Area-Depth Curves—A Useful Tool in Weather Modification Experiments

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1. Introduction

In evaluating the results of cloud seeding on surface rainfall, statistical evaluations are normally based upon comparisons of point or areal mean rainfall in target and control areas. This provides a measurement of a single parameter, the average volume of water falling on the experimental area or the total rainfall at one or more points in the experimental region.

However, it is important not only to determine average precipitation on the experimental area, but the spatial distribution within it, both from the standpoint of agricultural and water-supply applications. Additionally, it would be desirable to specify the spatial distribution changes with time during seeding operations. One should ascertain, if possible, whether the rainfall gradient and rain rate are being increased or decreased from seeding, and if the spatial distribution characteristics are being substantially modified. If so, are the modifications desirable or harmful with respect to such factors as runoff, infiltration and soil erosion? Answers can only come from definition of the time and space modifications produced by seeding.

Assuming that the experimental area has a network of raingages to provide a reasonably reliable isohyetal pattern (and this should be a minimum requirement for any cloud seeding evaluation), much pertinent information can be obtained from a relatively simple analysis of the rainfall distribution through the use of area-depth curves. This analysis will provide a more comprehensive evaluation of seeding effects (both beneficial and harmful) and may yield pertinent information on physical changes produced in the precipitating cloud system by the seeding process.

2. Raingaging requirements

Raingaging requirements for the construction of area-depth curves depend upon the spatial and temporal variability of the precipitation being measured, which, in turn, is affected by topography, size of sampling area, precipitation type, intensity, and duration, and other factors. The normal climatic network in the United States, used in the evaluation of some past weather modification experiments, is inadequate for area-depth analyses. However, other experiments, such as the Arizona studies described by Battan and Kassander (1960), employed dense networks suitable for this purpose. Precipitation sampling requirements on areas up to 400 mi^2 for storm, weekly, and monthly rainfall under midwestern conditions of climate and topography have been determined by Huff and Neill (1957). Other work on this problem has been reported by Light (1947), Linsley and Kohler (1951), and McGuinness (1963). Various Illinois studies have led to the conclusion that a density of 1 gage per 10 mi^2 is desirable for consistently accurate definition of storm area-depth relations on areas of county size (400–600 mi^2); however, lesser densities would still provide valuable but less detailed information on spatial distribution characteristics. If primary interest is in weekly, monthly, or longer period summations of precipitation, the density requirements would be lowered substantially. Studies presently underway by the author are expected to clarify density requirements further.

3. Curve construction

The area-depth curve, a basic relation frequently used in hydrologic design problems, provides a simple mathematical expression of the spatial distribution of rainfall within a raingaged area. With a recording gage network, the technique can also provide a measurement of time variation in the spatial distribution as a storm progresses, and this may provide clues on how seeding is affecting treated cloud systems.

The area-depth curve is constructed from isohyetal maps, or in the case of approximately uniform raingage networks, from a ranking of the gage rainfalls (Light, 1947). The usual method of construction from an isohyetal map is based on

$$P_a = \frac{\Sigma(\Delta A \cdot P)}{A}, \qquad (1)$$

where P_a is the average depth for a particular value of area A on the area-depth curve, ΔA an increment of area between two successive isohyets, P the value midway between two isohyets, and the summation sign represents accumulations in decreasing order of magnitude of rainfall.

The intercept represents the maximum point rainfall in the gaged area, the lowest point on the curve is the areal mean rainfall, and the slope provides a measure of the rainfall gradient. Thus, three descriptive parameters are readily available for 1) defining the spatial distribution characteristics for any selected period of rainfall, 2) comparing changes between target and control areas, or 3) for evaluating distribution changes with time on a given area. These parameters can be readily tested for significance with available statistical techniques. Although the area-depth curve is normally used in storm analyses, it may be applied to longer rainfall periods, such as a week, month, season, or year, when primary interest is in the distribution characteristics of rainfall summed over extended periods of time.

4. Application of curve

Through use of a 260-storm sample from a dense recording raingage network, Huff (1968) tested eight general equations for fitting the area-depth curve as the sampling area is increased from 50 to 400 mi^2. He found that an equation relating P_a to $A^{0.50}$ provided the best fit most frequently in midwestern storms, but that the appropriate equation is strongly dependent upon the relative variability and skewness of the rainfall distribution in the sampling area, when storms are similar with respect to rain volume, duration and storm type.

In conjunction with various hydrometeorological studies, area-depth curves have been developed for over 1000 Illinois storms on several densely gaged networks with areas ranging from 10–550 mi^2 (Huff and Changnon, 1966). These studies have shown that an excellent curve fit is usually obtained if one employs adequate sampling density and is not inflexible in the general equation used for fitting the curves from storm to storm. It is primarily this experience that has convinced the author that the technique should at least be tried in weather modification experiments.

A typical set of area-depth curves is illustrated in Fig. 1 for a squall-line passage on a densely gaged network of raingages (1 gage per 10 mi^2) on a 550-mi^2 area in southern Illinois on 16 August 1959. The best-fit was obtained by relating P_a to $A^{0.5}$, and curves were drawn for each hour and for the 4-hr storm total. The hourly curves show a typical time distribution, in

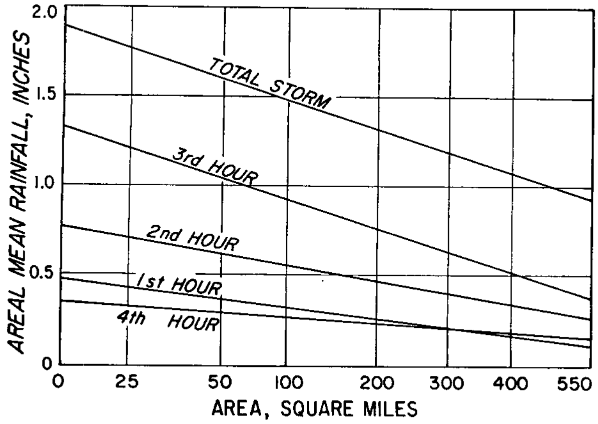

FIG. 1. Area-depth relations in storm of 16 August 1959.

TABLE 1. Hypothetical seeding effects on area-depth relation for natural storm rainfall on 29 April 1963.

Area (mi²)	Average depth (inches) for given conditions Original distribution	10% slope decrease	Constant slope	20% slope increase	P_a vs $A^{0.25}$
Intercept	1.35	1.40	1.47	1.62	1.62
25	1.16	1.23	1.28	1.40	1.26
50	1.09	1.16	1.21	1.31	1.17
100	0.98	1.06	1.10	1.17	1.05
200	0.83	0.92	0.95	1.00	0.91
400	0.60	0.72	0.72	0.72	0.72

which the thunderstorm rainfall gradient (curve slope) intensifies as the rainfall output of the storm system increases over the sampling area. As the storm ends, the rainfall gradient is greatly reduced, and a much more uniform spatial distribution occurs in the light precipitation at the trailing edge of the storm. The total storm curve represents the integration of several bursts within the squall line, the maximum intensity varying spatially in these bursts; therefore, although the sum of the hourly 550-mi² means is equal to the total storm mean, the total storm intercept is not equivalent to the sum of the hourly rainfall maxima.

A potential application of partial storm curves (such as the hourly curves of Fig. 1) in precipitation modification experiments would be in evaluation of the effects seeding may have on the time distribution of rainout from the associated cloud system. This could be done through comparisons between curves derived for target and control areas in a series of storms. Also, analyses of the area-depth curves could reveal tendencies for seeding to intensify or decrease the average rainfall gradient in treated storms, and, consequently, indirectly provide information on modification of the physical processes in the treated cloud system.

Major shifts in the natural spatial distribution resulting from seeding would modify the skewness of the distribution and would be reflected in the area-depth fitting. For example, a modification of the natural distributions in Fig. 1 that would decrease the rainfall gradient over most of the area, but intensify it in the core of the rain cells producing the hourly curves, would increase the skewness of the spatial distribution, and this would be reflected in the type and properties of the best-fit curve. Again, such observed changes could provide information on the cloud physics associated with such modifications.

Several potential effects of seeding that would be reflected in the area-depth curve are illustrated in Table 1. In this table, the original distribution was obtained from a typical storm of moderate intensity on a recording raingage network (1 gage per 8 mi²) in central Illinois. Data for the selected areas along the area-depth curve were obtained by relating P_a to $A^{0.5}$. Next, a 20% increase in areal mean rainfall from seeding was assumed. Resulting area-depth relations were then determined assuming 1) a decrease in the mean rainfall gradient (curve slope) of 10%, 2) the gradient remained constant, 3) the gradient increased 20%, and 4) a pronounced modification of the spatial distribution took place resulting in a skewness change that shifted the best-fit equation to P_a vs $A^{0.25}$, with maximum rainfall equal to case 3). The type and magnitude of the changes produced by the hypothetical seeding are summarized in the table.

Assumption 3) assumes a multiplicative effect from seeding; that is, the mean rainfall is increased 20% over all unit parts of the area. Assumptions 1) and 2) result in changes in the characteristics of the spatial distribution pattern; for example, the maximum point rainfall (intercept) increases only 4% and 9%, respectively, with assumptions 1) and 2) superimposed on the areal mean rainfall increase of 20%. Also, with assumptions 1) and 2), the 50% of the area with heaviest rainfall (0–200 mi²) has an average increase of 11% and 14%, respectively, in mean rainfall compared to 41% and 32% for the lighter 50% (200–400 mi²). This greater intensification of the lighter rainfall areas would be a desirable achievement in many seeding operations, if it could be accomplished. Assumption 4) in Table 1 produces a distribution in which the mean rainfall gradient is relatively intense near the storm center (0–25 mi²), but flatter than any of the other distributions over 75% of the area. This type of distribution occurs quite frequently in warm air mass showers in the Midwest.

The area-depth curve can be applied readily in seeding experiments in which the cross-over, target-control design is used, or in which a single-area seeding is carried on through a randomized storm-to-storm selection of seeded and unseeded cases, such as used in the Arizona experiments (Battan and Kassander, 1960). In most regions of the country, raingage networks with sufficient length of record to establish area-depth frequency relations are not available; therefore, the technique is less applicable to fixed target-control experiments, unless they are homogeneous with respect to precipitation.

As indicated earlier, the area-depth curve which includes both the mean and maximum rainfall, along with an integrated measure of the rainfall gradient, provides an easily derived mathematical expression of rainfall distribution. Lopez and Nason (1967) have developed a plane-fitting technique for possible use in weather modification evaluations. It would appear that the area-depth curve is a simpler method of defining the spatial distribution, provides equal or greater information on the rainfall distribution, and is equally applicable for individual storm comparisons. Work is presently underway on an NSF grant (GA-1360) to verify the foregoing statement and to define further various applications of area-depth relations in weather modifications.

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