THE PROBLEM OF SAMPLING RAINFALL IN MOUNTAINOUS AREAS

E. L. HAMILTON

CALIFORNIA FOREST AND RANGE EXPERIMENT STATION

A GENERAL APPROXIMATION of the rainfall on a given unit of land surface can be obtained from a single rain gage placed at some convenient spot within the land unit. The rain caught by the gage is assumed to represent the amount of rain caught by the whole land unit. The single gage, however, provides no measure of the variations in amount of rainfall on different slopes and at different altitudes in the unit. For the management of a mountain area in which water is an important product, it is necessary to have an adequate estimate of precipitation, not only for the area as a whole but for each of its component drainage basins.

The San Dimas Experimental Forest in the mountains of southern California is a field research center set apart for the study of water yield from forest watersheds [**5**].[1] Here it is necessary to make accurate determinations of the amount of water produced by the streams and springs. These are fed by rainfall in the mountains, and the facility with which rainfall is transformed into streamflow is dependent on the varying soil, vegetation, and geological composition of the many mountain slopes comprising the watershed. Hence we must know not only the total amount of rainfall reaching the mountains but also how it is distributed on the component slopes of each watershed. This calls for representative sampling by means of rain gages.

By way of definition, a rain gage may be described as a vertical cylinder with an orifice eight inches in diameter, usually placed so that this orifice is about three feet above the ground.

The map reproduced as figure 1 indicates the intensity of rainfall sampling over the entire Experimental Forest, which comprises an area of about 25 square miles, or 16,000 acres. Here some two hundred gages have been installed in order to establish a lateral and vertical distribution of samples.

Let us narrow the problem of sampling to the small shaded area, the Bell Multiple Watersheds. These four small drainage basins, ranging in area from 38 to 100 acres, have been selected for certain intensive studies of streamflow, erosion, and the like, and for this purpose it is necessary to know the rain catch of their various slopes. The surface runoff, subsurface runoff, evaporation, interception by vegetation, and transpiration by plants must, in their sum, equal the rainfall, plus or minus the loss or gain, during any given period, of the stock of water stored in catchment, that is, in soil, rock, streams, lakes, marshes, and reservoirs [**1**].

The Bell Watersheds are characterized by the steep slopes, the narrow canyons, and in general the sharply dissected topography typical of southern

[1] Boldface numbers in brackets refer to references at the end of the paper (p. 475).

California mountains. They are covered with a dense mantle of brush called chaparral. In order to place rain gages in the area it was necessary to construct access trails. These were laid out on contours at 300 foot intervals in elevation. A coördinate system of gage distribution on the trails, as indicated in in figure 2, was devised which gave a satisfactory sampling of the various aspects of the slopes according to the eight cardinal points of the compass and also provided for an altitudinal distribution [**10**]. Accordingly, sixty-nine rain gages were installed throughout the Bell drainage basins, as shown in the figure.[2]

Rainfall sampling now appeared to be on a good working basis, as indicated by analysis of the data for the first three years [**6**], [**10**]. Later, however, when more data were available, a careful scrunity of the records indicated that some gages, for no apparent reason, appeared to deviate strongly from normal behavior. That is, certain gages which had hitherto shown positive deviations from the watershed average gave negative deviations, then later reverted to their original trends. It seemed at times as if the nature of the storm had something to do with inconsistencies in the catch of gages in different parts of the watershed with reference to the catch of other gages and to the average catch on the watershed. This, coupled with implications in the work of other investigators [**1**], [**3**], [**4**], [**7**], aroused the suspicion that, although the arrangement of sampling units was adequate, the technique of measuring rainfall might be subject to question.

In order to put this suspicion to the test, three studies were undertaken. These were designed (1) to test the accuracy of the conventional rain-gage; (2) to discover, by inquiry into the behavior of the rain-producing storms, how rain actually reaches the earth's surface; and (3) to devise, by changes in gage placement, a more accurate measurement of rainfall.

From a comparative study of several types of rain gages it was found that the standard vertical gage, when used on steep mountain slopes, gave results consistently low compared with the rain catch of an adjacent control surface 78 square feet in area. (The surface was of concrete laid flush with the ground and parallel to the slope. It was 10 feet in diameter and was provided with a sheet metal rim 10 inches high to prevent loss or gain by splash. The lower end of the surface was connected to a tank having a basal area of one-tenth that of the control surface, affording convenient magnification of the depth of rain for greater accuracy in measurement of the rain catch.) The same study showed, however, that the depth of rain caught by a gage tilted to bring its vertical axis normal to the slope, and its funnel edge parallel to the slope, compared very closely with the depth caught by the control surface [**9**].

The storm-behavior experiments showed that several physical variables complicated our problem [**2**]. The direction from which the rain came, the velocity of the wind, the inclination of rainfall from the vertical, and the varying raindrop size, all combined to cause variations in the catches of rain-gages. The different types of storms were classified into groups governed by the predominant direction from which the rain came. For instance, we found

[2] Figure 2 shows only three watersheds, the fourth having been added later.

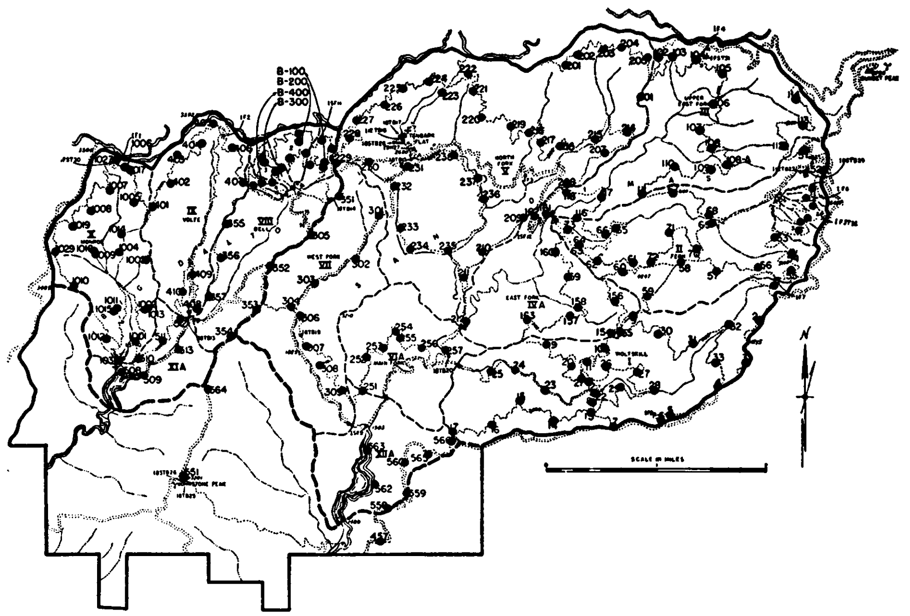

Fig. 1. Outline map showing rainfall-sampling network over the San Dimas Experimental Forest. The large black dots represent rain gages. Shaded area comprises the Bell Multiple Watersheds.

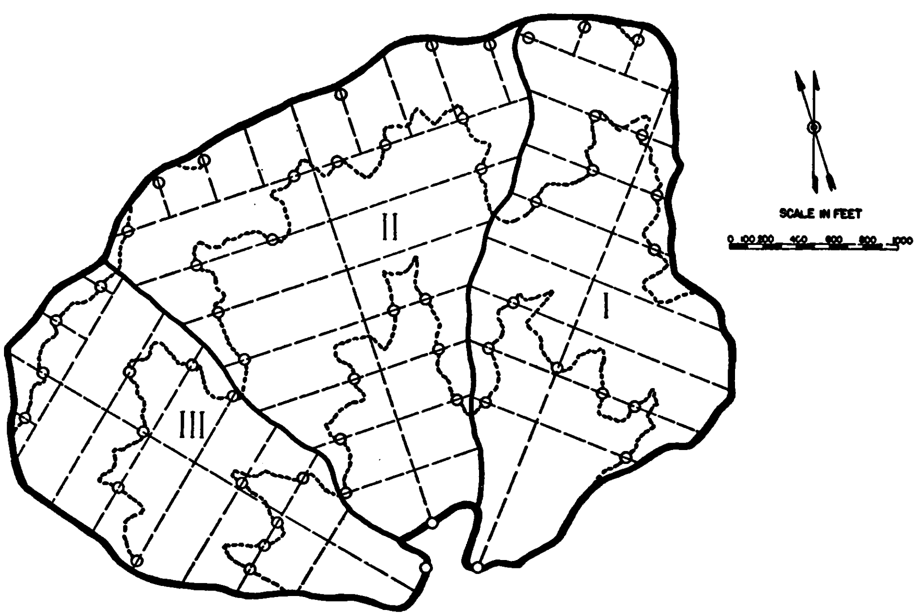

Fig. 2. The method adopted for determining rain-gage distribution in the Bell Multiple Watersheds is indicated by dashed lines. The contour trails are represented by dotted lines, the gage locations by circles.

that northerly storms comprised 40 per cent of the total number of storms but produced only 28 per cent of the total rainfall. Southerly storms comprised 60 per cent of the total number of storms and accounted for 72 per cent of the rainfall, most of which came from a relatively small number of southwesterly storms. In fact, the latter produced one-fourth of all the rain. These southwesterly storms are especially significant in that they are usually accompanied by high winds causing the rain to fall at a sharp angle. Horton [3],

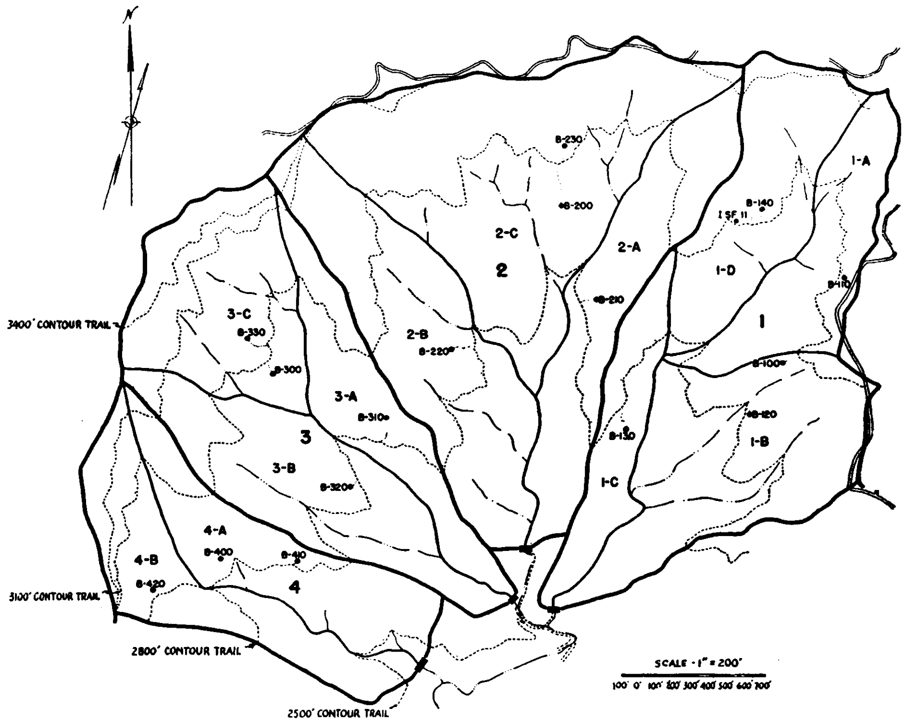

Fig. 3. Map of Bell Multiple Watersheds showing subdivision of area into equivalent facets, which are bounded by solid lines and designated as 1-A, 1-B, etc. Gages numbered 110, 120, 130, etc., are the watershed subfacet gages; gages numbered 100, 200, 300, and 400 are for the entire watershed facet.

Pers [7], and Fourcade [1] have all demonstrated mathematically that sharply inclined rain falling on sharply inclined slopes cannot be measured accurately in vertically placed gages. In the current problem the windy southwesterly storms assume special importance because the predominant aspect of our mountain watersheds is southerly.

Having obtained this supplementary information about storms and rainfall characteristics, and having devised an improved means of measurement in the tilted rain gage, we felt that satisfactory rainfall sampling could now be accomplished. Further, it was decided to employ a rain-gage network wherein there would be fewer gages to maintain, and hence a smaller volume of data to process, but still enough to give the requisite information for the component parts of the watersheds. We wished to strike a balance between the theoretically desirable and the practically possible [8].

The device selected as the basis for revising the rain-gage network is called the "equivalent facet." It was originally recommended by Horton [4] in 1932 and was later employed experimentally in the French Alps by Pers [7]. Also it was described in 1942 by Fourcade [1]. An equivalent facet may be defined as a plane which has the same horizontal projection as a given unit of land surface and whose position in space is determined by the average slope and

Bell Multiple Watersheds, Season 1944-45

Storm no.	Average rainfall on watershed (inches depth)		Difference	
	69 vertical gages	12 facet gages (tilted)	Plus	Minus
1.....	1.38	1.42	0.04	....
2 & 3...	9.69	10.37	0.68	....
4.....	0.39	0.39	....	....
5.....	1.42	1.46	0.04	....
6.....	0.54	0.55	0.01	....
7.....	5.94	6.15	0.21	....
8.....	0.59	0.61	0.02	....
9.....	2.63	2.69	0.06	....
10.....	2.44	2.68	0.24	....
11.....	0.56	0.53	....	0.03
12.....	0.69	0.72	0.03	....
13.....	0.71	0.72	0.01	....
14.....	0.95	0.93	....	0.02
15.....	0.50	0.53	0.03	....

the average aspect of that surface. It will catch the same amount of rain as the topographic area it represents, provided that at any given instant the rain has the same inclination and direction everywhere over the facet, although these components of the storm vector may vary with time.

The next step in our problem was to divide the area into a suitable number of facets. These were resolved into equivalent facets by a method originated by Horton [4]. Figure 3 shows the subdivision of the watersheds into equivafacets. As a supplement to the partitioning of the small watersheds an equivalent facets was computed, first for the whole of each watershed, and finally for the drainage basin comprising all four units.[3]

The tentative location of the rain gages on the equivalent facets was accomplished by a careful study of a topographic map of the area. Each gage was placed as near the geographical center of the facet as possible, with the further provision that the immediate environment of the gage had to have the same aspect and slope as the computed plane. The gages as installed were tilted according to the slope and aspect of their respective equivalent facets.

[3] Acknowledgment is made to Glendora Civilian Public Service Camp No. 76 and particulary to W. E. Sherley, R. S. Thompson, and R. C. James for assistance in the development of the equivalent facets.

The map locations had to be adjusted to some extent in the field when the gages were actually installed. As they were placed, care was exercised to ensure that the gages would not be subjected to excessive wind action by installing them in small openings in the chaparral or brush cover which would shield the gages from local wind effects.

A brief summary of the first season's records obtained from the two parallel sampling systems that were used in the Bell Watersheds may be of interest. The table above gives the arithmetic average for each of the two rain-gage networks by individual storms, and shows the departure of the catch by tilted gages from the simultaneous catch by vertical gages. Here the rainfall-sampling problem rests for the time being. The original sampling system, quasi-random in nature, was tried and found unsatisfactory. A second system was devised wherein the placement of rain gages was adapted to the terrain on an areal basis. We shall continue the program of rainfall measurement, using both systems, until enough measurements are available to provide data for a thorough analysis. The forester will turn again to the mathematician for assistance in setting up the statistical design necessary to compare the sampling methods and to devise the most efficient arrangement of a fixed number of gages.

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