MONTHLY WEATHER REVIEW

Editor, EDGAR W. WOOLARD

Vol. 72, No. 5
W. B. No. 1415

MAY 1944

Closed July 5, 1944
Issued August 1, 1944

A METHOD OF MEASURING RAINFALL ON WINDY SLOPES

By G. L. Hayes, Associate Forester [1]

[Appalachian Forest and Range Experiment Station, Asheville, North Carolina]

THE object of precipitation measurement, as stated by Brooks (**1**), is to obtain "a fair sample of the fall reaching the earth's surface over the area represented by the measurement." The area referred to is horizontal, or map area. Even when measured on a slope, precipitation is always expressed as depth of water on a horizontal area.

On wind-swept areas, whether flat or sloping, many factors hinder the accurate measurement of precipitation. Koschmieder (**5**), Brooks (**2**), Riesbol (**6**), and many others have adequately demonstrated that a rain gage of conventional design, conventionally installed with the receiver two or more feet above the ground surface, will not catch from wind-borne rain a representative sample of the catch at the earth's surface. This failure is attributed to the turbulence produced in the wind stream by the gage—an "upward diversion and marked acceleration of air over the gage" (**1**), and eddy currents within the mouth of the receiver, which whip away many raindrops that would otherwise enter the gage. The catch by a gage mouth elevated above the earth's surface is therefore less than the amount actually reaching the earth.

This error is accentuated when measurements are attempted on mountain slopes. There, in addition to the turbulence caused by the gage in the air stream, the horizontal receiver is exposed to the rain-bearing winds at a different angle than is the ground surface and therefore intercepts the falling rain differently. The significance of this factor was recognized by the Hydrologic Division of the Soil Conservation Service in a recent publication (**7**) in which it was stated, "The exposure of the individual gages (on the North Appalachian Experimental Watershed) ranged from poor to excellent, due to the steep and highly dissected topography of the area and to the presence of much woodland and numerous farmsteads."

All of these measuring difficulties were encountered during the summers of 1935–1936 when, as part of a study of the topographic distribution of forest-fire danger,[2] rainfall was measured with conventionally exposed gages at six mountainside and one valley-bottom stations on the Priest River Experimental Forest in northern Idaho.

The precipitations recorded differed so markedly and illogically between stations having different aspect, elevation, and exposure to wind that some had to be judged erroneous. As previous investigations, already cited, had shown wind to be a common cause of gaging inaccuracies, some special installations to eliminate wind effects were designed in 1937. These were then operated alongside the conventional installations. Three season's data revealed a much more logical and what is believed to be a more true relationship between the stations in the amounts of rain recorded.

DESCRIPTION OF GAGES AND THEIR INSTALLATION

Each special installation consisted of a "sloped-orifice" gage in pit exposure. Exposing gages in pits with their receivers even with the ground surface had been shown (**2, 5, 6**) to be an effective means of shielding them from the accuracy-destroying winds. To place them in a pit on a slope, however, and still keep the orifice even with the surrounding surface required either that the gage be tilted from its usual vertical position, or that the orifice be sloped. If the gage were tilted, its catch would have to be multiplied by the secant of the angle which the orifice made with the horizontal (**1**) to convert it to a true measure of the fall on unit horizontal area.

As it was obviously desirable to avoid this mathematical correction, and as W. A. Rockie[3] had reported that rainfall, as collected by large concrete run-off tanks located on sloping ground near Pullman, Washington, had been reliably sampled by sloped-orifice gages in above-ground exposure, sloped-orifice gages were adopted. The sloping orifice permitted each gage to be placed with the plane of the orifice parallel to and contiguous with the surrounding ground surface, and yet be kept in a vertical position so that its catch was a direct measure of the fall on unit horizontal area.

The sloped-orifice gage, shown in figure 1, consists of a Forest Service type gage with a sloped, galvanized, sheet-iron extension added to the receiver. Each receiver was sloped individually to fit the incline of the station where it was to be used. The extensions were added in a local (Missoula, Mont.) metal-working shop at a cost of $1.89 each which, when added to the $1.31 unit cost of the

[1] When this report was prepared the author was Assistant Forester at the Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Mont.

[2] A complete description of the study area and rain-gage locations is presented in the United States Department of Agriculture Circular No. 591, "Influence of altitude and aspect on daily variations in factors of forest-fire danger" by G. Lloyd Hayes. This gives in detail the results of the major study of which the rain measurements treated in this paper were part.

[3] In an unpublished paper presented before the Northwest Scientific Association at Spokane, Wash., in December, 1936.

596494—44——1

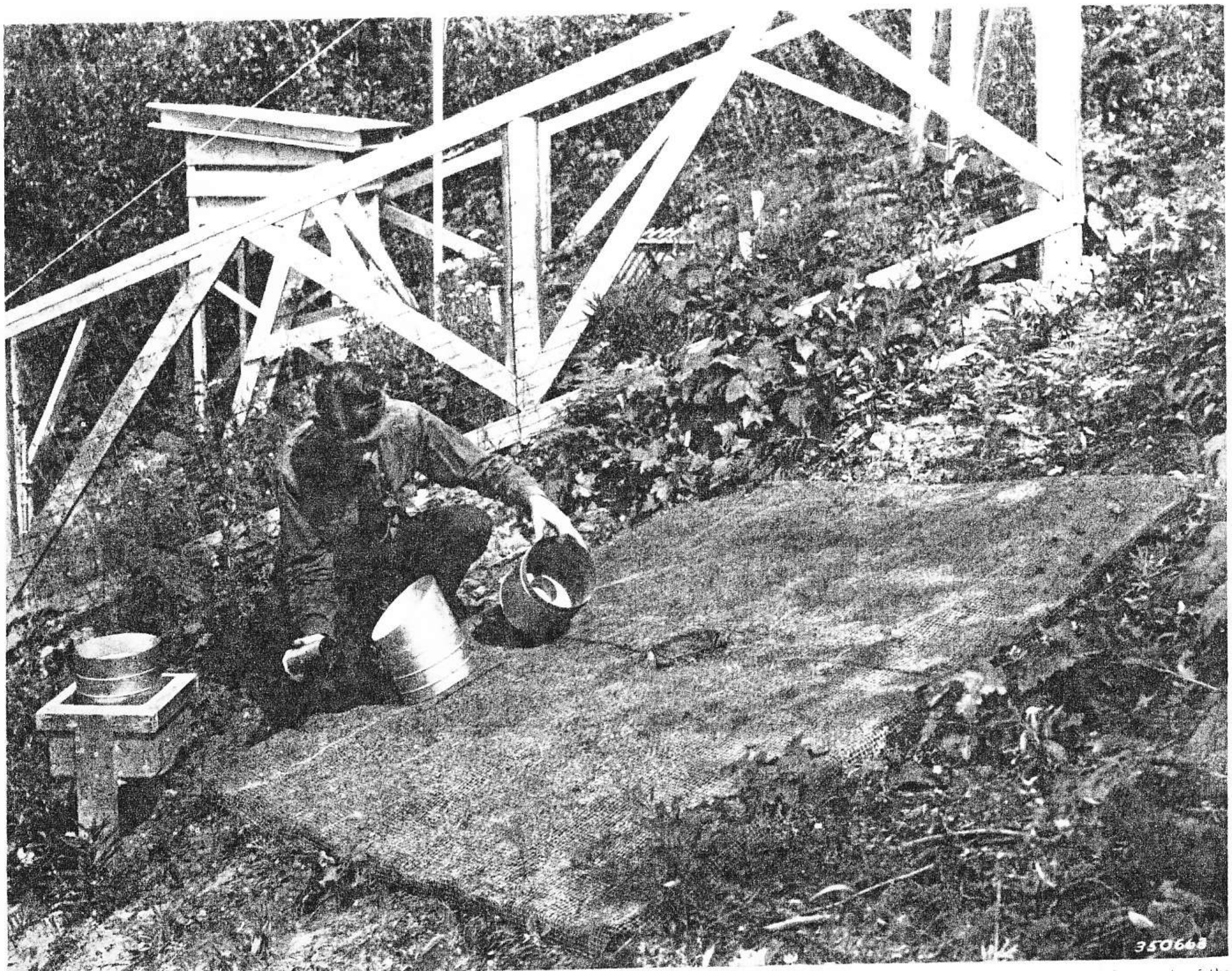

FIGURE 1.—The 2,700-foot, north-slope installation, showing on the left the Forest Service rain-gage exposed in the "conventional" manner, and center, the various parts of the slope-orifice gage. The sloping orifice of the gage fits flush with the surface when the gage is placed in the hole in the center of the splash-preventing mat. (Photo F350663 by K. D. Swan, U. S. Forest Service.)

Forest Service gages, made a total cost of only $3.20 for each specialized instrument.

To shield the pit-exposed gages from surface splash, they were surrounded by 6 by 6 foot square, splash-preventing mats of ordinary excelsior covered by half-inch mesh hardware cloth as shown in figure 1. This mat design stopped rain splash efficiently but was ineffective for large hail. All storms that included hail were, therefore, excluded from the analyses. Riesbol (**6**) found that under some conditions a spray from breaking raindrops might be swept by the wind along the ground surface and erroneously increase the catch of a pit gage, but it is believed that the herbaceous and brushy ground cover around these stations (fig. 1) was a protection against such an occurrence during this study.

The "conventional" installation at each station consisted of a Forest Service type rain gage exposed about two feet above ground as shown at the left in figure 1. This gage is similar in pattern to the Weather Bureau standard type but differs from it in capacity and materials. Hayes (**3**), using 330 comparative measurements of rainfall with the Forest Service and Weather Bureau standard type gages, and 311 comparative measurements with a Friez tipping-bucket type, has demonstrated the comparability of the Forest Service type to these common standard designs. As the sloped-orifice gages were but modified Forest Service gages, the two installations at each station differed only in the shape of the gage orifice, length of rim above the funnel, and in the relation of the gage orifice to the ground.

RAIN-GAGING STATIONS

Rain was measured at seven different stations; one on the valley bottom and the other six on the mountain slopes above. It was at the latter six stations that the sloped-orifice gages were used. The valley-bottom station was on a flat where, although it was quite open to wind movement, the storm winds which frequently accompanied rain were not so strong as at some of the stations above. Only a conventionally exposed rain gage was used at the valley station until 1939, when a pit-exposed gage was added. No significant difference was found between a season's catch of the two gages, indicating that accurate measurements could be obtained there by either method of exposure.

The six slope stations were paired at elevations of 2,700, 3,800, and 5,500 feet respectively; one of each pair on a true north and one on a true south slope. The two stations which comprised each pair were in no case more than 300 feet apart, nor more than 50 vertical feet below the crest of the ridge that separated them. They differed only in that one faced north, the other south, and in the steepness of the slope.

The south-slope stations were subject to greater wind effects than the north, as the storm winds were predominantly from a southerly direction. The average velocities for August 1935–38, measured 7½ feet above the ground, for example, were 3.9, 3.6, and 4.5 m. p. h. respectively at 2,700, 3,800, and 5,500 feet on the south slope, but only 2.4, 2.0, and 3.4 m. p. h. at corresponding elevations on the north slope. When the wind was stronger than average, as it frequently was during rainstorms, the contrast between aspects was much greater. During one such storm on October 4, 1939, it averaged over a four-hour period 11.1, 12.7, and 11.8 m. p. h. respectively at 2,700, 3,800, and 5,500 feet on the south slope, but only 3.1, 2.2, and 5.1 m. p. h. on the north.

The 3,800- and 5,500-foot south slope gages were subject to the greatest wind effects. In addition to being on the windward side of the mountain, there was very little shrubbery or other vegetation near the gages that was high enough to shelter them from the full effects of the wind. The gages at the third south-slope station, at 2,700 feet, were also on the windward side of the mountain of course, but they were partly sheltered from the wind. The station there was in a 32- by 32-foot clearing in a brush patch that undoubtedly reduced the wind at rain-gage height, although it had little apparent effect at anemometer height.

The north-side stations differed considerably in degree of openness to wind. At 5,500 feet the gages were fully as exposed as at the 3,800 and 5,500-foot stations on the south side, but at 2,700 feet the north station, like the south, was in a clearing in a brush patch (fig. 1) where the gages were undoubtedly partly sheltered. The 3,800-foot north station was the most sheltered of all. This station was in a clearing in dense green timber where, even though the gages were from 100 to 250 feet from the edges of the clearing, strong winds never penetrated. Even at the anemometer height of 7½ feet, a velocity of as much as 6 m.p.h. for as much as one hour was never recorded in five seasons of measurements.

In relation to steepness of slope, another factor that affects rain-gaging accuracy, the 3,800-foot stations were least favorable for accurate gaging. There the ground sloped 28° on the south, and 27° on the north side. The 2,700-foot south station was most favorable with a slope of only 15°, and the other three stations were approximately average; 21° at 2,700 north, and 20° at each of the 5,500 foot stations.

RESULTS

The results of the measurements in 1935–36 by conventional methods, shown in table 1, illustrate well the deficiencies of the conventional-type gages when used in conventional exposure on windy slopes. The catch of the partially sheltered 2,700-foot gages was nearly the same on both aspects, the south side catch being only three percent greater than the north, indicating that approximately equal amounts of rain probably fell on each side of the ridge. At 3,800 and 5,500 feet, however, the catches of the exposed gages on the windy south

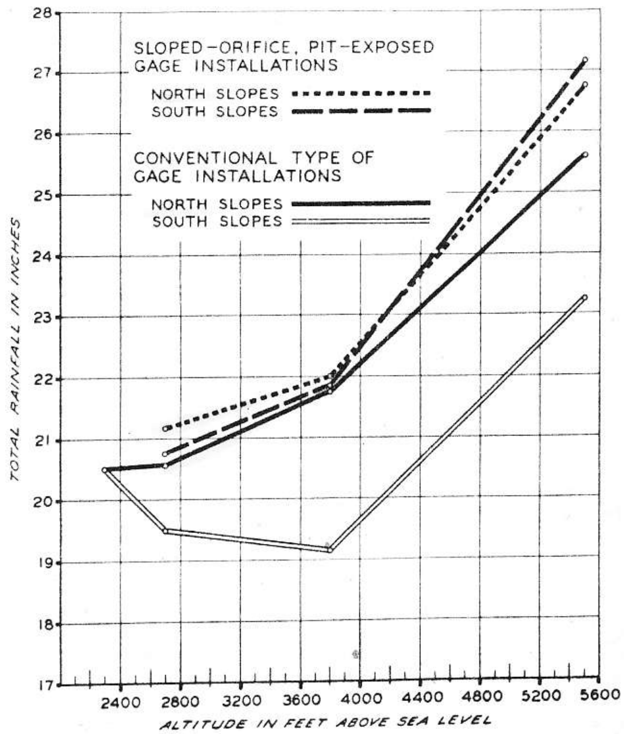

FIGURE 2.—Total rainfall for the 1937–39 seasons as measured by both the slope-orifice, pit-exposed gages, and the conventional type gages and exposure. Priest River Experimental Forest. Length of season: 1937, June 1–October 6; 1938, June 10–October 10; 1939, May 29–October 9.

slope were far less than the catches on the less windy north slope, being only 83 and 91 percent respectively. If as much rain fell on the windward south slope as on the leeward north slope at these elevations, the gages did not catch as much of it.

Further evidence that the gages on the windward side were deficient in catch was furnished by the rainfall-altitude relationships on the two sides of the ridge. On the leeward north side the rainfall catch increased progressively with elevation in accordance with frequently demonstrated rainfall-altitude relationships (**4**), but on the windward south aspect the catch, even as high as 3,800 feet, was actually less than on the valley bottom 1,500 feet below.

In 1937–39 the results from the conventional installations continued to show these same serious discrepancies, but the pit-exposed, sloped-orifice gages revealed an entirely different relationship between stations. For contrast the results from both types of installations have been shown in figure 2. Instead of the large differences that were shown by the regular installations between aspects, the north and south sides were now shown by the special gages to receive about equal amounts of rain. In fact, it is shown by table 2 that the rainfall on the two aspects, as caught by the sloped-orifice gages, did not differ by a statistically significant amount except at the 2,700-foot stations.

Furthermore, instead of decreasing with elevation up to 3,800 feet, the rainfall on south slopes was shown to increase in the usual manner. These results are believed for two reasons to represent a high degree of gaging accuracy. First, the design and exposure of the gages were based upon the sound and demonstrated principles that on windy slopes, rain gages should be installed with their receivers parallel to the slopes (**1**), and that pit exposure, if properly protected from splash, effectively eliminates the wind disturbance created by a standard gage conventionally exposed (**5, 2, 6**).

Second, the differences between the catches of the sloped-orifice and conventionally exposed gages were greatest where the gages were most exposed to strong winds and were the least where the gages were most sheltered. This is clearly evident in table 3 which shows that at the exposed and windswept 3,800- and 5,500-foot south stations the sloped-orifice gages caught 2.68 and 3.87 inches, respectively, more during the three seasons than did the conventional type, whereas at the very well sheltered 3,800-foot north station the totals differed by but 0.21 inch. There where the wind velocity 7½ feet above ground averaged but 2 m. p. h. and never exceeded 6 m. p. h. for as much as 1 hour even during the most violent storms, any soundly designed gage should sample rainfall accurately and there, according to table 3, the two types of installations gave measurements that agreed so closely that no statistical significance can be attached to the small difference. At all the other stations the excess of the catch of the sloped-orifice over the conventional gage installation was statistically significant at the 0.01 level of probability.[4]

SUMMARY AND CONCLUSIONS

The accurate measurement of rainfall is very difficult on wind-swept mountain slopes. Conventional methods are inadequate for such situations. A high degree of accuracy has been obtained, however, with sloped-orifice gages in pit exposure.

Numerous measurements of rainfall, now made by conventional methods on open, windy slopes, could be made much more accurately by the methods herein described. On the National Forests of Montana and northern Idaho, for example, over 700 conventionally-exposed rain gages are used as aids to forest fire control management. Many of these are located on mountain summits where the winds that accompany summer convectional rainstorms frequently reach velocities of 35 to 50 miles per hour.

TABLE 1.—*Precipitation during 1935 and 1936 seasons [1] as measured by conventionally exposed rain gages at 1 valley-bottom and 6 mountainside stations*

Situation and elevation (feet)		1935	1936	Mean
		Inches	*Inches*	*Inches*
Valley bottom	2,300	3.01	6.55	4.78
North aspect	2,700	3.57	6.14	4.86
	3,800	3.98	6.31	5.14
	5,500	4.64	6.93	5.78
South aspect	2,700	3.41	6.61	5.01
	3,800	2.92	5.66	4.29
	5,500	3.88	6.59	5.24

[1] Priest River Experimental Forest. Length of season: 1935, May 22–Oct. 7; 1936, May 20–Oct. 2.

[4] Meaning that there is a probability of only one or less in 100 that the difference found was due to chance or that data for three other seasons might show opposite results.

Under such conditions Koschmieder (**5**) found that conventionally exposed gages may catch less than 30 percent of the actual rainfall as measured by pit gages. For selected storms during the present study the conventionally installed gage at the windy 5,500-foot, south-slope station caught as little as 50 percent of the catch of the sloped-orifice, pit-exposed gage. Measurements under such conditions by conventional installations cannot be sound aids to fire-control management.

TABLE 2.—*Comparison of north- and south-aspect rainfall as measured by sloped-orifice gages in pit exposures at 3 elevations* [1]

Elevation (feet)	Number of storms	Total rainfall		
		North slope	South slope	Difference
		Inches	*Inches*	*Inch*
2,700	48	21.20	20.73	[2] 0.47
3,800	49	21.98	21.88	.10
5,500	50	26.73	27.16	.43

[1] Priest River Experimental Forest for the 1937–39 seasons.
[2] Statistically significant at the 0.05 level of probability.

TABLE 3.—*Comparison of rainfall as measured by sloped-orifice rain-gages in pit exposures, and by conventional-type rain-gages in conventional exposures at 6 mountainside stations* [1]

Situation and elevation (feet)	Number of storms	Total rainfall		
		Forest Service gage	Sloped gage	Difference
		Inches	*Inches*	*Inches*
North aspect:				
2,700	49	20.61	21.22	[2] 0.61
3,800	49	21.77	21.98	.2.
5,500	52	25.61	26.76	[2] 1.15
South aspect:				
2,700	48	19.54	20.73	[2] 1.19
3,800	49	19.20	21.88	[2] 2.68
5,500	50	23.29	27.16	[2] 3.87

[1] Priest River Experimental Forest, for June 7 to Oct. 6, 1937; June 10 to Oct. 10, 1938; May 29 to Oct. 10, 1939
[2] Statistically significant at the 0.01 level of probability.

LITERATURE CITED

(1) **Brooks, Charles F.** 1938. Need for universal standards for measuring precipitation, snowfall and snow cover. Reprinted from Trans. Intl. Comm. of Snow and of Glaciers, Edinburgh, September 1936. Intl. Assoc. Hydrol. Bull. 23, 52 pp. illus. Riga. 1938.

(2) ———. 1938. Wind shields for precipitation gages. Trans. Amer. Geophys. Union, pp. 539–542. Illus.

(3) **Hayes, G. L.** 1942. Reliability of Forest Service type rain gage. U. S. W. B. Mo. WEA. REV. 70: 267–268, illus.

(4) **Henry, Alfred J.** 1919. Increase of precipitation with altitude. U. S. W. B. Mo. WEA. REV. 47: 33–41, illus.

(5) **Koschmieder, H.** 1934. Methods and results of definite rain measurements. III. Danzig Report. U. S. W. B. Mo. WEA. REV. 62: 5–7, illus.

(6) **Riesbol, Herbert H.** 1938. Results from experimental rain gages at Coshocton, Ohio. Trans. Amer. Geophys. Union, pp. 542–550.

(7) **U. S. Soil Conservation Servive.** 1941. Hydrologic data, North Appalachian Experimental Watershed, Coshocton, Ohio, 1939. Hydrologic Bull. 1, 193 pp., illus.