Wyo., which is used as a storage

[1] For a description of the plains of Snake River in southern Idaho above Weiser see Russell, I. C., U. S. Geol. Survey Bull. 199 and 217.

reservoir, to a point in T. 3 S., R. 46 E. Boise meridian. At this point, which is 125 miles below its source, the river enters Idaho and turns to flow northwest 71 miles to the junction with Henrys Fork of Snake River between St. Anthony and Idaho Falls. From this junction the river flows southwest for 100 miles and then in a general west and northwest direction for 270 miles to the boundary between Oregon and Idaho, 50 miles south of Weiser. At this point the river turns north, and for about 200 miles it forms the boundary between Idaho and Oregon and for 30 miles the boundary between Idaho and Washington. At Lewiston, Idaho, it is joined by the Clearwater, and thence it flows west 120 miles to its confluence with Columbia River. The total drainage area is about 108,000 square miles, of which 68,000 square miles lies upstream from Weiser, Idaho, near which the investigations outlined in this report were begun.

Between the Oregon Short Line bridge near Huntington, Oreg., the point where the survey began, and Homestead (mile 187.8 to mile 127.0 (from Lewiston), sheets F, G, and H, Snake River survey), the river is paralleled on the west bank by the Homestead branch of the Oregon Short Line Railroad. The track is 30 to 50 feet above the water surface. This part of the river valley is fairly well settled, and small towns have grown up along the railroad. Agriculture is the principal occupation, although Homestead, the largest town, owes its size to copper mines, and the smaller town of Gypsum to gypsum deposits. The towns serve as centers for small rural communities and as feeders to the cattle and sheep country that occupies the high lands east and west of the river. The valley is wide throughout this stretch. The river flows in a plain of alluvium, which is of unknown depth and consists of unconsolidated and more or less open-textured sand and gravel, chiefly deposited in water but locally including talus. The basalt which no doubt forms the bed of the river throughout its course can be seen in a structural depression between the axes of the Seven Devils and Cuddy mountains. The total fall throughout the 60-mile stretch between Huntington and Homestead is 375 feet, or an average fall of 6.2 feet to the mile. There are 19 well-defined rapids in this stretch, but they are fairly well spread out and offer no serious trouble to small boats. Scows, if heavily loaded, would have some difficulty because of the shallow places at rapids and sand bars.

Between Homestead and the mouth of Kinney Creek (mile 127 to mile 115.6, sheet F), the valley and the river narrow gradually; there is little bench land, and the country contains few inhabitants. A wagon road on the west bank between Homestead and Ballards Landing, about 2.7 miles long, connects with the ferry at Ballards and running eastward over the mountain connects with the road to Gypsum, which follows up the valley of Indian Creek. The

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next ferry on the river is at Pittsburg Landing, 47 miles farther down. The road on the Oregon side continues downstream to a point opposite Limepoint Creek, 5 miles below Homestead. From this point a fair trail continues to a ranch at the mouth of Lynch Creek, across the river from Kinney Creek (mile 115.5, sheet F). The average fall of the river in this stretch is 7.2 feet to the mile. There are five well-defined rapids, all of which may be safely run with a small boat even though fairly well loaded. Below Homestead the columnar basalt is not noticeable near the river, the side walls changing to rocks of the older basaltic series. These older rocks are much better adapted for foundations than the more recent basalt above Homestead. The river no longer traverses an alluvial plain, and no doubt there are better opportunities to uncover bedrock, but all the rapids are caused by débris washed in by the tributaries, and consequently no estimate is made as to the probable distance of bedrock below the water surface.

Near Kinney Creek (mile 115.6, sheet F) the river enters a canyon generally known as Hell's Canyon. To one in the bottom of the canyon the size is not evident, but a study shows that in cross section the canyon is entirely comparable with any part of the Grand Canyon of the Colorado, being deeper and narrower from rim to rim than the far more famous canyon in Arizona. In the stretch below Kinney Creek the canyon is cut through a huge uplifted mass from which the Wallowa, Seven Devils, and adjoining mountains have been carved. If this cut were filled the river would find an outlet westward across the plains of southern and central Oregon to Deschutes River long before it would rise high enough to follow its present course northward. The upper 2,500 feet or more of the canyon walls consists largely of Columbian lava; the lower parts consist of the older rocks, chiefly greenstone, with smaller quantities of argillite, slate, schist, and limestone. Aside from the impressive boldness and height of the steep walls, perhaps the most striking feature of the canyon is the extreme roughness of the solid rock faces. Where not vertical the walls are in many places badly ruptured and much steeper than the angle of repose, a condition generally conducive to rock slides or avalanches. This condition would make blasting for construction especially hazardous at many places and would also tend to impose a very heavy maintenance charge on any railroad through the canyon. The river in this section narrows in places to less than 100 feet in width and appears from a distance like a small mountain stream. The average fall through Hell's Canyon is 12.8 feet to the mile. There are 12 very well-defined rapids in this stretch; those at the mouths of Kinney Creek, Squaw Creek, Buck Creek, and Thirtytwo Point Creek are especially rough, and all are dangerous to navigate at any stage of water.

Between Rush Creek and Kloptant Creek (mile 92 to mile 77, sheets D and E), the valley and river are generally wider than the section through Hell's Canyon. The rocks apparently contain minerals, as claim monuments and evidences of old workings were observed at short intervals. Benches on which ranches have been established are more numerous. The largest ranch in this stretch is the Brockman ranch, at the mouth of Temperance Creek, which is connected by means of a summit trail along the Oregon side a considerable distance back from the river with Pittsburg Bar, from which a good road extends over the divide between Salmon and Snake rivers to Whitebird, Idaho. There are six rapids in this stretch, but all of them can be easily run by small boats and during favorable stages by high-power motor boats, which occasionally run from Lewiston as far upstream as the Brockman ranch.

Between miles 77 and 74 (sheet D) the valley widens to nearly 4,000 feet at a level 300 feet above the river surface, compared to a width of 700 feet or less upstream and downstream. This is the only opening of any size in the canyon. At Pittsburg Bar or Pittsburg Landing (mile 75.6) there is a ferry that connects the cattle and sheep country with a fairly good road to Whitebird. There are several fair-sized ranches in the opening; the largest is on the Idaho side and contains tracts irrigated by water diverted from Kloptant and Kinney creeks. Until recently the raising of cattle has been the principal industry, but sheep are now being introduced. The river through this stretch has an average fall of 11 feet to the mile; the rapids, of which there are three, can be run with a small boat.

One mile downstream from Pittsburg Bar the side walls again close in, and between Pleasant Valley and High Ridge creeks (mile 74 to mile 67, sheet D) the river flows in a narrow V-shaped canyon, almost boxed. The side walls are composed of the older basaltic series, covered in part with talus slopes. The sides are steep, and vertical bluffs at short intervals make travel along either bank almost impossible. There is little bench land and few ranches. The average fall of the river is 7.8 feet to the mile. Four well-defined rapids occur in this stretch, all of which can be easily navigated.

Between High Ridge Creek and Thorn Creek (mile 67.1 to mile 60.4, sheet D) the river has a westerly course and is generally wider than above and the side walls open somewhat and are not so high. The columnar basalt is again exposed at the water's edge. There is considerable bench land, part of which is being irrigated from small tributaries. The average fall is 7.9 feet to the mile. There are four rapids, all of which may be navigated.

Between Thorn Creek and Cherry Creek (mile 60.4 to mile 46, sheets C and D), the river narrows and except for an occasional strip of bench land and flows in a canyon almost boxed and difficult of access except by boat. Imnaha River, the largest tributary from the Oregon side below the mouth of Powder River, enters the Snake 52.5 miles above Lewiston; and Salmon River, the only tributary of any size from the Idaho side below Weiser River, enters 49 miles above Lewiston. Both of these large tributaries flow in narrow canyons, that of Imnaha River being almost boxed. A short distance up Imnaha River is the Eureka mine, which is no longer being operated. A tunnel of considerable size and length has been driven into the south wall of the Imnaha Canyon, and a narrow-gage railroad, portions of which are still in place, constructed to a stamp mill on Snake River a short distance below the mouth of the Imnaha. Copper and silver were the principal products of the mine, which is the largest mine directly in the canyon below Homestead, and if good transportation facilities were available this and many other claims would probably be worked. On the bench across from the mouth of Salmon River and at one or two other places above the mouth of the Imnaha are large sheep sheds. Supplies are brought to these sheds and wool taken out by high-powered motor boats running to Lewiston. The average fall of the river in this stretch is only 8.7 feet to a mile. There are seven rapids, which with skill and good luck can be run by small boats if empty or lightly loaded, but for complete safety of food and camp equipment several short portages are necessary. The river below the mouth of Salmon River does not appear considerably larger than above, although its flow is about two-thirds greater. The canyon walls are almost without exception composed of the older basaltic series, with a few intrusions of granite. The rocks are hard and flintlike and show little surface weathering.

Between Cherry Creek and Lewiston (mile 46 to mile 0, sheets A, B, C) the canyon walls recede and become much lower and the river gradually widens to nearly 1,000 feet. Columnar basalt forms a considerable part of the side walls, although near the mouth of China Garden Creek (mile 37) granite has been quarried for building stone, and opposite the mouth of Grand Ronde River there are large deposits of limestone. Grand Ronde River enters from the Washington side at mile 29.5. Regular boat service is maintained between Lewiston and this point and during certain portions of the year is extended to Pittsburg Bar and points upstream. At the mouth of Captain John Creek there is a ferry connecting with a road to Asotin, Clarkston, and Lewiston. The average fall of the river in this 46-mile stretch is 2.7 feet to the mile. There are 10 well-defined rapids, all of which are spread out and can be easily navigated. At Lewiston Clearwater River enters and the Snake turns westward to the Columbia.

EXPLORATION.

Lewis and Clark, the first white men known to have seen Snake River, reached the confluence of Clearwater and Snake rivers October 10, 1805, and Columbia River six days later. In May of the following year, on their return, they retraversed the Snake as far as Lewiston and thence went eastward along the Clearwater and tributaries. In 1811 two detachments of the Astor party, under the leadership of Wilson Price Hunt and Ramsay Crooks, having left their horses at what is now St. Anthony and lost their boats in the rapids of the Snake near the present city of Twin Falls, attempted to follow down the Snake on foot. In the vicinity of the Seven Devils, at the upper end of Hell's Canyon, they were forced to turn back in December of that year. The Hunt party, which was on the Idaho side of the river, effected a crossing near the mouth of Weiser River, and with the Crooks party, which had been following on the Oregon side, went up Burnt River and finally reached the Columbia.

Although the central Northwest as a whole has made a progressive growth, the Snake River canyon between Homestead and Lewiston, owing to its inaccessibility and lack of agricultural possibilities, remains practically the same as before the coming of the white man. Between 1880 and 1890 examinations and surveys were made by the Corps of Engineers, United States Army, to determine the feasibility of navigation on the Snake, but they reported invariably that the river was unfavorable for navigation. During May, 1895, when the river was at flood stage, Capt. W. P. Gray, of Pasco, Wash., with a crew of 13 men, ran the steamer *Norma,* a stern-wheeler 165 feet long, 35 feet wide, and 6 feet 6 inches deep, from Huntington Bridge to Lewiston. The trip was made without loss of life or the destruction of the boat, but Captain Gray's description of it would not warrant the statement that the river can be safely navigated. During 1911 engineers for the Northwestern Railroad Co., a subsidiary of the Oregon Short Line Co., made a location survey for a railroad between Homestead and Lewiston. Before completing the work the party lost the personal effects of all the men and nearly all the boats. The location stakes of this party, however, were seen at many places throughout the canyon ten years later by the writer.

Engineers, geologists, and topographers have at different times made surveys and investigations at several places along the river.

BIBLIOGRAPHY.

The publications listed on page 34 contain data relative to the history, geology, and topography of Snake River canyon. An asterisk (*) preceding the title of a Geological Survey publication indicates that the stock for free distribution has been exhausted. Many papers so marked, however, may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C.

McConnell, W. J., Early history of Idaho, The Claxton Printers, 1913.

Brosnan, C. J., History of the State of Idaho, Charles Scribner's Sons, 1918.

Chief Eng. U. S. Army Repts., 1882, 1883, 1891, 1900.

Oregon's opportunity in national preparedness, Salem, State Engineer of Oregon, 1916.

*Russell, I. C., Geology and water resources of the Snake River plains of Idaho: U. S. Geol. Survey Bull. 199, 1902.

*Russell, I. C., Notes on the geology of southwestern Idaho and southeastern Oregon: U. S. Geol. Survey Bull. 217, 1903.

*Russell, I. C., A reconnaissance in southeastern Washington: U. S. Geol. Survey Water-Supply Paper 4, 1897.

*Russell, I. C., Geology and water resources of Nez Perce County, Idaho, Parts I and II: U. S. Geol. Survey Water-Supply Papers 53 and 54, 1901.

*Russell, I. C., Preliminary report on artesian basins in southwestern Idaho and southeastern Oregon: U. S. Geol. Survey Water-Supply Paper 78, 1903.

*Profile surveys in Snake River basin, Idaho: U. S. Geol. Survey Water-Supply Paper 347, 1914.

Profile surveys along Henrys Fork, Idaho: U. S. Geol. Survey Water-Supply Paper 420, 1916.

*Lindgren, Waldemar, The gold and silver veins of Silver City, Delamar, and other mining districts in Idaho: U. S. Geol. Survey Twentieth Ann. Rept., pt. 3, pp. 65–256, 1899.

*Lindgren, Waldemar, The gold belt of the Blue Mountains of Oregon: U. S. Geol. Survey Twenty-second Ann. Rept., pt. 2, pp. 531–776, 1901.

*Lindgren, Waldemar, A geological reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho: U. S. Geol. Survey Prof. Paper 27, 1904.

*U. S. Geol. Survey Geol. Atlas, Boise folio (No. 45), 1898.

*U. S. Geol. Survey Geol. Atlas, Nampa folio (No. 103), 1904.

U. S. Geol. Survey Geol. Atlas, Silver City folio (No. 104), 1904.

Pardee, J. T., and Hewett, D. F., Geology and mineral resources of the Sumpter quadrangle: Mineral Resources of Oregon, vol. 1, No. 6, pp. 3–128, Oregon Bur. Mines and Geology, October, 1914.

Grant, U. S., and Cady, G. S., Preliminary report on the geology of the Baker district: Idem, pp. 129–161.

Swartley, A. M., Ore deposits of northeastern Oregon: Idem, vol. 1, No. 8, December, 1914.

Livingston, D. C., and Laney, F. B., The copper deposits of the Seven Devils and adjacent districts: Idaho Bur. Mines and Geology Bull. 1, 1920.

Plan and profile of Snake River, Lewiston, Idaho, to Huntington, Oreg., U. S. Geol. Survey, 1923.

Data showing flow of Snake River, collected by the Geological Survey in cooperation with State and public-utility officials, are contained in the following water-supply papers:

Year.	No.	Year.	No.	Year.	No.
1899	*38	1907–8	*252	1916	*443
1900	51	1909	272	1917	*463
1901	*66, *75	1910	292	1918	483
1902	85	1911	312	1919–20	513
1903	100	1912	*332B	1921	[a] 533
1904	135	1913	*362B	1922	[a] 553
1905	178	1914	*393	1923	[a] 573
1906	*214	1915	*413		

[a] In preparation.

CLIMATE.

As the valley of Snake lies west of the Continental Divide, it is exposed to winds from the Pacific Ocean, which contribute materially to the mildness of the climate. Local chinooks also play an important part in ameliorating winter temperatures. The extreme cold waves that occur in middle western Canada and the adjacent part of the United States are seldom felt in the basin of the Snake, which is cut off by high mountains on the east. The mean temperature between Lewiston and Weiser, Idaho, is from 50° to 55° F.; the mean summer temperature is 70° to 80°, with daily maxima of 100° to 110°. The summer temperature in the canyons, owing to their shelter from the winds and the radiated heat from the rock surface, is invariably higher than it is on the uplands. In the winter, however, owing to the influence of the water and protection from winds, the temperature is higher in the canyons than on the plains, snow lies on the ground for only a few days at a time, and complete ice cover rarely forms. The summer days are hot, but owing to the extreme dryness the heat is seldom oppressive. Under the prevailing clear skies radiation is rapid, and the nights are nearly always cool. Warm nights occur when the sky is clouded and radiation from the heated ground and rocks is checked. At the higher altitudes in the Seven Devils and other ranges the mean yearly temperature ranges from 36° to 40° and the peaks are flecked with snow the greater part of the year. Nearly the entire basin lies outside the path of general storms, and the valleys may be classified as arid. The mean annual precipitation is about 15 inches in the canyon, but in the mountains adjacent to the river it amounts to about 40 inches.

STUDIES OF STREAM FLOW.

The water of Snake River and its tributaries, before it reaches the power section extending downstream from Huntington, contributes largely to the welfare of southern Idaho and southeastern Oregon. Without the use of water for irrigation the plains area of this semiarid region would be almost a desert. By irrigation much of this arid land has been made into excellent farming communities, furnishing homes for thousands of people and annually producing crops worth millions of dollars. The use and control of the water for irrigation has already had a marked effect upon the regimen of the river, and as additional development takes place further changes will occur. These changes in the regimen of the river will continue as long as lands susceptible of irrigation remain in the basin and water flows in the river available for such use. Naturally it is impossible to predict with certainty the extent to which future irrigation is feasible within the Snake River basin. Owing to the combination of fertile soil, favorable climate, and accessible water, irrigation as practiced in this basin has been very successful. The science of irrigation has now been so highly developed that there is every reason to believe that eventually all lands within the basin which are susceptible of successful irrigation at a reasonable cost will be brought under cultivation. Unfortunately the unappropriated waters of Snake River are insufficient to supply all the arable lands that are susceptible of irrigation. It is estimated that tracts amounting to at least 1,500,000 acres in the basin upstream from Homestead, Oreg., are so situated that they could be irrigated if water were available. It seems apparent, therefore, that at some future time irrigation systems will be constructed which, by means of storage, will use practically the total annual flow of Snake River above Milner, Idaho, the lowest point of practical diversion other than by pumping. Many new irrigation projects, as well as extensions to old ones, have been proposed. The project that will probably be constructed first and that will have the greatest effect upon the flow of Snake River is a large storage reservoir at American Falls. In making the accompanying estimates of the probable future discharge of Snake River it has been assumed that by reason of the construction of the reservoir at or above American Falls, with the incident diversions, there will be no appreciable flow past Milner at any time of the year and that diversion for irrigation from surface tributaries of the Snake will use all the normal summer flow and on many of them the flood flow. However, owing to an unusual geologic condition existing on the plains of southern Idaho, a well-sustained flow may be expected to occur in the stretch downstream from Homestead, regardless of any future storage on or diversion from Snake River above Milner. There is practically no surface run-off from the area lying north of Snake River between Henrys Fork and Malad River, a distance of more than 250 miles. The underground run-off from this area, augmented by seepage losses from the irrigation districts adjacent to the river on the north, reaches the Snake apparently without loss in the famous groups of springs in the canyon between Twin Falls and the mouth of Malad River and amounts to a continuous inflow of more than 5,000 second-feet.

From records of flow collected at gaging stations maintained by the Geological Survey in cooperation with the States of Idaho, Oregon, and Washington and public-utility companies, the present and future flow in the Snake River canyon between Homestead and Lewiston is estimated as follows:

Estimated flow of Snake River between Homestead and Lewiston, in second-feet.

	Present.		Minimum future.[a]	
	90 per cent of time.	50 per cent of time.	90 per cent of time.	50 per cent of time.
Between Homestead and mouth of Salmon River	8,000	16,500	6,900	11,200
Between mouth of Salmon River and Lewiston	15,000	21,500	12,200	16,300

[a] Not considering increase in flow which may result below Milner on account of irrigation with water stored at American Falls or above, storage on Salmon River, or any diversions from the Salmon River basin into the Snake River basin for either power or irrigation.

During the period 1911 to 1920 the minimum daily flow and the minimum mean monthly flow of Snake River at Weiser occurred nine times during August and once during September. A minimum flow of 5,500 second-feet occurred August 28 and 29, 1915, and August 1, 1919. The minimum monthly flow was 6,060 second-feet in August, 1915. The next larger minimum monthly flow, 6,180 second-feet, occurred during August, 1919. The minimum mean flow for two consecutive months occurred in August and September, 1915, and amounted to 6,300 second-feet, and the next larger occurred in August and September, 1919, and amounted to 6,420 second-feet. The minimum mean flow for a three-month period occurred in July to September, 1915, and was 6,580 second-feet. The next larger occurred in July to September, 1919, and was 6,600 second-feet. The normal low-water period occurs without exception during the later part of the irrigation season and lasts for about three months. The total inflow between Weiser and the mouth of Salmon River during the irrigation season probably does not exceed 150 second-feet. This inflow comes principally from the basins of Powder, Burnt, and Imnaha rivers. The minimum flow of Salmon River, unlike that of the middle Snake, occurs during the winter; consequently the minimum flow of Snake River below the mouth of Salmon River is comparatively large. From a study of the flow of Snake River at Weiser, of Salmon River at Whitebird, and of Snake River as recorded by the United States Weather Bureau gage at Lewiston, it is estimated that the absolute minimum flow of Snake River below the mouth of Salmon River is about 7,000 second-feet, and that the minimum mean monthly flow is between 8,000 and 9,000 second-feet.

The earliest flood at Weiser during the period 1911 to 1920 was 58,400 second-feet and occurred March 22, 1916; the latest was 63,400 second-feet and occurred June 24, 1918; the largest was 73,800 second-feet and occurred June 15, 1912. Records collected by engineers of the Idaho Power Co. during the period 1908 to 1913 indicate that on March 3 and 4, 1910, a flow of about 130,000 second-feet occurred at the site of the Ox Bow power plant. The peak at

Weiser on this date must have been somewhat above 100,000 second-feet. This flood was due to the fact that a heavy snow cover on the basin between Weiser, Idaho, and Copperfield, Oreg., was suddenly melted by a chinook accompanied by rain. It is believed that the maximum flood at Weiser is about 150,000 second-feet. Almost without exception the maximum stage occurs on Snake River at Weiser and at Lewiston and on Salmon River at Whitebird within the same two or three day period. This coincidence is very significant, as the resulting flood in the canyon below the mouth of the Salmon must be nearly the sum of the maximum flow of the Snake above the Salmon and of the Salmon. A study of the records indicates that a flood of 300,000 second-feet may be expected in Snake River below the mouth of the Salmon.

DEVELOPED POWER.

The only developed power on the river between Weiser and Lewiston is at the Ox Bow, near Copperfield, Oreg. (developed plant No. 12HK 1 [2]). In sec. 9, T. 7 S., R. 48 E. Willamette meridian, Snake River makes a decided bend and forms a horseshoe 1,200 feet across and 3.5 miles around. At this site the Idaho Power Co. operates a plant the construction of which was begun during 1907. A concrete-lined tunnel was cut through the solid rock of the ridge. The tunnel is about 26 by 26 feet in cross section, and there are extensive concrete structures at both ends. The portal at the intake end is about 90 feet wide and 50 feet high and is equipped with motor-operated steel gates. The tunnel discharges into a concrete forebay that forms part of the power house. The hydraulic equipment consists of two 48-inch double-runner horizontal Leffel turbines, made by S. Morgan Smith, having a rated capacity of 6,200 horsepower each under the head for which they were designed. The electrical equipment consists of a Westinghouse 3,600 kilovolt-ampere horizontal-type generator driven by a 5,000-horsepower Morse chain consisting of eight chains, each 21 inches wide. The distance between the centers of the shafts is 12 feet. The head varies, but the average is probably 17 feet; the average output is about 1,800 kilowatts. The output at this plant may be increased by building a dam below the intake, thus increasing the flow through the tunnel and the head on the wheels. The feasible height of a dam at this point is limited by the railroad that cuts across the Ox Bow through a tunnel upstream from the power tunnel, at an altitude of about 45 feet above the water.

[2] Numbers are those used in the records of the Geological Survey.

UNDEVELOPED POWER.

Snake River has certain general features that make it a possible source of large blocks of power. The flow is well sustained, the gradient is steep, the cross section is comparatively narrow, and the geologic formation in the canyon would probably make good foundations for a dam of any height. On the other hand, construction would be difficult and undoubtedly expensive, for the working quarters would be cramped and material would have to be transported long distances. The river is also subject to large floods, and the problem of by-passing flood water both during construction and after the dam is completed will require very careful engineering. In developing many of the sites a railroad to transport materials will be necessary, and if the project has to bear this expense in addition to the cost of the power development the unit cost per horsepower will be high. If, however, a railroad is constructed between Homestead and Lewiston at such a height that it will not interfere with the development of water power, the construction of dams will be facilitated. High dams will probably be more feasible than low dams, but, on the other hand, if dams are built so high that flood waters can not pass with safety over the crests, tunnels or other artificial spillways will have to be constructed at great cost. No sites were found at which it would be possible to construct large rock-filled dams and divert at small expense flood waters through short tunnels across narrow necks. Even if such sites were found, the problem of making rock dams water-tight would be difficult, for comparatively little silt is carried in the water and there is little dirt on the river bottom or sides that could be moved.

As far as known there are no available records of borings to determine the depth to bedrock in the canyon. Until detailed geologic investigations and borings are made to determine depth to and character of bedrock and side walls, the sites here described should be classified as tentative.

No dam-site surveys were made in the stretch of the river paralleled by the railroad between Huntington and Homestead. In this stretch the side walls consist of more or less columnar basalt and the river flows in an alluvial plain of unknown depth. The height of any dams in this stretch would be limited by the railroad, which is 25 to 50 feet above the water surface. On account of the geologic conditions the cost of construction would be high. Three sites were found above Homestead, however, which may be worth further investigation. They are the first three of the sites described below.

In the tables showing potential power the symbols "Q90" and "Q50" indicate flow or power available 90 per cent of the time and 50 per cent of the time. The horsepower is based on an over-all efficiency of 70 per cent and a reduction of head during high-water periods.

Site 12HK 1 (mile 145.3, sheet G): In a section extending from a point between the SE. ¼ sec. 2, T. 17 N., R. 5 W. Boise meridian, Idaho, to a point in the SE. ¼ sec. 25, T. 8 S., R. 47 E. Willamette meridian, Oreg., basalt appears on both sides of the river, and this section may constitute a dam site. The altitude of low water is approximately 1,798 feet and that of the railroad about 1,834 feet. A dam having a head of 25 feet, if properly equipped with gates for handling flood flows, could probably be maintained without interference with the railroad. The width of the section at the water surface is about 370 feet and at the 1,830-foot contour about 620 feet. A 25-foot dam would back the water about 7 miles. Whether this site is feasible will depend largely upon the porosity of the columnar basalt on the Oregon side and the depth of alluvial fill over the bedrock.

Potential power at site 12HK 1.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	16,000	26,400
With ultimate use of river for irrigation	6,900	11,200	13,800	17,900

Site 12HK 2 (mile 143.3, sheet G): In a section extending from a point in sec. 36, T. 18 N., R. 5 W. Boise meridian, Idaho, to a point in sec. 19, T. 8 S., R. 48 E. Willamette meridian, Oreg., basalt occurs on both sides of the river. This section constitutes a poor site and is probably not worth further investigation. The altitude of the river at low water is about 1,783 feet, and that of the railroad is about 1,820 feet. The width of the section at the water surface is about 220 feet and at the 1,820-foot contour about 640 feet. A dam having a head of 25 feet, if properly equipped with flood gates, could be maintained without material interference with the railroad. Water would be backed upstream about 5 miles and would drown out site 12HK 1. Of the two sites 12HK 1 seems to have the better physical features.

Potential power at site 12HK 2.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	16,000	26,400
With ultimate use of river for irrigation	6,900	11,200	13,800	17,900

Site 12HK 3 (mile 135.7, sheet G): In a section extending from a point in the SE. ¼ sec. 29, T. 19 N., R. 4 W. Boise meridian, Idaho, to a point in the SE. ¼ sec. 16, T. 7 S., R. 48 E. Willamette meridian, Oreg., fairly compact basalt occurs on both sides of the river, and this section constitutes the best site observed between Huntington and the Ox Bow. The railroad passes the abutment on the Oregon side through two short tunnels. The basalt on the Idaho side seems particularly compact; on the Oregon side it is slightly seamed. The altitude of the water at low and high stages is 1,712 and 1,727 feet; that of the railroad is 1,756 feet. The width of the section at the water surface is 250 feet and at the 1,750-foot contour 430 feet. A dam 30 feet in height might be maintained without material interence with the railroad. Such a dam would back water 4 miles and would not interfere with other sites upstream.

Potential power at site 12HK 3.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	19,200	33,000
With ultimate use of river for irrigation	6,900	11,200	16,500	22,400

Site 12HK 4 (mile 123.2, sheet F): From a point in the NW. ¼ sec. 23, T. 20 N., R. 4 W. Boise meridian, Idaho, to a point in the NW. ¼ sec. 12, T. 6 S., R. 48 E. Willamette meridian, Oreg., rock crops out on both sides of the river. The rock appears to be badly seamed and fractured at the surface, and considerable would have to be removed before compact rock would be reached. The altitude of the water surface at low water is 1,620 feet; at ordinary high water, 1,635 feet; and at maximum high water, 1,650 feet. The width of the section at the water surface is 240 feet and at the 1,670-foot contour 520 feet. The head that can be developed at this site is limited by the altitude of the railroad at Homestead (about 1,680 feet) and by the tail water of the Ox Bow power plant. Water could be raised to an altitude of 1,670 feet and a head of 50 feet obtained.

Potential power at site 12HK 4.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	32,000	59,400
With ultimate use of river for irrigation	6,900	11,200	27,600	40,300

Site 12HK 5 (Nelson Creek site, mile 120.8, sheets F and J): At this site, which is on unsurveyed land 1 mile downstream from the boundary between Wallowa and Baker counties, Oreg., a survey was made on a scale of 1 inch = 200 feet, with a contour interval of 10 feet. (See map on sheet J.) The site was surveyed largely because of the narrow cross section. The side walls are but slightly fractured. On the Idaho side the rock slope breaks at about 70 feet above the water, and a grass-covered slope extends at an angle of 45° up several hundred feet to a nearly vertical rock face. The abutment on the Idaho side is apparently bedrock and not a slide, as it is apparently in many other places. The rock wall on the Oregon side extends at a uniform slope for several hundred feet. The altitude at low water is 1,607 feet; at ordinary high water, 1,622 feet; at maximum high water, about 1,630 feet. The head at the site is limited by the altitude of the railroad at Homestead and of the tailrace of the Ox Bow power plant. A head of 65 feet could be obtained without interference with either the railroad or the power plant, but such development would drown out site 12HK 4.

Potential power at site 12HK 5.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	41,600	79,200
With ultimate use of river for irrigation	6,900	11,200	35,900	53,800

Site 12HK 6 (mile 118.7, sheet F): This site lies between Spring Creek, on the Oregon side, and Eckels Gulch, on the Idaho side, and extends from a point in the SW. ¼ sec. 31, T. 21 N., R. 3 W. Boise meridian, Idaho, to a point on unsurveyed land in Oregon. Though the rock walls are badly seamed and fractured, a compact surface could be easily uncovered. The river is pooled and apparently is deep. The low-water altitude at the site is 1,595 feet. No detailed surveys were made here. The cross section ranges from 190 feet at the water surface to 430 feet at the 1,700-foot contour. Any development at this site should contemplate the full use of the river to the Ox Bow plant. A head of 75 feet can be obtained without interference with the railroad or the Ox Bow plant. Such a development would flood the valley to the 1,670-foot contour and drown out sites 12HK 4 and 12HK 5.

Potential power at site 12HK 6.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	48,000	92,400
With ultimate use of river for irrigation	6,900	11,200	41,400	62,700

Site 12HK 7 (Thirtytwo Point Creek site, mile 112.2, sheets F and J): This site extends from a point about 2,000 feet upstream from the mouth of Thirtytwo Point Creek on unsurveyed land. A survey was made of the site on a scale of 1 inch=400 feet. (See sheet J.) The side walls come fairly close together, and though they are badly seamed and fractured on the surface, a reasonable amount of excavation should uncover compact rock. The wall on the Idaho side is nearly vertical and appears more compact than the more sloping and broken Oregon wall. The altitude of low water is 1,520 feet and of high water about 1,556 feet. The water is pooled at the site by the obstruction that causes the Pine Tree Rapids, at the mouth of Thirtytwo Point Creek. The maximum head at this site is one that would flood the valley to an altitude of 1,670 feet, or a head of 150 feet. Such a development would drown out sites 12HK 4, 12HK 5, and 12HK 6, lying between this point and the Ox Bow plant.

Potential power at site 12HK 7.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	96,000	185,000
With ultimate use of river for irrigation	6,900	11,200	83,000	125,000

Site 12HK 8 (Granite Creek site, mile 101, sheet E): This site is about 2,500 feet upstream from the mouth of Granite Creek. The section extends from a point in sec. 12, T. 23 N., R. 3 W. Boise meridian, to a point in Oregon on unsurveyed land. The canyon wall on the Idaho side is massive and compact, but that on the Oregon side is broken and covered with slide rock, so that considerable excavation would be necessary to uncover a compact surface. This site was not surveyed. The cross section increases from 200 feet at the water surface to 1,000 feet at the 1,700-foot contour. The type of development will depend upon the head desired, which will depend in turn upon the cost of one high-head development as compared with two or more low-head developments. For the purpose of this report a high-head development is considered. The maximum head possible at the site without interference with the Ox Bow plant is 280 feet, which would drown out sites 12HK 4, 12HK 5, 12HK 6, and 12HK 7. The fall between sites 12HK 7 and this site is 130 feet, which should be the minimum head utilized.

Potential power at site 12HK 8, with a head of 280 feet.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	179,000	356,000
With ultimate use of river for irrigation	6,900	11,200	154,000	242,000

Site 12HK 9 (mile 97.2, sheet E): This site is 6,000 feet upstream from the mouth of Saddle Creek and extends from a point in sec. 31, T. 24 N., R. 2 W. Boise meridian, Idaho, to a point on unsurveyed land in Oregon. The abutment on the Idaho side is a rock point about 175 feet high with a saddle about 140 feet high, which may be a slip and not bedrock. It will be necessary to make borings or geologic examinations to determine whether the Idaho side wall will provide satisfactory abutments. The wall on the Oregon side is little fractured. The altitude of low water at this site is 1,343 feet. No survey was made of the site. The cross section ranges from 275 feet at low water to 1,160 feet at the 1,700-foot contour. Any development at this site would drown out site 12HK 8, 4 miles upstream. Development to a head of 325 feet, backing the water to the Ox Bow plant, is assumed to be the most feasible, and the following estimates are based on this head.

Potential power at site 12HK 9, with a head of 325 feet.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	208,000	415,000
With ultimate use of river for irrigation	6,900	11,200	180,000	280,000

Site 12HK 10 (Squaw Creek site, mile 95.7, sheets E and J): This site extends from a point in sec. 20, T. 24 N., R. 2 W. Boise meridian, Idaho, to a point on the Oregon side in unsurveyed land. It is at the head of a decided rapid, which may be caused by bedrock rather than by débris washed in by side drainage, and if this is true the site is worthy of special consideration, as it is the only rapid observed between Huntington and Lewiston where bedrock may be close to the water surface. This site has the further advantage that one-half the channel is out of water at low stages, thus facilitating the placing of foundations. The side walls, though seamed, are not openly fractured. The altitude of the water at low and medium stages is 1,320 and 1,352 feet. A survey was made of the site on a scale of 1 inch=400 feet. (See sheet J.) A head of 350 feet would flood the valley to the Ox Bow plant and drown out sites 12HK 4 to 12HK 9, inclusive.

Potential power at site 12HK 10, with a head of 350 feet.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	224,000	450,000
With ultimate use of river for irrigation	6,900	11,200	193,000	305,000

Site 12HK 11 (Hominy Creek site, mile 83.5, sheet E). This site is 1,200 feet upstream from the mouth of Salt Creek and extends from a point in sec. 36, T. 26 N., R. 2 W. Boise meridian, Idaho, to a point on the Oregon side on unsurveyed land. At this locality the river makes a sharp bend to the west and back again. Although the section is wide and the rock on the Oregon side is badly broken up on the surface, it is possible that an earth and rock-filled dam could be constructed in the bend and flood water taken care of through tunnels driven about 2,000 feet through the solid rock point. The altitude of the water surface is about 1,197 feet; width at water surface, 600 feet; width at 1,700-foot contour, about 2,500 feet. A dam 475 feet high would back water to the Ox Bow plant.

Potential power at site 12HK 11.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q50	Q50
With present flow	8,000	16,500	304,000	608,000
With ultimate use of river for irrigation	6,900	11,200	262,000	412,000

Site 12HK 12 (Corral Creek site, mile 77.4, sheets D and J): A dike of gneissoid granite about 20 feet thick cuts through the older rocks at a point about 400 feet upstream from the line between secs. 4 and 9, T. 26 N., R. 1 W. Boise meridian, Idaho, and extends to a point in sec. 33, T. 2 N., R. 51 E. Willamette meridian, Oreg. The canyon walls on both sides rise nearly vertically a thousand feet or more above the surface of the water. The rock on both sides is fairly free from surface fractures, and it is believed that a very small amount of excavation would disclose bedrock that would be impervious under any head. A special survey of this site was made on a scale of 1 inch=400 feet. (See sheet J.) The altitude of the water surface is 1,145 feet. The width of cross section ranges from 300 feet at low water to 1,400 feet at the 1,700-foot contour. The size of development at this site may depend somewhat upon the scheme for developing power by means of a tunnel diverting water from Salmon River. (See power scheme 12JJ 1, p. 48.) If this tunnel is constructed without a diversion dam in Salmon River and the diverted water is used to augment the flow of the Snake, the altitude of the top of the dam would be about 1,586 feet, or 440 feet above low water. Such a development would leave about 80 feet of undeveloped head below the Ox Bow plant, which could be developed by means of site 12HK 5 or 12HK 6. If the water from Salmon River is diverted by means of a diversion dam and used to increase the flow of the Snake, the site could be developed to the 1,670-foot contour, creating a head of 540 feet. If the Salmon River tunnel project contemplates the direct diversion into water wheels on the Snake, the site may be developed up to a 540-foot head, provided the tailrace from the tunnel project is downstream from the Corral Creek site. The estimates of potential horsepower are based on the full development to a head of 540 feet without reference to the Salmon diversion scheme.

Potential power at site 12HK 12.

	Flow in second-feet.		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	345,000	700,000
With ultimate use of river for irrigation	6,900	11,200	298,000	475,000

Site 12HK 13 (Imnaha River site, mile 52.7, sheet C): A special dam-site survey was made by engineers of the State of Oregon [3] from a point about 700 feet upstream from the mouth of Imnaha River, about on the line between sec. 25, T. 29 N., R. 4 W., and sec. 30, T. 29 N., R. 3 W., to a point in sec. 24, T. 4 N., R. 48 E. Willamette meridian, Oreg. The altitude of the water surface is 953 feet. The length of the dam at the water surface is 180 feet; at the 1,200-foot contour, about 943 feet. Detailed surveys and careful engineering investigation might show that it would be possible to discharge flood water into Imnaha River canyon near its mouth, or to use an overflow dam and place the power house in Imnaha Canyon. Development at this site should not be permitted to drown out the Corral Creek site (12HK 12); consequently the head is limited to about 190 feet.

Potential power at site 12HK 13, with a head of 190 feet.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	122,000	238,000
With ultimate use of river for irrigation	6,900	11,200	105,000	161,000

Site 12HN 1 (Mountain Sheep site, mile 50.7, sheets C and J): A special dam-site survey was made from a point immediately upstream from Mountain Sheep Creek, in sec. 23, T. 29 N., R. 4 W. Boise meridian, Idaho, to a point in sec. 11, T. 4 N., R. 48 E. Willamette meridian, Oreg. (See sheet J.) This section is typical of many sites from the mouth of Salmon River as far downstream as the mouth of Cottonwood Creek, in sec. 18, T. 30 N., R. 4 W. The rock walls

[3] Oregon's opportunity in national preparedness, State Engineer of Oregon, 1916.

have no open fractures and should withstand any pressure. It is possible that a better site might be found immediately above the mouth of Salmon River, into which flood water could be discharged through tunnels. Development in this stretch of the river would drown out the Imnaha site (12HK 13) but should not drown out the Corral Creek site (12HK 12). Consequently the head is limited to about 220 feet.

Potential power at site 12HN 1, with a head of 220 feet.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	8,000	16,500	140,000	277,000
With ultimate use of river for irrigation	6,900	11,200	121,000	187,000

Site 12HN 2 (Coon Hollow site, mile 41.5, sheet C): A dam-site survey has been made by the Engineering Department of the State of Oregon[4] at a section immediately below Coon Hollow, extending from a point in sec. 18, T. 30 N., R. 4 W. Boise meridian, Idaho, to a point in Oregon on unsurveyed land. It is not believed to be better adapted for power development than many other sites below the mouth of Salmon River but probably was chosen because it marks the lower end of the narrow portion of the canyon. The rock at this site is of the older basaltic series and should hold against any pressure. The altitude of the water surface at low water and at extreme flood stage is about 872 and 920 feet. The width of the cross section ranges from 320 feet at the water surface to 760 feet at 1,100-foot contour. This site will probably be developed with a high dam, and if so, provision should be made for using the entire fall between the site and the Corral Creek site (12HK 12). If this method of development is followed a head of 260 feet can be obtained. Such a dam would back water up Salmon River to sec. 34, T. 31 N., R. 2 W. Boise meridian, Idaho.

Potential power at site 12HN 2, with a head of 260 feet.

	Flow (second-feet).		Horsepower.	
	Q90	Q50	Q90	Q50
With present flow	15,000	21,500	312,000	430,000
With ultimate use of river for irrigation	12,200	16,300	254,000	326,000

Salmon-Snake diversion scheme: In T. 26 N., Rs. 1 E. and 1 W. Boise meridian, Idaho, Snake and Salmon rivers are less than 8

[4] Oregon's opportunity in national preparedness, State Engineer of Oregon, 1916.

miles apart. The altitude of Salmon River is 465 feet higher than that of the Snake, and this head could be used for power development by driving a tunnel through the divide. During the season of 1920, in connection with the Snake River surveys, a survey of this divide was made on a scale of 2 inches = 1 mile. (See sheet I.)

The mountain slope [5] on the east side of the divide is almost completely mantled by angular rock fragments, so that bedrock can not be observed. The material is largely granitic. Observations along Salmon River and the presence of greenstone in the loose material indicate that the rocks on the Salmon side of the divide consist of greenstone intricately and irregularly intruded by fine-grained granite, and a tunnel would probably encounter these two kinds of rock alternately. On the Snake River side of the divide greenstone is thought to predominate with a few dikes of granite. The most suitable place for the outlet of a tunnel from Salmon River would be in either sec. 4 or sec. 9, T. 26 N., R. 1 W.. where the rock is largely greenstone with some intrusive granite.

During 1921 detailed surveys were made of sites for possible diversion dams at the mouth of Poodle Dog Creek (12JJ 1), in secs. 22 and 23, T. 26 N., R. 1 E., and at the mouth of Rhett Creek (12JJ 2), in sec. 2, T. 26 N., R. 1 E., and sec. 35, T. 27 N., R. 1 E.[6]

It is believed that the most feasible location for a tunnel would be between the mouth of Poodle Dog Creek on Salmon River and Corral Creek on Snake River. At the Poodle Dog site it would be possible either to construct a diversion dam about 1,000 feet above the mouth of Poodle Dog Creek and extend a canal or pipe line 1,300 feet long to the heading of the proposed tunnel, 300 feet below Poodle Dog Creek, or to construct a diversion dam below the tunnel heading and divert directly into the tunnel.

At the upper site the altitude of the water surface is 1,599 feet;[7] width, 302 feet. The altitude of the proposed headwater at this site is 1,692 feet, and the width 510 feet. At the lower site the altitude of the water surface is 1,595 feet; width, 344 feet. The altitude of the proposed headwater at this site is 1,692 feet, and the width 542 feet.

The next most feasible location for a diversion dam is immediately below Rhett Creek (12JJ 2). Salmon River at this point is paralleled by a new north-south State highway, which has been blasted out of solid rock on the right bank, at a height of about 45 feet above the water surface. The altitude of the water surface is 1,550 feet;

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[5] From observations by A. C. Spencer, of the U. S. Geological Survey.

[6] Maps of dam sites on Salmon River are contained in a manuscript report entitled "Water-power resources of Salmon River," by W. G. Hoyt, copies of which are open for public inspection at the offices of the Geological Survey, Interior Department Building, Washington, D. C., and at 615 Idaho Building, Boise, Idaho.

[7] Corrected to correspond to sea level datum. Plan and profile maps of Salmon River as published in Water-Supply Paper 347 and included in manuscript reports are not based on sea level datum.

width, 311 feet. A diversion dam to raise the water to the 1,692-foot contour, the same as proposed for the diversion dam at Poodle Dog Creek, would contain nearly twice as much yardage as that at the Poodle Dog Creek site, besides flooding more of the highway; for this reason the estimate of potential power was based on the tunnel scheme with the tunnel heading at the Poodle Dog site.

The altitude of Salmon River is 1,600 feet (sea level datum); of Snake River, 1,145 feet; theoretical head, 465 feet. The horizontal distance at the 1,600-foot contour is 7.38 miles (39,000 feet). The following schemes of development are possible:

1. A low-head diversion dam in Salmon River without appreciably raising the water surface, a tunnel to Snake River, and a power house at the outlet of the tunnel.

2. A high diversion dam in Salmon River, a tunnel, and a power house on the Snake.

3 and 4. Either scheme 1 or scheme 2 with a dam in Snake River at Corral Creek raising the headwater to the altitude of the tunnel outlet, discharging the water diverted from Salmon River into the pond, and utilizing the flow of the Snake and the Salmon in one power house.

It is assumed that the tunnel should be designed to carry the flow available in Salmon River for 50 per cent of the time, or 5,300 second-feet. The horsepower that could be generated under the various schemes is set forth below:

Scheme 1. Low diversion dam and 39,000-foot tunnel:	
Altitude of low water in Salmon River........feet..	1, 600
Head loss in tunnel and diversion works......do...	25
Altitude of low water in Snake River.........do...	1, 145
Head.........do...	430
Flow 90 per cent of the time..........second-feet..	3, 800
Flow 50 per cent of the time..........do...	5, 300
Horsepower 90 per cent of the time..........	130, 000
Horsepower 50 per cent of the time..........	183, 000
Scheme 2. 100-foot diversion dam in Salmon River:	
Head..........feet..	530
Horsepower 90 per cent of the time..........	161, 000
Horsepower 50 per cent of the time..........	225, 000
Scheme 3. Low diversion dam on Salmon River, dam on Snake River creating head of 430 feet, combined flow:	
Flow 90 per cent of the time..........second-feet..	15, 000
Flow 50 per cent of the time..........do...	21, 500
Horsepower 90 per cent of the time..........	516, 000
Horsepower 50 per cent of the time..........	730, 000
Scheme 4. Diversion dam on Salmon River and dam on Snake River, creating a head of 530 feet, based on continual flow of Snake and Salmon rivers:	
Horsepower 90 per cent of the time..........	636, 000
Horsepower 50 per cent of the time..........	910, 000

The diversion of the water of Salmon River into Snake River would entirely destroy the power value of five excellent power sites on the Salmon between Whitebird and the mouth, at which 176,600 horsepower could be developed for 90 per cent of the time and 247,800 horsepower for 50 per cent of the time. On the assumption of a gradual growth of a market for power, the lower sites on Salmon River have characteristics that would seem to warrant their construction first. If, however, there should arise a market for a block of power exceeding 300,000 horsepower, the demand might be more cheaply met by the tunnel scheme than by the construction of a series of dams and power houses.

The diversion of water would very materially lower the cost of highway or railroad construction in the Salmon Valley below Whitebird, and the drying up of the channel for the greater part of the year would allow placer mining in a stretch of the river that is undoubtedly rich with gold.

If a market ever exists for over 600,000 continuous horsepower it could be met as described by the construction of the tunnel in connection with the full development of the Corral Creek site on Snake River (12HK 2), which would make possible the development, under one roof, of 636,000 horsepower for 90 per cent of the time and 910,000 horsepower for 50 per cent of the time.

The following table summarizes the estimates above given:

Estimates of power at undeveloped power sites on Snake River between Huntington, Oreg., and Lewiston, Idaho.

[Based on static head and over-all plant efficiency of 70 per cent.]

Site.	Distance upstream from Lewiston (miles).	Maximum head (feet).	With existing flow.				With regulated flow.			
			Discharge.		Horsepower.[a]		Discharge.		Horsepower.[a]	
			Q90	Q50	Q90	Q50	Q90	Q50	Q90	Q50
12HK 1	145.3	25	8,000	16,500	16,000	26,400	6,900	11,200	13,800	17,900
12HK 2	143.3	25	8,000	16,500	16,000	26,400	6,900	11,200	13,800	17,900
12HK 3	135.7	30	8,000	16,500	19,200	33,000	6,900	11,200	16,500	22,400
12HK 4	123.2	50	8,000	16,500	32,000	59,400	6,900	11,200	27,600	40,300
12HK 5	120.8	65	8,000	16,500	41,600	79,200	6,900	11,200	35,900	53,800
12HK 6	118.7	75	8,000	16,500	48,000	92,400	6,900	11,200	41,400	62,700
12HK 7	112.2	150	8,000	16,500	96,000	185,000	6,900	11,200	83,000	125,000
12HK 8	101.0	280	8,000	16,500	179,000	356,000	6,900	11,200	154,000	242,000
12HK 9	97.2	325	8,000	16,500	208,000	415,000	6,900	11,200	180,000	280,000
12HK 10	95.7	350	8,000	16,500	224,000	450,000	6,900	11,200	193,000	305,000
12HK 11	83.5	475	8,000	16,500	304,000	608,000	6,900	11,200	262,000	412,000
12HK 12	77.4	540	8,000	16,500	345,000	700,000	6,900	11,200	298,000	475,000
12HK 13	52.7	190	8,000	16,500	122,000	238,000	6,900	11,200	105,000	161,000
12HN 1	50.7	220	8,000	16,500	140,000	277,000	6,900	11,200	121,000	187,000
12HN 2	41.5	260	15,000	21,500	312,000	430,000	12,200	16,300	254,000	326,000
Salmon-Snake tunnel	77.4	530	3,800	5,300	161,000	225,000	3,800	5,300	161,000	225,000
					861,000	1,430,000			750,000	1,080,000

[a] Equivalent to 0.08 times the head times the discharge.

NOTE.—Total includes only those sites which will utilize full fall of river, namely, sites 12HK 1, one-half of 12HK 2, 12HK 3, 12HK 12, 12HN 2, and Salmon-Snake tunnel site with a 100-foot diversion dam in Salmon River.

The industrial development of the Northwest during the next few decades will no doubt be enormously increased. To keep pace with the demands for additional power, sites will have to be developed, and the sites at which power can be developed and delivered to the market most cheaply will naturally be developed first. There are sites on Columbia and Deschutes rivers at which larger blocks of power could be developed and which lie nearer the present market on the coast than those on the Snake. Near the Spokane market are sites on Clark Fork and Kootenai river. The power demands of Montana can possibly be met for years by development on Flathead River, and the upper Snake will be used to meet demands of southern Idaho. All these sites are nearer present markets than those on the lower section of Snake River between Homestead and Lewiston, and, other things being equal, they will probably be developed first. If, however, a new market should be made, or it is found that power can be developed and delivered from the sites on the Snake at a lower cost than from the other sites, their early development will naturally follow.

BASE EXCHANGE IN GROUND WATER BY SILICATES AS ILLUSTRATED IN MONTANA.

By B. Coleman Renick.

INTRODUCTION.

Changes in the chemical character of ground water with increase in depth have received considerable attention from students of ore deposits in connection with investigations of enrichment. These investigations have had to do mostly with reactions involving the heavy metals and their derivatives. The brines from deep levels in mines and oil fields have also been studied by numerous investigators.

In field studies of the geology and ground-water conditions in Rosebud County, Mont., which is in the Great Plains province (fig. 6), the writer encountered ground waters which appeared to show evidences of changes taking place in the ground different from those considered in various types of ore enrichment or in deep brines. All the samples discussed in this paper came from depths less than 600 feet.

The rocks of the Colorado and Montana groups (Upper Cretaceous) and the Lance (Tertiary?) and Fort Union (Tertiary) formations crop out in Rosebud County, and samples were obtained from all these formations, but the statements in succeeding paragraphs are made on the basis of data obtained from the Lance and Fort Union, unless otherwise specified, as these formations are the only aquifers that yield potable water of good quality over any considerable area, and as a result more samples were collected from these formations than from the others. The waters from the underlying Upper Cretaceous deposits are with local exceptions more highly mineralized, and many of them are not potable.

The conclusions contained in this paper were presented at the New York meeting of the Society of Economic Geologists May 24, 1924.

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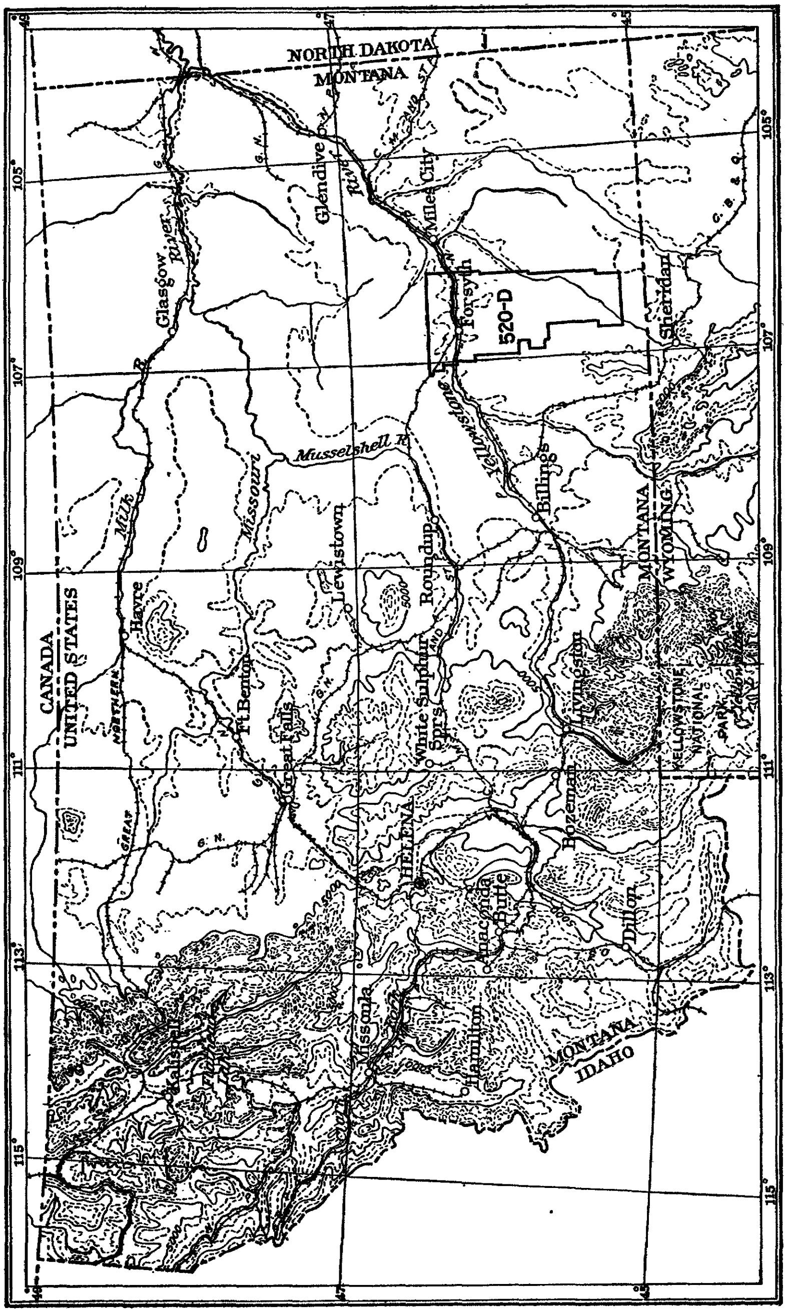

FIGURE 6.—Topographic index map of Montana. Contour interval 1,000 feet.

Collins, and D. F. Hewett. Special acknowledgments are due to H. B. Riffenburg for analyses of the water samples; to Clarence S. Ross, who has offered helpful suggestions and assistance in the petrologic determinations and who has kindly prepared the section of this paper which appears under his name; and to C. E. Dobbin and N. W. Bass for cooperation and courtesies extended in the course of the field work.

GEOLOGY.

For detailed geologic descriptions the reader is referred to the work of Bowen[1] in adjacent regions for the Upper Cretaceous rocks, and of Rogers and Lee[2] for the Lance and Fort-Union formations. Thom and Dobbin[3] in a recent paper have discussed in detail the stratigraphic correlations in this and adjacent regions, and a report by Dobbin and Bass[4] embracing a portion of southern Rosebud County, confined for the most part to an area of Lance and Fort Union beds, is being prepared. A detailed report on the geology and ground-water conditions in central and southern Rosebud County is also in preparation.[5] Only the most essential features of the geology are mentioned in the following paragraphs. The petrologic descriptions of the Lance and Fort Union formations are, however, based on thin sections cut from samples collected by the writer. The samples consisted of sandstone and sandy shale, because most of the material in the interbedded shale in these formations is so fine textured that in general individual mineral grains can not be identified, but in some places coarser mineral fragments could be identified within the fine-grained matrix of the shale. The samples were cut from outcrops and therefore presumably contain more calcite and secondary minerals than would be found in material from drill cuttings. No samples of drill cuttings could be obtained.

LANCE FORMATION.

The Lance formation is of fresh-water origin and is made up of two members.[6] The lower member, known as the Hell Creek member, averages 675 feet in thickness and is made up of gray and buff

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[1] 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, pp. 11–21, 1919.

[2] Rogers, G. S., and Lee, Wallace, Geology of the Tullock Creek coal field, Mont: U. S. Geol. Survey Bull. 749, 1923.

[3] 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. — (in press).

[4] Dobbin, C. E., and Bass, N. W., Geology of the Forsyth coal field, Rosebud, Treasure, and Big Horn Counties, Mont.: U. S. Geol. Survey Bull. — (in preparation).

[5] Renick, B. C., Geology and ground-water resources of central and southern Rosebud County, Mont.: U. S. Geol. Survey Water-Supply Paper — (in preparation).

[6] Rogers, G. S., and Lee, Wallace, Geology of the Tullock Creek coal field, Mont.: U. S. Geol. Survey Bull. 749, p. 19, 1923. Dobbin, C. E., and Bass, N. W., op. cit.

sandstone and gray shale; in places the shale is calcareous. Thin seams of carbonaceous material are present locally. With the exception of the heavy sandstone at the base of this member, which is especially persistent and is believed to be in part the equivalent of the Lennep[7] and Fox Hills[8] sandstones, most of the sandstones in the Hell Creek member are lenticular and locally grade into shale.

The upper part of the Lance formation, which is known as the Tullock member, averages 250 feet in thickness in this region and is made up of yellow sandstone and shale, the shale in places somewhat calcareous. Unlike the Hell Creek member, the Tullock member contains a number of thin beds of coal and carbonaceous shale. A persistent sandstone, which gives rise to a rim rock throughout the region, defines the top of the Tullock member.

Thin sections[9] from samples of so-called sandstone from the Lance formation show that it consists predominantly of angular and subangular grains of quartz and fragments of volcanic rock. Many of the rock fragments contain a glassy groundmass, which is considerably altered. (See Pl. III.) The quartz has been strained, undoubtedly before deposition, and appears biaxial, being therefore extremely difficult to distinguish from the orthoclase that is also present in these rocks. In thin section the quartz is seen to be generally more angular than the orthoclase, which is more altered than the quartz. Examination of the crushed fragments in index of refraction liquids shows that the orthoclase never exceeds 3 per cent of the sample and averages about 1 per cent. In many slides a chertlike material, which may represent altered rock grains of sedimentary (?) origin, is conspicuous (Pl. III, *B*). All slides of the Lance rocks also contain a few grains of plagioclase (Pl. III, *B*), muscovite, biotite, and detrital calcite. Glauconite grains were also identified. An examination by heavy solution of one sample of sandstone showed that the Lance rocks also contain garnet, pink and white zircon, and a pyroxene, probably augite.

The freshest material in the rock fragments consists of quartz and feldspar in a matrix of secondary material which is mostly leverrierite and an allied mineral. Leverrierite and the allied species are discussed by Clarence S. Ross on page 60. All thin sections contained some leverrierite, and in some sections as much as 10 per cent

[7] Calvert, W. R., Geology of certain lignite fields in eastern Montana: U. S. Geol. Survey Bull. 471, pp. 187–201, 1910.

[8] Stone, R. W., and Calvert, W. R., Stratigraphic relations of the Livingston formation, Mont.: Econ. Geology, vol. 5, pp. 551–557, 652–669, 741–764, 1910.

[9] All the samples were first treated with bakelite in order to make them sufficiently coherent for grinding. Bakelite has a high index of refraction and appears isotropic through crossed nicols, as can be seen by observing the interstitial material in the thin sections shown in Plates III and IV. This method of hardening incoherent rock material with bakelite before grinding was devised by Clarence S. Ross and is described by him in a recent paper (A method of preparing thin sections of friable rock: Am. Jour. Sci., 5th ser., vol. 7, pp. 483–485, 1924).

was observed. Secondary claylike material and calcite are present in all slides, and chlorite was also noted. These secondary minerals are derived from the alteration of the feldspars and rock fragments. It is problematical just how much secondary material would be shown in thin sections made from drill cuttings.

FORT UNION FORMATION.

The Fort Union formation is divisible into two distinct lithologic units, a lower so-called somber member, known as the Lebo andesitic [10] or shale[11] member, which averages 175 feet in thickness, and an upper light-colored coal-bearing member approximating 1,600 feet in thickness, which is known as the Tongue River member.[12] The preponderance of dark-gray and drab shale in the Lebo member makes it easy to distinguish in this region from the light-colored Lance below and the light-colored overlying beds of the Tongue River member. In general, the materials in the Tongue River member are better assorted than those of the Lebo member and the Lance formation.

The Lebo in this region, though made up largely of shale with numerous iron-stained calcareous and siliceous concretionary bands, everywhere contains well-developed sandstone lenses. The shale portions of this member are too fine textured for the identification of individual grains, but in the sandstone lenses quartz, rock fragments with glassy groundmass, chertlike fragments, orthoclase, plagioclase, calcite, chlorite, claylike material, and leverrierite and its allied iron mineral were found in approximately the same proportions and the same relations as in the Lance and the Tongue River member. (See Pl. IV, *A*.) Because of similar relations in the underlying and overlying beds it is somewhat doubtful whether these beds can be correlated by the petrologic methods suggested by Rogers.[13]

Five thin sections of the Lebo member were examined. The samples from which the sections were cut came from widely distributed regions and were selected as representative of the Lebo member in Rosebud County. Because of the fact that plagioclase is not more abundant in the Lebo member, as shown in these thin sections, than in the underlying Lance formation or in the overlying beds of the

[10] Stone, R. W., and Calvert, W. R., Stratigraphic relations of the Livingstone formation of Montana: Econ. Geology, vol. 5, pp. 551–557, 652–669, 741–764, 1910. Woolsey, L. H., Richards, R. W., and Lupton, C. T., The Bull Mountain coal field, Musselshell and Yellowstone counties, Mont.: U. S. Geol. Survey Bull. 647, pp. 24–27, 1917.

[11] Rogers, G. S., The Little Sheep Mountain coal field, Dawson, Custer, and Rosebud counties, Mont.: U. S. Geol. Survey Bull. 531, pp. 159–172, 1913.

[12] Thom, W. T., and Dobbin, C. E., Stratigraphy of Cretaceous-Eocene transition beds in eastern Montana and the Dakotas: Geol. Soc. America Bull., vol. 35, pp. — (in press). Dobbin, C. E., and Bass, N. W., op. cit.

[13] Rogers, G. S., A study in the petrology of sedimentary rocks: Jour. Geology, vol. 21, pp. 715–727, 1913.

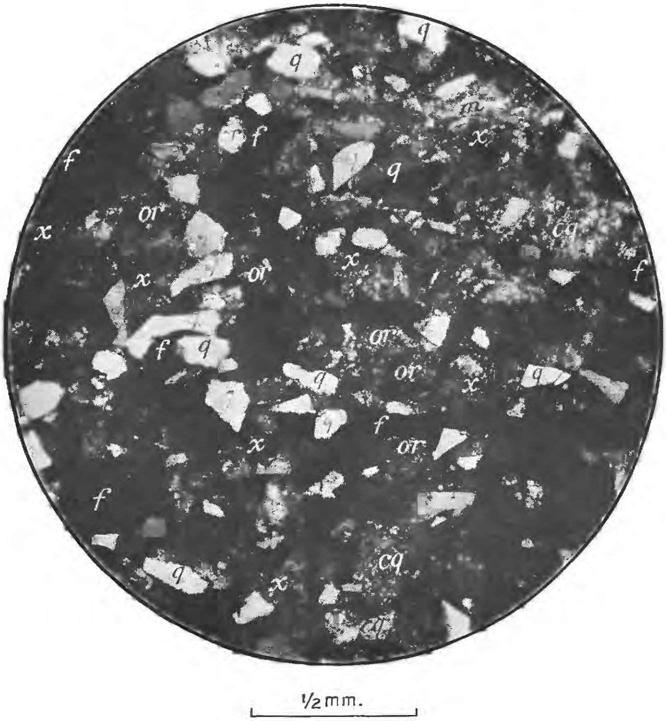
PLATE III.

PHOTOMICROGRAPHS OF THIN SECTIONS SHOWING TEXTURE AND MINERALS OF ROCKS FROM LANCE FORMATION.

A, Sandstone from NE. ¼ sec. 7, T. 5 N., R. 41 E., nicols crossed.

B, Basal sandstone from NW. ¼ sec. 26, T. 6 N., R. 39 E., showing grains of altered igneous rock containing phenocrysts (also altered), nicols crossed.

cq, Chertlike material, in part possibly secondary, in part probably altered sedimentary rock grains; *f*, impure iron oxide, mostly limonite; *l*, leverrierite; *m*, colorless mica; *or*, altered mineral grains, probably orthoclase; *pl*, plagioclase; *q*, quartz; *x*, impure claylike interstitial material, in some places containing small amounts of disseminated calcite, probably in considerable part leverrierite.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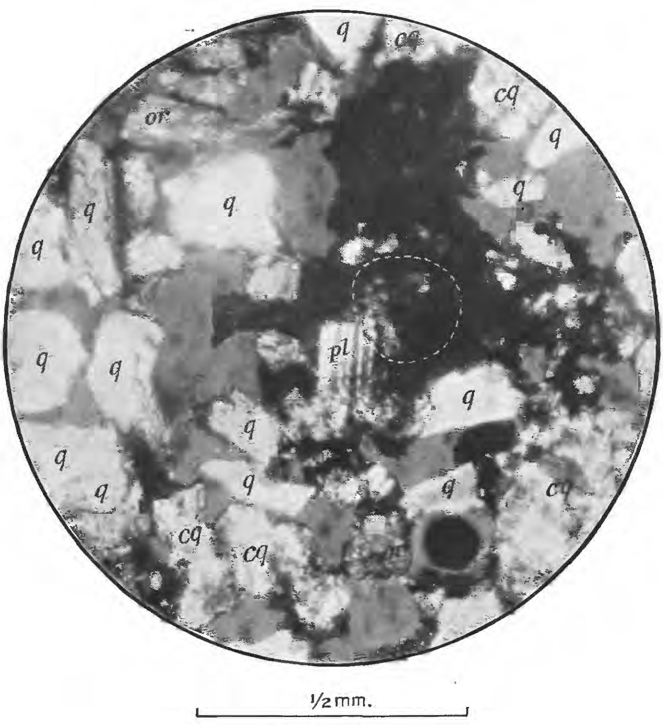
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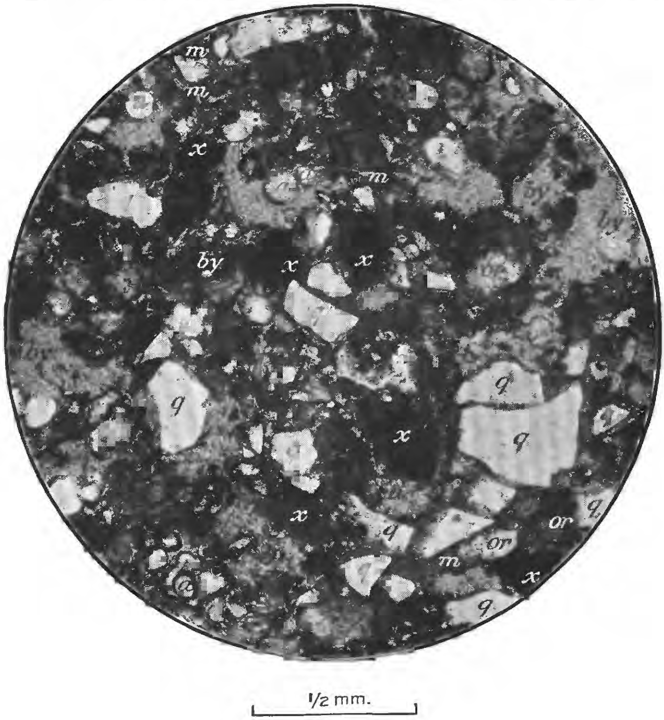

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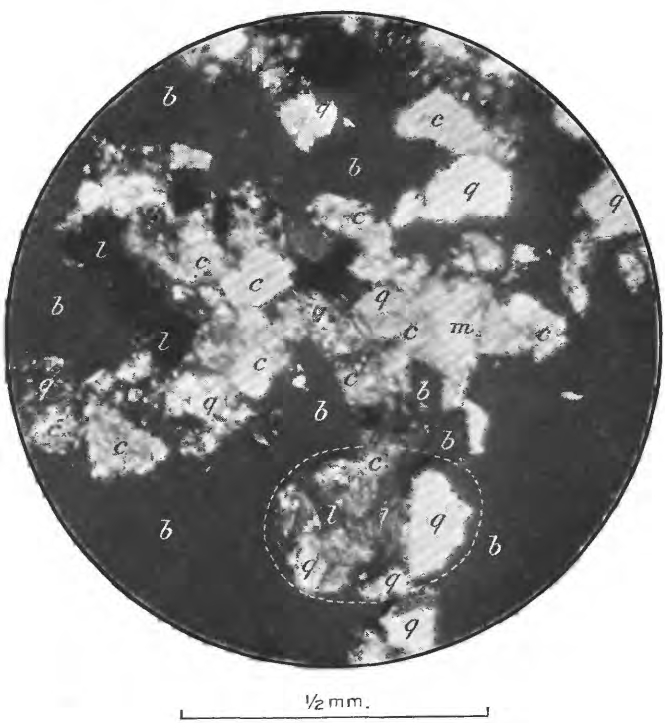

B.

PLATE IV.

PHOTOMICROGRAPHS OF THIN SECTIONS SHOWING THE TEXTURE AND MINERALS OF THE ROCKS IN THE FORT UNION FORMATION.

A, Lebo shale member, sandy facies, from NW. ¼ sec. 34, T. 8 N., R. 42 E.; one nicol.

B, Sandstone near base of lower light-colored member in NW. ¼ sec. 33, T. 2 N., R. 43 E.; nicols crossed. Section shows grains of altered igneous rock containing plates of leverrierite.

a, Air hole; *b*, bakelite mounting; *by*, claylike material stained with bakelite; *c*, calcite; *cq*, chertlike material, in part possibly secondary, in part probably altered sedimentary rock grains; *l*, leverrierite; *m*, colorless mica; *or*, altered mineral grains, probably orthoclase; *q*, quartz; *x*, impure claylike interstitial material, in some places containing small amounts of disseminated calcite, probably in considerable part leverrierite.

Fort Union, where it always amounts to less than 1 per cent, the descriptive term "andesitic" for this member is not applicable in Rosebud County.

The samples of waters from the Tongue River member discussed on page 62 were obtained within the lower 500 feet of this member. In many places the coals of the Tongue River member have been burned along the outcrop. This burning oxidizes the iron present and fuses and slags the overlying sandstone and shale, giving rise to beds of different hues of red rock above the ash of the burned coal.

Like the Lance formation, the Tongue River member of the Fort Union is made up of angular grains, predominantly strained quartz, rock fragments of igneous origin, and cherty quartzose fragments of probable sedimentary origin. The grains of igneous origin contain much glass, which has been highly altered. Orthoclase, plagioclase, muscovite, biotite, claylike material, and chlorite are also present. In general, sections of these rocks contain considerably more secondary calcite than those from the Lance beds. Leverrierite[14] and its allied iron mineral (see p. 61), both secondary after the glassy material, are present in considerable amounts but on the whole are not so abundant as in the Lance formation. Most of the feldspar, especially the orthoclase, is greatly altered.

Rogers[15] doubtless included leverrierite and its associated iron-bearing mineral when in describing the petrologic character of some Fort Union rocks in southeastern Montana he said: "There is usually much fine clayey interstitial material, commonly iron stained."

LEVERRIERITE AND RELATED MINERALS.

By Clarence S. Ross.

In a recent description of leverrierite, by Larsen and Wherry,[16] the following statements regarding the chemical and optical properties of this group of minerals are made:

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[14] Since this paper was written an article by Pierre Termier on the presence of leverrierite in the Tonstein of the Sarre coal formations has appeared (Soc. franç. minéralogie Bull., vol. 46, pp. 18–20, 1923; Chem. Abstracts, vol. 18, p. 649, 1924). The leverrierite described by Termier occurs in small crystals in clay beds of the coal-bearing group of rocks, but the leverrierite referred to in the present paper is not confined to argillaceous beds but is plentiful in the sandstone—in fact, the petrographic descriptions in this paper are based on the leverrierite in the sandstones. It it interesting to note that in both localities the leverrierite is associated with coal-bearing rocks and that the leverrierite of the Sarre coal formations is associated with detrital quartz, carbonaceous vegetable débris, calcite, dolomite, siderite, and to a less extent with biotite, muscovite, and chlorite, a mineral association which is very similar to that found in the rocks of the Lance and Fort Union formations of Montana.

[15] Rogers, G. S., Baked shale and slag formed by the burning of coal beds: U. S. Geol. Survey Prof. Paper 108, p. 5, 1917.

[16] Larsen, E. S., and Wherry, E. T., Leverrierite from Colorado: Washington Acad. Sci. Jour., vol. 7, pp. 208–217, 1917.

Chemically it differs from kaolinite chiefly in the fact that it retains only 7 per cent of its H_2O at 110° and very little at 350°, while kaolinite retains nearly all of its 14 per cent of H_2O up to 400°. Optically leverrierite has higher indices of refraction, much stronger birefringence, and much smaller axial angle than kaolinite, and it is commonly found in larger plates.

The leverrierite group includes, then, the micaceous hydrous silicates of aluminum with small amounts of Fe_2O_3, RO, and R_2O, in which the ratio $Al_2O_3:SiO_2$ varies at least from 1.85 to 3.95; the H_2O content under normal conditions is from 15 to 25 per cent, of which all but about 7 per cent is given off below 110°. In physical and optical properties leverrierite resembles muscovite, but its cleavage is less prominent, it is rather brittle when dry and very plastic when wet, and its axial angle is commonly very small.

The thin sections made from samples of sandstone from the Lance and Fort Union formations show that in many of the rock fragments the mineral grains have no characteristic outline and the nature of the original rock is not evident, but in others euhedral feldspar in a fine-grained groundmass indicates derivation from a volcanic rock. The groundmass in these rock grains is an aggregate of secondary material. Part of this is undoubtedly leverrierite, as it agrees in appearance and optical properties with that mineral. The same kind of material also forms a scant cement between mineral grains.

In the section from which Plate III, *A*, was made, a pale-brown material with a silvery luster forms rather definite masses between other grains. In thin section it is seen that these masses have a micaceous structure, but instead of being plates, many of them are made up of groups of plates with random orientation, or of fan-shaped or rudely radial aggregates of plates. The best of these plates give a negative optical figure with a small axial angle. The indices are 1.60 to 1.70, and the birefringence is about 0.03. In habit and general appearance and in all optical properties but the indices of refraction this brown material resembles the leverrierite that occurs in the same rock. The ferric iron content of this brown mineral is high, and in consequence the indices of refraction are high. The nature of this material is not entirely clear, but it is probably related to the hydrous ferric iron silicate nontronite, or possibly it is an iron-bearing leverrierite. Nontronite and leverrierite are probably related, as the former is a hydrous ferric iron silicate and the latter a hydrous aluminum silicate. Therefore, a mineral near nontronite in chemical composition but with the habit and relations of leverrerite is not at all improbable.

CHEMICAL CHARACTER OF THE GROUND WATER.

Twenty analyses of waters from the Lance formation are shown in Plate V, *A*, and ten analyses from the Fort Union formation are shown in Plate V, *B*. These analyses are platted graphically by reacting values or milligram equivalents[17] in both figures.[18] All samples were collected from wells that begin in the formation from which they obtain their water. Well No. 28, which obtains water from the Lebo member, begins in the upper light-colored Tongue River member of the Fort Union formation. In wells reaching a depth of 100 feet or more and in many shallower wells the upper water is cased off, and it is reasonably certain that the waters discussed come from depths approximating those shown in Plate V.

The analyses represented in these diagrams show that on the whole the waters from the Lance formation are more highly mineralized than those from the Fort Union formation. The maximum total dissolved solids in the Lance waters shown in Plate V, *A*, is 2,911 parts per million (No. 12), and the maximum in the Fort Union waters shown in Plate V, *B*, is 1,231 parts per million (No. 3), but locally a Fort Union bed yields water that contains as much dissolved mineral matter as any of the waters from the Lance formation.

Of the waters from the Lance formation platted in Plate V, *A*, those from wells less than 125 feet deep contain from 43 to 162 parts per million of calcium and magnesium, and those from wells more than 125 feet deep contain from 5.2 to 18.1 parts per million. Of the waters from the Fort Union formation (including at the base the Lebo member) platted in Plate V, *B*, those from wells less than 80 feet deep contain from 99 to 212 parts per million of calcium and magnesium, and those from wells more than 80 feet deep contain from 5.2 to 23 parts per million. These statements, exemplified on Plate V, indicate clearly that the waters from the shallow wells are relatively high in calcium and magnesium and that those from the deeper wells contain little calcium and magnesium but are relatively high in sodium—that is, the water in the shallow wells is hard and that in the deeper wells is soft.

After averaging the analyses of the shallow hard waters and the deeper soft waters in both the Lance and Fort Union formations it is clear that there is no noteworthy difference in the total quantity of dissolved salts in these two types of waters. In the Lance forma-

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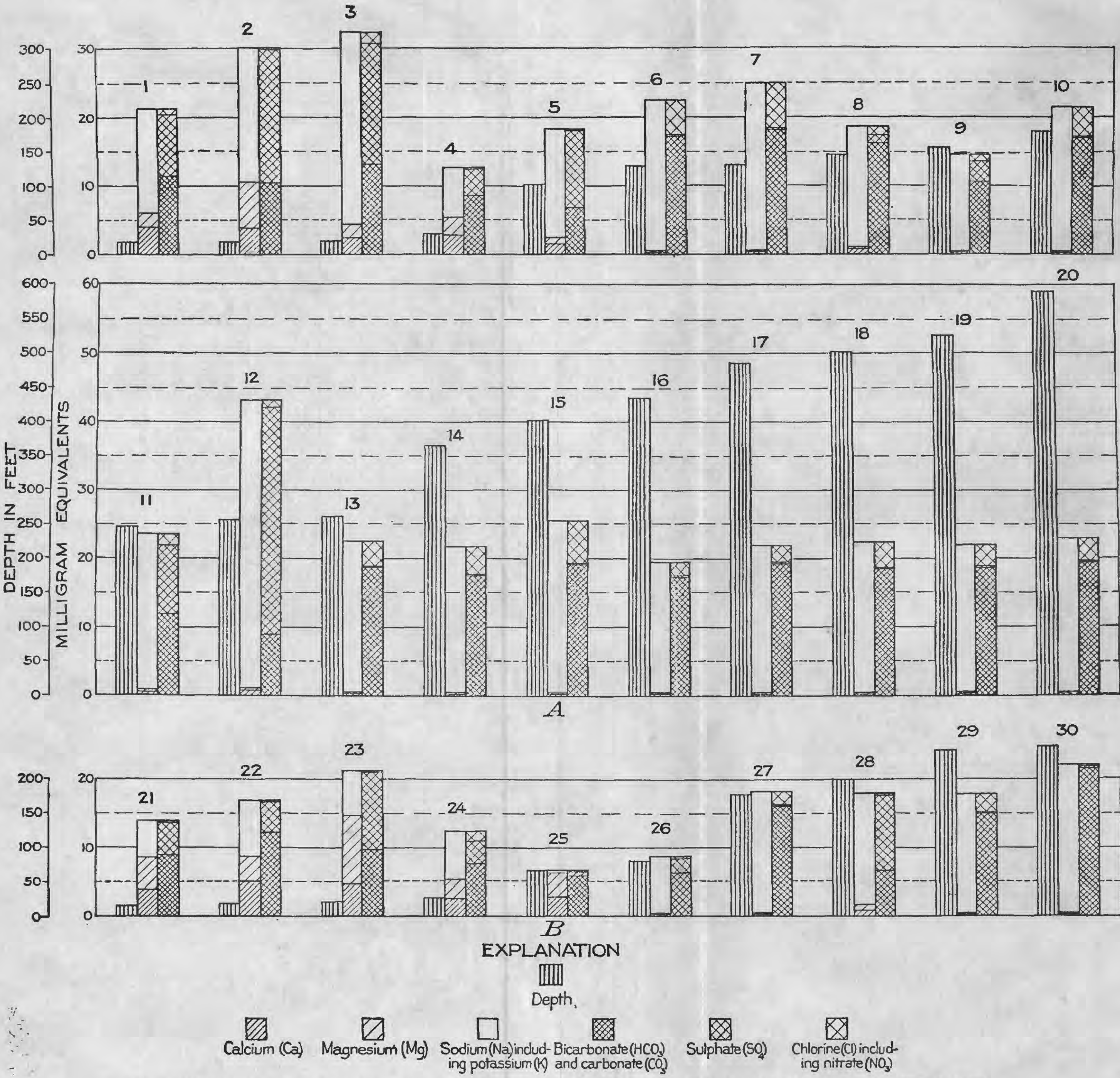
[17] Palmer, Chase, The geochemical interpretation of water analyses: U. S. Geol. Survey Bull. 479, 1911. Rogers, G. S., The interpretation of water analyses by the geologist: Econ. Geology, vol. 12, pp. 56–88, 1917. The milligram equivalents are calculated as follows:

$$\text{Combining weight of radicle} = \frac{\text{atomic weight or sum of the atomic weights}}{\text{valence of the radicle}}.$$

$$\text{Number of milligram equivalents} = \frac{\text{parts per million}}{\text{combining weight of the radicle}}.$$

In the diagrams 1 milligram equivalent=23 parts per million Na, 39 K, 20 Ca, 12 Mg, 61 HCO_3, 30 CO_3, 48 SO_4, 35 Cl.

[18] The legend used in Plate V has been adapted from that suggested by W. D. Collins (Graphic representation of water analyses: Ind. and Eng. Chemistry, vol. 15, No. 4, p. 394, 1923).



GRAPHIC REPRESENTATION OF WELL DEPTHS AND ANALYSES OF WATERS FROM ROSEBUD COUNTY, MONT.

***A*, Waters from Lance formation; *B*, waters from Fort Union formation. See text for explanation.**

tion the average total dissolved solids in the shallow well waters (Nos. 1 to 5) is 1,416 parts per million and in the deeper well waters (Nos. 6 to 20) 1,362 parts per million. In the Fort Union formation, where the waters are less mineralized, the average total dissolved solids in the shallow well waters (Nos. 21 to 25) is 792 parts per million and in the deeper well waters (Nos. 26 to 30) 961 parts per million.

Potassium is comparatively low in all these waters. Nine potassium determinations in the 30 analyses were made by Mr. Riffenburg; the maximum amount of potassium determined was 24 parts per million (Nos. 12 and 15), as compared with a maximum of 957 parts per million of sodium (No. 12). This small amount of potassium, though not referred to in the following discussion, is included with the sodium.

Considerable tracts of alluvial land along Yellowstone River are irrigated, and the waters from shallow wells in the alluvium in these tracts are in general more highly mineralized than they would be under natural conditions. These waters are not typical or representative of the shallow wells in other parts of the region and are therefore eliminated from consideration in this paper.

BASE-EXCHANGE SILICATES.

On the basis of some experiments carried on in 1845 Thompson [19] pointed out that certain soils possess the power of decomposing and retaining the salts of ammonia. He stated that he had not studied the reaction sufficiently to account for the manner in which it was accomplished. About the same time Way,[20] an English investigator, observed that this power of soils is not confined to ammonium salts but that the bases of different alkaline salts may be separated from solution and retained by ordinary soils. Summarizing his previous work in a later paper [21] he made the following pertinent statements:

> But further, this power of the soil was found not to extend to the whole salt of ammonia or potash, but only to the alkali itself. If, for instance, sulphate of ammonia were the compound used in the experiments, the ammonia would be removed from solution, but the filtered liquid would contain sulphuric acid in abundance—not in the free or unconfined form, but united to lime; instead of sulphate of ammonia we would find after the experiment sulphate of lime in solution; and this result was obtained whatever the acid of the salt experimented on might be. * * * It was satisfactorily proved that the quantity of lime acquired by solution corresponded exactly to that of ammonia removed from it; the action was therefore a true chemical decomposi-

19 Thompson, H. S., On the absorbent power of soils: Roy. Agr. Soc. Jour., vol. 11, pp. 68–74, 1850.

20 Way, J. T., The power of soils to absorb manure: Roy Agr. Soc. Jour., vol. 11, pp. 313–379, 1850.

21 Way, J. T., Roy. Agr. Soc. Jour., vol. 13, pp. 123–143, 1852.

tion. * * * It was found that the process of filtration was by no means necessary; by the mere mixing of an alkaline solution with a proper quantity of soil, as by shaking them together in a bottle and allowing the soil to subside, the same result was obtained; the action, therefore, was in no way referable to any physical law brought into operation by the process of filtration.

Again it was found that the combination between soil and alkaline substance was rapid, if not instantaneous. * * * It was shown that the power to absorb alkaline substances did not exist in sand; that the organic matter of the soil had nothing to do with it; that the addition of carbonate of lime to a soil did not increase its absorptive power for these salts; and indeed that a soil in which carbonate of lime did not occur might still possess in a high degree the power of removing ammonia or potash from solution, and it was evident that the active ingredient in all these cases was clay. * * * The stiffest and most tenacious clays taken from considerable depths, which had never since their deposition been exposed to atmospheric influences, and which also were absolutely free from organic matter, or carbonate of lime, possessed to the fullest extent the absorptive property. By these experiments the subject was so far narrowed that the origin of the power in question had been traced to the clay existing in all soils. * * * It soon became evident that the idea of the clay as a whole being the cause of the absorptive property was inconsistent with all the ascertained laws of chemical combination. * * *

I was, indeed, convinced at a very early period of this inquiry that the absorptive property was due to a small quantity of some definite chemical compound existing in the clay and possibly not constituting more than 4 or 5 per cent of its whole weight. I had hoped that, although I might not be able to separate this substance from clay—for of that there was little prospect—it might yet be possible to form it artificially from other sources at the disposal of the chemist, and by producing a compound, or compounds, having the same properties as those shown to be possessed by clay to prove their identity with the active principles of clay itself and thus indirectly establish its real nature.

After eliminating lime (CaO), lime carbonate, sulphate, nitrate, and other simple salts of lime from consideration as the material that gave to soils this reactive power, Way concluded that it must be due to some silicate. After preparing a simple lime silicate, which he found did not possess this property, he turned his attention to the preparation of double silicates of alumina with the alkalies and alkaline earths. He observed that these silicates possessed the property of exchanging their bases and concluded that the base-exchange material in soil was similar in chemical composition but that it was not feldspar or other undecomposed minerals from granitic rocks. Way furthermore brought out the important point that these silicates contain water of combination and that if it is driven off by strong heating the base-exchange property is destroyed, the silicate being no longer reactive.

From the foregoing description of the work of Way it is evident that much was known about base-exchange silicates at a relatively early date. It has long been known that the mineral zeolites are capable of readily exchanging their bases, and after Way's discovery of base-exchange silicates in soils many agriculturists came to regard the reactive material as zeolites. This base-exchange material in soils is referred to as the zeolitic portion of soils even to the present time, though ordinary soils almost certainly do not contain zeolites.

Sullivan,[22] in addition to summarizing the work of earlier investigators on base exchange in natural and artificial silicates, made a noteworthy contribution to the subject. He effected numerous base-exchange reactions between natural silicates and the base of numerous salts in solution. Some of his conclusions follow:

The fact of prime significance geologically seems to be that by a process of simple chemical exchange the metal may be removed from solution and fixed in a solid state and thus concentrated, by contact with even the most stable of the silicates. The changes under consideration involve the action of the alkali or alkaline-earth salt of a weak acid (silicic or alumino-silicic) and are thus analogous to the more familiar behavior of sodium carbonate with solutions of salts of the metals. Owing to hydrolysis the precipitates caused by sodium carbonate tend to split up into the acid and base (carbonic acid and metal oxide or hydroxide), and the weaker the base the more marked is this action. The precipitate from solutions of salts of strong bases, such as calcium chloride, is the normal carbonate; a weaker base, such as nickel, is precipitated as basic carbonate or a mixture of the normal carbonate with hydroxide or oxide; while the very weak bases, as iron in ferric salts, are precipitated as hydroxide or oxide containing little or no carbonate, and the corresponding quantity of carbon dioxide is set free.[23]

Sullivan discussed the mechanics of the reaction and by way of summary said:

The natural silicates precipitate the metals from solutions of salts, while at the same time the bases of the silicates are dissolved in quantities nearly equivalent to the precipitated metals. The bases most commonly replacing the metals in these processes are potassium, sodium, magnesium, and calcium. Where exact equivalence is wanting, it is attributable either to solubility of the mineral in pure water or to the precipitation of basic salts.

The specific materials on which work was done are albite, amphibole, augite, biotite, enstatite, garnet, clay gouge, kaolin, microcline, muscovite, olivine, orthoclase, prehnite, shale, talc, tourmaline, and vesuvianite, with cupric sulphate solution; and orthoclase with salts of sodium, potassium, magnesium, calcium, strontium, barium, manganese, iron, nickel, copper, zinc, silver, gold, and lead. Experiments were also made on the action of kaolin on solutions of salts of zinc and iron, and of glass, fluorite, and pyrite on cupric sulphate and of carbonic and sulphuric acids on orthoclase.[24]

Sullivan's conclusions differ somewhat from those previously arrived at by Lemberg,[25] who says:

In addition to these [the zeolites] I have experimented with the various feldspars, hornblende, cordierite, serpentine, and scapolite, but up to the

[22] Sullivan, E. C., Interaction of minerals and water solutions: U. S. Geol. Survey Bull. 312, 1907. Also an earlier shorter paper, The chemistry of ore deposition—precipitation of copper by natural silicates: Econ. Geology, vol. 1, pp. 67–73, 1905.

[23] Sullivan, E. C., op. cit. (Bull. 312), pp. 61–62.

[24] Sullivan, E. C., op. cit., p. 64.

[25] Lemberg, J., Deutsch. geol. Gesell. Zeitschr., vol. 22, p. 335, 1870; vol. 24, p. 187, 1872; vol. 28, p. 591, 1876. Cited by E. C. Sullivan, U. S. Geol. Survey Bull. 312, p. 23, 1907.

present only in the case of hornblende could an exchange of substance be proved with certainty.

This conflict in statement may be due to a difference in viewpoint—that is, Lemberg might not have regarded an exchange as taking place unless it was fairly complete, while Sullivan regarded an experiment as highly successful and demonstrative of base exchange if only a very small part of the silicate was exchanged.

Although these base-exchange silicates had been prepared and most of their properties understood for over half a century, Gans, by publishing two papers[26] in 1905 and 1906, aroused considerable interest in them. He apparently was the first one to conceive of the idea of utilizing artificially prepared sodium base-exchange silicates for softening water by allowing hard water containing salts of calcium and magnesium to flow over it, the calcium and magnesium being removed by exchange with the sodium to give a mixed calcium, magnesium, and sodium base-exchange silicate and soft water. This artificial water softener, which he considered must contain the essential molecules soda, alumina, silica, and water of combination, he named permutite and patented.

When the sodium capable of exchange has been exhausted the base-exchange silicate is regenerated by passing a strong solution of a sodium salt, preferably chloride, through it. Regarding the ability of these double silicates to be regenerated by reversing the reaction Way[27] erred when he wrote, "Of course, the reverse of this action can not occur."

In 1907 Feldoff[28] reported on the success of this method of softening water for use in boilers, and furthermore showed that permutite could be used to remove iron and manganese quantitatively from drinking water. Gedroiz[29] has since stated that this exchange may take place between the base of any metallic salt and a base-exchange silicate. As pointed out in a recent thesis by Baker,[30] artificial softeners have been patented which substitute the oxides of zinc, tin, lead, titanium, zirconium, chromium, and iron for alumina, and boric acid has been used in place of silica.

Since 1907 the use of so-called artificial zeolites has become of considerable economic importance in municipal and industrial water-

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[26] Gans, Robert, Zeolites and similar compounds, their constitution and their importance for technology and agriculture: Preuss. geol. Landesanstalt Berlin Jahrb., Band 26, Heft 2, pp. 179–211, 1905; The constitution of zeolites, processes of obtaining and technical importance: Idem, Band 27, Heft 1, p. 63, 1906.

[27] Way, J. T., Power of soils to absorb manure: Roy. Agr. Soc. Jour., vol. 13, p. 132, 1852.

[28] Feldoff, A., Natural and artificial zeolites (permutite) and their technical application: Centralbl. Zuckerindustrie, vol. 15, pp. 1307–1310, 1907; Chem. Abstracts, vol. 1, p. 2755, 1907.

[29] Gedroiz, K. K., Colloidal chemistry as related to soil science: Russia Bur. Agr. and Soil Sci. Communication 8, p. 25, 1912 (U. S. Dept. Agr. translation, p. 18). Recent papers of Dr. Gedroiz, of Petrograd, published between 1912 and 1923, have been translated into English by Dr. S. A. Waksman and mimeographed by the United States Department of Agriculture in order that they may be available to American investigators.

[30] Baker, G. C., Water softening by base exchange: Am. Waterworks Assoc. Jour., vol. 11, pp. 128–149, 1924.

softening plants. Many investigators in Europe and America have studied the permutite reaction, but in spite of much detailed work, different investigators have arrived at different conclusions with regard to the mechanics of the reaction, some contending that this exchange is ionic, and others that it is a phenomenon of adsorption.[31] Rideal,[32] in referring to the reaction of carbonate of lime with natural mineral zeolites, said, "The reaction suggests another way by which nearly pure alkali may originate in nature." Numerous papers by Gedroiz are especially noteworthy, as they contain not only much valuable original work but also discussions of the papers of earlier workers. The mechanics of the reaction has also been discussed by numerous investigators, including Wiegner,[33] Don,[34] Raumann, Marz, Biesenberger, and Spengel,[35] Rothmund and Kornfeld,[36] and Raumann and Junk.[37]

Gans, like his predecessors, assumed that the soil contains mineral zeolites. Since Gans's papers appeared many writers on this subject have referred to these complex aluminum silicates capable of base exchange found in the soil as "zeolites." As ordinary soil does not contain mineral zeolites, it seems that the usurping of a definite mineralogic term to describe any complex hydrated aluminum silicate capable of base exchange gives an erroneous concept. For such material the term "base-exchange silicates" instead of zeolite seems appropriate.

Gedroiz [38] concludes that this exchange is ionic and states that

> The zeolitic (and humic) part of every soil contains a well-defined quantity of zeolitic cations. These cations can be replaced by any cation or mixture of any cations. The replacement takes place as a result of the reaction of mutual exchange of the cations between the zeolitic (and humic) part of the soil and the solution of the salt or acid taken. As a reaction of double exchange, the replacement takes place in equivalent concentrations.

Besides artificial base-exchange silicates, many of which utilize kaolin, quartz, and feldspar, there are certain natural minerals and rock materials that will soften water and have been used for that purpose. These natural materials are rendered more efficient by

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[31] Gedroiz prefers the use of the word absorption. Some writers include both phenomena under the general term sorption.

[32] Rideal, S., Origin of carbonate of soda in natural waters and mineral deposits: Chem. World, vol. 1, p. 16, 1912.

[33] Wiegner, George, The exchange of bases in cultivated soil: Jour. Landw., vol. 60, pp. 197–222, 1912: Chem. Abstracts, vol. 6, pp. 2477, 3304, 1912.

[34] Don, J., The use of permutit and polarit in water purification: Glasgow Kolloid Zeitschr., vol. 15, pp. 132–134, 1914: Chem. Abstracts, vol. 9, p. 676, 1915.

[35] Raumann, E., Marz, S., Biesenberger, K., and Spengel, A., The exchange of bases of silicates—Exchange of alkalies and ammonium by hydrous aluminum-alkali silicates permutites): Zeitschr. anorg. allgem. Chemie, vol. 95, pp. 115–128, 1916; Soc. Chem. Industry Jour., vol. 35, p. 1129, 1916: Chem. Abstracts, vol. 11, p. 2174, 1917.

[36] Rothmund, V., and Kornfeld, G., Basic exchange in permutit: Zeitschr. anorg. allgem. Chemie, vol. 103, pp. 129–163, 1918; Chem. Abstracts, vol. 13, p. 2823, 1919.

[37] Raumann, E., and Junk, H., Basic exchange in silicates—III: Zeitschr. anorg. allgem. Chemie, vol. 114, pp. 90–104, 1920; Chem. Abstracts, vol. 15, p. 2592, 1921.

[38] Gedroiz, K. K., op. cit., p. 26 (U. S. Dept. Agr. translation, p. 19).

various treatments, many of which are relatively simple. The most useful of these minerals are greensand or glauconite, bentonite, and clay or kaolin. Bentonite, though containing more than one mineral, always consists chiefly of leverrierite, or one of the group of micaceous clay minerals which includes the mineral commonly known as leverrierite. This group possesses the property of readily exchanging its bases and is considerably more reactive than the ordinary natural clays. The bentonite from Ardmore, S. Dak., consists mostly of leverrierite but contains a considerable quantity of disseminated carbonate (probably calcite) and a few grains of biotite and muscovite. This leverrierite-bearing material from Ardmore after being treated to render it more reactive and to prevent it from swelling (a characteristic property of leverrierite) is used as a commercial water softener.

ORIGIN OF THE SOFT WATERS.

It is believed that the difference in the composition of water in deep and shallow wells in this area of Lance and Fort Union rocks can be explained as the result of natural softening. This exchange of the calcium and magnesium in the water for sodium can be accounted for by the minerals of the leverrierite group, which exchange their bases easily and which are plentiful in these formations. The hypothetical reactions might be written as follows:

(1) Na (or K) base-exchange silicate+$Ca(HCO_3)_2$ (or $Mg(HCO_3)_2$)= Ca (or Mg) base-exchange silicate+$2NaHCO_3$ (or $2KHCO_3$).

(2) Na (or K) base-exchange silicate+$CaSO_4$ (or $MgSO_4$)=Ca (or Mg) base-exchange silicate+Na_2SO_4 (or K_2SO_4).

Analyses of minerals of the leverrierite group.[a]

	1	2	3	3a	4	5	6	7	8
SiO_2	47.28	47.84	47.56	789	47.95	49.90	50.55	49.4	48.43
Al_2O_3	20.27	20.88	20.57	256	32.67	37.02	19.15	45.1	41.63
Fe_2O_3	8.68	8.48	8.58		.23	3.65	--------	--------	--------
MnO	--------	.24	.24	89	--------	--------	4.40	--------	--------
CaO	2.75	2.52	2.52		.41	Tr.	.63	--------	2.13
MgO	.70	.91	.80		.46	.30	--------	--------	2.13
Na_2O	.97	1.58	1.28		2.47	--------	--------	--------	--------
K_2O	Tr.	Tr.	--------	--------	.24	1.13	--------	--------	--------
H_2O+	19.72	6.65	6.65	--------	7.03	8.65	24.05	5.6	7.70
H_2O+		10.95	12.01	--------	8.56	(?)		(?)	(?)
	100.37	100.05	100.21	--------	99.36	100.65	98.78	100.1	99.89
$Al_2O_3:SiO_2$	--------	--------	1:2.76	--------	1:2.34	1:2.11	1:3.95	1:1.86	1:1.94

[a] Larsen, E. S., and Wherry, E. T., Leverrierite from Colorado: Washington Acad. Sci. Jour., vol. 7, No. 8, p. 213, 1917.

1 and 2. Material from Beidell, Colo. New analyses by E. T. Wherry.
3. Average of 1 and 2.
3a. Molecular proportions of 3.
4. Average of two analyses of "rectorite," Garland County, Ark. Brackett, R. N., and Williams, J. F., Am. Jour. Sci., 3d ser., vol. 42, p. 16, 1891.
5. Leverrierite, Rochelle, France. Termier, P., Soc. min. Bull., vol. 22, p. 29, 1899. Analysis made on material dried at 110°–130°. Older analyses show 13.21 and 18.0 per cent of total water.
6. "Montmorillonite, var. delanouite," Millac, France. Quoted from Lacroix, A., Minéralogie de la France.
7. "Batchelorite," Tasmania. H_2O stated as "combined H_2O." Gregory, J. W., Australian Inst. Min. Eng. Trans., vol. 10, p. 187, 1905.
8. Kryptotile. Quoted from Dana. The original article reports H_2O without a statement as to whether it represents total water or water above 100°.

These analyses of minerals of the leverrierite group show that there is considerable variation in the quantity of bases in different species and thus suggest easy base exchange among the leverrierite minerals.

Although it is believed that leverrierite is the principal mineral that brings about this natural softening of the water in the area here considered, it is recognized that other hydrated aluminum silicates, such as kaolin, feldspars, and mica, are also capable of exchanging wholly or in part their sodium and potassium for other bases.

An inspection of Plate V shows that the calcium and magnesium have been essentially removed by exchange for sodium by the time the water reaches a depth of 125 feet and in some localities before it reaches 80 feet. The diagrams might convey the impression that the calcium and magnesium are more readily exchanged in the Fort Union rocks than in those of the Lance formation. This may or may not be the case, for this apparent difference may be accounted for by the fact that no analyses of samples of water from wells in the Lance formation between the depths of 30 and 100 feet are at hand.

It is not intended to convey the idea that the hard near-surface ground water is softened by direct downward percolation through a given number of feet of these leverrierite-bearing strata, because most of the deeper soft water has moved laterally through many feet and even miles, and it is impossible to say just how necessary or important this lateral movement may be. But owing to the facts that these reactions between dissolved salts and base-exchange silicates are rapid and that the exchange has been accomplished in all waters beyond a given depth, the conclusion seems justified that ground water will have its calcium and magnesium essentially removed by percolating through relatively few feet of rock containing leverrierite.

It is apparent from Plate V that there are notable differences in the acid radicles in the Lance and Fort Union waters. The most striking feature is that some of the waters contain sulphate and others do not. It is not within the scope of this paper to discuss the acid radicles in these waters. The cause of the elimination of the sulphate, which, on the whole, is less abundant in the waters from the deeper wells, is considered in another paper.[39] Bicarbonate and carbonate are usually the most abundant acid radicles, especially in the waters from the deeper wells.

The noteworthy fact that the mineral content of these waters from the Lance and Fort Union formations does not appreciably

[39] Renick, B. C., Some geochemical relations of ground water and associated natural gas in the Lance formation, Montana (to be published in Jour. Geology).

increase with increasing depth indicates that the amount of dissolved salts is determined relatively near the surface, and that any subsequent change that the basic radicles suffer is in the nature of an exchange. This exchange is probably not of the nature of an absorption phenomenon but is more likely an ionic exchange, as contended by Gedroiz.[40]

The possibility of the removal of calcium and magnesium by means of a reaction between calcium bicarbonate and magnesium sulphate dissolved in the ground water, with the consequent deposition of gypsum ($CaSO_4.2H_2O$) and nesquehonite ($MgCO_3.3H_2O$), has been considered, but because of the relatively slight concentrations existing in these waters such a reaction seems improbable. If calcium and magnesium had been removed in this way, the total solids in the deeper waters would be less (calcium and magnesium having been removed), and, as pointed out on page 62, there is no essential difference in the amount of total solids in the shallow and in the deep waters.

The dissolved salts in the upper hard waters are derived from the soluble materials resulting from the decomposition of minerals in the sedimentary beds and also to some extent from soluble salts deposited in the interstices between mineral grains. The distance through which it is necessary for these hard waters to percolate before they are softened depends upon the quantity of leverrierite and related mineral species in the rocks, and these minerals, although distributed throughout the Lance and Fort Union section in this area, are more abundant in some places than in others. It is probable that the distance may also depend somewhat on the character of the material—that is, whether it is rock in place or alluvium—because aggregates of leverrierite swell and go to pieces when wet, and this would happen when the Lance and Fort Union beds are converted into soil and alluvium. The leverrierite might thereby lose its effectiveness by being disintegrated and decomposed when the Lance and Fort Union beds are converted into alluvium, while that in the Lance and Fort Union beds would be prevented from being disintegrated when wet by the containing walls formed by adjacent mineral grains.

The rate of erosion would, no doubt, be another factor influencing the depth necessary for softening. Where the land was being rapidly degraded it would probably not be necessary for the water to pass through as great a distance as in a region where degradation was relatively slow, for in the region of rapid erosion the base-exchange material would be removed at a rate somewhat proportional to the rate at which its property to exchange alkali for alkaline-earth bases was exhausted, whereas in the region of rela-

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[40] Gedroiz, K. K., op. cit., p. 26 (U. S. Dept. Agr. translation, p. 19).

tively slow erosion there would accumulate a considerable thickness of rock débris whose base-exchange material had exhausted its property to exchange alkali for alkaline-earth bases, and under these conditions unsoftened water would be encountered at a somewhat greater depth. In this connection it is interesting to note that Way (see p. 64) long ago found that the deeper clays which had not been exposed to weathering were the most effective in producing base exchanges.

Other factors that affect the depth requisite for softening include the structure of the rocks, which would influence the rate of lateral flow underground, and the texture and porosity of the strata, which would influence the rate of downward and lateral percolation.

The discussion of the origin of the soft waters given in this paper is based entirely on data obtained from the Lance (Tertiary?) and Fort Union (Tertiary) formations. It seems very probable that this exchange of bases has also taken place in the underlying Upper Cretaceous beds in this region, but complete data to establish this point are not yet available.

Soft sodium bicarbonate or carbonate and sodium sulphate waters at depths comparable to those of the waters described above are known to occur at many places in the United States, but their origin and their depth relations have not been explained. It is likely that they originated in much the same way as the soft waters in the Lance and Fort Union formations in central Montana and that the natural softening was effected by some mineral having base-exchange properties, not necessarily of the leverrierite group but very probably closely related to it.

SUMMARY.

Studies of ground water in an area of Lance (Tertiary?) and Fort Union (Tertiary) formations in east-central Montana, in the Great Plains province, show that near the surface the water is relatively high in calcium and magnesium, which, with increasing depth, are exchanged for sodium (and potassium?), the result being a natural softening. The minerals of the leverrierite group, which are plentiful though disseminated in these formations and are believed to be derived from the decomposition in place of the glassy constituents of rock fragments, are considered the principal agents in effecting this exchange of bases, though the exchange may be aided by such minerals as kaolinite, feldspar, and mica, which are also present in these rocks. This exchange of bases is accomplished by the time a depth of 125 feet or less is reached. There is no tendency for the water to acquire more dissolved material with increasing depth. The amount of total dissolved solids is therefore determined relatively near the surface.

In this paper the discussion of base exchange by silicates is confined to reactions involving the alkalies and alkaline earths, but similar exchange reactions take place between the most resistant mineral silicates and the bases of salt solutions of the heavy metals. Perhaps the data presented will be of assistance in estimating the number of feet through which it is necessary for ground water carrying salts of the heavy metals in solution to percolate under natural conditions in order to deposit the bases of the metals by exchange with the bases of silicates.

THE ARTESIAN WATER SUPPLY OF THE DAKOTA SANDSTONE IN NORTH DAKOTA, WITH SPECIAL REFERENCE TO THE EDGELEY QUADRANGLE.

By Oscar E. Meinzer and Herbert A. Hard

INTRODUCTION.

The Dakota sandstone and the overlying dense plastic shales form the most remarkable artesian basin in the United States with respect to its great extent, the long distances through which its water has percolated from the outcrops of the sandstone in the western mountains to the areas of artesian flow, and especially the tremendous pressure under which the water in the sandstone was originally held by its thick and continuous cover of impermeable shales. In 1882 a well was drilled to the Dakota sandstone at Aberdeen, S. Dak., by the Chicago, Milwaukee & St. Paul Railway Co. This well was reported by Nettleton[1] to have been "the first bore put down which reached the artesian basin of the Dakotas." In 1896 Darton[2] estimated that about 400 artesian wells had been drilled to the Dakota sandstone, presumably in South Dakota and adjacent parts of the artesian basin in North Dakota which he investigated.[3] The strongest of these wells had pressures ranging from 100 to more than 200 pounds to the square inch and flows ranging from 1,000 to more than 4,000 gallons a minute.

The discovery of this remarkable artesian basin naturally caused much excitement and gave rise to extravagant theories as to the quantity of artesian water available and the extent to which it could be used for power and irrigation. The water from the famous well at Woonsocket, S. Dak., was jetted to a height of more than 100 feet and must have produced a spectacle comparable to that of Old Faithful Geyser in Yellowstone National Park (Pl. VI). Many of the wells yielded considerable gas, which must have heightened the spectacular effect with which the water was discharged. On account of the great pressure it was very difficult to finish the wells, and

[1] Nettleton, E. S., Artesian and underflow investigation: 52d Cong., 1st sess., S. Ex. Doc. 41, pt. 2, p. 46, 1892.

[2] Darton, N. H., Preliminary report on artesian waters of a portion of the Dakotas: U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, p. 609, 1896.

[3] Idem, pl. 69.

occasionally a well would get out of control, throw up immense quantities of sand and other material, cause the caving of adjacent land, and, in short, perform in a most sensational manner.

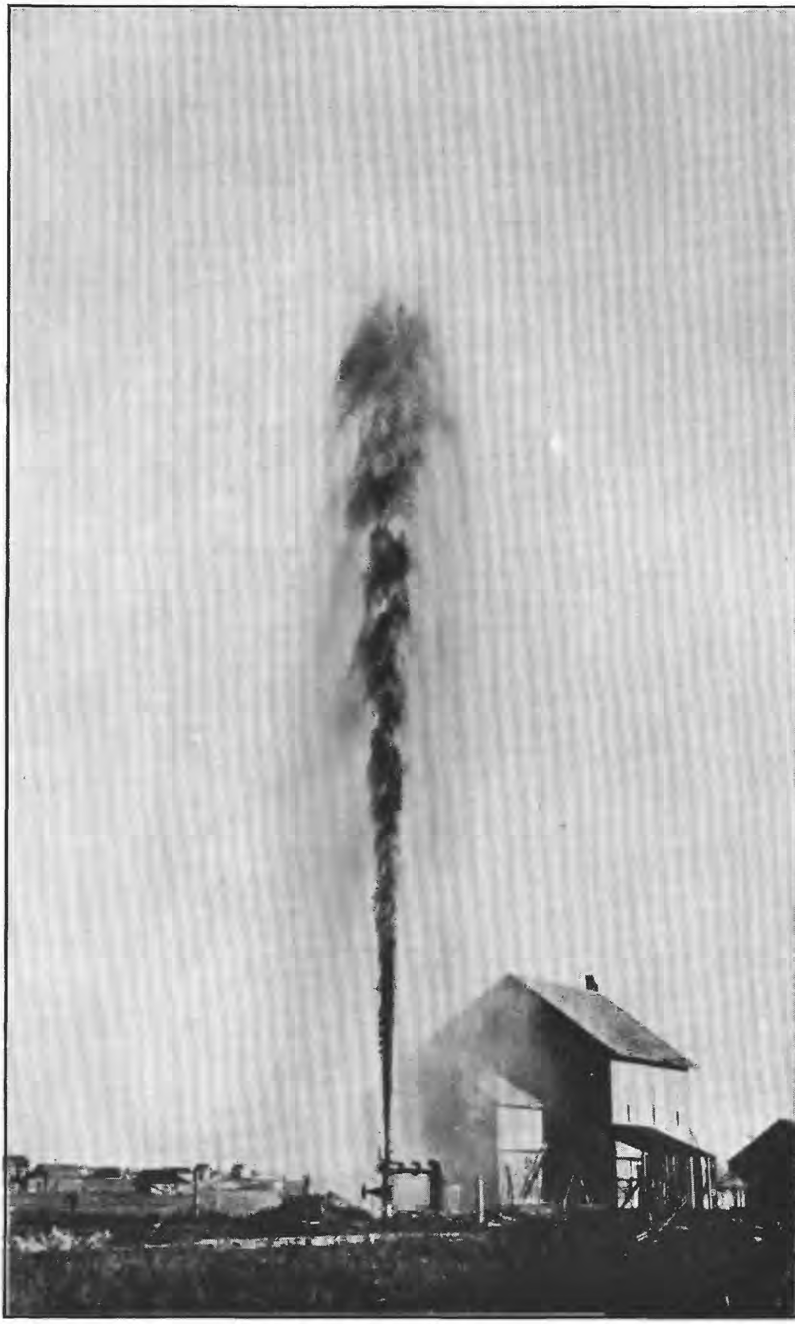
It is exceedingly interesting and gratifying to note that in March, 1890, when the excitement over the artesian wells must have been about at its maximum, Maj. J. W. Powell, Director of the United States Geological Survey,[4] made a statement on the subject before the Committee on Irrigation of the House of Representatives which must have seemed unduly conservative at that time but which clearly indicated the temporary character of the high pressures and discharges and gave an estimate of permanent yield that appears remarkably accurate after 34 years of artesian development and decline. In the summary of his statement appear the following conclusions:

> It has been shown that the supply of water to be obtained through artesian wells is narrowly limited, the limitation arising from natural conditions of reception by reservoirs [water-bearing formations], transmission through them, and leakage from them and being expressed practically through the interference of wells one with another. The permanent flow is in some cases much less than the initial flow. * * * While the Dakota sandstone is one of the most important of the known artesian reservoirs, the amount of land which can be redeemed to agriculture through its aid is yet so small that disastrous results might follow if great expectations were aroused in regard to it.
>
> It is estimated that if all the water received by the Dakota sandstone could be brought to the surface by artesian wells, it would cover to the depth of 1 foot an area of land equivalent, at the utmost, to a belt one-fifth of a mile wide and extending from the Canadian boundary to the Mexican.
>
> This is the outside limit for permanent flow. The temporary flow may be large but can not be estimated from existing data. Such is the complexity of conditions and so great is the danger of disaster through expensive exploitation in ignorance of the true conditions that the subject demands the most skillful investigation which can be bestowed.

In 1890 and 1891 an investigation of the artesian basin was made by the United States Department of Agriculture, and the report prepared by E. S. Nettleton, already cited, contains a large number of specific data on individual wells, which are of great value as a record of conditions in the early part of the period of artesian development.

In the ensuing years extensive and somewhat detailed investigations of the geology and hydrology of the artesian basin were made by the United States Geological Survey, the work being done under the direction of N. H. Darton, and numerous reports on the subject were published. Most of these reports relate to areas in South Dakota, which contains the most productive part of the area of

[4] Artesian irrigation on the Great Plains: U. S. Geol. Survey Eleventh Ann. Rept., pt. 2, pp. 260–276, 1891.



ARTESIAN WELL AT WOONSOCKET, S. DAK., ABOUT 1895

The original pressure (1890) was reported to be 250 pounds to the square inch. In 1892 the pressure was reported to be 130 pounds and the flow 1,150 gallons a minute. By 1915 the pressure at Woonsocket had declined to 45 pounds, and by 1923 to 35 pounds. Photograph by N. H. Darton

artesian flow,[5] but some reports covered parts of the artesian basin that lie in other States, including North Dakota.[6]

It is now evident that the decline in artesian head began when the first wells punctured the confining beds and that it has progressed steadily. During the first decade or two of artesian development, however, the head was still so large that not much attention was paid to the obvious symptoms of decline, and it was customary to ascribe notable decreases in head and flow to mechanical difficulties in individual wells. Doubtless considerable decline had already taken place at the time of Nettleton's survey in 1890 and 1891.

Many of the early wells were several inches in diameter, but in later years wells of small diameter came into extensive use. They had two great advantages—they were much less expensive than the larger wells and they could be finished with much less difficulty and less danger of getting out of control. Near the end of the last century and in the first decade of the present century thousands of wells 1¼ or 1½ inches in diameter were drilled to the Dakota sandstone, and eventually artesian wells were to be found on a large proportion of the prosperous farms. In 1915 there were said to be about 10,000 artesian wells in South Dakota,[7] and in 1923 it was estimated that there were between 6,000 and 8,000 artesian wells in North Dakota.[8] During and after the period of active drilling the artesian head dropped rapidly.

In 1914 and 1915 a survey of the geology and artesian conditions of the Edgeley and La Moure quadrangles, N. Dak., was made for the United States Geological Survey by Herbert A. Hard. In 1915 a survey of artesian pressures and flows in South Dakota was made by Homer M. Derr,[9] State engineer of South Dakota. Both investigations showed that the artesian pressure had largely been dissipated and that many of the wells had already ceased to flow. Both Hard and Derr warned against the further waste of artesian water and made correct predictions as to the further decline of artesian head and flow.

In order to obtain definite data as to the rate at which the artesian head and flow are declining, the Edgeley quadrangle, which includes

[5] The following publications of the United States Geological Survey relate to artesian water in South Dakota: Eleventh Ann. Rept., pt. 2; Seventeenth Ann. Rept., pt. 2; Twenty-first Ann. Rept., pt. 4; Prof. Papers 32, 65; Geol. Folios 85, 96, 97, 99, 100, 107, 108, 113, 114, 128, 156, 164, and 165; Water-Supply Papers 34, 90, 227, 428.

[6] The following publications of the United States Geological Survey relate to artesian water in North Dakota: Eleventh Ann. Rept., pt. 2; Seventeenth Ann. Rept., pt. 2; Mon. 25; Geol. Folios 117 and 168.

[7] Derr, H. M., Report on artesian wells: South Dakota State Engineer Sixth Bienn. Rept., for 1915–16, p. 145.

[8] Hard, H. A., Artesian wells of North Dakota: Report to the Governor of North Dakota on flood control for 1919–20, p. 7 [1923].

[9] Derr, H. M., op. cit., pp. 143–282.

the towns of Edgeley, Monango, and Ellendale (fig. 7 and Pl. VII), was resurveyed in 1919 and 1920 by Mr. Hard, who was at that time chief engineer of the State Flood Control Commission. Mr. Hard also made investigations of artesian conditions in other parts of North Dakota. For a number of years the artesian and other ground waters of the entire State have been under investigation by Howard E. Simpson, of the North Dakota Geological Survey. In this project the United States Geological Survey has cooperated with the State Geological Survey.

As a result of the work of Hard and Simpson, and largely through the influence of the North Dakota Well Drillers Association, a law was enacted by the State of North Dakota on March 10, 1921,

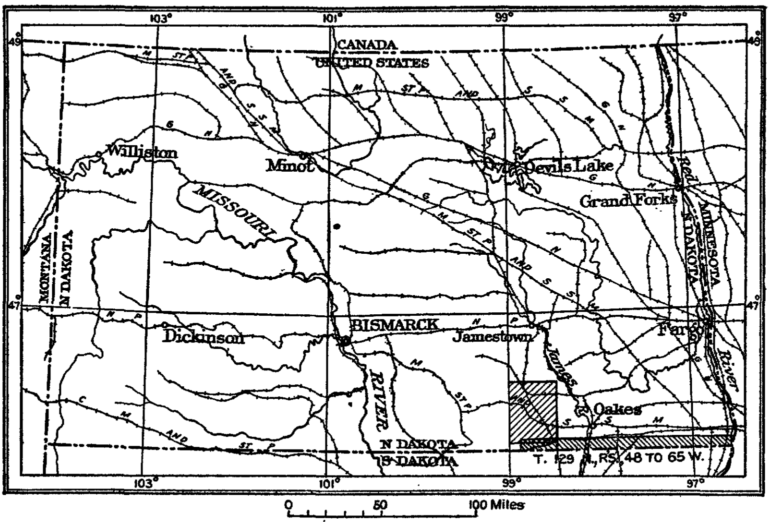


FIGURE 7.—Index map of North Dakota, showing location of Edgeley quadrangle and the row of townships (T. 129 N., Rs. 48–65 W.) on which estimates of artesian-water supply were made.

prohibiting the further waste of artesian water and charging the State geologist or his deputy with the duty of enforcing this law. The State geologist, A. G. Leonard, assigned to Professor Simpson the duty of applying the artesian-water law. Mr. Simpson has given a great deal of serious study to the difficult problems involved in carrying out an effective program of conservation. The annual meeting of the North Dakota Well Drillers Association, held at Grand Forks in February, 1922, was devoted largely to this subject, and in conjunction with this meeting an interstate conference on conservation of the artesian water was held, at which representatives of the North Dakota Geological Survey, the South Dakota Geological Survey, and the United States Geological Survey were present. In 1923 Professor Simpson, with his deputy, C. E. Turnbaugh, began to inspect systematically the artesian wells in the State and to instruct the well owners as to reductions in discharge that should be made.

In order to bring the study in the Edgeley quadrangle up to date a questionnaire covering the present condition of the artesian wells was sent to the owners of wells in or near this quadrangle through the cooperation of the postmasters at Ellendale, Edgeley, Forbes, and Monango. Thanks are due to the postmasters for their helpful cooperation and to the well owners for their hearty response to this questionnaire. In November and December, 1923, through the cooperation of the State Geological Survey, practically all the artesian wells in the quadrangle were examined by Mr. Turnbaugh. This assignment was especially fortunate, because he has been an artesian-well driller in this quadrangle since 1902.

The present brief paper is based chiefly on the data that have been obtained in the successive surveys in regard to about 230 artesian wells in or near the Edgeley quadrangle. A table of these well data is on file in the United States Geological Survey and is to be published in the detailed report on the geology and hydrology of the Edgeley and La Moure quadrangles that has been prepared by Mr. Hard. The well data obtained by Mr. Hard have already been published in a report prepared by him in his capacity as State flood-control engineer.[10]

Mr. Meinzer wishes to express his appreciation to Professor Simpson for his generosity in furnishing essential data obtained in his own field work and to Mr. Hard for his generosity in approving publication of this brief joint report in advance of his detailed report on the Edgeley-La Moure area.

TOPOGRAPHY AND GEOLOGY OF THE EDGELEY QUADRANGLE.[11]

The eastern two-thirds of the Edgeley quadrangle belongs to the so-called James River valley. It is in general a plain that slopes gently toward the east and is underlain by glacial drift, except in a few places where the Pierre shale is exposed. The western third belongs to the Coteau du Missouri—an upland that has a deep cover of glacial drift and an irregular morainal topography. The Coteau stands a few hundred feet above the plain of the James River valley on the east, and in the southern part of the quadrangle it forms a conspicuous escarpment. (See Pl. VII.)

[10] Hard, H. A., op. cit., table opposite p. 96.
[11] Summarized from the unpublished report by Herbert A. Hard.

So far as is known, throughout the quadrangle the drift is underlain by the Pierre shale, below which lie in downward succession the Niobrara shale, the Benton shale, and the Dakota sandstone. On the plain the depth to the Dakota sandstone ranges from about 1,000 to 1,500 feet. On the Coteau the depth is doubtless a few hundred feet greater. The following log was reported for the artesian well drilled at Ellendale in 1886. In this well the glacial drift apparently extends to a depth of 110 feet, where the Pierre shale was presumably struck. The well ends in the Dakota sandstone.

Log of artesian well at Ellendale, N. Dak., drilled in 1886.[a]

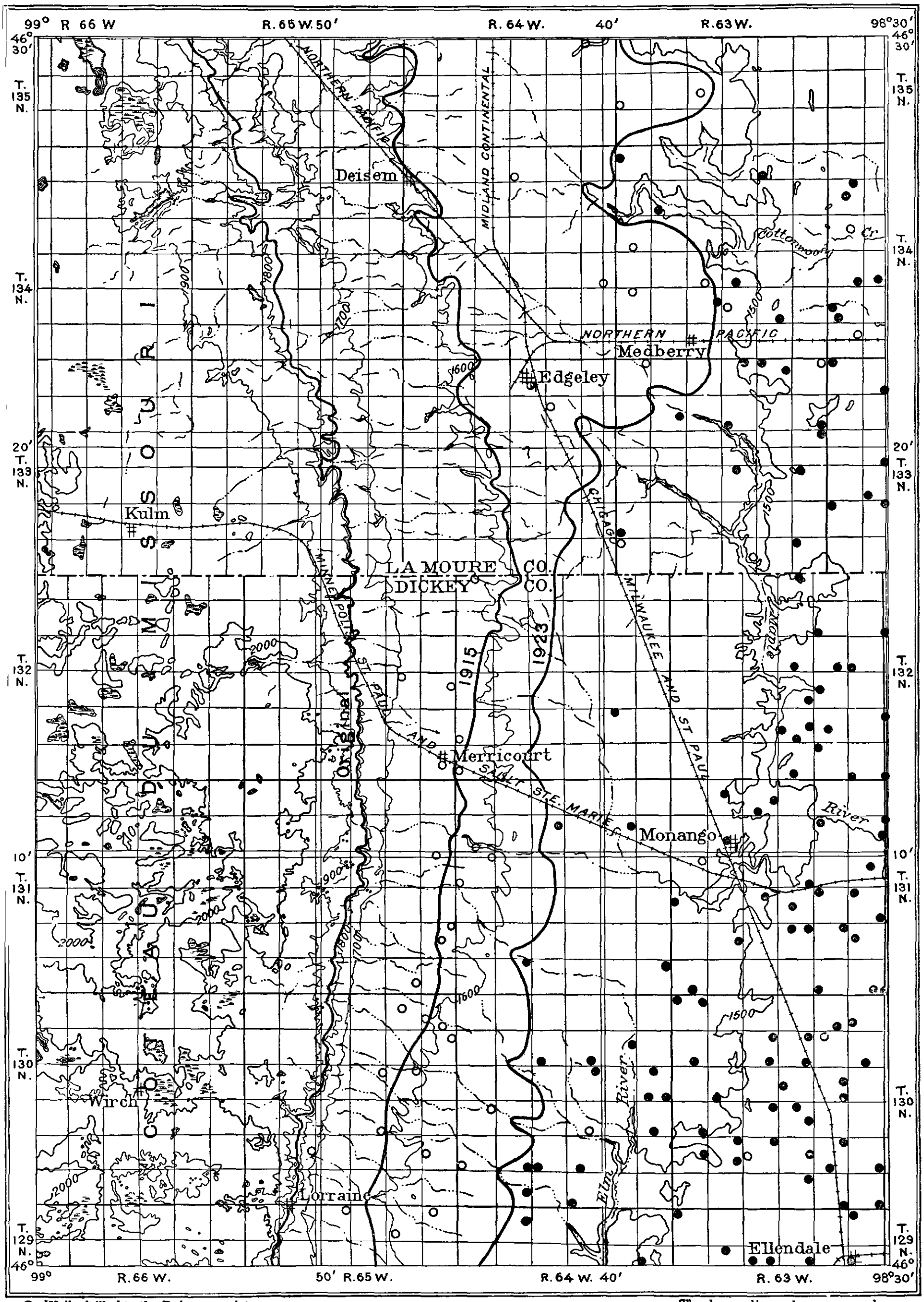
	Thickness.	Depth.
	Feet.	*Feet.*
Yellow clay	25	25
Blue clay	85	110
Shale	925	1,035
Hard sandstone	7	1,042
Soft sandstone	45	1,087

[a] Darton, N. H., U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, pl. 96, 1896.

The following log was reported by George Norbeck, of the Norbeck & Nicholson Co., for the well drilled for the city of Ellendale in November and December, 1923. In this well the glacial drift apparently extends to the depth of 68 feet.

Log of artesian well at Ellendale, N. Dak., drilled in 1923.

	Thickness.	Depth.
	Feet.	*Feet.*
Soil and clay	10	10
Boulders	10	20
Gravel and sand	30	50
Soft blue clay	18	68
Dark sticky shale; thin layer of hard shale at 220 feet	152	220
Dark, nearly black shale	15	235
Firm dark shale	115	350
Hard shale	200	550
Soft dark shale	150	700
Hard grayish shale	20	720
Limestone	25	745
Hard dark shale interspersed with harder layers	75	820
Tough sticky shale	80	900
Shale with traces of sand; thin hard shale at 1,030 feet	130	1,030
Soft gray shale	22	1,052
Sandstone	28	1,080
Gray shale	3	1,083
This is the depth at which the well was completed, but a 3-inch test hole was sunk in search of additional sandstones to a depth of 1,260 feet through formations as follows:		
Gray shale; hard shell 7 inches thick at 1,135 feet	52	1,135
Soft gray shale	55	1,190
Sand	3	1,193
Gray shale	4	1,197
Sand	2	1,199
Gray shale (shading lighter)	61	1,260



● Wells drilled to the Dakota sandstone, that were still flowing in 1923

○ Wells drilled to the Dakota sandstone that originally flowed but had ceased flowing by 1923

1 0 1 2 3 4 5 6 7 MILES

Contour interval 100 feet

The heavy lines show, as nearly as could be determined, the original west boundary of the area of artesian flow and the boundaries in 1915 and 1923

MAP OF THE EDGELEY QUADRANGLE, N. DAK., SHOWING DECLINE IN ARTESIAN HEAD

The Edgeley quadrangle is well adapted for a study of decline in artesian head. Originally the area of artesian flow covered the entire plain and extended high up the escarpment, but apparently it never extended across the Coteau. As the head declined the boundary of the area of artesian flow gradually receded toward the east, but in 1923 it was still in the Edgeley quadrangle. (See Pl. VII.)

ARTESIAN HORIZONS IN THE DAKOTA SANDSTONE.

The artesian well drilled at Ellendale in 1886 is 1,087 feet deep and ends in what is regarded as the upper part of the Dakota sandstone; an artesian well drilled at the same place in 1908 extends to a depth of 1,385 feet and ends in sandstone that is regarded as belonging to the lower part of the Dakota. The sandstone of the upper part does not form a single stratum but rather an indefinite group of sandstone strata and lenses interbedded with shale; the sandstone of the lower part has been reached by so few wells that there is no very definite information as to its thickness and character. However, the upper and the lower sandstones are separated from each other by an effective and widespread confining bed, as is shown by the striking differences in both chemical composition and artesian head of the waters from the two sources.

The upper water is relatively soft, whereas the lower water is extremely hard; moreover, the upper water contains large amounts of common salt and tastes salty, whereas the lower water contains relatively small amounts of common salt but very large quantities of the sulphates. The upper water is generally regarded as less objectionable for household uses than the lower water. It is excellent for laundry and toilet uses and is everywhere used for livestock, but it is too salty to be satisfactory for drinking by man and is injurious to vegetation when used for irrigation. The lower water is very unsatisfactory for laundry and toilet uses or for drinking by man, but it can be used for livestock and is not very injurious when used for irrigation. Prior to the completion of the new well in 1923 both kinds of water were supplied by the city waterworks to the people of Ellendale. Over Sunday and Monday the smaller supply of soft water from the upper part of the Dakota was pumped into the system to furnish water for toilet and laundry uses, but later in the week the hard water from the deep well was pumped into the system and was used for sprinkling lawns and irrigating gardens.

The differences in the chemical composition of the upper and lower waters are shown by the following analyses:

Analyses of water from artesian wells at Ellendale, N. Dak.

[Samples collected June 28, 1921, by Howard E. Simpson; analyzed by H. B. Riffenburg. Parts per million.]

	Upper.	Lower.
Silica (SiO_2)	19	17
Iron (Fe)	2.0	2.3
Calcium (Ca)	30	204
Magnesium (Mg)	13	64
Sodium and potassium (Na+K)	990	320
Bicarbonate radicle (HCO_3)	495	171
Sulphate radicle (SO_4)	236	1,200
Chloride radicle (Cl)	1,150	70
Nitrate radicle (NO_3)	Trace.	Trace.
Total dissolved solids at 180° C	2,700	2,079
Hydrogen sulphide (H_2S)		3.4
Total hardness as $CaCO_3$ (calculated)	128	772

The difference in head of the water from the two sources is as notable as the difference in chemical composition. In 1908, when the 1,385-foot well was drilled, the water is reported to have had a pressure at the surface of 193 pounds to the square inch, or sufficient to rise to a level 1,895 feet above sea level. This was a somewhat higher head than the original head reported for the 1,087-foot well and apparently about 300 feet higher than the head of the 1,087-foot well in 1908. So few wells have been drilled to the lower horizon that in 1923 the deep well at Ellendale still had a pressure of 50 to 60 pounds to the square inch, giving a head of about 115 to 140 feet above the surface, whereas the new 1,083-foot well at the time it was completed in December, 1923, had a pressure just sufficient to bring the water to the surface without overflowing. The deep well at La Moure, which also extends to the hard-water horizon, was tested in 1923 and was found to have a pressure of 97 pounds to the square inch.

Nearly all the artesian wells in the Edgeley quadrangle and adjacent region end in the so-called upper part of the Dakota sandstone and draw from the same general group of strata as the 1,087-foot and 1,083-foot wells at Ellendale. The present paper relates entirely to this upper part of the Dakota sandstone.

HISTORY OF ARTESIAN-WELL DRILLING IN THE EDGELEY QUADRANGLE.

The first well drilled to the Dakota sandstone in the Edgeley quadrangle was doubtless the well at Ellendale, which was put down in 1886. It was started with an 8-inch or 10-inch casing but was finished at the bottom with 3¾-inch casing, the lower 40 feet of which was perforated with ¾-inch holes. The next well drilled to the Dakota sandstone in the quadrangle of which there is any record is the city well at Edgeley, which is reported to have been 6 inches in diameter and to have been put down in 1892. C. E. Turnbaugh, who made the survey in 1923 for the present report, has been a driller in the Edgeley quadrangle since 1902. In so far as he has information these two wells were the only wells drilled to the Dakota sandstone prior to 1902. In 1902 he drilled a 2½-inch well for the village of Monango. About this time wells with small diameter came into use throughout the artesian basin, and owing to their low cost numerous 1¼ and 1½ inch wells were put down for farm supplies. Most of the artesian wells in the Edgeley quadrangle were drilled between 1904 and 1912; drilling was most active between 1905 and 1910, and very few artesian wells have been drilled since 1915.

ORIGINAL HEAD AND AREA OF ARTESIAN FLOW.

The original artesian head in different parts of the area can never be ascertained with great precision. The artesian-water map of South Dakota by Darton,[12] which was published in 1909 but which doubtless shows the approximate conditions at a considerably earlier time, indicates that in the southern part of the Edgeley quadrangle the area of artesian flow extended westward nearly to the 1,800-foot contour. It also indicates that in this part of the artesian basin the hydraulic gradient, or eastward decrease in artesian head, was about 4 feet to the mile. This agrees approximately with an original hydraulic gradient of 4⅓ feet to the mile from Highmore to Huron, S. Dak., as given by Powell[13] in 1890. According to Powell's report,[14] made in 1890, the pressure of the water in the well at Ellendale drilled in 1886 was 175 pounds to the square inch. According to Mr. J. R. Lacey, a resident of Ellendale, who was present when this well was drilled and who is probably the best-informed man on the entire history of the artesian wells at Ellendale, the pressure in this well was measured on the day the well was completed and was found to be 145 pounds. In the report by Nettleton,[15] published in 1892, a pressure of 115 pounds is given for this well, apparently based on measurements made by Nettleton in 1890. It seems reasonable to believe that the records of very high original pressure in the earliest wells drilled to the Dakota sandstone are approximately

[12] Darton, N. H., Geology and underground waters of South Dakota: U. S. Geol. Survey Water-Supply Paper 227, pl. 11, 1909.
[13] Powell, J. W., op. cit., p. 273.
[14] Idem, p. 269.
[15] Nettleton, E. S., op cit., pp. 67, 68, table opposite p. 74.

correct. Such pressures were doubtless maintained only a short time and hence were not corroborated by reliable measurements a few years later. It is evident also that those who made and reported the reliable measurements a few years later were not alert for data as to decline but rather assumed that the high pressures and flows were permanent. A pressure of 145 pounds at Ellendale would give a head of about 1,785 feet with reference to sea level—that is, it would be sufficient to raise the water in a casing or standpipe to an altitude of 1,785 feet above sea level. If the original head at Ellendale was 1,785 feet and the original hydraulic gradient 4 feet to the mile, the original west boundary of the area of artesian flow was about 16 miles west of Ellendale, at an altitude of about 1,850 feet above sea level.

An artesian-water map, by Darton and Willard,[16] of the Jamestown quadrangle, which lies immediately north of the Edgeley quadrangle, was published in 1909 but is based on studies made in earlier years. It shows the west margin of the area of artesian flow at the boundary between the Jamestown and Edgeley quadrangles to have been at about 1,725 feet above sea level. According to the available record, the city well at Edgeley, drilled in 1892, had an original pressure of 60 pounds to the square inch, or a head of about 1,690 feet with reference to sea level. Therefore if in 1892 the gradient was 4 feet to the mile, the west margin of the area of artesian flow lay about 6 miles west of Edgeley, or about 1,715 feet above sea level. The original pressure in the vicinity of Edgeley was probably somewhat greater than the pressure recorded in 1892.

In view of these data it seems reasonable to assume that the original west boundary of the area of artesian flow in the Edgeley quadrangle ranged from somewhat less than 1,800 feet above sea level in the northern part to somewhat more than 1,800 feet in the southern part and had an average altitude of fully 1,800 feet.

DECLINE IN HEAD FROM 1886 TO 1923.

The well at Monango, drilled in 1902, is reported to have had an original pressure of 70 pounds to the square inch, or a head of about 1,660 feet with reference to sea level—about 125 feet less than the Ellendale well in 1886, about 55 feet less than the Ellendale well in 1890, and about 30 feet less than the Edgeley well in 1892. Other data (given in the unpublished table) indicate a considerable drop in head prior to 1902.

During the period from 1902 to 1915, which was the period of active well drilling, the artesian head dropped rapidly. According to computations on 20 wells for which more or less satisfactory data

[16] Willard, D. E., U. S. Geol. Survey Geol. Atlas, Jamestown-Tower folio (No. 168), 1909.

are available, the average annual decline during this period was 12.7 feet, which for the whole period would amount to 165 feet.

During the period from 1915 to 1920 the decline, according to similar computations on 12 wells, averaged about 4 feet a year, or about 20 feet for the period. During the period from 1920 to 1923 the decline, according to computations on 20 wells, averaged about 4 feet a year, or about 12 feet for the period.

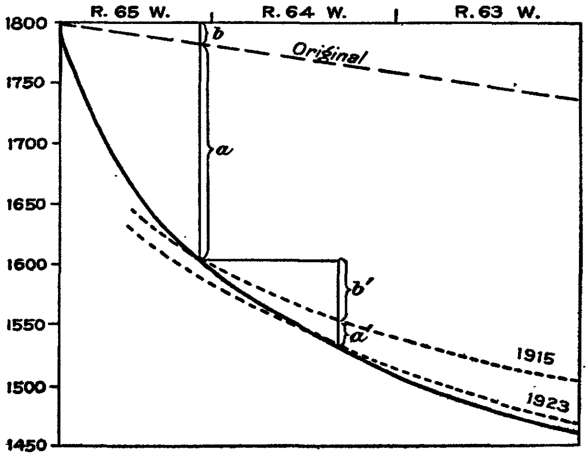


FIGURE 8.—Generalized east-west section of the area of artesian flow in the Edgeley quadrangle, N. Dak., showing approximately the profile of the land surface, the original hydraulic profile, and the hydraulic profiles in 1915 and 1923. The hydraulic profile for any particular year indicates how high the water from the upper part of the Dakota sandstone would rise at each point along the section in that year. *a*, Decline in head prior to 1915 in wells at position of artesian boundary in 1915; *b*, original difference in head between wells at original boundary and wells at boundary in 1915; *a′*, decline in head from 1915 to 1923 in wells at position of artesian boundary in 1923; *b′*, difference in head in 1915 between wells at boundary in 1915 and wells at boundary in 1923. $a+b$, Descent of artesian boundary prior to 1915; $a'+b'$, descent of artesian boundary from 1915 to 1923; $(a+b)+(a'+b')$, total descent of artesian boundary prior to 1923.

The foregoing computations are based on available wells within the original area of artesian flow in the Edgeley quadrangle and in a belt several miles wide adjacent to this quadrange on the south. They indicate a decline of about 200 feet from 1902 to 1923 and a considerably greater decline from 1886 to 1923. Computations that take into account the geographic distribution of the wells (see pp. 84 and fig. 8) indicate, however, that the average decline for the entire area has not been quite so great. On the assumption that the original pressure in the Ellendale well was 145 pounds to the square inch, they indicate that the decline in the southeast corner of the quadrangle amounted to over 300 feet, but that the average for the entire area was more nearly 250 feet. If the original pressure at Ellendale was 175 pounds to the square inch the total decline was about 70 feet greater.

SHRINKAGE IN THE AREA OF ARTESIAN FLOW.

According to the lower assumption as to the original head, the area of artesian flow originally extended westward to an altitude of somewhat less than 1,800 feet near the north margin of the Edgeley quadrangle and to an altitude of somewhat more than 1,800 feet near the south margin. In 1902 it apparently still extended to an altitude of 1,700 feet or more, except possibly near the north margin of the quadrangle. By 1915 the west boundary of the area of artesian flow had come down the slope about 200 feet, so that it lay somewhat below the 1,600-foot contour in the northern part of the quadrangle and somewhat above the 1,600-foot contour in the southern part (Pl. VII and fig. 8). By 1923 this artesian boundary had migrated eastward to the flat land, where the slope of the surface nearly coincided with the hydraulic gradient, and over a wide belt the artesian water rose to about the surface—slightly above the surface in some wells and slightly below in others. Therefore, in 1923 the boundary of the area of artesian flow was a less definite line than it had been originally or in 1915. It is, however, approximately correct to say that from 1915 to 1923 the boundary descended about 75 feet, and that in 1923 it was about 1,500 feet above sea level at the north margin of the quadrangle and about 1,550 feet at the south margin (Pl. VII and fig. 8). A considerable part of this descent occurred between 1920 and 1923. According to the lower assumption as to the original head, the total descent of the west boundary of the area of artesian flow from the time the first wells were drilled until 1923 was about 275 feet. The belt in which flowing wells were originally obtained but in which the wells have ceased to flow is about 10 miles wide in the northern part of the quadrangle and 5 miles wide in the southern part (Pl. VII). Fully half of this belt has "gone dry" in the 8-year period since 1915, during which only a few wells were drilled.

INCREASE IN HYDRAULIC GRADIENT.

A geographic analysis of the data indicates that the decline in artesian head has been greater along the east margin of the Edgeley quadrangle than farther west and hence that the hydraulic gradient has increased. According to the best information available, the original gradient was only about 4 feet to the mile, whereas the gradient in 1923 was about 10 feet to the mile in the eastern part of the quadrangle and fully 15 feet to the mile west of the 1,600-foot contour (fig. 8). These figures may be considerably in error, the original gradient especially being in doubt, but the available records of decline from year to year in artesian head and in depths to the water level in wells that have ceased to flow give evidence of relatively small decline in head in the western part of the original area of artesian flow. They seem to lead to the significant conclusion that the effect of the great decline in head becomes slight or dies out entirely long before the western outcrops of the sandstone are reached.

CORRELATION OF DECLINE IN HEAD WITH DESCENT OF ARTESIAN BOUNDARY.

According to the computations, the results of which have been given, the descent of the artesian boundary was less than the average decline in head during the period prior to 1915 but much greater than the average decline during the period from 1915 to 1923. To the casual reader these differences may appear to be discrepancies in the results. On account of the fragmentary and uncertain data in regard to conditions in the early years of artesian development, no claim of accuracy can be made for these computations, but it should be noted that the results are about as would be expected when the topography and the changes in hydraulic gradient are taken into consideration.

In Figure 8 the vertical distance a represents the decline in head prior to 1915 at the point shown, and the vertical distance $a+b$ represents the descent of the artesian boundary prior to 1915. Because of the steep slope of the land surface the large decline in head did not produce any great lateral movement of the artesian boundary. For this reason and because of the slight original hydraulic gradient the descent of the artesian boundary ($a+b$) was only slightly greater than the decline in head (a) at the point shown. But farther east the decline in head was greater than at this point, as is indicated in Figure 8 by the increased vertical distance to the east between the original hydraulic profile and the hydraulic profile in 1915. Hence the vertical distance through which the artesian boundary descended during this early period was somewhat less than the average decline in head.

The vertical distance a' represents the decline in head from 1915 to 1923 at the point shown, and the vertical distance $a'+b'$ represents the descent of the artesian boundary during this period. Because of the more gentle slope of the land surface in the belt through which the artesian boundary had to pass in this later period the relatively small decline in head (a') produced fully as great a lateral movement of the artesian boundary as had been produced by the great decline (a) in the period prior to 1915. For this reason and because of the greater hydraulic gradient the descent of the artesian boundary $(a'+b')$ was much greater than the decline in head at the point shown (a') and also much greater than the average decline in head.

YIELD OF FLOWING WELLS AND DECLINE IN YIELD.

The flow of the 3¾-inch well at Ellendale drilled in 1886 was 600 gallons a minute according to Powell's report,[17] published in 1891, and 700 gallons a minute in 1890 according to the Nettleton report,[18] published in 1892. The original flow of the 6-inch well at Edgeley drilled in 1892 is reported to have been 500 gallons a minute.[19] The 2½-inch well drilled at Monango in 1902 is reported by C. E. Turnbaugh, the driller, to have had an original flow of only 45 gallons a minute.

According to an estimate by Hard, the original discharge of 1¼-inch wells drilled prior to 1915 in the Edgeley and La Moure quadrangles was about 50 to 100 gallons a minute. According to the estimates of Turnbaugh and other drillers and well owners, as given in the unpublished table, the original discharge of 116 wells drilled in the Edgeley quadrangle from 1902 to 1914, inclusive (not including the deep well drilled at Ellendale in 1908 to a deeper horizon), was only 22⅓ gallons a minute. These 116 wells were nearly all 1¼ or 1½ inches in diameter.

Hard also estimated for the Edgeley and La Moure quadrangles that in 1915 the flow from 1¼-inch wells was 5 to 10 gallons a minute near the west side of the area of artesian flow and 15 to 40 gallons farther east. However, the average discharge of 20 wells measured in 1915 by H. M. Derr,[20] State engineer of South Dakota, in Brown County, which lies south of these quadrangles, was only about 11 gallons a minute.

The flow of 41 wells measured by Hard in the Edgeley quadrangle in 1919 and 1920 ranged from a fraction of 1 gallon a minute to 20 gallons a minute and averaged 7⅔ gallons.

In 1923 the flow of 111 artesian wells was measured by Turnbaugh—all in the Edgeley quadrangle except a few that were just outside. This list included nearly but not quite all the flowing wells in the quadrangle. The 111 wells were found to have an aggregate flow of 343 gallons a minute, or an average flow of 3.09 gallons a minute. With few exceptions the flows were measured after the wells had been opened as much as possible, and the results therefore represent more than the actual discharge of the wells in their normal condition.

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[17] Powell, J. W., op. cit., p. 269.
[18] Nettleton, E. S., op. cit., table opposite p. 74.
[19] Darton, N. H., U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, p. 661, 1896.
[20] Derr, H. M., op. cit., pp. 177–187, 244–248.

SPECIFIC CAPACITIES OF FLOWING WELLS.

The specific capacity of a flowing well is its flow per foot of head. If there is no change in the intake facilities of a well, its specific capacity will remain nearly the same whether the head is high or low. Thus if the specific capacities of the wells that tap the Dakota sandstone can be determined they will give a check on the reported flows of the wells in the earlier years when the heads were high and will also give a clue as to the permeability of the sandstone and hence as to the rate of recharge.

For 23 wells in the Edgeley quadrange there is fairly reliable information as to head and flow, which was used in calculating the specific capacities of these wells. For four of these wells check calculations could be made, because this information was available for different years and hence for different heads. In one of these four wells the specific capacity was 0.40 gallon a minute for each foot of head in 1906 and 0.25 in 1920; in another it was 0.15 in 1909 and 0.24 in 1915; in a third it was 0.28 in 1902 and 0.29 in 1920; and in the fourth it was 0.09 in 1920 and 0.09 in 1923. Thus the calculations for different years and very different heads agreed as closely as could be expected.

The data in regard to the specific capacities of the 23 wells for which calculations could be made are summarized in the following table:

Specific capacities of wells in the Edgeley quadrangle.

Diameter (inches).	Number of wells.	Specific capacity (gallons a minute for each foot of head).		
		Maximum.	Minimum.	Average.
6	1	3.62	3.62	3.62
3¾	1	2.64	2.64	2.64
2½	1	.29	.29	.29
2	4	1.40	.57	.80
1½	3	.57	.20	.35
1¼	12	.36	.09	.22
1	1	.14	.14	.14
1 to 2 (inclusive).	20	1.40	.09	.25

If the average flow of the small wells is one-fourth gallon a minute for each foot of head, then the average flow should have been 50 gallons a minute when the head was 200 feet, 25 gallons when it was 100 feet, 10 gallons when it was 40 feet, 3 gallons when it was 12 feet, and so on.

TOTAL DISCHARGE OF FLOWING WELLS.

As the water in the Dakota sandstone comes from the west and moves in general toward the east, a study of discharge, recharge, and depletion of the artesian-water supply should obviously relate to an east-west belt extending across the entire area of artesian flow unless a complete survey of the entire basin can be made. Hence for this purpose calculations have been made for the tract covered by T. 129 N., Rs. 48–65 W., and not for the Edgeley quadrangle (fig. 7, p. 76).

It was estimated by Darton [21] that in 1896 the total discharge from flowing wells which ended in the Dakota sandstone in the area that he covered was 104,000 gallons a minute. This area included most of the area of artesian flow of the Dakota sandstone in North and South Dakota and had a north-south extent of nearly 300 miles. His estimate therefore gives an average discharge of a little more than 2,000 gallons a minute for an east-west row of townships in the area. As most of the strong wells were in South Dakota, the average for the part of the area that lies in North Dakota must have been much less than 2,000 gallons a minute. The only well in the T. 129 row shown by Darton's report was the Ellendale well, with a flow of 700 gallons a minute.

In 1923, in connection with the enforcement of the artesian-water law, practically all flowing wells in this row of townships were inspected by Howard E. Simpson, water geologist of the North Dakota Geological Survey, and his deputy, C. E. Turnbaugh. The data obtained in this inspection were generously furnished by Professor Simpson for use in this report. They show that in T. 129 N., Rs. 50 to 65 W., inclusive, there were 320 flowing wells supplied by the Dakota sandstone, which were normally discharging an aggregate of 965 gallons a minute, or an average per well of 3.02 gallons a minute. In addition were the wells that supplied the waterworks in six towns and five farm wells that were closed except when the faucets were turned on. It was estimated that an average of about 40 gallons a minute was drawn from these wells, making an aggregate flow of 1,005 gallons a minute. It was estimated by Simpson and Turnbaugh that the aggregate flow in this row of townships in 1923 was about one-half the aggregate flow in 1920—that is, that the flow from all wells in this row of townships in 1920 was about 2,000 gallons a minute, or about 6 gallons a minute per well. No flowing wells were reported in T. 129 N., Rs. 48 and 49 W.

On the basis of all available data and with the assumption that the history of well drilling in the T. 129 row was similar to that given for the Edgeley quadrangle, a rather elaborate calculation was made of the quantity of water that has been discharged from the Dakota sandstone through wells in this row of townships. This calculation gave an average discharge during the 38-year period from

[21] Darton, N. H., U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, p. 609, pl. 69, 1896.

1886 to 1923 of somewhat less than 3,000 gallons a minute. The peak discharge doubtless occurred at some time between 1905 and 1910 and probably did not exceed 10,000 gallons a minute. It is recognized that these estimates may be very inaccurate, but they are probably as good as can ever be made and are believed to be worth presenting in order to give some tangible conception of the quantities of water that are involved and the stage of depletion that has been reached. It is believed that the total quantity of artesian water discharged at the surface in an average row of townships in this artesian basin in North Dakota did not exceed the quantity represented by these figures—that is, 3,000 gallons a minute for a period of 38 years. No estimate can be made of the underground waste through leaky casings. However, it is generally believed by those best qualified to judge that the aggregate underground waste is not very large, because of the great thickness of plastic clay that tends to seal the old wells when the casing becomes corroded.

BENEFICIAL FLOW AS ESTIMATED BY THE STATE GEOLOGICAL SURVEY.

On the basis of the information obtained in the inspection a careful estimate was made by Professor Simpson of the extent to which each of the 320 wells can be reduced in order to stop all unnecessary discharge without depriving the farmer of any beneficial use or working any hardship. The term "unnecessary discharge" is used to designate the discharge that serves no useful purpose. Reasonable allowances were made for a flow of water that will run to waste but will be necessary to prevent freezing of the pipes or clogging of the well. The results of this work showed that by stopping the unnecessary discharge the flow can be reduced to 377 gallons a minute from the 320 wells, or to an average of 1.18 gallons a minute per well. This makes the aggregate beneficial flow amount to 417 gallons a minute from existing wells in this row of townships, including the necessary flow from the waterworks wells and the closed farm wells.

RATE OF RECHARGE.

An effort was made to estimate for the T. 129 row of townships the rate at which the water in the Dakota sandstone is percolating eastward in the direction of the hydraulic gradient. It was assumed that, whereas the townships both to the north and to the south have similar artesian-water developments, this row of townships is supplied by the artesian water directly west of it and neither draws from nor contributes to the adjacent townships. Such an estimate would be of great practical value, because it would serve as a basis for judging how much further the discharge must be reduced, either by natural lowering of the head or by voluntary or enforced conservation, before a balance is struck between discharge and recharge. Unfortunately the information in regard to both thickness and texture of the water-bearing sandstone strata is so meager and unsatisfactory that it is impossible to make any estimate in which much confidence can be placed. Calculations based on Slichter's formula[22] show, however, that if the hydraulic gradient is 10 feet to the mile and the sandstone strata which supply the wells under consideration have a thickness of 60 feet, a porosity of 35 per cent, and an effective size of grain of 0.17 millimeter—the same as that of the St. Peter sandstone as determined in numerous tests[23]—the rate of recharge or eastward percolation is about equal to the 417 gallons a minute estimated by Simpson as the quantity needed for present beneficial use without any unnecessary discharge and without allowing anything for possible underground leakage. There are no good reasons for believing that the rate of recharge is greater than this amount.

It is at least interesting to recall that in 1890, when the artesian wells still had tremendous pressure and flow, Major Powell, at that time Director of the United States Geological Survey, estimated in a hearing before a Congressional committee, on an entirely different basis, that the total recharge amounted to about 475 gallons a minute for each row of townships and the recoverable recharge to one-half that amount.[24]

WITHDRAWAL OF STORED WATER AND COMPRESSION OF THE DAKOTA SANDSTONE.

The foregoing considerations raise the question as to the source of the artesian water that has been discharged during the last 38 years and that is being discharged at present. If the rate of discharge in the area of artesian flow has been more rapid than the rate at which water percolated into the sandstone underlying this area, some of the water discharged must have been derived from storage in the sandstone underlying the area. This requires a reduction in the interstitial space occupied by water. Either the water was replaced in some of the interstices by gas, or else the sandstone has a volume elasticity, so that, as the buoying force of artesian pressure within the sandstone was relieved, the sandstone underwent a certain amount of

[22] Slichter, C. S., Field measurements of the rate of movement of underground water: U. S. Geol. Survey Water-Supply Paper 140, pl. 2, 1905.

[23] Dake, C. L., The problem of the St. Peter sandstone: Missouri Univ. School of Mines and Metallurgy Bull., August, 1921, pp. 152–177. See also Meinzer, O. E., U. S. Geol. Survey Water-Supply Paper 489, pp. 119, 120, 1924.

[24] Powell, J. W., op. cit., p. 274.

compression in which its total interstitial space was reduced by a volume equal to the volume of the stored water that was discharged. The theory of gas accumulation is believed to be untenable. In his unpublished report Hard states that the gas discharged by some of the wells seems to occur as an unsaturated solution in the artesian waters of the Dakota sandstone and apparently is released from solution by the reduction of pressure incident to the rise of the water to the surface. There is no indication that gas occurs in the sandstone in the gaseous state at the present time.

If the theory of gas accumulation is dismissed the theory of volume elasticity and resulting compression of the sandstone is supported by two other lines of evidence—the apparently rapid dying out toward the west of the decline in artesian head, and the long period required for a flowing well to recover its full pressure after it has been closed and a pressure gage has been attached.

If the formation were perfectly rigid any lowering in artesian head ought to result in a prompt readjustment of the hydraulic gradient all the way to the outcrop from which the water is derived, hundreds of miles away, and ought to produce a somewhat more rapid percolation in all this distance. The comparatively small decline in the water level in wells near the west side of the original area of artesian flow, however, seems to indicate that in all these years readjustment of the hydraulic gradient has not extended west many miles, or, at least, that long before the western outcrops are reached the readjustment becomes very small. If this is true the hydraulic profile is like the profile of a water table where there has been depletion of storage in the vicinity of heavily pumped wells; it is not the profile that would be developed in a rigid pressure system.

In testing the artesian pressure of the flowing wells Hard found that after a well was closed and the gage was attached the pressure would increase gradually for some time. This confirmed the observations of earlier investgators.[25] Different wells behaved very differently, but the time required for the pressure to reach a maximum in some wells amounted to several hours. When the Ellendale well was tested in 1890 it was found that a few hours was required for the water to reach its maximum pressure after the flow had been shut off.[26] The explanation seems to be that the water-bearing bed has a certain amount of volume elasticity, that it became compressed when the artesian pressure was relieved, and that before the pressure in the well could again reach the pressure that was general in the formation sufficient time had to elapse to allow the water to

[25] Nettleton, E. S., op. cit., pp. 40–74.
[26] Idem, p. 68.

percolate into the depleted and compressed part of the formation immediately surrounding the well and to expand the interstitial space.

If the foregoing calculations were accurate they would afford a basis for computing the amount of compression which, according to this theory, was involved. If in the last 38 years the average rate of discharge was 3,000 gallons a minute and the average rate of recharge only 500 gallons a minute, the average withdrawal from storage amounted to 2,500 gallons a minute. If the area of depletion consists of the 18 townships described as T. 129 N., Rs. 48–65 W., a total discharge of 3,000 gallons a minute for 38 years would amount to a layer of water 5.3 inches deep over all of this area, and a withdrawal from storage of 2,500 gallons a minute would amount to a layer of water 4.4 inches deep.

The first well at Ellendale, according to the log on page 78, reached the Dakota sandstone at a depth of 1,035 feet and penetrated the Dakota 52 feet. The beds above the Dakota are chiefly soft shale, which, with the water they contain, must have a specific gravity of about 2. Hence these beds, owing to their weight, exert a pressure equal to that of a column of water about 2,070 feet high, or 898 pounds to the square inch. If the original head of the artesian water in this well was 333 feet at the surface (145 pounds to the square inch), then the artesian pressure at the top of the Dakota sandstone was that of a column of water 1,368 feet high, or 594 pounds to the square inch. Therefore, 594 pounds to the square inch of the pressure exerted by the beds that overlie the Dakota sandstone was supported by the water in the sandstone, and only 304 pounds by the sandstone itself. If at any point within the area of artesian flow the head at the surface was as great as the depth to the Dakota sandstone the artesian pressure must have been great enough virtually to float the overlying beds. As the head at Ellendale has declined approximately 333 feet (145 pounds to the square inch) the burden placed on the sandstone has increased from about 304 pounds to 449 pounds, or 47½ per cent. If the original pressure in the Ellendale well was 175 pounds the burden has increased 61⅓ per cent. It has long been known that at least slight compression of water-bearing beds may result from additional loads at the surface, such as tides or even railroad trains.[27] It is also well known that, other things being equal, the porosity of rocks decreases with depth because of increase in the weight they must support.[28] It seems within the range of

[27] Veatch, A. C., Fluctuations of the water level in wells, with special reference to Long Island: U. S. Geol. Survey Water-Supply Paper 155, pp. 65, 75, 1906.

[28] Sorby, H. C., On the application of quantitative methods to the study of the structure and history of rocks: Geol. Soc. London Quart. Jour., vol. 64, p. 214, 1908. Meinzer, O. E., U. S. Geol. Survey Water-Supply Paper 489, p. 8, 1924.

possibility, therefore, that the upper part of the Dakota sandstone, which is here being considered, should have undergone a compression of a few inches—probably less than 1 per cent—as a result of the release of the expansive force of artesian pressure and a consequent increase of about one-half in the load upon the formation.

In order to obtain a more adequate basis for conclusions as to the behavior of the artesian water precise data are greatly needed (1) as to the mechanical composition, porosity, and permeability of the sandstone in each stratum of the Dakota sandstone and (2) as to the fluctuation of the artesian head in flowing wells and of the water level in nonflowing wells that end in the Dakota sandstone—in the areas of artesian flow, at the outcrops, and so far as possible at intermediate points. These observations on artesian head and water levels are needed not only to determine the hydraulic profile and its progressive modification but also to ascertain to what extent seasonal fluctuations in the water table at the outcrops are transmitted to the remote parts of the formation.

BENEFICIAL EFFECT OF THE CONSERVATION POLICY ADOPTED BY THE STATE OF NORTH DAKOTA.

All the theoretical considerations above set forth have an intensely practical bearing on the policy of conservation of the artesian water that has been adopted by the State of North Dakota. The great and progressive decline in artesian head is well established, and the desirability of preventing further decline and of saving the wells that are still flowing is generally recognized. The only question that remains is whether the decline can be stopped by the measures that are being put into effect. Although satisfactory data as to the rate of recharge are lacking, enough information has been obtained on the subject to indicate that the conservation already effected and the further conservation outlined by Howard E. Simpson, the water geologist of the State Geological Survey, will tend to keep the wells flowing.

Decline in artesian head will cease when a balance is reached between the discharge from the artesian wells and the natural recharge. Apparently this balance has not yet been reached. Between 1920 and 1923 there was considerable decline, and a number of wells ceased flowing. The annual recharge for each row of townships across the area of artesian flow east of the Coteau du Missouri is probably less than the 1,000 gallons a minute that was being withdrawn in the T. 129 row in 1923. The decrease in flow from 2,000 to 1,000 gallons a minute from 1920 to 1923 has been due only in part to natural decline. In large part it is due, according to the observations of Simpson and Turnbaugh, to the reduction of discharge openings in the artesian wells which have been made by the well owners since the artesian-water law went into effect, March 10, 1921. The reductions were made in part as a result of education and the influence of the drillers through the North Dakota Well Drillers Association. It was also estimated by Simpson that in T. 129 N., Rs. 63, 64, and 65 W., largely owing to the detailed work done in these townships by Hard, the reduction from 1920 to 1923 amounted to fully two-thirds. It is probably no exaggeration to say that the saving that has been accomplished in this row of townships through the reduction of the discharge openings of wells since the law was enacted is as great as the waste that was still going on in 1923—in other words, that one-half of the possible conservation had already been accomplished in 1923, largely through the intelligent, reasonable, and helpful campaign of education conducted by the State Geological Survey. Obviously so great a saving must have an appreciable effect in checking the rate of decline and in keeping wells flowing that would otherwise have failed by this time or would fail in the near future.

Although the rate of recharge is not definitely known, it probably amounts to a few hundred gallons a minute for each row of townships but not to as much as 1,000 gallons a minute. For the sake of seeing more clearly what will be the beneficial effect of carrying out the recommendations for further reductions made by the State water geologist, let it be assumed that the rate of recharge is equal to the 417 gallons a minute of flow recommended by him. In 1923 this amount of water was being discharged by the 48 strongest wells among the total number of a little more than 330 wells that were inspected. Obviously with this amount of recharge and no further attempt at conservation, most of the available supply will ultimately be discharged by a few of the strongest wells, and a large majority of the wells that are now flowing will either fail entirely or will not yield enough for practical purposes. On the other hand, with this amount of recharge, if all reductions are made as recommended, there will be no further decline and all the existing flowing wells will be saved. The basal assumption may be inaccurate, but the principle illustrated by it is sound. It is possible that the recharge is so small or that the underground leakage is so considerable that the ultimate failure of most of the flowing wells can not be prevented even if the program of the State Geological Survey is faithfully carried out, but the conditions are certainly hopeful enough to justify a thorough trial of this program. Every owner of a flowing well in this artesian basin should, for his own good and that of his neighbors, give his utmost support to this program for saving the artesian water.

The question is often asked whether conservation in North Dakota can be effective without conservation in South Dakota. It is highly desirable that the States should cooperate in this movement. However, the present investigation has shown that the effects of depletion in one area are not rapidly transmitted to other areas. Doubtless wells near the State line in North Dakota will suffer by waste from near-by wells in South Dakota, but this should not deter the State of North Dakota from proceeding with its well-planned program of conservation. Such a program is of course equally desirable in South Dakota.

TEMPERATURE OF WATER AVAILABLE FOR INDUSTRIAL USE IN THE UNITED STATES.

By W. D. Collins.

INTRODUCTION.

The importance of water supply as a limiting factor in industrial development is becoming more evident each year. The limitation in a particular instance may be the quantity of water available, the quality determined by the mineral matter in solution or in suspension or by organic pollution, or the temperature of the water. Generally it is a combination of two or more of these factors..

Many publications of the Geological Survey give data in regard to the quantity of surface water and ground water obtainable at different points. Other publications of this Survey and of other organizations give data on the quality of waters available for industrial use. The temperature of these waters is discussed in the present report.

Data in regard to ground water have been obtained from Geological Survey water-supply papers, from the publications indicated in footnotes, and from an unpublished compilation of temperature records prepared by C. E. Van Orstrand, of the Geological Survey, in connection with studies of deep earth temperature. Data on temperature of surface water have been obtained mainly from officials of waterworks, as noted in the accompanying table. Data on air temperature have been obtained from reports of the United States Weather Bureau. The maps showing temperature of ground water and surface water (Pls. VIII and IX) are taken directly from Weather Bureau charts of temperature distribution.

GROUND WATER.

The temperature of water in the ground at any place is in general about the same as the mean annual air temperature. Near the surface the temperature of the water follows the changes in air temperature; at greater depths the water has a higher temperature corresponding to the increase of the earth temperature with increasing depth.

The annual range in temperature of the ground decreases rapidly in the first few feet. Results of measurements of earth temperature in Japan cited by Tamura[1] show annual ranges of 51° F. at the surface, 34° at a depth of 2 feet, 9.4° at 10 feet, and only 0.7° at 23 feet. Data by Spence[2] show a similar decrease of range with depth in North Dakota. With an extreme variation in air temperature of 133° F., as given in the Weather Bureau report, the range in earth temperature was 80° at a depth of 1.2 feet, 42° at 3.7 feet, 25° at 6.6 feet, and 18° at 9.0 feet. A curve showing these results indicates that at about 30 feet the annual range would not be more than 1°. From a study of over 3,000 records of temperature of ground water C. E. Van Orstrand has computed that under normal conditions the temperature of ground water obtained at a depth of 30 to 60 feet will generally exceed by 2° or 3° the mean annual air temperature. In exceptional localities the excess may amount to 5° or 6°.

After careful examination of the available data relating to increase of earth temperature with depth a committee of the British Association for the Advancement of Science adopted as the most probable average rate an increase of 1° F. for each 64 feet of depth.[3] On this basis water from a depth of 640 feet would have a uniform temperature of 10° F. above the temperature at 30 or 60 feet. At 200 feet the increase would be only 3°.

It may be stated, then, for practical purposes that a ground-water supply obtained at any depth from 20 to 200 feet will have a uniform temperature ranging from about 3° to 6° F. above the mean annual air temperature. If the supply comes from a depth more than 300 feet the difference in temperature due to increased depth must be taken into account.

The map that shows the probable temperature of ground water in the United States at depths of 20 to 60 feet (Pl. VIII) is based on the map of the United States Weather Bureau showing normal annual air temperature. It is necessarily generalized. Closer approximation to the ground-water temperature at any place can be obtained from the detailed data in reports of the Weather Bureau, which give the normal temperatures at individual stations.

SURFACE WATER.

The relation between surface-water temperature and air temperature is much more variable than the relation between ground-water temperature and air temperature. Obviously the range in temperature of surface water will be considerable, but it is much less than the range in air temperature. Reports of the Weather Bureau give daily, mean monthly, and mean annual temperatures of the air. Of

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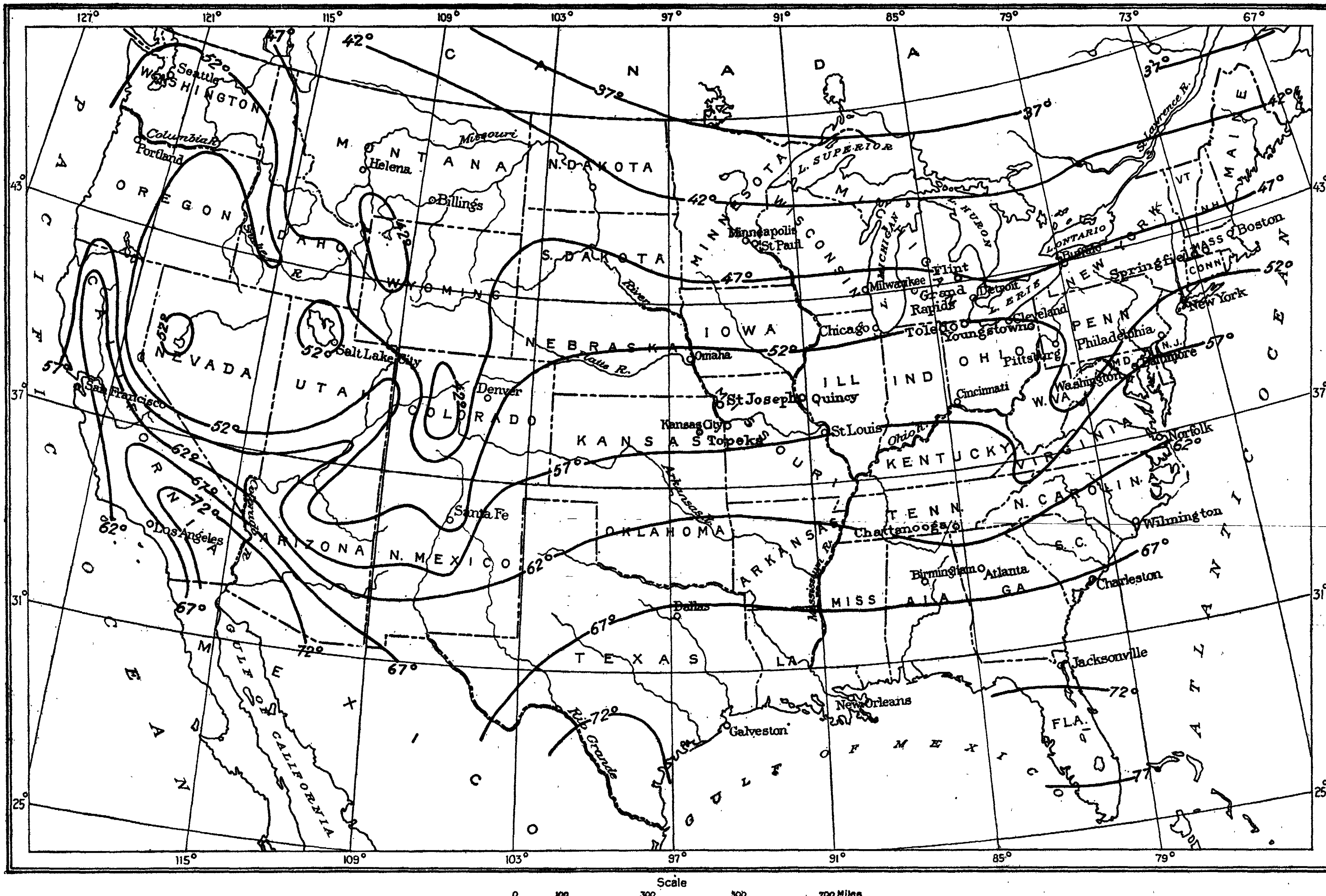
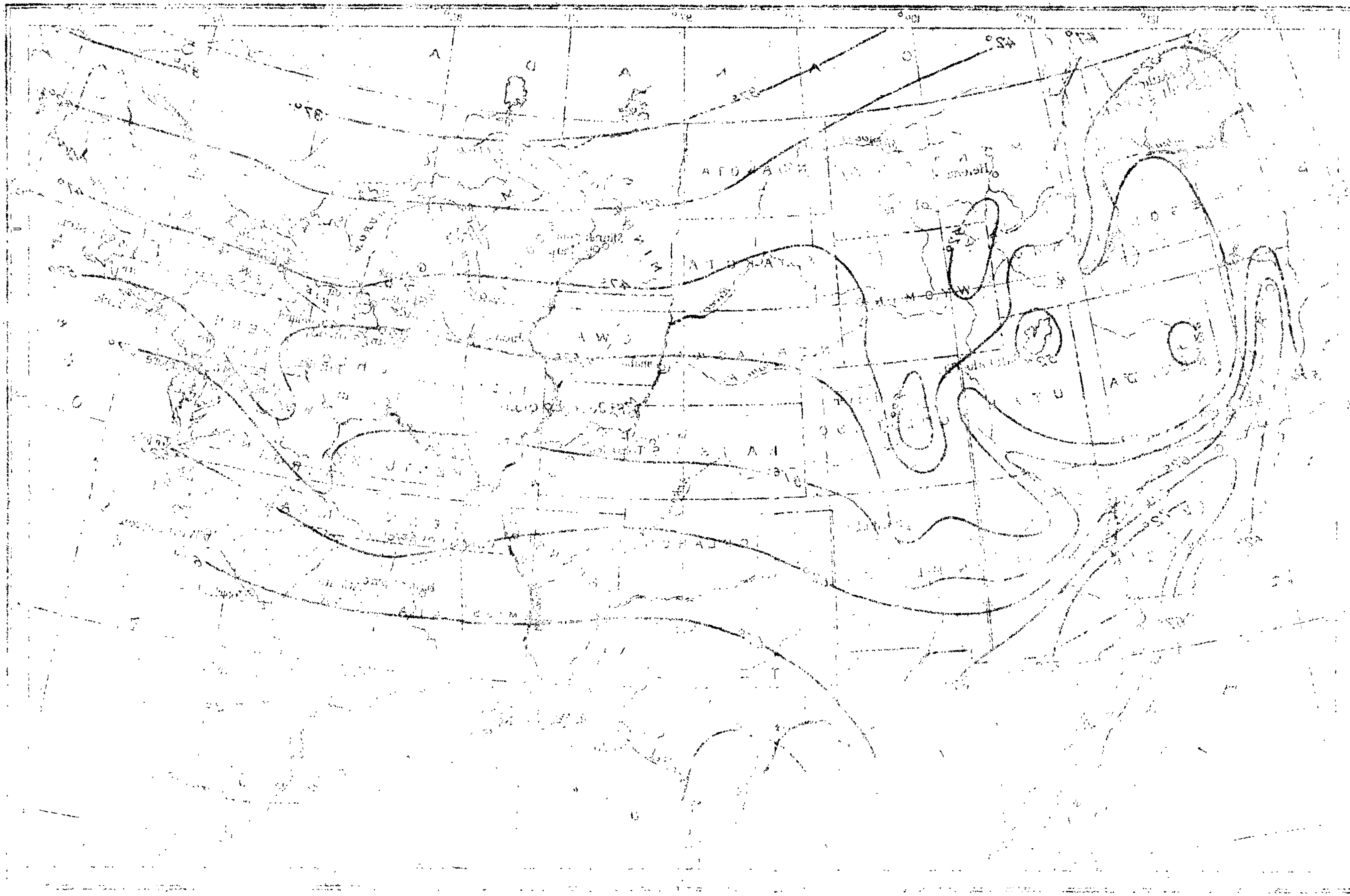
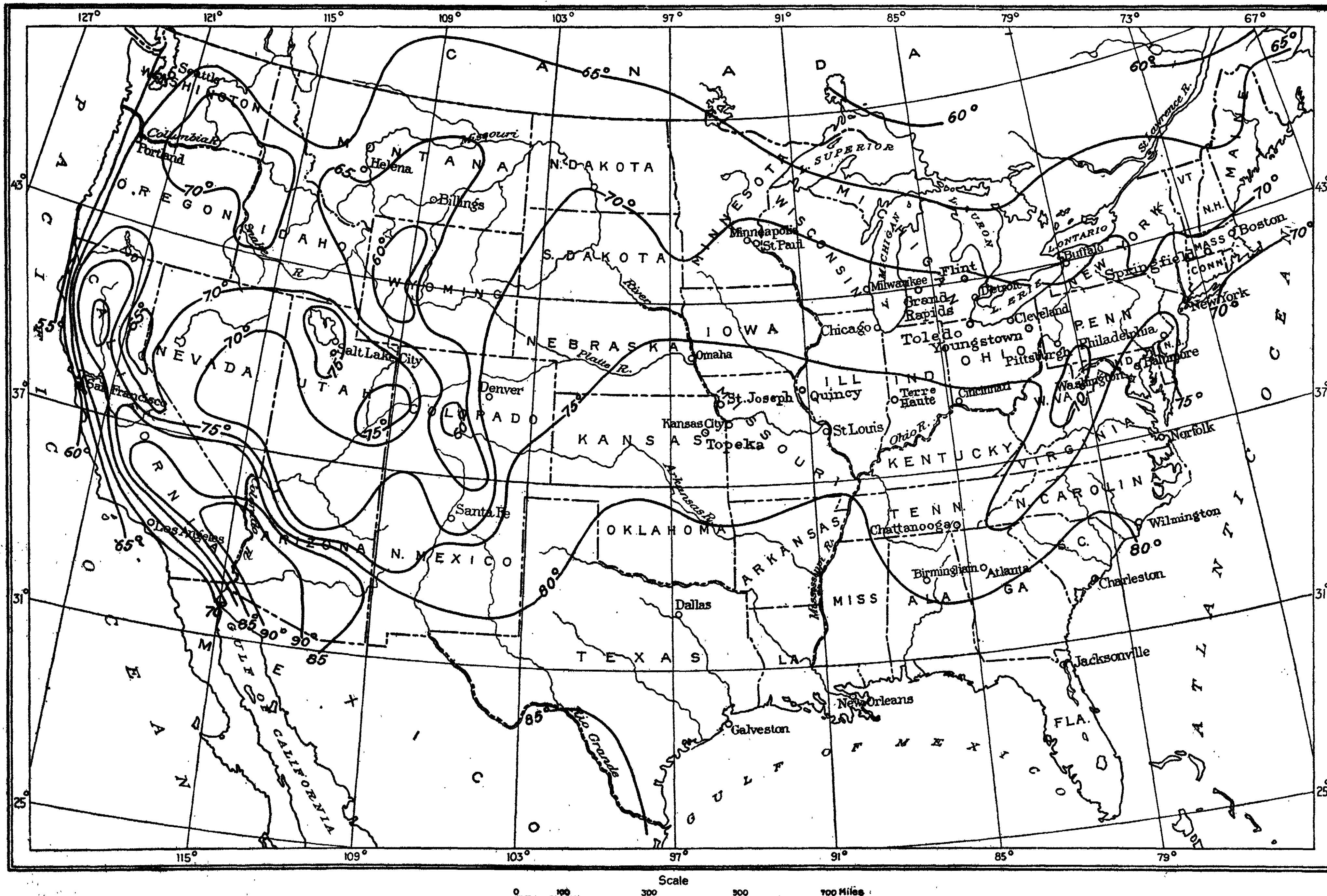
[1] Tamura, S. T., Monthly Weather Review, 1905, p. 296.
[2] Spence, B. J., North Dakota Univ. Quart. Jour., vol. 8, pp. 233–238, 1918.
[3] British Assoc. Adv. Sci. Rept. Fifty-second Meeting, p. 88, 1882.

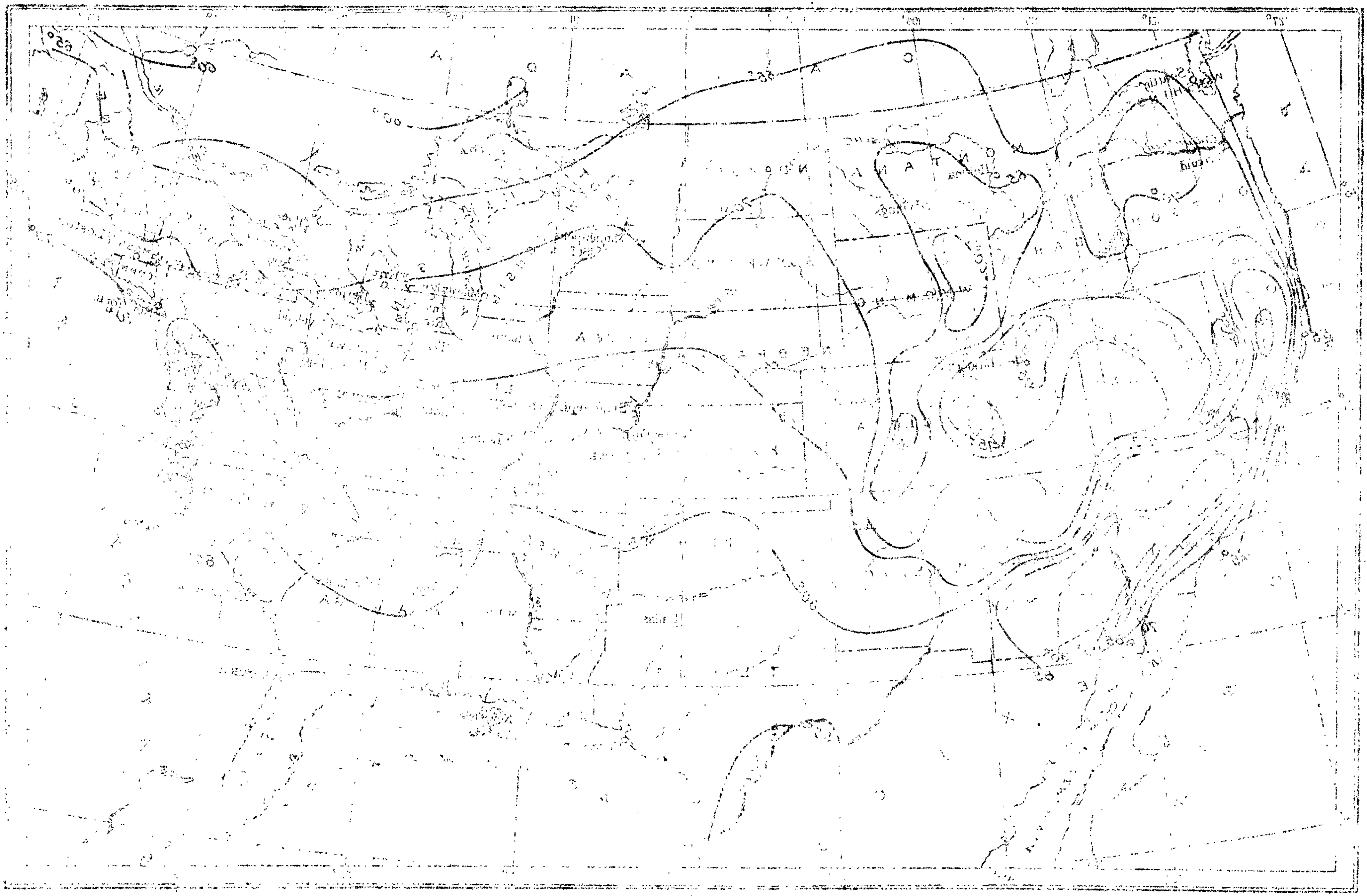


APPROXIMATE TEMPERATURE OF WATER FROM NONTHERMAL WELLS AT DEPTHS OF 30 TO 60 FEET





APPROXIMATE MEAN MONTHLY TEMPERATURE OF WATER FROM SURFACE SOURCES FOR JULY AND AUGUST



APPROXIMATE MEAN MONTHLY TEMPERATURE OF WATER FROM SHALLOW SOURCES FOR JULY AND AUGUST these the mean monthly temperature is evidently the best for comparison with the temperature of water in a river or lake.

The records of water temperature given in the table were obtained from the sources indicated. Those of air temperature were taken from the Monthly Weather Review. Information was not obtained as to the types of thermometers used to measure the water temperature, or the exact conditions prevailing when the measurements were made—factors which might affect the reliability of the figures. For the purposes of this report an error of 1° or 2° would not have much significance. There is no reason to believe that any of the figures given are in error by more than 2°, and it is doubtful if many errors exceed 1°. The water and air temperatures given are all rounded off to the nearest whole degree.

Comparisons of the mean monthly water temperature and air temperature at certain places are shown in Plates X and XI, which also show the maximum water temperature. It can be seen that during the warm months the mean monthly water temperature is generally within 3° above or below the mean air temperature and the maximum water temperature is rarely more than 4° above the mean monthly water temperature.

It is not possible to give a map showing the probable surface-water temperature as closely as the probable ground-water temperature is indicated in Plate VIII, but Plate IX gives a basis for estimating probable maximum monthly surface-water temperature. The map is the United States Weather Bureau map showing normal July temperature. It is quite certain that during July and August the surface water at most places will have a temperature not much below the mean monthly air temperature. On the average the water temperature will be within 3° above or below the mean monthly air temperature in July and from 2° to 5° above the mean in August. From the data in the table and in Plates X and XI it appears that at some places the surface-water temperature shows much more than the average difference from the mean monthly air temperature. The reasons for these departures are not hard to find.

The minimum recorded water temperature will be from 32° to 34° F. during the coldest months. As the monthly air temperature rises the water temperature is likely to rise more slowly. Early in the spring melting ice may keep the water considerably below the air temperature.

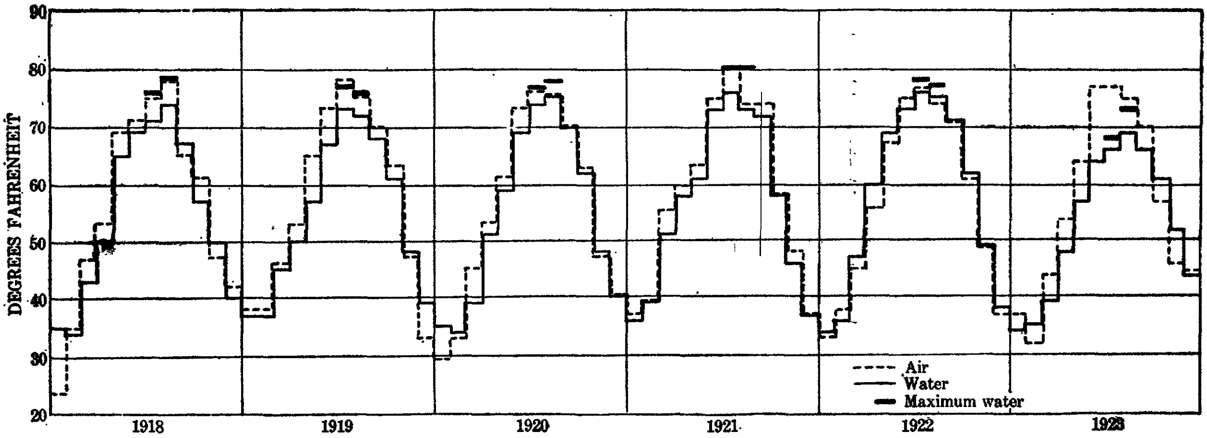
Water in a lake or large reservoir is slow in warming up to the summer air temperature. The upper 25 feet of water follows the air temperature the same as a river water. The temperature of the water below this depth rises very slowly throughout the summer, and that of the water below 75 or 100 feet may rise to only a few degrees above the temperature corresponding to the maximum density of water. This effect can be noted in the records of temperature at Baltimore, Md., shown in Plate X, *A*. The height of the waterworks dam at Baltimore was raised to make a large increase in reservoir capacity between the summers of 1922 and 1923. The difference between water temperature and air temperature from 1918 to 1922 was about 3° in July and 1° in August; in 1923 the water was 11° cooler than the mean air temperature in July and 6° in August. A similar lag in warming of the water is shown in the table for Lake Erie water at Cleveland, Ohio.

Mountain streams, which may be formed largely from melting snow and may flow quickly into plains where the temperature is high, will have a temperature much below the mean monthly air temperature in the plains. This effect is not confined to mountain streams, although it is most pronounced in them.

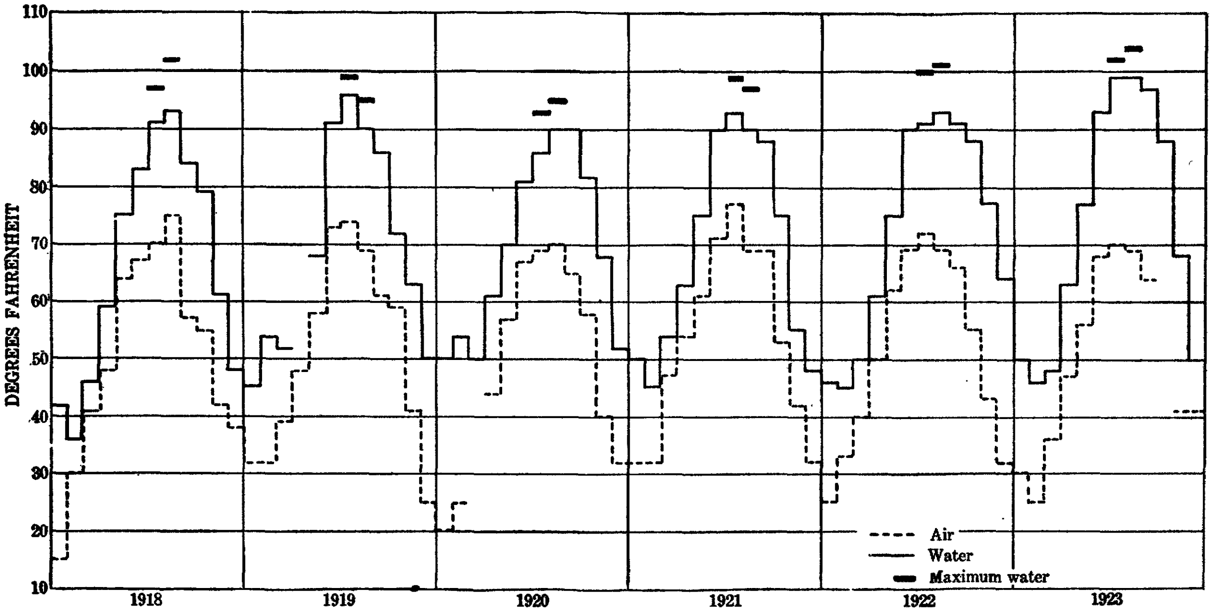
Mississippi River at New Orleans, La. (Pl. XI, *A*), shows the effect of large volumes of cold water brought a long distance. The normal January air temperature at Minneapolis, Minn., is 41° F. below the normal air temperature at New Orleans. From a point a little above Cairo, Ill., northward the normal January air temperature is below freezing. Thus a large part of the water reaching New Orleans comes from much colder places, and because the discharge is great early in the spring the colder water does not have a chance to be warmed to the air temperature of New Orleans. In summer, however, the air temperature in the upper Mississippi and Ohio basins is not so much below the temperature at New Orleans. The normal July temperature at Minneapolis is only 10° below that at New Orleans. The discharge of the river is smaller in summer. There is less water to be warmed, it moves less rapidly and therefore has more time to be warmed, and as it enters the lower Mississippi at a temperature nearer that of the air at New Orleans it requires less warming to approach that temperature than the water brought down by the river in winter and spring.

In Plate X, *C*, the characteristic changes in temperature at different places on Mississippi River are shown from the data for 1923 at four points. In general the water temperature lags behind the air temperature as it changes from month to month. The water temperatures at Quincy and St. Louis are close together, as would be expected, and follow the air temperature during the cold months more closely than those at Minneapolis or New Orleans.

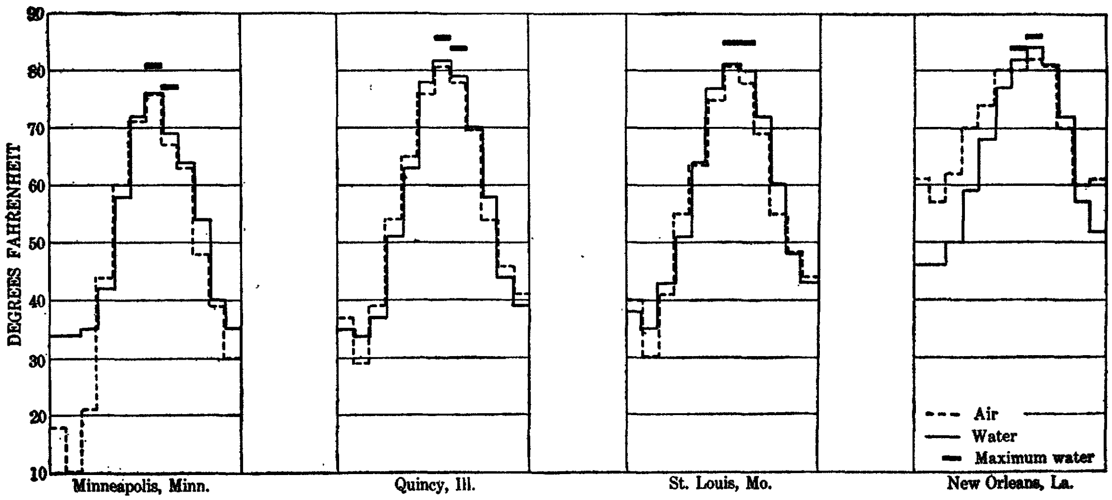
The greatest departure of water temperature from air temperature shown in the table is at Youngstown, Ohio (Pl. X, *B*). The temperatures recorded represent filtered water and must be slightly below the temperature of water in the river. The high temperature of the river water results from its use for cooling at industrial plants above Youngstown. This use raises the temperature of the water



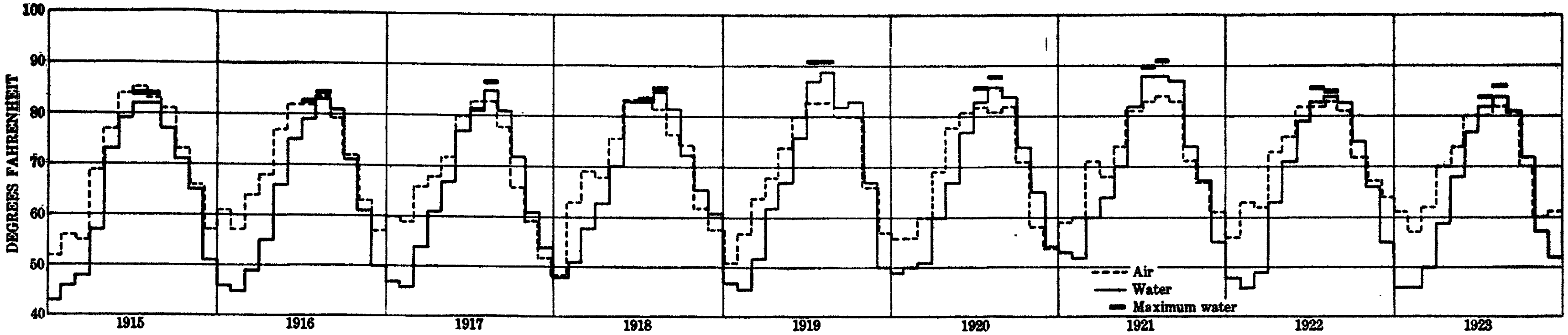
A. TEMPERATURE OF SURFACE WATER AND OF AIR AT BALTIMORE, MD.



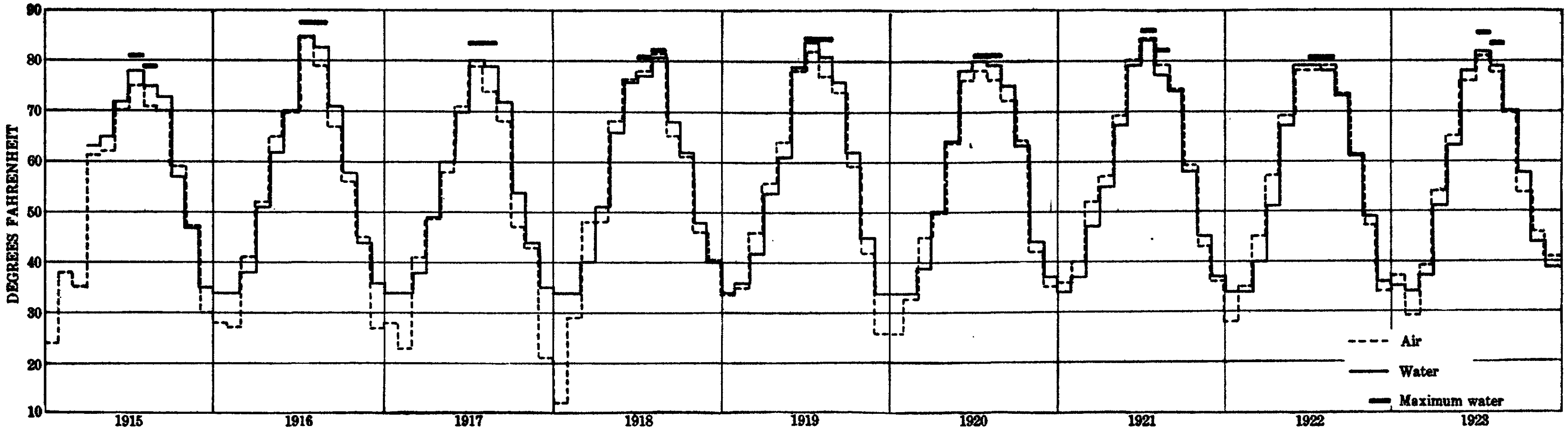
B. TEMPERATURE OF SURFACE WATER AT YOUNGSTOWN AND OF AIR AT WARREN, OHIO



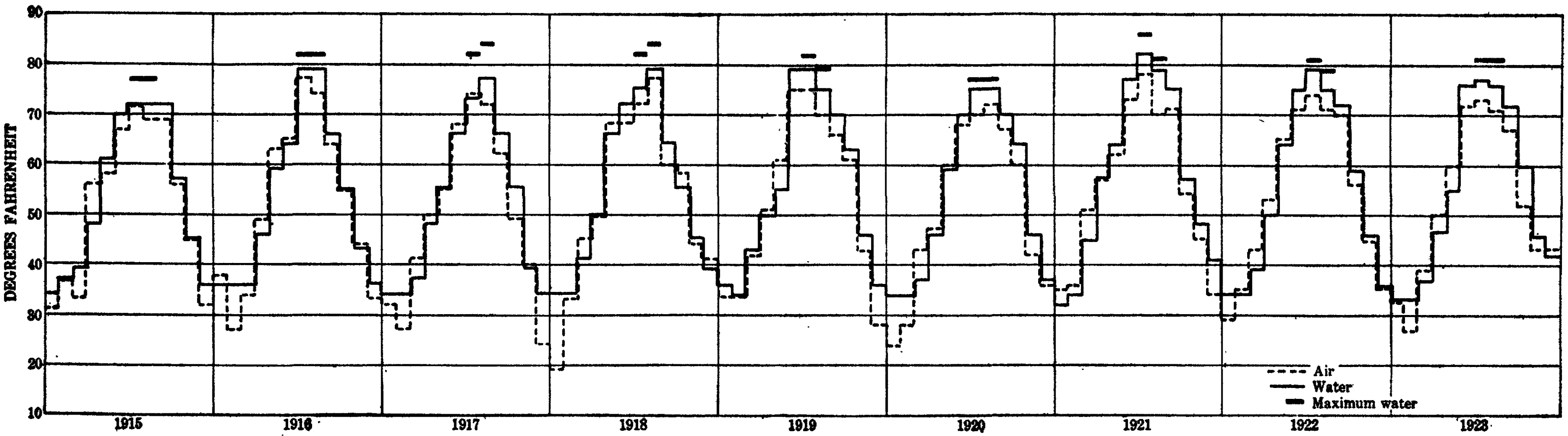
C. MEAN MONTHLY TEMPERATURE OF WATER AND OF AIR AT POINTS ON MISSISSIPPI RIVER AND MAXIMUM WATER TEMPERATURE IN JULY AND AUGUST



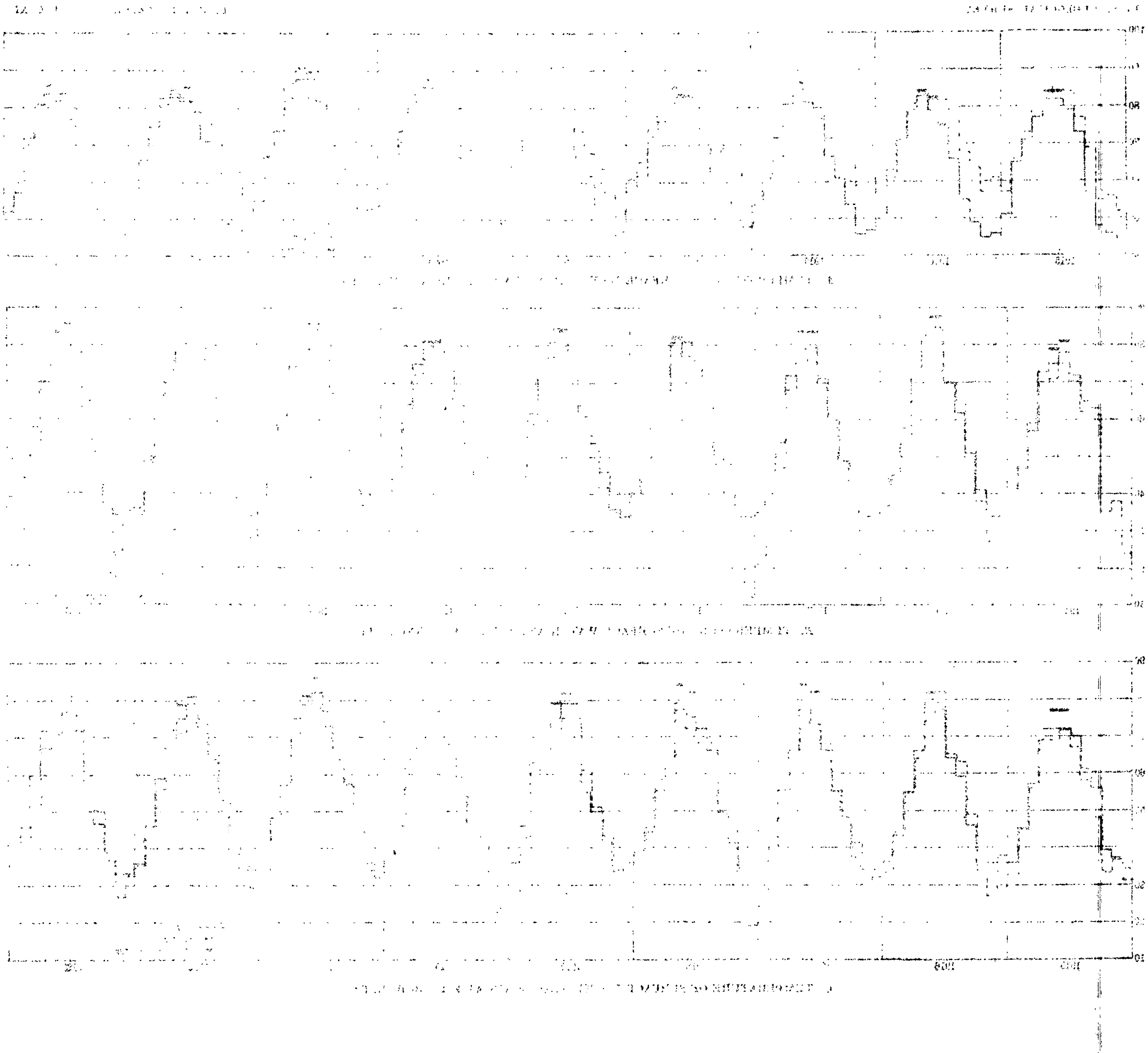
A. TEMPERATURE OF SURFACE WATER AND OF AIR AT NEW ORLEANS, LA.



B. TEMPERATURE OF SURFACE WATER AND OF AIR AT QUINCY, ILL.



C. TEMPERATURE OF SURFACE WATER AND OF AIR AT PITTSBURGH, PA.



approximately 20° F. above the temperature a normal surface water would be expected to have at Youngstown in July and about 25° F. above the normal temperature for August. Industrial use of river water undoubtedly accounts for the higher temperature of Monongahela River water at Rankin (12b in the table) as compared with air temperature. Allegheny River at Colfax (12a) shows little increase over the air temperature, and Ohio River at Brunot Island (12c) is between the two branches in the relation of water temperature to air temperature.

The conditions outlined above cause the temperature of surface water to vary from mean monthly air temperature at many places, but the results presented in the table show that unless some easily noted influence affects a surface water its mean monthly temperature is quite likely to be within a few degrees of the mean monthly air temperature for each month that the air temperature is above the freezing point.

SUMMARY.

The temperature of ground water available for industrial supplies is generally from 2° to 3° F. above the mean annual air temperature if the water is between 30 and 60 feet below the surface of the ground. At a depth of 10 feet the temperature may range from 10° above to 10° below the mean annual temperature. An approximate average for the increase in temperature with depth is about 1° F. for each 64 feet.

The mean monthly temperature of a surface water at any place is generally within a few degrees of the mean monthly air temperature when the air temperature is above the freezing point. The maximum water temperature in any of the warmer months is usually from 2° to 6° higher than the mean monthly water temperature.

Mean monthly temperature of surface water and of air and maximum daily temperature of water at certain localities.

[Water temperatures (W) furnished by municipal or private waterworks officials except as noted. Air temperatures (A) from published reports for U. S. Weather Bureau stations at cities listed or at near-by points.]

Locality.	Year.	Mean monthly temperature.																								Maximum daily temperature of water.	
		January.		February.		March.		April.		May.		June.		July.		August.		September.		October.		November.		December.			
		W	A	W	A	W	A	W	A	W	A	W	A	W	A	W	A	W	A	W	A	W	A	W	A	July.	Aug.
1. Baltimore, Md.	1918	35	24	34	35	43	47	50	53	65	69	69	71	71	75	74	78	67	65	57	61	50	47	40	42	76	78
	1919	37	38	37	38	45	46	50	53	57	65	67	73	73	78	72	75	68	70	61	63	48	47	39	33	77	76
	1920	35	29	34	33	39	45	51	53	59	61	69	73	74	76	75	75	70	70	62	63	48	47	40	40	77	78
	1921	36	37	39	39	51	55	58	59	61	63	73	75	76	80	73	74	72	74	58	58	46	48	37	37	80	80
	1922	34	33	36	38	47	45	60	56	69	67	73	75	76	77	75	74	71	71	62	61	49	49	38	37	78	77
	1923	34	37	35	32	39	44	48	54	57	64	64	77	66	77	69	75	66	70	61	57	52	46	44	45	68	73
2. Birmingham, Ala.	1923	48	52	47	46	51	54	58	62	67	69	72	77	80	78	81	78	78	76	69	64	63	52	53	53	-----	-----
3. Chattanooga, Tenn.	1923	49	47	49	42	52	51	58	59	65	65	73	75	77	77	79	77	76	73	69	61	56	50	52	49	-----	-----
4. Cincinnati, Ohio	1923	39	36	37	28	43	40	52	52	64	61	79	72	81	76	82	74	75	68	64	54	50	44	44	44	-----	-----
5. Cleveland, Ohio	1923	36	30	33	24	36	35	40	46	47	54	59	71	66	71	69	69	68	65	65	52	52	42	43	40	68	72
6. Detroit, Mich.	1918	32	13	32	24	32	40	37	45	45	62	60	67	67	71	70	75	60	57	55	56	46	42	38	36	-----	-----
	1919	33	31	32	29	35	36	41	46	51	57	-----	74	71	75	70	70	66	67	59	56	44	39	33	23	-----	-----
	1920	32	17	-----	23	-----	38	-----	41	49	56	64	69	68	70	69	69	66	66	59	59	44	39	37	33	-----	-----
	1921	32	30	32	30	36	43	44	53	49	62	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
7. Flint, Mich.	1920	34	12	34	19	38	-----	45	-----	59	56	71	69	71	69	68	69	66	64	60	57	41	36	38	31	79	75
	1921	35	29	35	27	42	40	55	52	69	61	74	71	81	78	74	68	69	67	58	50	46	36	40	28	85	80
	1922	38	20	40	26	40	34	51	47	63	64	74	69	77	71	74	69	68	64	56	51	46	39	35	27	79	79
8. Grand Rapids, Mich.	1923	34	26	34	20	35	29	47	45	60	57	75	72	76	73	72	68	65	63	54	50	42	40	38	37	78	79
9. Minneapolis, Minn.	1923	34	18	34	10	35	21	42	44	58	60	72	71	76	76	69	67	64	63	54	48	40	39	35	30	81	77
10. New Orleans, La.	1915	43	52	46	56	48	55	57	69	73	77	79	84	82	85	82	83	77	81	71	73	65	66	51	57	84	84
	1916	46	61	45	57	49	64	55	68	66	77	75	82	79	82	83	83	81	79	71	72	61	63	50	57	82	84
	1917	47	60	46	59	54	66	61	68	67	72	77	80	82	83	85	83	81	78	72	66	61	59	54	52	82	87
	1918	48	48	51	63	58	69	63	68	70	76	82	83	83	83	85	82	82	77	73	75	66	62	61	58	84	86
	1919	47	51	46	57	52	64	62	68	67	74	76	80	87	83	89	83	82	80	83	80	67	66	50	57	91	91
	1920	49	56	50	56	51	60	60	69	67	78	77	81	83	82	86	81	84	82	74	71	65	58	54	54	86	88
	1921	53	59	52	60	60	71	64	68	70	74	82	81	88	83	88	84	87	83	74	71	67	67	55	61	90	91

	1922	48	56	46	63	49	62	63	73	71	76	79	82	83	82	84	83	83	81	75	72	66	67	55	64	86	85
	1923	46	61	46	57	50	62	59	70	68	74	77	80	82	80	84	82	81	81	72	70	57	60	52	61	84	86
11. Pittsburgh, Pa.	1912		20	34	25	36	35	48	53	61	64	70	68	75	73	70	69	68	69	57	56	45	44	36	36	81	75
	1913	37	40	34	29	39	43	46	52	61	61	70	70	75	74	77	73	68	65	59	54	46	45	39	36	81	81
	1914	34	34	36	24	37	37	46	49	59	63	75	71	77	74	75	73	68	64	61	58	45	43	37	30	79	77
	1915	34	31	37	37	39	33	48	56	61	58	70	67	72	72	72	69	72	69	57	56	45	45	36	32	77	77
	1916	36	38	36	27	36	34	46	49	59	63	64	65	79	77	79	74	66	64	55	55	43	44	36	33	82	82
	1917	34	32	34	27	37	41	48	50	55	55	66	68	73	74	77	72	66	62	55	49	39	40	34	24	82	84
	1918	34	19	34	33	41	45	50	49	66	68	72	68	75	72	79	77	64	60	55	58	45	44	39	41	82	84
	1919	36	34	34	34	43	42	50	51	55	61	79	75	79	75	75	70	70	66	63	61	46	43	36	28	82	79
	1920	34	24	34	28	37	43	46	47	59	60	70	68	75	70	75	72	70	67	64	60	46	42	37	36	77	77
	1921	32	35	34	36	45	51	57	57	64	62	77	73	82	78	79	70	75	71	57	54	48	45	41	34	86	81
	1922	34	29	34	35	39	43	50	53	64	65	75	71	79	74	75	71	72	70	59	56	46	45	36	36	81	79
	1923	33	33	33	27	37	39	47	50	55	60	76	72	77	73	76	71	72	67	60	52	46	43	42	43	81	81
12. Pittsburgh region:																											
a	1923	35	33	38	27	41	39	48	50	60	60	74	72	76	73	75	71	69	67	58	52	44	43	41	43		
b	1923	40	33	40	27	45	39	52	50	64	60	78	72	79	73	80	71	77	67	71	52	54	43	46	43		
c	1923	36	33	36	27	38	39	48	50	60	60	74	72	76	73	77	71	72	67	62	52	48	43	42	43		
13. Quincy, Ill.	1913	34	29	34	25	36	37	51	54	64	65	74	77	80	82	80	83	71	70	58	54	46	49	40	38	82	82
	1914	35	34	34	23	37	39	50	54	66	68	77	79	80	82	79	79	70	69		60		45		24	84	81
	1915		24		38		35	63	61	65	62	72	70	78	75	75	71	73	70	57	59	47	47	35	30	81	79
	1916	34	28	34	27	38	41	51	52	62	65	70	70	85	85	83	79	71	67	58	56	44	45	36	27	88	88
	1917	34	28	34	23	38	41	49	49	60	58	70	71	80	79	79	74	72	68	54	47	44	43	35	21	84	84
	1918	34	12	34	29	40	48	51	48	66	68	76	76	77	78	81	82	68	65	62	61	48	46	40	41	81	82
	1919	34	34	36	35	42	46	54	56	61	64	79	78	84	82	81	77	76	74	62	59	45	42	34	26	84	84
	1920	34	26	34	33	39	45	50	50	64	64	78	76	80	78	79	76	75	72	63	64	44	42	37	35	81	81
	1921	34	36	37	40	47	52	55	57	67	69	79	80	84	84	77	79	74	74	58	59	45	43	37	36	86	82
	1922	34	28	34	35	40	45	51	57	67	69	79	78	79	78	78	79	73	73	61	61	49	47	36	34	81	81
	1923	35	37	34	29	37	39	51	54	63	65	78	76	82	81	79	78	70	70	58	54	44	46	39	41	86	84
14. St. Louis, Mo.	1921							57	58	68	68	80	78	85	83	80	78	74	74	61	60	49	47	39	39	87	83
	1922	34	30	36	36	44	46	55	58	68	69	78	78	79	79	80	79	74	74	61	62	51	49	38	37	83	83
	1923	38	40	35	30	43	41	51	55	64	64	77	75	81	81	80	78	72	69	60	55	48	48	43	44	85	85
15. St. Joseph, Mo.	1923	34	37	34	29	34	37	48	54	64	62	72	74	78	79	77	76	68	69	61	52	43	45	36	37		
16. Springfield, Mass.	1920	33	19	33	24	33	35	37	45	48	56	59	66	64	70	64	72	59	58	54		42		36		66	66
	1921	33	27	33	30	36	42	44	53	52	58	58		66	74	65		65		54	53	43	40	36		69	68
	1922	33		33	29	34	38	39		51		61		66	74	65	72	61	68	52	57	42	43	35	37	70	67
	1923	33	23	33	23	33	34	39	48	50	57	60	68	65	69	65	68	63	63	52	50	40	39	37	40	66	66
17. Terre Haute, Ind.	1919		34		34		44		54		61	81	76	84	80	81	74	75	71	66	60		42		27	88	86
	1920		24		31		44	52	48	66	63	73	72	77	75	73	73	70	71	61	62		42		34	82	79
	1921		36		38		51	54	57	66	67	79	78	81	81	75	74	70	72	55	57		46		37	86	81
	1922		27		34		44	52	56	63	68	70	75	72	76	73	76	66	72	54	59		46		34	75	77
	1923		36		27		40	48	52	63	62	75	73	72	78	73	74	70	67	54	54		45		43	86	82
18. Toledo, Ohio	1917	33	26	33	22	40	38	50	45	54	53	69	66	75	73	76	71	67	62	49	46	42	39	34	22	82	84
	1918	34	14	34	28	40	42	49	46	66	65	74	68	74	72	78	76	62	58	56	56	46	43	39	38	79	80
	1919	33	33	32	31	40	37	49	47	58	57	77	74	77	76	73	71	70	68	60	57	44	40	34	24	80	77
	1920	34	18	34	25	39	40	45	42	59	57	71	70	74	71	73	70	70	67	60	61	44	40	38	33	77	77

Mean monthly temperature of surface water and of air and maximum daily temperature of water at certain localities—Continued.

Locality.	Year.	Mean monthly temperature.																								Maximum daily temperature of water.	
		January.		February.		March.		April.		May.		June.		July.		August.		September.		October.		November.		December.			
		W	A	W	A	W	A	W	A	W	A	W	A	W	A	W	A	W	A	W	A	W	A	W	A	July.	Aug.
18. Toledo, Ohio	1921	34	32	34	32	46	45	54	54	64	62	77	73	82	79	74	71	73	70	56	53	43	40	37	32	88	79
	1922	34	24	34	31	38	38	51	49	65	63	74	70	76	72	75	71	71	68	58	55	46	43	36	30	79	79
	1923	34	30	34	23	36	34	47	47	58	55	76	72	76	73	73	70	68	65	56	51	44	41	39	39	79	79
19. Topeka, Kans.	1923	42	39	31	30	58	39	52	54	71	62	71	74	82	79	82	77	77	70	68	53	39	46	37	37	-----	-----
20. Wilmington, N. C.	1923	49	50	48	46	58	57	63	61	72	68	81	77	84	78	84	79	80	74	68	62	57	53	51	54	86	86
21. Youngstown, Ohio	1918	42	15	36	30	46	41	59	48	75	64	83	67	91	70	93	75	84	57	79	55	61	42	48	38	97	102
	1919	45	32	54	32	52	39	-----	48	68	58	91	73	96	74	90	69	86	61	72	59	63	41	50	25	99	95
	1920	50	20	54	25	50	-----	61	44	70	57	81	67	86	69	90	70	90	65	82	58	68	40	52	32	93	95
	1921	50	32	45	32	54	47	63	54	75	61	90	71	93	77	90	69	88	69	75	53	55	42	48	32	99	97
	1922	46	25	45	33	50	40	61	50	75	62	90	69	91	72	93	69	91	66	88	55	77	43	64	32	100	102
	1923	50	30	46	25	48	36	63	47	77	56	93	68	99	70	99	69	97	64	88	-----	68	41	50	41	102	104

1. Gunpowder River impounded for public water supply of Baltimore, Md.
2. Cahaba River impounded for public water supply of Birmingham, Ala.
3. Tennessee River at waterworks intake, Chattanooga, Tenn.
4. Ohio River at waterworks intake, Cincinnati, Ohio.
5. Lake Erie at waterworks intake, Cleveland, Ohio.
6. Detroit River at waterworks intake, Detroit, Mich.
7. Flint River at waterworks intake, Flint, Mich.
8. Grand River at waterworks intake, Grand Rapids, Mich.
9. Mississippi River at waterworks, Minneapolis, Minn.
10. Mississippi River at Carrollton filtration plant of municipal waterworks, New Orleans, La.
11. Allegheny River at Aspinwall filtration plant of municipal waterworks, Pittsburgh, Pa.
12. a, Allegheny River at Colfax, Pa.; b, Monongahela River at Rankin, Pa.; c, Ohio River at Brunot Island. Water temperature furnished by the Philadelphia Co. of Pittsburgh, Pa., from records at plants of the company. Air temperature at Pittsburgh, Pa.
13. Mississippi River at waterworks intake, Quincy, Ill.
14. Mississippi River at waterworks intake, St. Louis, Mo.
15. Missouri River at waterworks, St. Joseph, Mo.
16. Westfield Little River impounded for public water supply of Springfield, Mass.
17. Wabash River at waterworks, Terre Haute, Ind.
18. Maumee River at waterworks, Toledo, Ohio.
19. Kansas River at waterworks, Topeka, Kans.
20. Cape Fear River at waterworks, Wilmington, N. C.
21. Mahoning River at waterworks, Youngstown, Ohio. Temperature of filtered water. Air temperature at Warren, Ohio.

SOME FLOODS IN THE ROCKY MOUNTAIN REGION.

By Robert Follansbee and Paul V. Hodges.

SCOPE OF REPORT.

In 1923 severe floods occurred on the larger streams in Wyoming and a number of cloudburst floods on small streams in Wyoming and especially in Colorado. An investigation of the principal floods in each State was made, and the results are given in this paper, together with descriptions of two Colorado floods of 1922. In addition a study was made of all cloudburst floods to determine the areas chiefly subject to them.

GENERAL FEATURES OF THE FLOODS.

TYPES.

Floods in the Rocky Mountain region are of two types—the floods in the larger streams due to general rains of several days' duration over large areas and the so-called cloudburst floods due to intense rains of short duration covering well-defined small areas. Floods of the first type are relatively infrequent, and, as they are well understood, their characteristics will not be discussed. Only the severe floods of this type that occurred in 1923 are described in this report. Cloudburst floods cause the streams to rise and fall suddenly. Although they cause much less damage than those of the first type, they occur frequently and are especially disastrous to railroads and highways.

AREAS SUBJECT TO CLOUDBURST FLOODS.

Records of nearly 100 floods in Colorado were compiled to determine the areas most subject to cloudburst floods. For many of these floods the available information covered only the date and location of the rises in small streams that were sufficiently pronounced to be called floods by residents. Most of these floods occurred in the eastern foothill region, which extends from the New Mexico line on the south to the Wyoming line on the north, and in a strip of plains area 50 miles wide just east of the mountains. In this area the severest floods occurred between Canon City and Pueblo, in the triangular valley of the Arkansas. These floods have been described in connection with the Arkansas River flood of June 3–5, 1921.[1]

Another region in which cloudbursts are prevalent lies along the western foothills, in the western part of the State. In this region the area most subject to cloudburst is the extreme upper end of the Uncompahgre Valley, where the sides converge and join the main mass of the San Juan Mountains above Ouray. Cloudbursts have been noted in this area from Dallas Creek near Ridgway southward to and including the streams draining the almost vertical walls of the

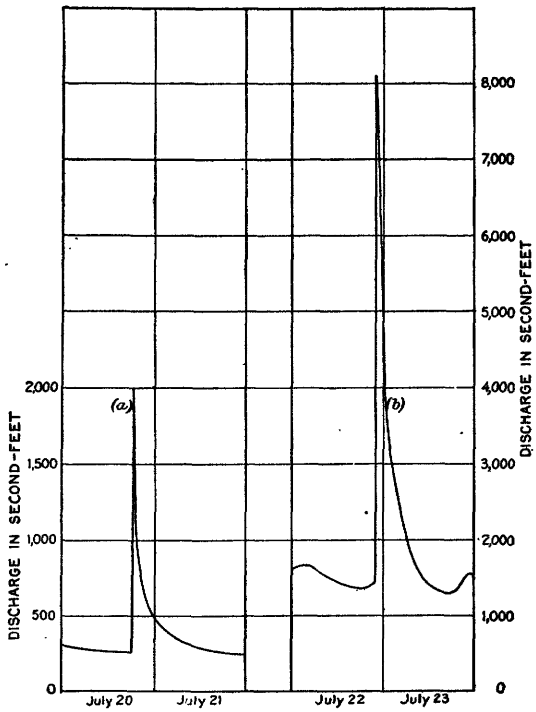


FIGURE 9.—Hydrographs of cloudburst floods. *a*, Skyrocket Creek at Ouray, Colo.; *b*, North Fork of Shoshone River near Wapiti, Wyo.

mountain amphitheater that nearly surrounds Ouray. The cloudburst on Skyrocket Creek is a good example of cloudbursts near Ouray (fig. 9, *a*). Several cloudbursts have been noted on small streams that drain the sides of the Uncompahgre Plateau and the Grand Mesa near Delta and on streams that drain the slopes of the Grand Hogback and Book Cliffs from Rifle to DeBeque.

Few cloudbursts have been recorded within the main mountain area. A small area south of Eagle is subject to occasional heavy

[1] Follansbee, Robert, and Jones, E. E., The Arkansas River flood of June 3-5, 1921: U. S. Geol. Survey Water-Supply Paper 487, 1922.

rains, which are locally termed cloudbursts, and the east side of the Arkansas Valley between Granite and Buena Vista, embracing the western slope of the Park Range, is also subject to occasional cloudbursts, which, however, are not so severe as those in the foothill region. Cloudbursts have also been recorded near the mouth of Texas Creek above the Royal Gorge and on Williams Fork near Hot Sulphur Springs, in Middle Park.

The eastern slope of the Big Horn Mountains is subject to cloudbursts, but it is impossible to determine the other areas in Wyoming where they occur most frequently, as very few records of cloudbursts are available for Wyoming.

Most cloudbursts occur at altitudes between 6,000 and 7,000 feet, although those near Ouray are between 8,000 and 9,000 feet, those near Granite about 9,500 feet, and the one series of cloudbursts recorded on North Fork of Shoshone River in northern Wyoming at 10,000 feet. Cloudbursts occur only where there is a marked range in temperature within a relatively small area. This condition exists chiefly in the foothills, where the warm air from the plains drifts toward the mountains, is deflected upward, and rapidly cools at the higher altitudes near the heads of the canyons. For this reason, cloudbursts generally occur in the afternoon or early evening of an unusually warm day. It is readily seen that they can seldom occur at higher altitudes in the mountains, as there the differences in temperature are usually insufficient and the mass of warm air in the high valleys is not great enough to cause any decided drift toward the adjacent mountains.

The cloudbursts on North Fork of Shoshone River, which occurred at an altitude that is generally considered above the limit for cloudbursts, followed several days of unusually warm weather (p. 114) during which the air in the valleys became so much warmer than the air at higher altitudes as to drift toward the mountain sides, where it was rapidly deflected upward.

INTENSITY OF RAINFALL.

The Weather Bureau maintains regular stations at Denver, Pueblo, and Grand Junction, Colo., and at Cheyenne, Sheridan, and Lander, Wyo., where continuous rainfall records are kept. The stations at Denver, Pueblo, Cheyenne, and Sheridan are on the plains, a short distance east of the mountains, in the zone subject to cloudbursts; and the rainfalls of greatest intensity recorded at these stations are given in the following table. Grand Junction is in western Colorado, in the region of flat-topped mesas, and Lander is in the mountainous area of central Wyoming. At neither Grand Junction nor Lander has the intensity of rainfall been sufficient to be termed excessive.

Rainfalls of greatest intensity in Colorado and Wyoming, recorded by Weather Bureau.

Length of rainfall (minutes).	Denver.[a]		Pueblo.[b]		Cheyenne.[c]		Sheridan.[d]	
	Rainfall (inches).	Frequency in years.	Rainfall (inches).	Frequency in years.	Rainfall (inches).	Frequency in years.	Rainfall (inches).	Frequency in years.
5	0.87	34	0.44	24	0.48	20	0.48	15
	.59	17	.38	12	.46	10	.41	7.5
	.52	11.3	.35	4	.38	6.7	.30	3.8
	.47	8.5	.34	3	.35	5.0	.29	3.0
	.41	5.7	.33	2.4	.33	4.0	.28	2.1
10	1.20	34	.80	24	.73	20	.69	15
	.97	17	.71	12	.68	10	.51	7.5
	.89	11.3	.68	8	.61	5	.50	3.8
	.86	8.5	.64	6	.60	4	.49	3.0
	.70	4.9	.61	4.8	.57	3.3	.46	2.5
15	1.52	34	.97	24	.89	20	.85	15
	1.14	17	.93	12	.84	10	.77	7.5
	1.04	11.3	.90	8	.81	6.7	.69	5.0
	.95	8.5	.81	6	.71	5.0	.68	3.8
	.94	6.8	.80	4.8	.69	4.0	.59	3.0
20	1.62	34	1.20	24	1.13	20	.97	15
	1.24	17	1.12	12	.93	10	.85	7.5
	1.19	11.3	1.04	8	.86	6.7	.81	5.0
	1.18	8.5	.99	6	.81	5.0	.78	3.0
	1.10	6.8	.95	4.8	.74	4.0	.69	2.5
30	1.72	34	1.59	24	1.19	20	1.04	15
	1.49	17	1.45	12	1.01	10	.97	7.5
	1.39	11.3	1.37	8	.98	6.7	.91	5.0
	1.35	8.5	1.28	6	.93	4.0	.81	3.8
	1.24	6.8	1.12	4.8	.90	3.3	.78	3.0
60	2.20	34	2.08	24	1.36	20	1.53	15
	1.90	17	1.82	12	1.35	10	1.28	7.5
	1.72	11.3	1.75	8	1.25	6.7	1.00	5.0
	1.36	8.5	1.45	6	1.15	5.0	.91	3.8
	1.35	6.8	1.32	4.8	1.10	4.0	.78	3.0

[a] 34 years' records.
[b] 24 years' records.
[c] 20 years' records.
[d] 15 years' records.

NOTE.—Column headed "Frequency in years" indicates the probable time interval between the occurrence of rainfalls of approximately the same intensity, as determined from existing records.

As the above-recorded rainfalls occurred outside the foothill region, in which the cloudbursts are heaviest, the intensity during such storms is probably greater. A local observer stated that during the Arkansas River flood of June 3–5, 1921, within the area of severest cloudbursts recorded (pp. 105–106), 5 inches of rain fell in 30 minutes in Boggs Flat, in or near sec. 35, T. 21 S., R. 66 W., but the method of obtaining this measurement is not known.

FLOODS IN BIG HORN RIVER BASIN, WYO.

FLOOD OF JULY 23–24, 1923.

GENERAL FEATURES.

From July 22 to 26 a series of heavy rains in the Big Horn River basin caused the greatest flood on the Big Horn at Thermopolis in the last 24 years for which records are available. The following table shows all available Weather Bureau records of rainfall in the Big Horn drainage basin during that period:

Rainfall in Big Horn drainage basin, Wyo., July 14–26, 1923, in inches.

Station.	14	15	16	17	18	19	20	21	22	23	24	25	26	Total.
Pavillion								0.40			1.20		0.70	2.30
Diversion dam	Tr.	0.19	Tr.			Tr.			Tr.	0.10	.38	2.32	.03	3.06
Lander [a]	0.16	.22					0.02	.05	0.86	.10	.21		.36	1.98
Middle Fork	.45	.22	0.03						.39	.39	.24	.05	.65	2.42
Riverton	.40	.58							.07	.02	1.90	.12	.02	3.11
Ervay	.54									.38		.25	.30	1.47
Thermopolis										.17	1.20	1.22	.40	2.99
Worland [b]		.81								.02	.94		.16	1.93
Hyattville											1.50			1.50
Basin		.15						Tr.					Tr.	.17
Cody	.05								.30		.20	.65	.12	1.32
Clark		.11	Tr.	Tr.				.18	Tr.	.15	.12	.10	.33	1.02
Shoshone dam									.30	.10		.60	.10	1.10
Deaver [b]								.31	.11			.04	Tr.	.47
Lovell	Tr.											.07		.08
Powell [b]		Tr.	Tr.					.13	.07	Tr.	Tr.	.24	Tr.	.49

[a] Regular Weather Bureau station; precipitation for 24-hour period ending at midnight.
[b] Precipitation measured in morning for 24-hour period ending at that time.

NOTE.—Except as otherwise indicated, observations are generally made late in the afternoon, near sunset, and precipitation recorded is for 24-hour period ending at that time.

One account of the storm on the Big Horn was given by U. S. G. Early, agent of the Chicago, Burlington & Quincy Railroad at Bonneville, who stated that a severe electric storm began about 10.30 p. m. July 23, and heavy rain fell until 3.30 a. m. July 24. The total amount of rainfall during this period was estimated at several inches, although no measurement was made. A storm appeared to come from the southwest and met one from the northeast about 20 miles east of Bonneville (about the center of the Badwater drainage basin).

H. D. Comstock, of the Bureau of Reclamation, project manager at Riverton, made the following statement regarding the storm near Riverton:

> Heavy, scattered showers fell on the evening of July 21 but did little damage. Very heavy rain fell between 4 and 7 p. m. July 22. One cloudburst extended some 15 or 20 miles east of Hudson, which is 17 miles southwest of Riverton. I reached Hudson near the end of the storm and estimated that at least 1.5 inches fell there in 1½ hours. To the east the rain was probably heavier. Simultaneously there was a heavy storm beginning near Lander and extending northwest along the foot of the mountains. The heavy general rain began at Riverton about 10 p. m. July 23 and lasted until 3 a. m. July 24. Riverton seems to be near the south boundary of the storm area, which extended at least 50 miles east and over 50 miles northwest and north to a point beyond the Owl Creek Mountains. About 5 p. m. July 24 a very severe cloudburst occurred over an area 10 miles in diameter, centering over sec. 23, T. 3 N., R. 2 W., during which 2.20 inches of rain fell in less than an hour. Heavy rains occurred at various points every afternoon and evening until July 27. The area just west of Pavillion received its most intense rainfall on the evening of July 25.

Stream-flow records at regular gaging stations, estimated maximum run-off of small tributaries in the drainage basin (p. 111), and statements of residents show, in connection with the rainfall records, that there were three distinct areas in which the rainfall was high. The main area, the rain in which was the chief cause of the flood, centered above Bonneville; it had an east-west diameter of 90 miles and a north-south diameter of 65 miles. The rainfall was highest in the northern third of this area. The other areas were on Wood River above Meeteetse, Wyo., and on Paintrock Creek (Pl. XII). The North Fork of Shoshone River was also subject to heavy rains during this period, but as the flood waters were stored in Shoshone reservoir, they did not contribute materially to the flood in the lower Big Horn.

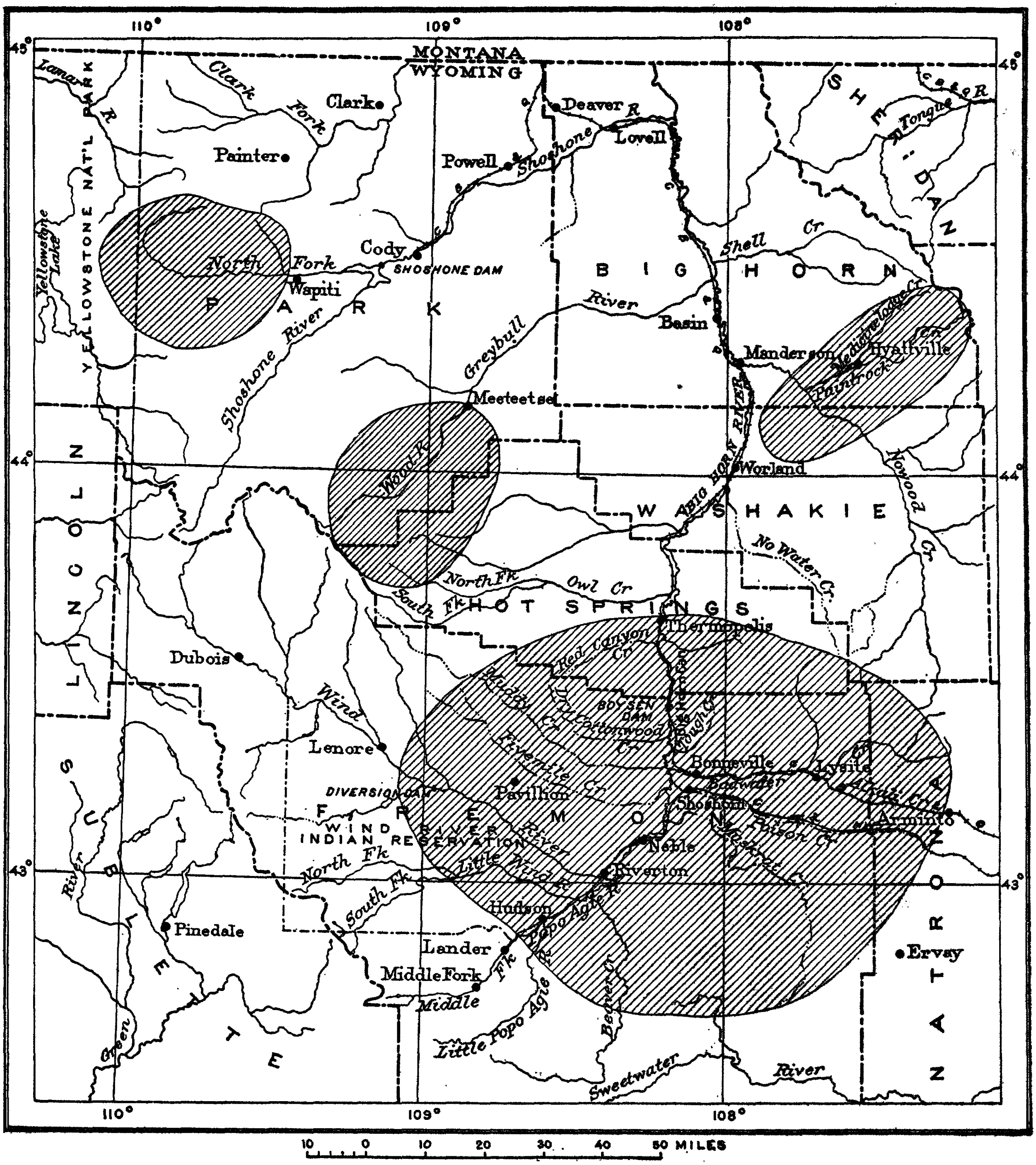
The flood caused the greatest damage along Badwater Creek and below the mouth of the Badwater as far as the head of the Big Horn Canyon. In this stretch the Chicago, Burlington & Quincy Railroad had 20 miles of track washed out, of which about 8 miles was subsequently relocated away from the river bottom. Three steel bridges were destroyed. The entire town of Bonneville was covered with 2 to 5 feet of water. Several buildings and 10 freight cars were washed downstream, and additional buildings were wrecked. Just east of the railroad station, where the railroad formerly crossed Badwater Creek on a 120-foot steel bridge, the channel is now more than 300 feet wide. In front of the station the 80-foot channel was widened to 500 feet. The loss to the railroad alone was estimated at more than $1,000,000. Two lives were lost near Shoshoni, and a 13-year-old boy was carried by the flood for more than a mile before being rescued.

The heavy rains caused many slides on the railroad track through Big Horn Canyon and filled two tunnels with water from 2 to 5 feet deep. The new highway that is being constructed through the canyon was severely damaged. The Wyoming Power Co.'s plant at Boysen dam was put out of commission by 2 feet of water over the floor of the power house, which is inside the dam. The water was 20 feet deep over the dam and 4.9 feet deep in the railroad tunnel at that point. Transmission lines along Badwater, Poison, and Muskrat creeks were destroyed.

The Chicago & Northwestern Railway lost five bridges and 500 feet of track between Shoshoni and Hudson.

Thermopolis was flooded as far east as the Burlington station, and buildings at the Hot Springs resort on the east side of the river were considerably damaged. At the crest of the flood the water surface was 2.3 feet above the top of the center arches of the concrete bridge at the lower end of the town and 3.7 feet above the top of the arches at each end of the bridge. This submergence of the arches caused backwater above the bridge, which amounted to a maximum of 0.8 foot. The main channel carried 22,000 second-feet before overflow began; overflow occurred at a stage of 13.4 feet on the Geological Survey gage located on the bridge.

The Hanover and Big Horn County canals, which divert water from the Big Horn a few miles above Worland for the irrigation of



MAP OF BIG HORN RIVER BASIN, WYO., SHOWING RAINFALL AREAS CAUSING FLOOD OF JULY, 1923

35,000 acres, were badly damaged; and the Illinois Pipe Line Co.'s line was broken between Chatham and Grass Creek and several thousand barrels of oil was lost. At Manderson the water surface reached the ties of the railroad track, but the railroad embankment prevented flooding of the town.

An investigation of this flood was made soon after it occurred, and the slope and cross sections of the maximum discharge were obtained from well-defined high-water marks on streams that had no gaging stations. The results are summarized in the following table:

Maximum discharge of streams in the Big Horn drainage basin, July 24–26, 1923.

[Localities in Wyoming except as otherwise specified.]

Stream.	Locality.	Maximum discharge (second-feet).		Drainage area (square miles).	Time of flood crest.	Source of information.
		Total.	Per square mile.			
Wind River	Riverton	11,100	4.8	2,320	4 a. m. July 25	Recording gage chart at gaging station.
Muskrat Creek	Sec. 16, T. 2 N., R. 6 E.	[a] 6,400	8.3	770	4 a. m. July 24	Slope measurement.
Fivemile Creek	Sec. 17, T. 3 N., R. 6 E.	3,500	9.5	368	do	Estimated by Bureau of Reclamation.
Poison Creek	Shoshoni	3,000	5.8	518	do	Do.
Badwater Creek	Bonneville	[b] 18,600	23.4	794	9.45 a. m. July 24	Slope measurement.
Muddy Creek	Sec. 29, T. 4 N., R. 6 E.	[c] 16,300	41.8	390	do	Do.
Tough Creek	Sec. 28, T. 39 N., R. 94 E.	1,500	62.5	24	do	Estimated by Bureau of Reclamation.
Big Horn River	Sec. 2, T. 5 N., R. 6 E.	28,700	3.7	7,740	5 p. m. July 24	Estimated at Boysen dam by E. C. Bebb, Federal Power Commission.
Do	Thermopolis	29,800	3.7	8,080	11 p. m. July 24	Measurement of overflow area and extension of gaging-station rating curve.
Do	Manderson			10,900	9.30 a. m. July 26	State Highway Department.
Do	Greybull			14,500	9 p. m. July 26	Observer.
Do	Hardin, Mont.	29,500	1.4	20,700	9 p. m. July 27	Gaging-station record.
Paintrock Creek	Sec. 25, T. 50 N., R. 89 W.	5,580	34.0	164	1 a. m. July 24	Recording gage chart at gaging station.
Greybull River	Meeteetse	2,200	3.2	690	5.30 a. m. July 24	Do.

[a] On cross section measured and slope determined as 0.007 from high-water marks 550 feet apart; "n" taken as 0.040.

[b] Fairly uniform channel found beginning 2,000 feet below railroad station. Two cross sections measured 737 feet apart. Upper section had not scoured out as badly as lower section, and original banks remained. Slope determined by difference in altitude of high-water marks at each section and also by altitude of high-water marks 2,000 feet above upper section. Both methods give slope of 0.0040, "n" taken as 0.030. Maximum discharge based on mean of upper and lower sections was 20,900 second-feet, but to eliminate possible scour in lower section the discharge was computed by using upper section alone, which gave 16,200 second-feet. The most probable maximum discharge was taken as the average of the two figures, or 18,600 second-feet.

[c] Two cross sections measured 313 feet apart. Slope from high-water marks 0.0095; "n" taken as 0.045.

The only point on Big Horn River at which fairly complete records of the flood are available is Thermopolis, where a gaging station is maintained on the concrete highway bridge that connects the town with the Hot Springs resort. It was impossible to read the gage at the highest stage at Thermopolis, because the water was over each end of the bridge, but from high-water marks, levels run to determine the overflow area, and statements of citizens a hydrograph showing the entire flood discharge has been prepared (fig. 10). At 6 p. m. July 23 the river started to rise, and by 2 a. m. July 24 it was discharging 24,800 second-feet. It then fell rapidly until 8 a. m., when the discharge was 15,000 second-feet. A second rise began at that time and continued until 11 p. m., when the maximum discharge of 29,800 second-feet was reached at a stage of 16.2 feet above the zero of the gage. From the peak, which was of relatively short duration, the discharge fell to 22,300 second-feet at 8 a. m. July 26 and to 14,500 second-feet at midnight on the 27th. A slight rise occurred during that night, but after that time the river fell steadily until

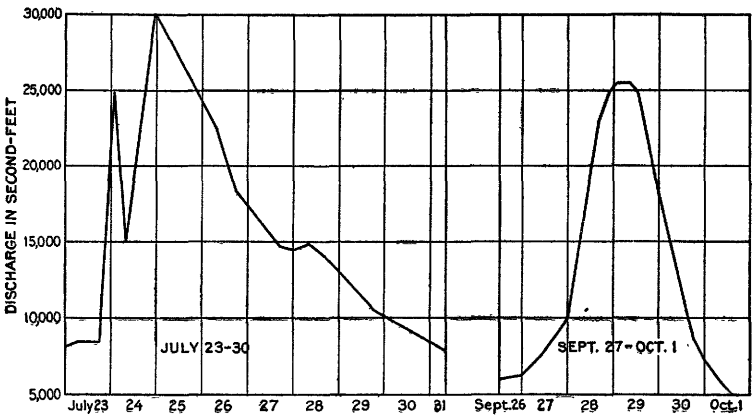


FIGURE 10.—Hydrographs of floods in 1923 on Big Horn River at Thermopolis, Wyo.

the discharge was 8,000 second-feet on July 31. During this period a total of 235,000 acre-feet passed Thermopolis.

The first rise was undoubtedly caused by a cloudburst in Red Canyon, a small tributary that enters Big Horn River a few miles above Thermopolis. The flood was so severe on this tributary that it washed out the railroad bridge and several hundred feet of track.

A study of the time at which the tributaries were at crest stage indicates that the chief source of the main flood was the crest flows from Badwater and Muddy creeks and, to a lesser extent, from Muskrat, Fivemile, Poison, and Tough creeks. Wind River did not reach its maximum stage at Riverton until 4 a. m. July 25, and as this point is 64 miles above Thermopolis by river, it took at least 12 hours for this peak to reach Thermopolis. If the Wind River crest had coincided with the others the discharge at Thermopolis would have increased by at least 5,000 second-feet.

The maximum discharge probably decreased below Thermopolis, because the flood crest flattened out. Nowood Creek contributed about 3,400 second-feet to the Big Horn at Manderson, but this flow reached the river 24 hours ahead of the crest stage. The maximum flow from the Greybull entered the Big Horn during the night of July 24, nearly 24 hours ahead of the crest flow in that stream.

BADWATER CREEK.

The severest flood in the entire region occurred in the Badwater drainage basin, which was within the area of heaviest rainfall. The residents at Lysite stated that the flood was the highest in 20 years. An Associated Press item of July 25 stated that a rancher and his family barely escaped from a wall of water 6 miles west of Lysite. The crest at that point occurred about 4 a. m. July 24. The Chicago, Burlington & Quincy Railroad agent at Bonneville stated that the creek started to rise there at 1.30 a. m. and rose gradually until 6 a. m., when the rise was much more rapid, being as much as 1 foot every five minutes just prior to the crest, which occurred at 9.45 a. m. The creek fell gradually for two days. The total rise was about 12 feet.

PAINTROCK CREEK.

The heavy rain that fell during the night of July 23 flooded the entire Paintrock Creek basin and swept away practically every bridge. The maximum stage occurred about midnight, when the creek at the gaging station rose from 470 to 5,580 second-feet, an increase in stage of 4½ feet, in an hour's time. The observer reported that high water lasted several hours. Residents state that it was the largest flood ever experienced since white settlers have lived in the valley. Medicine Lodge Creek, which joins Paintrock Creek below the gaging station, had a severe flood, the crest of which was 45 minutes earlier.

GREYBULL RIVER.

The hydrograph for the gaging station on Greybull River at Meeteetse, Wyo. (not included in this report), shows that the upper basin of that stream was subject to almost daily cloudbursts from July 21 to 26. The chief area of cloudburst was on Wood River, a tributary of the Greybull. The floods caused by these cloudbursts did not exceed 2,200 second-feet, which was not excessive for that stream, and the resulting damage was not great.

North Fork of Owl Creek, whose drainage area adjoins that of Wood River on the south, was at the highest stage known, but the South Fork was not very high.

NORTH FORK OF SHOSHONE RIVER.

The series of cloudbursts that occurred in northern Wyoming during July culminated on the night of July 22 in a somewhat general rainfall covering a large territory. Heavy rains in the mountains near Sylvan Pass caused a serious landslide 14 miles east of the eastern entrance to Yellowstone Park and stopped all traffic for two days. C. C. Spencer, forest ranger at Wapiti, gives the following description of the storm:

On July 19, 20, 21, and 22 we had a spell of unusually hot, sultry weather. In fact, it was about the worst I can remember in this country during the past 18 years. The cloudbursts followed this on July 22 and seemed to strike all of the high divides, as well as a few places lower down. Most of them struck near or above timber line (about 10,000 feet elevation). The ten which struck the North Fork of the Shoshone and its tributaries came between 6 and 8 p. m. They came down the following streams: Main North Fork, Grinnell, Gunbarrel, Clearwater, Blackwater, and Sweetwater creeks about 6 p. m., and Elk Fork, Clocktower, Canyon, and Big creeks at 8 p. m. Canyon Creek carried the largest volume of water for the area drained, and the run lasted for more than an hour. Very little rain fell in the valley, and the storm on the divides lasted but a few minutes. We have no records of precipitation. One thing I have noticed during the last few years is that these cloudbursts always come about the last of July and follow a period of hot, sultry weather. Those this year (1923) were many times larger and worse than any others of which I have knowledge in this section.

A map of the North Fork drainage basin shows that the creeks subject to the earlier cloudbursts were at a higher general altitude than those on which the cloudbursts occurred about 8 p. m.

The Bureau of Reclamation maintains a gaging station in sec. 15, T. 52 N., R. 104 W., 6 miles east of Wapiti, and the recording gage at that point showed that the river started to rise at 10 p. m., when its flow was 1,460 second-feet, and rose to a maximum discharge of 8,100 second-feet in a few minutes' time. The period of crest flow was equally short, and the river quickly fell again, although it did not reach normal stage until noon of the following day (fig. 9, *B*). The almost instantaneous rise shows that the floods from both the upper and lower areas described above reached the gaging station at the same time, a condition which would cause the severest flood for that amount of rainfall over the basin.

FLOOD OF SEPTEMBER 27–29, 1923.

Heavy rains from September 27 to 29 covered the entire central and northern parts of the State and caused a flood on Big Horn River that was second in size only to that of July 23–24 at Thermopolis and exceeded it in the lower river.

The following table shows all available Weather Bureau rainfall records in the Big Horn River drainage basin:

Rainfall in Big Horn River drainage basin, Sept. 26–30, 1923, in inches.

Station.	26	27	28	29	30	Total.
Dubois	2.00	1.01				3.01
Pavillion		2.00	0.88	0.18	Tr.	3.07
Diversion dam		1.77	1.19	.09	Tr.	3.06
Lander [a]		2.87	.92	Tr.	0.01	3.81
Riverton		2.14	1.79	.26	.06	4.25
Middle Fork		3.00	2.05	.17	.03	5.25
Thermopolis [b]					4.94	4.94
Worland [c]		.91	.53	1.01	.19	2.64
Basin		.76	.23	.23	.28	1.50
Cody		.65	.90	.35	.36	2.26
Deaver [c]		.31	.26	.10	.18	.85
Lovell		.21	.17	.15	.21	.74
Powell [c]		.70	.03	.28	Tr.	1.02

[a] Regular Weather Bureau station; precipitation for 24-hour period ending at midnight.
[b] Precipitation recorded on Sept. 30 is accumulation for four days.
[c] Precipitation measured in morning for 24-hour period ending at that time.

NOTE.—Except as otherwise indicated, observations are generally made late in the afternoon, near sunset, and precipitation is recorded for 24-hour period ending at that time.

Stream-flow records are also available at a number of points in the drainage basin, and the daily discharge for the period September 25–30 is given in the following table:

Daily and maximum discharge of streams in Big Horn River basin, Wyo., Sept. 25–30, 1923.

Station.	Distance (miles).	Discharge (second-feet).						Maximum discharge recorded (second-feet).			Drainage area (square miles).
		Sept. 25.	Sept. 26.	Sept. 27.	Sept. 28.	Sept. 29.	Sept. 30.	Time.	Total.	Per square mile.	
Wind River at Riverton.	0	860	831	1,470	4,880	2,330	1,860	1.30 p. m. Sept. 28	6,550	2.8	2,320
Big Horn River at Thermopolis.	64	1,640	1,640	3,720	18,900	20,400	11,100	2–4 a. m. Sept. 29	25,500	3.2	8,080
Big Horn River at Manderson.	124							Midnight Sept. 29			
Big Horn River at Greybull.	154							8–10 a. m. Sept. 30			
Big Horn River at Hardin.	284	4,270	6,280	4,690	4,460	28,900	35,100	8 p. m. Sept. 30	36,200	1.8	20,700
Middle Fork of Popo Agie River near Lander.		71	68	84	111	113	101	6 p. m. Sept. 28	152	1.8	84
Greybull River at Meeteetse.		280	260	610	905	580	590	4 a. m. Sept. 28	1,300	1.9	690
Shoshone River near Ishawooa.		375	315	699	733	585	548	6 p. m. Sept. 27	900	1.7	532
Tensleep Creek near Tensleep.		181	177	208	325	315	283	1 a. m. Sept. 28	366	1.6	238
Paintrock Creek near Hyattville.		240	215	225	282	290		11 p. m. Sept. 27	940	.6	164
Nowood Creek at Bonanza.		604	604	572	1,280	3,650	3,150	6 a. m. Sept. 29	3,850	2.2	1,790
Shell Creek at Shell		115	125		140	182	250				256

The records of precipitation and stream flow show that although the rainfall was general throughout the drainage basin, the heaviest precipitation occurred in the southeastern part, where the rainfall exceeded 2.5 inches. Within this area were two smaller areas where the rainfall ranged from 4 to 5 inches, one near Thermopolis and the other an oval area about 15 miles wide that extended 40 miles from the vicinity of Neble to a point above Lander. The fact that the floods on the tributaries had low unit run-offs indicates that the rainfall was a steady downpour rather than a series of short storms of cloudburst intensity.

The chief damage caused by the flood was in the Big Horn River basin, although a considerable stretch of the new roadbed of the Chicago, Burlington & Quincy Railroad near Bonneville was washed out. At Thermopolis the lower ground was flooded, but as the flood was 1.3 feet lower than that of July, the damage was not so extensive. The railroad fill south of the station at Manderson was washed away and the water entered the town and flooded it to a depth of 2 or 3 feet. People living on the lowlands near Basin and Greybull were forced to move. Many of the streets in Greybull were covered with water to a depth of 3 feet. Part of the fill between the two highway bridges over the Big Horn at that point was carried away, thus increasing the the carrying capacity of the channel.

A hydrograph of the flood (fig. 10) has been prepared from the records at the Thermopolis gaging station. This graph shows that the river rose gradually from 6,200 second-feet at midnight September 26 to 10,000 second-feet in 24 hours. In the succeeding 26 hours the river rose to its maximum stage of 25,500 second-feet, which was reached at 2 a. m. September 29; it remained at or near that stage for 10 hours and then steadily fell to 8,800 second-feet at 6 p. m. September 30 and to 5,000 second-feet by noon October 1. During that period a total of 110,000 acre-feet passed the station.

Practically the entire drainage basin above Thermopolis contributed to the flood at that point. As the crest at Riverton occurred 12 hours earlier, the average rate of travel for the crest between Riverton and Thermopolis was 5 miles an hour, and as its volume increased from 6,500 to 25,500 second-feet, all the intervening streams must have contributed. These streams, however, were not so high as during the July flood.

The crest flow increased considerably through the Big Horn River basin as rains occurred over its entire area; and the tributaries, notably Nowater and Nowood creeks, had moderate floods, the crests of which reached the Big Horn about the time of the main crest itself.

COMPARISON BETWEEN FLOODS OF JULY AND SEPTEMBER, 1923.

The following table summarizes the principal facts about the July and September floods:

Comparison between floods of July and September, 1923, on Big Horn River.

Point.	July crest (second-feet).	September crest (second-feet).	Remarks.
Riverton, Wyo.	11,100	6,550	
Thermopolis, Wyo.	29,800	25,500	Maximum stage, 1.3 feet lower in September.
Manderson, Wyo.			Maximum stage, 1 foot higher in September.
Hardin, Mont.	29,500	36,200	Do.

The chief difference in the two floods was that the July flood was caused by heavy rains of almost cloudburst intensity over a comparatively small area that centered chiefly over Badwater Creek, with little inflow below Thermopolis; and the September flood was caused by general rains of less intensity over the entire drainage basin, with considerable inflow below Thermopolis.

An idea of the relative size of the floods of 1923 on Big Horn River at Thermopolis as compared with the maximum discharge each year for which records are available is given by the following table:

Annual maximum discharge of Big Horn River at Thermopolis, Wyo., 1900–1923.

Year.	Date.	Discharge (second-feet).	Year.	Date.	Discharge (second-feet).
1900	June 8	14,600	1915	June 3	11,800
1901	May 22	17,500	1916	21	13,000
1902	June 12	9,890	1917	24, 27	19,400
1903	19	10,100	1918	17	19,200
1904	22	14,600	1919	1	5,000
1905	6, 8	10,600	1920	14	13,800
1911	19	18,000	1921	10	20,800
1912	11	19,500	1922	11	12,100
1913	May 31	17,700	1923	July 24	29,800
1914	June 5	12,800	1923	Sept. 29	25,500

NOTE.—Maximum discharge for extreme stage recorded except for 1902 and 1911–1914, when it is for the 24-hour period.

FLOOD ON POWDER RIVER, WYO.

GENERAL FEATURES.

The general rains which caused the September flood on Big Horn River covered the entire drainage basin of Powder River and extended north into Montana. The flood on Powder River was the largest that has occurred in the 40 years that white settlers have lived in the valley.

The following table shows all available rainfall records at Weather Bureau stations in the Powder River basin:

Rainfall in Powder River basin, Wyo., Sept. 26–30, 1923, in inches.

Station.	26	27	28	29	30	Total.
Ervay		2.47	1.20	0.27	0.13	4.07
Salt Creek [a]		.25	1.88	1.27	.35	3.75
Barnum		.81	1.75	.04	.15	2.75
Ninemile Creek [b]		.70	1.25		2.50	4.45
Buffalo		1.46	4.03	.61	.19	6.29
Gillette		Tr.	2.12	.40	.95	3.48
Echeta		.04	2.20	1.35	1.10	4.69
Clearmont [a]		1.00	1.00	1.90	.25	4.15
Sheridan [c]		2.04	2.23	.96	.94	6.17
Sheridan field station [a]		.44	2.20	1.74	1.51	5.89
Verona [a]	1.20	1.50	1.55	1.33	.38	5.96
Hunters station	.09	1.80	1.07	.90	.70	4.56

[a] Precipitation measured in morning for 24-hour period ending at that time.
[b] Precipitation recorded on Sept. 30 is accumulation for two days.
[c] Regular Weather Bureau station; precipitation for 24-hour period ending at midnight.

NOTE.—Except as otherwise indicated, observations are made late in the afternoon, near sunset, and precipitation is recorded for 24-hour period ending at that time.

Roughly approximate records were also obtained at other points. B. F. Horton, who lives 4½ miles northeast of Arvada, measured 8½ inches of rainfall from September 20 to 30 in a coffee can in his yard. William La Follett, who lives in sec. 23, T. 45 N., R. 87 W., had a water tank 3 by 8 by 2½ feet deep in an exposed position. The rain began at 4 a. m. September 27, and by 4 p. m. on the 29th the tank contained 5 inches of water; two days later this had increased to 6 inches. A rancher near Savageton, in T. 45 N., R. 76 W., stated that a 14-quart water pail with nearly vertical sides, which stood in an exposed place, was filled twice in 48 hours, indicating an almost unbelievable rainfall of 17 inches. At Ross, just east of the Powder River basin, in T. 40 N., R. 75 W., no records were kept, but the postmaster stated that the rainfall was the heaviest in years. As much of the basin is very sparsely settled, it is possible that heavy rainfall occurred at other points and was not recorded.

The available data show that the rainfall over practically the entire drainage basin was at least 4 inches and that in some small areas it was considerably greater.

The flood was severe throughout the valley, and channels were changed and rechanged by it. All residents in the valley were forced to abandon their homes temporarily, as the water was from 10 to 12 feet deep in the river bottom above the main channel. Houses were destroyed, practically all hay was washed away, and whole flocks of sheep, as well as much other livestock, were swept away.

At Arvada the Chicago, Burlington & Quincy Railroad's 270-foot steel-girder bridge of five spans resting on large concrete piers was destroyed. The first pier began to settle during the afternoon of September 29, and by the next morning the entire bridge was gone, the piers having been undermined and overthrown. About 300 feet of high railroad fill at the north end of the bridge was also washed out.

PROGRESS OF FLOOD.

Records of Salt Creek, taken by the Midwest Refining Co. below Salt Creek reservoir, in sec. 36, T. 41 N., R. 79 W. (drainage area 520 square miles), show that the creek rose from 1 second-foot about 4 p. m. September 27 to 32,000 second-feet[2] at 2.30 a. m. September 28 and fell to 1,000 second-feet at 3 p. m. September 29. By October 8 the discharge had fallen to 10 second-feet. The crest of the flood on Powder River occurred at Arvada at 8 p. m. September 29, 30 hours later than at the reservoir, and as Arvada is 145 miles distant by river the crest traversed this distance at an average rate of 4.8 miles an hour. Usually a flood crest flattens out as it

[2] Slope measurement from high-water marks and area of cross section checked by computation of flow through contracted openings.

proceeds downstream, but this one was augmented by floods from all the tributaries. Undoubtedly one of the chief contributors was Crazy Woman Creek, which rises in the south end of the Big Horn Mountains. Although no record of that stream is available, it is known that prior to the time of the flood in Powder River a heavy fall of wet snow, beginning September 24, occurred in the mountains. This was later followed by rain, which melted the snow and caused all the streams that flow eastward from the mountains to reach severe flood stages.

FLOOD AT ARVADA.

In order to obtain all available flood data the gaging station on Powder River at Arvada was visited on October 7 and 8. The gage is at the highway bridge in the outskirts of Arvada. Paint marks

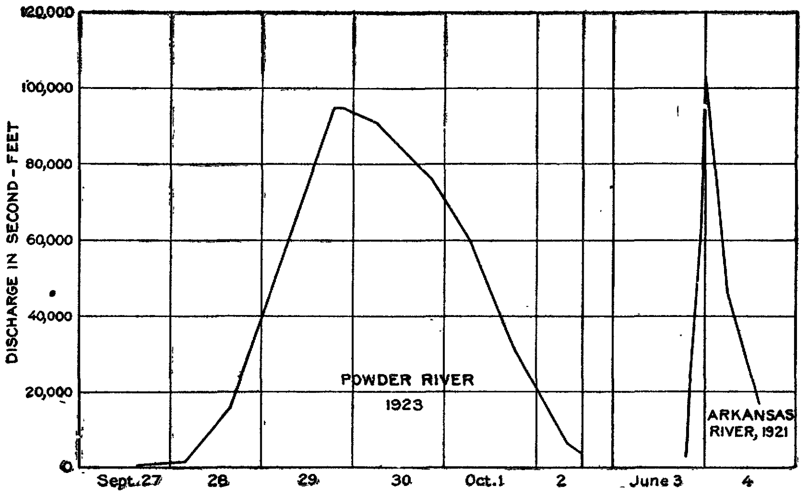


FIGURE 11.—Hydrographs of floods in 1923 on Powder River at Arvada, Wyo., and in 1921 on Arkansas River at Pueblo, Colo.

at each end of the bridge indicated the maximum stage; this was determined by level to be 4.7 feet above the floor of the bridge, or 23.7 feet above the zero of the gage. From statements of citizens the height of the river at various times during its rise and fall was determined. A fairly straight section of river beginning 200 yards below the railroad bridge was selected to measure the high-water slope and cross sections. The slope was well defined by fine drift on one side of the river; on the other the bank was formed by a nearly vertical shale cliff. Two cross sections 515 feet apart were measured to the water's edge, and the width of the river at each section was determined by triangulation. From this the maximum discharge was computed to be 95,000 second-feet, the value of "n" being taken as 0.030.

An approximate hydrograph for the period September 27 to October 2 has been prepared (fig. 11) and shows that the river rose from 300 second-feet on the 27th to 15,000 second-feet at 3 p. m. on the 28th. After that it rose rapidly to the maximum of 95,000 second-feet at 8 p. m. on the 29th. It remained at crest stage for an hour and then fell slowly to 90,000 second-feet at 6 a. m. September 30. After that the fall was more rapid, the discharge decreasing to 60,000 second-feet at 11 a. m. October 1 and to 32,000 second-feet at 6 p. m. the same day. By noon of October 2 the river was nearly back to normal stage. The total discharge during the flood was estimated at 438,000 acre-feet, which is greater than the total yearly flow for each year but one in the eight preceding years for which records are available.

An idea of the unprecedented discharge of the river during the flood is given by the following table, which shows the annual maximum discharge for the years during which records are available:

Annual maximum discharge of Powder River at Arvada, Wyo., 1916–1923.

Year.	Date.	Discharge (second-feet).	Year.	Date.	Discharge (second-feet).
1916	June 29	6,080	1920	June 19	10,700
1917	May 22	8,780	1921	June 3	6,680
1918	July 14	10,800	1922	Aug. 3	6,030
1919	Aug. 3	2,460	1923	Sept. 29	95,000

NOTE.—From 1916 to 1918, inclusive, the station was maintained just above the mouth of Clear Creek, 17 miles downstream.

The flood at Arvada is an excellent example of the type of floods to which plains streams are subject and is in sharp contrast to floods on mountain streams having steep slopes, an example of which is shown by the flood of June 3, 1921, on Arkansas River at Pueblo, Colo. (See fig. 11.) The maximum stages were almost equal, but the Arkansas rose and fell very rapidly, and the total discharge during the portion of the flood shown by the hydrograph in Figure 11 was less than 90,000 acre-feet.

FLOODS AT SHERIDAN, WYO.

Sheridan lies just north of the Powder River basin at the confluence of Goose and Little Goose creeks. The storms that caused the flood in Powder River were very severe near Sheridan and on the eastern slope of the Big Horn Mountains, a few miles distant.

Goose and Little Goose creeks rose suddenly on the night of September 27. Sheridan was flooded, 300 basements being filled with water, and scores of citizens were driven from their homes. Much of the wooden-block street paving was scattered or carried down Goose Creek. The total damage at Sheridan was estimated at $500,000.

Sheridan experienced another flood on the night of September 30, caused by a rise on Little Goose Creek which flooded some of the houses to a depth of 5 feet. Part of the best residential section was reported to have suffered considerably by the overflow. No discharge estimates for these floods are available.

CLOUDBURST FLOODS.

TEMPLETON GAP NEAR COLORADO SPRINGS, COLO.[3]

Between 6 and 9 p. m. May 27, 1922, a very heavy rain above Templeton Gap, 5 miles northwest of Colorado Springs, Colo., produced a flood that caused much damage to property in and near Colorado Springs. An investigation of the flood by the United States Geological Survey was made a few days after it occurred.

Northeast of Colorado Springs is a semicircular range of hills, which rise abruptly from the plains and reach an altitude 800 feet higher than that of Colorado Springs. The hills are of rocky formation and support little vegetation. They inclose a basin having a narrow outlet called Templeton Gap.

About 6 p. m. May 27 heavy clouds from the southwest passed over Colorado Springs and upon reaching the hills above Templeton Gap were forced upward until their moisture was condensed and precipitated in a rainfall that reached cloudburst intensity. A rancher living above the gap estimated from the amount of water caught in a pail standing in his yard that the rainfall was 7 inches. It was reported that farther up toward the summit of the hills 10 inches of hail fell.

The resulting flood reached Papeton, 1 mile below Templeton Gap, about 8.30 p. m., flooded some of the streets to a depth of 4 feet, and washed out fences, barns, streets, and sidewalks. Half a mile below Papeton it destroyed a considerable stretch of railroad track. A peculiarity of the flood was the mud balls left in the channel. These were composed of black clay or gumbo and ranged from 6 to 30 inches in diameter. So fine was their texture that they closely resembled black boulders.

A straight section of channel was found a short distance below Templeton Gap, and three cross sections 200 feet apart were measured. The total slope between the sections was determined from high-water marks to be 0.0108, and the maximum discharge was computed as 6,120 second-feet, or 862 second-feet a square mile from 7.1 square miles of drainage area. The total discharge was estimated at 757 acre-feet. The area above Templeton Gap is subject to frequent cloudbursts, but residents state that this flood was the greatest in 50 years or more.

[3] Abstracted from Hodges, P. V., Cloudburst flood near Colorado Springs, Colo.: Eng. News-Record, Nov. 30, 1922.

CHERRY CREEK NEAR PARKER, COLO.

During the afternoon of July 28, 1922, heavy rain fell near Parker, Colo., about 20 miles southeast of Denver, causing a severe flood in the upper Cherry Creek basin and filling the channel of the stream at Denver. An investigation of this flood was made by the United States Geological Survey in cooperation with the State engineer's office.

The area of heavy rainfall extended from a point 3 miles north of Parker to a point 1 mile south of Franktown and from the county line on the east to a point 4 miles west of the creek. The heaviest rainfall was in the basin of Bayou Gulch.

Mrs. William Boegle, who lives 3 miles above the mouth of Bayou Gulch, in sec. 30, T. 7 S., R. 65 W., stated that the storm, which came from the west, began about 2 p. m. and lasted for two hours. The total rainfall was about 3½ inches as measured in an iron wheelbarrow with nearly vertical sides. The water stood 2 feet deep in the road, and the resulting flood was the highest in nearly 50 years. A rancher at the mouth of the gulch stated that two storms met over the gulch; one came from the north and the other from the west. Heavy rain lasted one hour. A rancher living 1 mile above the mouth of the gulch stated that the heavy rain lasted 45 minutes and that the flood crest was reached at 3.45 p. m. and remained near that stage for 1 hour. A. W. Payne, a rancher living in sec. 3, T. 7 S., R. 66 W., near Cherry Creek, halfway between Bayou Gulch and Parker, stated that the rain lasted from 2 to 4 p. m. and amounted to 2 inches as measured in a wash tub in the yard. The rise in Cherry Creek came about 3 p. m. The total discharge of the Cherry Creek flood was estimated at 3,960 acre-feet.

Maximum discharge of Cherry Creek at the points measured, July, 1922.

Stream.	Locality.	Maximum discharge (second-feet).		Drainage area affected (square miles).
		Total.	Per square mile of area affected.	
Bayou Gulch	Sec. 23, T. 7. S., R. 66 W.	8,670	460	19
Cherry Creek	Sec. 4, T. 6 S., R. 66 W.	17,000	195	87

The flood of July 14, 1912, the highest recorded at Denver, was caused by a storm which covered an area that extended from Parker for a distance of 5 miles toward Denver and by a very severe storm in Denver at the same time. At the point where the flood of 1922 was measured the flood of 1912 was at practically the same stage, but in Denver the maximum discharge was estimated at 11,000 to 14,000 second-feet and caused considerable damage and the loss of several lives. The maximum discharge of the flood of 1922 in Denver was about 6,000 second-feet. The difference between 17,000 second-feet near Parker and 6,000 second-feet at Denver shows the effect of the flattening out of the flood crest as it progressed downstream, owing to the channel and overflow storage afforded it. If the storm of 1922 had occurred nearer Denver, the resulting flood in Denver would probably have almost equaled that of 1912.

BUCKHORN CREEK NEAR LOVELAND, COLO.

From June 14 to 16, 1923, heavy rains occurred over an area that extended from a point a few miles east of Greeley, Colo., to the western edge of R. 70 W., in the foothill region.

The only Weather Bureau records within this area are those at Fort Collins, which show a precipitation of 2.07 inches; those at Waterdale, which show 2.39 inches; and those at Greeley, which show 2.63 inches during the entire period. The heaviest precipitation was south of Fort Collins, near Loveland, in the foothill area, and appeared to center over the lower part of the Buckhorn Creek basin. This caused the highest flood known on Buckhorn Creek and several of its tributaries. All bridges on the lower Buckhorn and on Big Thompson Creek below the Buckhorn were washed out, two lives were lost, thousands of acres of rich agricultural land was ruined, and much livestock was drowned.

The drainage area of the lower Buckhorn Creek consists of three narrow, troughlike valleys, which converge slightly toward the northwest. Narrow ridges 400 to 500 feet high separate these valleys. The middle valley is drained by Buckhorn Creek, which flows southeastward. The other two valleys are drained by a number of small tributaries that have cut through the narrow ridges, forming side canyons, and join the main stream at short intervals. These small tributaries drain fan-shaped areas which converge at the outlet canyons. The slopes are steep and rocky and support little vegetation except some scrubby pines and a small amount of brush.

The United States Geological Survey made an investigation of the flood within a week of its occurrence, determined the maximum discharge at three points by means of slope measurements from well-defined high-water marks, measured the cross sections of flood areas, and interviewed residents to obtain all possible information on the rainfall.

The storm came from the south and followed the course of Buckhorn and Redstone creeks. In its progress northward the storm was augmented by clouds from the southeast. Observers at Loveland stated that swiftly moving clouds passed over Loveland and continued northwestward to the foothills, where they appeared to join the main storm, which was traveling northward. The troughlike valleys up which the clouds traveled converge at their north ends, and their convergence caused a concentration of the clouds, which resulted in a cloudburst. The area thus affected extended from the mouth of Buckhorn Creek to a point near Fletcher Hill, 5 miles above Masonville; above that point little rain fell. The rain started about 5 p. m. June 15 and lasted for several hours. A rancher who lives a short distance above the mouth of Missouri Canyon reported that during the period of greatest intensity 2½ inches of water was caught in 30 minutes in a tub in his yard. The ground was well saturated from previous rains, being thus unable to absorb much of this rainfall. The following table shows the maximum discharge at the three points where it was measured:

Maximum discharge at points in Buckhorn Creek basin, June 15, 1923.

Stream.	Locality.	Maximum discharge (second-feet).		Drainage area (square miles).		Time of flood crest.
		Total.	Per square mile of area affected.	Total.	Area producing flood.	
Buckhorn Creek [a]	Half a mile south of Masonville.	10,500	262	134	40	10 p. m.
Redstone Creek [b]	Masonville	6,820	325	31	21	Do.
Missouri Canyon [c]	Near mouth (sec. 26, T. 6 N. R. 70 W.).	4,350	1,820	2.4	2.4	6.30 p. m.

[a] Two cross sections, measured 544 feet apart, and slope between found to be 0.0085; some brush and débris, otherwise smooth; "n"=0.045.
[b] Two cross sections measured 392 feet apart, and slope between found to be 0.0148; some brush but fairly smooth section; "n"=0.035.
[c] Three cross sections measured in distance of 280 feet, and slope of entire distance found to be 0.027; fairly smooth except in places where it is rocky; "n"=0.035.

The flood in Missouri Canyon occurred several hours before that in Buckhorn Creek and probably did not contribute greatly to the latter flood. As the point at which the Buckhorn flood was estimated is below the mouth of Redstone Creek, the measured flow in the Buckhorn includes the flow of the Redstone, which leaves about 3,700 second-feet to be contributed by the Buckhorn itself during the crest flow.

MINOR FLOODS.

Data on three minor floods in small areas are presented in the following table:

Maximum discharge of minor floods in the Rocky Mountain region, 1923.

Stream.	Date.	Maximum discharge (second-feet).		Drainage area square (miles).
		Total.	Per square mile.	
Magpie Gulch 1½ miles above Golden, Colo	July 26, 1923	[a] 1,900	1,270	1.5
Skyrocket Creek at Ouray, Colo	July 20, 1923	2,000	2,000	1.0
South Sand Draw in sec. 3, T. 3 N., R. 3 W. Wind River meridian, Wyo	Aug. 21, 1923	2,840		

[a] From two cross sections 194 feet apart; slope found to be 0.090; "n"=0.045.

Cloudbursts in the foothills above Golden, Colo., occurred July 26, 1923, and caused floods in all the gulches that enter Clear Creek from the north within 2 miles of Golden. At the mouth of Magpie Gulch the rainfall was moderate, but half a mile above it was a cloudburst. The rain began about 12.45 p. m., and the flood reached its crest by 1 p. m. and then fell so rapidly that by 1.40 p. m. the flow in the gulch was again normal. This flood deposited a gravel and boulder dam 10 feet high entirely across Clear Creek, a distance of about 70 feet. Some of the boulders moved by the flood weighed as much as 5 tons.

The recording gage on Uncompahgre River at Ouray, Colo., registered a severe flood on July 20, 1923. This flood was caused by a cloudburst on Skyrocket Creek, which drains the almost vertical walls of the mountains back of Ouray and enters the Uncompahgre at the gage. The hydrograph of the flood (fig. 9, *A*) shows that the discharge of the river increased from 275 to 2,000 second-feet in about 30 minutes and fell almost as quickly.

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