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NOTE ON THE EFFECTS OF RAINGAGE EXPOSURES.

By WILLIAM GARDNER REED.

[Dated: University of Chicago, July 15, 1915.]

For the past two years the University of California has been engaged in an intensive study of the rainfall conditions over the watershed of Strawberry Creek, which has an area of about 1 square mile, in the attempt to determine its possibilities as a source of water supply for the university grounds and buildings. Rainfall and runoff surveys were made during 1913–14 by Howard M. Loy,[1] and during 1914–15 by Marshall K. White, both senior students in the College of Civil Engineering. The work was done under the immediate direction of Prof. Charles G. Hyde, although the writer was consulted in regard to the meteorological aspects of the work. During 1913–14 rainfall measurements were made from 5 standard 8-inch gages, visited at the end of each storm. I the autumn of 1914 the number of gages was increased to 13, but the procedure remained the same.

From a strictly meteorological point of view the most important result so far seems to be the difficulty, if not the impossibility, of determining the precipitation on a watershed by means of ordinary raingages. It was hoped to make experiments with shielded gages, but this could not be carried out. As has often been recognized, the problem of determining the amount of water which falls on a given area is far from simple, and the complexity is greatly increased when the area is broken into valleys and ridges. The problem of rainfall measurement is apparently simple; it is merely to determine the depth of water which falls on a given area. But in practice numerous difficulties are met with. Theoretically an 8-inch gage exposed in a position where the rainfall is about the average for the area should give a sample of the precipitation of the whole region; but it has often been noted that the catch of the gage is largely controlled by local conditions. Prof. C. F. Marvin[2] has stated the exposure problem as follows:

> The exposure of raingages is a very important matter. The wind is the most serious disturbing cause in collecting precipitation. In blowing against the gage the eddies of wind formed at its top and about the mouth carry away rain and too little is caught.
>
> Raingages in slightly different positions, if badly exposed, catch very different amounts of rain. Within a few yards of each other two gages may show a difference of 20 per cent in the rainfall of a heavy storm. The stronger the wind the greater the difference is apt to be. * * * Since the value of the precipitation records depends so greatly upon proper exposure, particular care should be taken in selecting a place for the location of the gage. * * * If possible, a position should be chosen in some open lot, unobstructed by large trees or buildings. Low bushes and fences or walls that break the force of the wind in the vicinity of the gage are beneficial, if at a distance not less than the height of the object.

It is doubtful if there is a single good exposure in the area under investigation; it therefore becomes necessary to make the best of the exposures available. The results of the first year's work seemed to indicate that the ridge called Skyline Ridge (fig. 1) forming the southerly wall of the canyon was a region of heavier rainfall, and therefore 3 of the additional gages supplied for 1914–15 were located on it. The gages numbered 1 to 5 were located in the same positions as in 1913–14, and the others were placed in representative positions which seemed to have relatively good exposures. Gage 5′ was placed near gage 5, which had given the least consistent readings in 1913–14, in an effort to determine whether the irregularities represented real differences in rainfall or were due to poor exposure conditions. It was intended to shield gage 5′, but with the funds available no screen could be erected which would withstand the wind and the interference by horses and cattle. Gage 5′, however, gives more consistent measurements than gage 5, although its total catch is smaller. The map (fig. 1) and Table 1 give the details of the exposure of the 13 gages during 1914–15.

TABLE 1.—*Exposure of field raingages in the Strawberry Creek basin, 1914–15.*

[H = approximate elevation of gage above sea level. h_r = height of rim of gage above ground.]

Gage No.	H.	h_r.	Angle of slope. Maximum. Above gage.	Angle of slope. Maximum. Below gage.	Angle of slope. Normal to maximum. Above gage.	Angle of slope. Normal to maximum. Below gage.	Description of location.*
	Feet.	*Inches.*					
1	520	10–20	+ 4° N.	−28° S.	+ 5° E.	− 5° W.	On steep bank of Strawberry Creek, about 25 feet N. of the center of the channel and 5 feet below the break where the ground drops to the creek bed. Above and N. from this break the ground is practically level for 125 feet. Across the creek the canyon wall slopes about 40°. Gage is well protected from wind. Maximum slope N. to S.
2	730	22	+17° N.	−15° S.	+ 5° E.	−15° W.	East side of large slide into Strawberry Creek. 40 feet N. of center of channel. Across the creek the canyon wall slopes nearly 45°. Gage is well protected from wind. Maximum slope N. to S
3	880	13	+30° NE.	−23° SE.	+18° NW.	0° SE.	Slightly N. of ridge of spur between two branches of Strawberry Creek. Maximum slope N. 30° E. Fairly well protected from southerly winds.
4	1,225	18	+25° NE.	−20° SE.	+10° NW.	−20° SE.	In a shallow depression at the head of one of the branches of Strawberry Creek. Maximum slope N. 30° E. Gage surrounded by large pile of stones, with top 3 inches below and 6 inches away from the rim. Well protected from wind.
5	1,270	14	+12° N.	−22° S.	− 5° W.	− 8° E.	On ridge line of spur of Frowning Ridge. Maximum slope N. to S. Swept by winds deflected by the main ridge through 2 low passes from SE. to NW.
5′	1,270	18	+12° N.	−22° S.	+ 5° E.	−12° W.	15 feet W. of No. 5, slightly below the ridge of the spur. Maximum slope N. to S. Gage partly protected from wind by small pine tree.
6	1,250	22	+12° N.	+ 7° S.	− 3° E.	− 3° W.	In a flat saddle fairly well protected from winds. Pine tree 3 feet high, 8 feet NE.; another 10 feet SW. from gage.
7	1,190	16	+15° N.	−15° S.	−12° W.	− 5° E.	In a broad draw. Maximum slope N. to S. Gage unprotected from winds.
8	1,180	18	+15° NE.	+30° SW.	−30° SE.	−25° NW.	In a low pass NE. of Monument Hill. Maximum slope NE. to SW. Pass is swept by winds deflected along the face of the main ridge.
9	915	12	+ 3° SE.	−30° NW.	+ 2° NE.	− 3° SW.	On the lower edge of a small dell about halfway between Strawberry Creek and the top of Skyline Ridge. Maximum slope N. 30° W. Well protected from all southerly winds.
10	1,210	12	.....	.....	.....	.....	Unprotected from winds. All slopes flat for a radius of 40 to 60 feet from gauge. Records incomplete on account of interference with gage.
11	1,315	8	+20° NE.	+12° SW.	−18° NW.	−15° SE.	In a low pass at junction between Skyline Ridge and Frowning Ridge. Maximum slope N. 30° E. Swept by winds deflected from the face of Frowning Ridge.
12	1,655	16	.....	.....	.....	.....	On broad flat at the top of Frowning Ridge. All slopes flat within 100 to 200 feet of gage. Gage surrounded by a pile of stones to within 4 inches of rim. Though there is no evident protection from wind, strong winds are infrequent.

*For the larger topographic relations see the map, figure 1.

[1] **Reed, W. G., & Loy, H. M.:** The water resources of Strawberry Creek, Berkeley, Cal. Monthly Weather Review, 43; 35-39, Washington, January, 1915.

[2] **Marvin, C. F.** The measurement of precipitation. Washington, 1913, pp. 5-6. (U. S. Weather Bureau, Inst. Div. Circular E.)

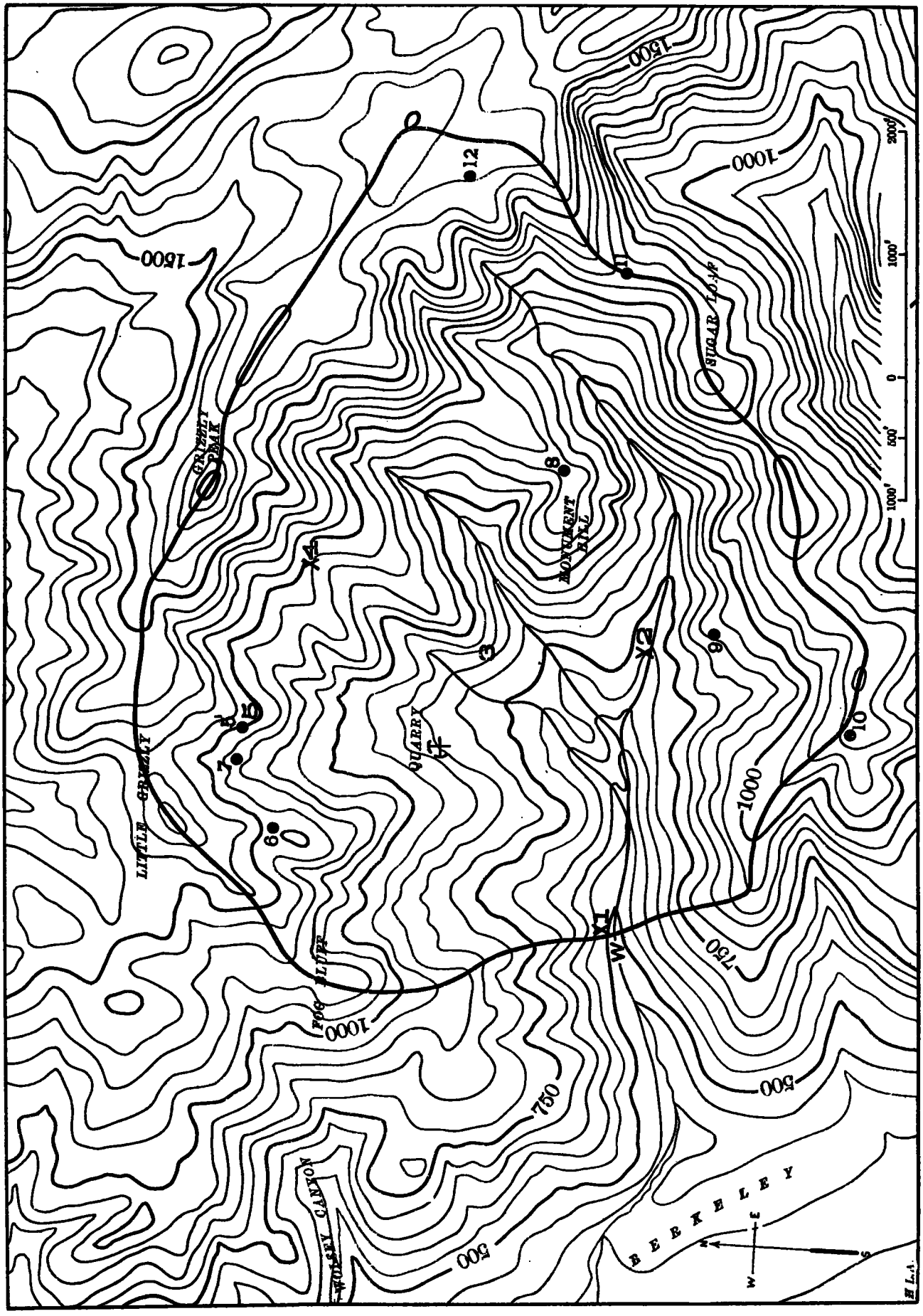

FIG. 1.—Contour map of Strawberry Creek, Berkeley, Cal., by W. H. Otis. Contour interval, 50 feet. Weir located at W.; raingages located at 1, 2, 3, etc.; gages 5' to 12 were installed in 1914.

TABLE 2.—*Rainfall of Strawberry Canyon from May 1, 1914 to Apr. 30, 1915, with ratios of individual gages to average, showing variation of rain from gage to gage and relative reliability of the individual gages.*

Date.	Students' Observatory.		C. E. building.		Gage No. 1.		Gage No. 2.		Gage No. 3.		Gage No. 4.		Gage No. 5.		Gage No. 5′.		Gage No. 6.		Gage No. 7.		Gage No. 8.		Gage No. 9.		Gage No. 10.		Gage No. 11.		Gage No. 12.	
	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.	Rain during storm.	Total for month.
1914.																														
May 8	0.21	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
25	0.41	0.62	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
June 7	0.38	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
24	0.10	0.48	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
July —	.....	0.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Aug. —	.....	0.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Sept. 7	0.02	0.02	0.02	0.02	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Oct. 10	0.02	.....	0.04	.....	0.03	.....	0.05	.....	0.04	.....	0.05	.....	0.00	.....	.....	.....	.....	.....	0.07	.....	0.05	.....	0.03	.....	0.02	.....	.....	.....	.....	.....
17	0.62	.....	0.57	.....	0.67	.....	0.78	.....	0.65	.....	0.67	.....	0.62	.....	0.79	.....	.....	.....	0.55	.....	0.81	.....	1.09	.....	.....	.....	0.85	.....	0.76	.....
20	0.21	0.84	0.19	0.80	0.28	0.98	0.30	1.13	0.23	0.92	0.27	0.99	0.24	0.92	0.23	.....	0.30	.....	0.26	0.88	0.32	1.18	0.31	1.43	.....	.....	0.35	.....	0.34	.....
Nov. 1	0.22	.....	0.20	.....	0.19	.....	.....	.....	0.19	.....	0.18	.....	0.18	.....	0.17	.....	0.20	.....	0.18	.....	0.19	.....	0.20	.....	0.19	.....	0.19	.....	0.19	.....
28	0.13	.....	0.13	.....	0.14	.....	0.15	.....	0.16	.....	0.17	.....	0.16	.....	0.16	.....	0.17	.....	0.16	.....	0.15	.....	.....	.....	.....	.....	.....	.....	0.17	.....
30	0.08	0.43	0.07	0.40	0.07	0.40	0.05	.....	0.04	0.39	0.02	0.37	0.04	0.38	0.04	0.37	0.06	0.43	0.05	0.39	0.05	0.39	.....	.....	.....	.....	.....	.....	0.05	0.41
Dec. 6	2.10	.....	1.74	.....	2.02	.....	.....	.....	1.73	.....	1.76	.....	1.68	.....	1.32	.....	2.00	.....	1.60	.....	2.07	.....	.....	.....	.....	.....	.....	.....	1.97	.....
10	1.55	.....	1.38	.....	1.70	.....	1.68	.....	1.49	.....	1.45	.....	1.47	.....	1.20	.....	1.52	.....	1.31	.....	1.54	.....	.....	.....	.....	.....	.....	.....	1.49	.....
18	2.60	.....	2.65	.....	2.97	.....	2.85	.....	3.02	.....	2.85	.....	2.80	.....	2.36	.....	2.75	.....	2.76	.....	1.96	.....	.....	.....	.....	.....	.....	.....	2.63	.....
27	0.33	6.58	0.25	6.02	0.35	7.04	0.32	.....	0.33	6.57	0.32	6.38	0.38	6.33	0.32	5.20	0.35	6.62	0.34	6.01	0.35	5.92	.....	.....	.....	.....	.....	.....	0.35	6.44
1915.																														
Jan. 7	1.25	.....	1.17	.....	1.20	.....	1.30	.....	1.17	.....	1.19	.....	1.04	.....	1.02	.....	1.29	.....	1.15	.....	1.19	.....	1.16	.....	1.29	.....	1.27	.....	1.19	.....
9	0.94	.....	0.89	.....	0.93	.....	0.95	.....	0.94	.....	0.97	.....	0.86	.....	0.82	.....	1.02	.....	0.90	.....	0.96	.....	0.99	.....	0.99	.....	1.00	.....	1.00	.....
15	1.46	.....	0.99	.....	1.27	.....	1.35	.....	1.11	.....	1.13	.....	0.83	.....	0.87	.....	1.40	.....	1.00	.....	1.37	.....	1.31	.....	0.84	.....	1.48	.....	1.35	.....
Feb. 4	4.78	8.43	4.51	7.56	5.46	8.85	.....	.....	4.75	7.97	4.90	8.19	3.40	6.13	3.74	6.45	5.56	9.27	4.52	7.57	5.85	9.37	5.82	9.28	6.70	9.82	6.97	10.72	5.89	9.43
11	2.83	.....	2.76	.....	3.32	.....	3.19	.....	2.94	.....	2.79	.....	2.15	.....	2.23	.....	1.97	.....	2.59	.....	3.18	.....	2.89	.....	2.53	.....	3.42	.....	3.10	.....
24	3.44	.....	3.10	.....	3.52	.....	3.33	.....	3.45	.....	3.18	.....	2.86	.....	2.78	.....	3.46	.....	3.79	.....	3.75	.....	3.47	.....	3.62	.....	3.71	.....	3.70	.....
28	0.44	6.71	0.42	6.28	0.43	7.27	0.43	6.95	0.43	6.82	0.40	6.37	0.50	5.51	0.45	5.44	0.43	5.86	0.48	6.86	0.40	7.33	0.37	6.73	0.44	6.59	0.41	7.54	0.40	7.20
Mar. 14	0.25	.....	0.25	.....	0.25	.....	.....	.....	0.28	.....	0.22	.....	0.11	.....	0.20	.....	0.21	.....	0.10	.....	0.18	.....	0.21	.....	0.20	.....	0.25	.....	0.25	.....
31	1.58	1.83	1.37	1.62	1.85	2.10	1.88	.....	1.83	2.11	1.63	1.85	1.44	1.55	1.24	1.44	.....	.....	1.65	1.75	1.68	1.86	1.94	2.15	.....	.....	1.77	2.02	1.93	2.18
Apr. 8	0.26	.....	0.22	.....	0.24	.....	0.24	.....	0.27	.....	0.21	.....	0.18	.....	0.15	.....	0.20	.....	0.20	.....	0.18	.....	0.22	.....	.....	.....	0.24	.....	0.24	.....
29	0.71	0.97	0.69	0.91	0.71	0.95	.....	.....	0.67	0.94	0.69	0.90	0.71	0.89	0.66	0.81	.....	.....	0.75	0.95	0.73	0.91	0.77	0.99	.....	.....	0.84	1.08	0.76	1.00
Total observed	26.91	.....	23.59	.....	27.59	.....	18.85	.....	25.72	.....	25.05	.....	21.71	.....	20.73	.....	22.89	.....	24.42	.....	27.06	.....	20.78	.....	16.82	.....	22.75	.....	27.76	.....
Expanded total	26.91	.....	24.49	.....	28.79	.....	28.79	.....	26.91	.....	26.10	.....	22.60	.....	21.53	.....	27.18	.....	25.30	.....	28.26	.....	29.06	.....	29.06	.....	32.03	.....	29.06	.....

Date.	Average of all records.	Ratios of individual gages to average.															
		Students' Observatory.	C. E. building.	Gage No. 1.	Gage No. 2.	Gage No. 3.	Gage No. 4.	Gage No. 5.	Gage No. 5′.	Gage No. 6.	Gage No. 7.	Gage No. 8.	Gage No. 9.	Gage No. 10.	Gage No. 11.	Gage No. 12.
1914.																
May 8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
June 7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
24	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
July —	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Aug. —	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Sept. 7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Oct. 10	0.04	0.50	1.00	0.75	1.25	1.00	1.25	1.50	.....	.....	1.75	1.25	0.75	0.50	.....	.....
17	0.72	0.85	0.79	0.93	1.08	0.90	0.93	0.86	1.10	.....	0.76	1.12	1.51	.....	1.18	1.06
20	0.27	0.78	0.70	1.04	1.11	0.85	1.00	0.89	0.85	1.11	0.96	1.19	1.15	.....	1.30	1.26
Nov. 1	0.19	1.16	1.05	1.00	.....	1.00	0.95	0.95	0.89	1.05	0.95	1.00	1.05	1.00	1.00	1.00
28	0.15	0.87	0.87	0.93	1.00	1.07	1.13	1.07	1.07	1.13	1.07	1.00	.....	.....	.....	1.13
30	0.05	1.60	1.40	1.40	1.00	0.80	0.40	0.80	0.80	1.20	1.00	1.00	.....	.....	.....	1.00
Dec. 6	1.82	1.15	0.95	1.11	.....	0.95	0.97	0.92	0.73	1.10	0.88	1.14	.....	.....	.....	1.06
10	1.48	1.05	0.93	1.15	1.14	1.01	0.98	0.99	0.81	1.03	0.89	1.04	.....	.....	.....	1.01
18	2.77	0.94	0.96	1.07	1.03	1.09	1.03	1.01	0.85	1.00	1.00	0.71	.....	.....	.....	0.95
27	0.33	1.00	0.76	1.06	0.97	1.00	0.97	1.15	0.97	1.06	1.03	1.06	.....	.....	.....	1.06
1915.																
Jan. 7	1.19	1.05	0.97	1.01	1.09	0.97	1.00	0.87	0.86	1.08	0.97	1.00	0.97	1.08	1.07	1.00
9	0.94	1.00	0.95	0.98	1.01	1.00	1.03	0.92	0.87	1.08	0.96	1.02	1.05	1.05	1.06	1.06
15	1.18	1.24	0.84	1.08	1.14	0.94	0.96	0.70	0.74	1.19	0.85	1.16	1.11	0.71	1.25	1.14
Feb. 4	5.20	0.92	0.87	1.05	.....	0.91	0.94	0.55	0.72	1.07	0.87	1.12	1.12	1.29	1.34	1.13
11	2.79	1.01	0.95	1.19	1.14	1.05	1.00	0.77	0.80	0.71	0.89	1.14	1.04	0.91	1.23	1.11
24	3.41	1.01	0.91	1.04	0.98	1.01	0.93	0.84	0.81	1.02	1.11	1.10	1.02	1.06	1.09	1.09
28	0.43	1.02	0.98	1.00	1.00	1.00	0.93	1.16	1.05	1.00	1.12	0.93	0.86	1.02	0.95	0.93
Mar. 14	0.21	1.19	1.19	1.19	.....	1.34	1.05	0.52	0.95	1.00	0.48	0.86	1.00	0.95	1.19	1.19
31	1.68	0.94	0.82	1.10	1.12	1.09	0.97	0.86	0.74	.....	0.98	1.00	1.15	.....	1.05	1.15
Apr. 8	0.22	1.18	1.00	1.09	1.09	1.23	0.96	0.82	0.68	0.91	0.91	0.82	1.00	.....	1.09	1.09
29	0.70	1.01	0.99	1.01	.....	0.96	0.99	1.01	0.95	.....	1.07	1.04	1.10	.....	1.20	1.09
Total observed	25.77	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Average ratio	.....	1.00	0.91	1.07	1.07	1.00	0.97	0.84	0.80	1.01	0.94	1.05	1.08	1.08	1.19	1.08
Maximum ratio	.....	1.24	1.19	1.19	1.14	1.34	1.13	1.16	1.10	1.19	1.12	1.19	1.51	1.29	1.34	1.26
Minimum ratio	.....	0.78	0.28	0.14	0.10	0.34	0.16	0.32	0.30	0.30	0.18	0.34	0.43	0.37	0.24	0.15
Greatest divergence from average	.....	0.24	0.28	0.14	0.10	0.39	0.16	0.32	0.30	0.30	0.18	0.34	0.43	0.37	0.24	0.15
Number of storms in which ratio diverged more than 10 per cent from its average value	.....	10	6	4	1	4	3	10	6	4	5	6	3	4	5	3
Total rain during storms in which ratio diverged more than 10 per cent from its average value	.....	4.85	1.77	1.02	0.04	0.74	0.24	12.50	2.69	3.06	6.01	5.12	1.19	5.45	7.82	3.47

The results of the work of 1913–14 were published in the MONTHLY WEATHER REVIEW for January, 1915.[3] Table 2 is the record for 1914–15 by rain periods. The field gages were visited at the end of each rain period. Readings of the gage at the Students' Observatory were made twice each day, at 8 a. m. and 8 p. m., Pacific time. The gage at the Civil Engineering Building, 60 feet above the ground, is an electrically recording tipping-bucket Friez gage, but check readings have been made by stick measurements. Both these gages are better exposed than most of those on the watershed. At the Students' Observatory the 25-year record shows apparent homogeneity, although the position of the gage has been changed twice, and for seven years this exposure was on the ground; the present Observatory exposure is 15 feet above the ground and is fair, although not ideal.[4] Comparisons of the gage at the Civil Engineering Building with that at the observatory made during 1914–15 by White indicate a probable total error of the recording gage due to elevation above the ground and inherent error of the recording device of less than 10 per cent. The relations between the two gages are shown in Table 2 for each rain period of the year. Neither of these gages is located on the drainage area. The records are introduced, as they probably show the general rainfall conditions better than the more poorly exposed gages on the watershed. They are both on the flatter slope which extends from the foot of the steep slope shown at the western edge of the map (fig. 1) to San Francisco Bay. The grade from the foot of the steep slope is about 300 feet to the mile for the first half mile, from an altitude of about 400 feet, and much flatter for the 2 miles to the Bay. The altitude of the observatory gage is 325 feet, and that of the recording gage is 410 feet.

A study of the records of the field gages for the two years of observation shows very wide variations in the catch of the different gages, and further that the variations in the catch of the individual gages are most irregular. The relations for each storm of the season 1914–15 are shown in Table 2. That some of the differences are the result of real differences in precipitation can hardly be doubted; the record for Oakland, about 5 miles south of Berkeley, shows differences of the same order as between these gages and of the same irregular character.

As a preliminary step in the study of the differences the records of all the gages were averaged for each storm. If the gage readings were true records of the precipitation at the place of exposure and the gages were well distributed, these averages would indicate the precipitation on the watershed. The ratios between the average and the individual catches are shown in Table 2. The average gage catch does not give a correct idea of the general precipitation conditions over the watershed because neither of the postulates agrees with the facts. Figure 1 shows that the gages are not uniformly distributed over the watershed, although when placing them the aim was to select districts as representative of the varying conditions as possible. The study of the records shows that the lowest catches are those of gages open to the sweep of the wind. However, the average is useful as a basis of comparing the gages with themselves; the errors due to faulty exposure will certainly be more irregular in the case of any particular gage than in the average for all the gages, as the differences for individual gages will tend to vary with different wind directions and velocities. It is, of course, obvious that the total precipitation over a drainage area where rain-gage exposure is faulty will be greater than that indicated by the catch of the gages.

When the records of the individual gages are compared with the average of all the gages an average ratio for the season can be determined for each gage. The consistency of the gage may then be ascertained by comparing the ratio for each storm with the average ratio for the gage. It is reasonable to suppose that the more irregular gages are those with poorer exposures. The more consistent ratios probably approach the actual precipitation conditions. The order of consistency of the ratios of the gages is as follows: 2, 4, 3, 1, 9, 5′, 6, 12, 8, 7, 10, 11, 5. This order is practically the same as that of the protection of the gages from the sweep of the wind. The relative consistency of gages 5 and 5′ is of interest; these gages, although only 15 feet apart, differ 20 per cent for certain storms. The exposure of both is undoubtedly bad, but 5′ is much more consistent than 5. This is probably due to better protection of 5′, which is partly sheltered by the crest of the ridge and also by the small trees near the gage. But the catch of 5′ is even smaller than that of 5. The indication, especially since the other gages in the vicinity show small records, is that this region is actually one of smaller rainfall and that the low readings are not wholly due to poor exposure.

While it is, perhaps, not legitimate to draw conclusions from the records of gages poorly exposed, the observations during the two years seem to indicate:

(1) That the rainfall over the drainage area is heaviest on the southeast ridge.

(2) That there is a considerable area of smaller rainfall in the line of the notch between Grizzly Peak and Little Grizzly.

(3) That the precipitation is greater near the heads of the valleys than on the ridges.

The first of these results was suggested by the work of 1913–14; it shows clearly from the records of 1914–15, and was to be expected, as the wind during precipitation is usually southerly or southeasterly. No results from shielded gages on the ridge or of conditions on the windward side are available. The area of low precipitation may be explained by the opportunity for considerable masses of air to pass through the gap without being forced upward to a height materially greater than previously attained in crossing the southern ridge. This ridge continues from the south to Grizzly Peak, so that the precipitation probably increases eastward from the drier area. It is, of course, wholly possible that the gages in this portion of the area read abnormally low because of the poor exposure and the sweep of the wind through the pass. The relations of the gage catch in the valley heads and on the ridges is also subject to the interpretation of better protection of the gages, and hence truer records in the valleys; but it is possible to regard the differences as due to the relations of the slopes. The gages were exposed near the places where the slope changes from the somewhat gentler stream profile to the steeper gully head. Casual observations show that the air movement is probably guided in part by the valleys, and that the change in slope tends to concentrate the rainfall near the place where the increase begins. These relations between rainfall and slope have been noted in the Sierra Nevada and elsewhere.[5]

[3] **Reed, W. G., & Loy, H. M.** Op. cit., p. 37.
[4] **Reed, W. G.** The rainfall of Berkeley, Cal. Univ. Cal. Publ. Geog., Berkeley, 1913. 1:63-79 (no. 2), pp. 65-66.
[5] **McAdie, A. G.** The rainfall of California. Univ. Calif., Publ. Geog. Berkeley, 1914. 1:127-240 (No. 4), p. 154.

The study of the rainfall over the drainage area of Strawberry Creek is in no sense finished. The conclusions here presented must be regarded as provisional. One result, however, is clearly evident, and that is that the exposure of raingages, local as well as general, needs much careful study. The attempt to determine the amount of water falling on a drainage area is beset with difficulties, relating first to the relation between the catch of the raingage and the actual rainfall in its immediate vicinity, and second to the distribution of precipitation in different parts of a diversified watershed. Studies like that upon which this report is based should be continued not only for Strawberry Creek, but for other areas, small and large, until the relations between rainfall and rainfall measurements are better known. A word of caution is necessary: Although it is probable that many rainfall records are not accurate statements of the actual precipitation, they are the best available and should not be rejected out of hand. Such records may and should in time be supplemented by more accurate data, but as they stand they represent accumulated material of great value, which should not be rejected, except for good reason. The purpose of this report is to indicate how detailed work may increase the information already obtained, and to show the relations upon which detailed water supply studies may be based. The most important single result of the two years' work is probably the clear indication that, at least in wind-swept regions, some kind of shielding of the gage is highly desirable if accurate records are to be obtained.

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DISTRIBUTION OF THUNDERSTORMS IN THE UNITED STATES.

By WILLIAM H. ALEXANDER, Local Forecaster.

[Dated: Weather Bureau, Cleveland, Ohio, July 28, 1915.]

INTRODUCTION.

The writer confesses to a peculiar admiration for the thunderstorm, being ever and always deeply impressed with the beauty and sublimity exhibited in its approach and passage. Led on by this natural impulse, direct and thoughtful attention has been given to these storms for quite a number of years and over a considerable area measured in degrees of latitude (17° to 44° N. lat.). Not only so, but all available literature bearing on them has been read with diligence. The primary purpose of this paper, however, is to present in a brief, simple way some data on the distribution of thunderstorms over the United States and the neighboring Canadian Provinces. The material has been collected by the approval of the Chief of Bureau and with the assistance extended by officials in charge of the various stations. There seems to be a real need for some more definite, detailed, and up-to-date statistics on the subject; perhaps the information will serve to supplement the paper on the thunderstorm by Prof. W. J. Humphreys.[1]

As suggested by Prof. Humphreys in his paper, "the geographic distribution of the thunderstorm may safely be inferred from the fact that it is caused by strong vertical convection of humid air." This distribution over the United States and southern Canada is clearly shown on the accompanying charts (W. H. A.—1 to 13; XLIII–71 to 83). These charts also bring out the relative frequency and distribution of these storms for the different months of the year; and when studied in conjunction with corresponding charts of temperature, humidity, and precipitation, they will suggest to the student of meteorology many interesting, intimate relations between these various factors.

The graphic charts are supplemented by detailed tabulated data for individual stations, having fairly long records, showing the number of storms for each month for the entire period covered by the record. It will be observed that in most cases there is a marked discrepancy between the number recorded in the early years of the record as compared with the number in recent years. This is probably due to the fact that the instructions governing the recording of thunderstorms were more definite and positive and the observers more careful during the latter part of the record.

METHODS OF THUNDERSTORM RECORDING USED BY THE UNITED STATES SIGNAL SERVICE AND THE WEATHER BUREAU.[2]

1871. The earliest edition of Instructions to Observer Sergeants on file in the Weather Bureau Library is that published in 1871. On page 19 of this work, in connection with instructions for entries in the "journal," is found the following:

> In the journal will be entered daily all matters of interest not provided for in the various forms, such as meteoric and auroral displays, earthquakes, and unusual atmospheric appearances and disturbances, giving in all cases, when possible, the time of beginning and duration of each. Especially will the observer enter a detailed account of the characteristic phenomena of every serious storm that passes over his station.

No specific mention of thunderstorms is made either in the paragraph above quoted or elsewhere in these instructions. This paragraph appears to have remained practically unchanged in the Instructions to Observer Sergeants until 1879. (See below.)

1874. An early mention of the recording of thunderstorms by the Signal Service is found in connection with the explanation of Form E—Division of Telegrams and Reports for the Benefit of Commerce. (See Annual Report, Chief Signal Officer, 1874, p. 290), as follows:

> *Thunderstorms.*—Time of occurrence and direction of motion * * *.

1879. In the instructions to Observer Sergeants, 1879, page 70, occurs the following reference to thunderstorms:

> The abstract [of the journal] should show clearly and briefly all matters of interest not provided for in the regular forms, such as flight of birds, early vegetation * * * meteoric and auroral displays, earthquakes, thunderstorms, distant lightning, high winds and gales * * * giving whenever practicable the time of beginning and duration of each.

1881. Instructions to Observers of the Signal Service, U. S. A., Washington, 1881, page 91, contains practically the same instructions for recording thunderstorms as that quoted above from the edition of 1879. In addition, on page 63 of the 1881 edition, appears the following:

> The state of the weather will be determined as follows:
> * * * thunderstorm with light or heavy rain, when a thunderstorm is prevailing at the moment of the observation, or the rain is still falling, although neither thunder has been heard nor lightning observed for some time previous to the observation.

Signal Service Order No. 16, April 5, 1881, contains the following:

> * * * Observers will record in their journals and, in a condensed form, under "Remarks," in Original Record and all other

[1] See this REVIEW, June, 1914, 42: 348-380.

[2] Contributed by the Weather Bureau Library, Prof. C. F. Talman in charge.