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W. E. HOWELL ASSOCIATES, INC.

LEXINGTON, MASSACHUSETTS

551.578. 1LL2

REPORT PREPARED FOR
SURINAME ALUMINUM COMPANY
PARAMARIBO, SURINAME

RAIN STIMULATION FOR THE BROKOPONDO WATERSHED SURINAME

W. E. HOWELL ASSOCIATES, INC.
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Prepared for the Suriname Aluminum Company, Paramaribo, Suriname

By W. E. Howell Associates, Inc., Lexington, Massachusetts

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INTRODUCTION AND SUMMARY

In January 1967, the water level in the reservoir of the Brokopondo powerhouse was so low as to limit severely the electric power delivered to the aluminum smelter at Paranam. This situation not only restricted aluminum production during a period of favorable market conditions but also resulted in direct loss of income to the Suriname government through loss to the local economy, heavily dependent on aluminum exports for foreign exchange, and hence indirectly reduction of many government revenues.

In this situation the Suriname Aluminum Company undertook to provide additional water in the reservoir and improve the efficiency of its use. A decision will depend partly upon economic benefits of this course of action if it is successful, partly upon feasibility of a practical rain stimulation program in this particular situation. It is the second of these two subjects to which the present report is addressed.

Feasibility of rain stimulation in the particular situation requires that four essential conditions be fulfilled:

1) There must be a substantial scientific basis for rain stimulation applicable to the conditions of weather prevailing over the watershed;

2) There must be reasonably sufficient means of evaluating the effectiveness of the proposed weather modification so that benefits may be compared with costs;

3) There must be a plan of action fulfilling both the practical and the scientific requirements for effective rain stimulation; and

4) There must be accordance between the immediate practical objective and an informed public policy that recognizes weather as a natural resource

of national importance.

These four topics are developed in the four main sections of the present report. The most important results are summarized below.

- A satisfactory scientific basis for rain stimulation over the Brokopondo watershed does exist. The local weather conditions are at least as favorable as those prevailing in tropical areas where practical success has been demonstrated over the experience of many years. A twenty percent increase in rainfall and a thirty percent increase in run-off over those that would occur without stimulation appear to be reasonable expectations for the outcome of a practicable plan of action.

- Evaluation must contend with uncertainties of the natural weather and will necessarily be in the form of probabilities, the implications of which will become clearer as the period of operation becomes longer. Nevertheless, through use of river discharge comparisons, the expectation is good that within one year of operation the evaluation will provide reliable guidance for both corporate and public policy decisions regarding continuance of the program.

- The plan of action that offers the greatest benefit-cost ratio and the least pecuniary risk is a program of cloud seeding with silver iodide released from generators situated on the ground at selected points, running for at least two years, with brief suspensions during the height of the dry season. Greater over-all rain stimulation can be achieved by supplementing this program with one of airborne cloud seeding with pulverized salt, but considerably greater operational cost and hence greater pecuniary risk.

- The proposed operational program does not involve perceptible danger to life or property nor threat of interference with natural weather as it affects other activities in Suriname. It is consonant with public policy as this has developed in the United States and in other countries of the Western Hemisphere where practical weather modification programs have been carried out.

I. METEOROLOGICAL SITUATION RELATIVE TO RAIN STIMULATION

The use of weather modification requires thorough examination of the scientific basis, careful review of the applicability to the situation under consideration, and analysis of the expected results of its application for its justification.

In the following paragraphs, after a condensed exposition of the physical principles involved, summaries are given of (1) the physical basis for the modification of supercooled clouds by seeding with ice-forming nuclei and the modification of warm clouds by seeding with coalescence elements, (2) the results of scientific experimentation in verifying the theoretical picture, (3) and the outcome of practical applications of these techniques undertaken over the past seventeen years. Finally, a synopsis is given of the re-orientation of official viewpoints that has taken place within the past eighteen months and the present perception of cloud seeding as a technological method of rain stimulation.

A. Scientific basis for rain stimulation - an introduction

1. Natural rainfall

Before rain falls, atmospheric water vapor first condenses into liquid water, forming clouds composed of great numbers of droplets, all too small to fall. However, in the climate of Suriname, most of the clouds form, develop, collapse, and dissipate without forming any rain. In rainclouds, something special occurs that combines the water from a million or so droplets, all too small to fall, into one raindrop big enough to reach the ground. The something special is cloud seeding.

Cloud seeding is essential for the formation of rain. In nature, cloud seeding occurs in one of two ways, or in combinations of them. One kind of seed is an extra-large particle of salty dust; because of the moisture-attracting quality of the salt, it condenses extra water and becomes a rudimentary raindrop, big enough to fall and collide with other droplets. By repeated collisions, it grows to raindrop size, sweeping the droplets out of the cloud. The key process is coalescence.

The other kind of seed is a particle capable of acting, when it reaches a part of the cloud where the temperature is below freezing, as the seed from which an ice crystal can spring. The ice crystal, once started, then grows much more rapidly than liquid droplets. The key process is sublimation.

When an ice crystal grows large enough to fall and collide with droplets, sublimation and coalescence usually work together, and the ice-seeded particle outstrips its liquid counterpart in rate of growth. Furthermore, the freezing of a few rudimentary raindrops appears to generate new ice crystals in large numbers.

When clouds grow very large, one or both of these natural cloud-seeding mechanisms becomes operative in one part of the cloud or another, and converts some of it to rain. In thunderstorms, about 20 percent of the moisture condensed to water comes down as rain; the rest goes off and eventually re-evaporates. In larger storms like hurricanes, the percentage raining out is higher; in isolated showers it is lower. The quantity of rainfall is therefore determined partly by the operation of forces, be they widespread or localized, that cause clouds to form and grow, and partly by the effectiveness of the cloud seeding that converts a variable proportion of the cloud to rain. Under certain circumstances, the occurrence of rain, by forming strong downdrafts of chilled air, promotes the growth of cloud in other nearby regions and thus tends to enlarge and perpetuate the shower.

The natural cloud-seeding process requires a certain amount of time before it produces rudimentary raindrops capable of starting a shower, a time that becomes shorter as the cloud becomes richer in condensed moisture and shorter if the cloud receives a richer supply of larger or more effective seeds. In smaller clouds, rudimentary raindrops often do not form within the lifetime of the cloud, or else form after the cloud has passed the peak of its development and is already dissipating. In the area of the Brokopondo watershed, about half of the clouds that reach a thickness of 12,000 feet produce rain; smaller clouds have a much poorer chance of raining, and larger clouds a better one.

2. Artificial stimulation

There are two ways of stimulating rain by artificial cloud seeding, corresponding to the two natural cloud-seeding mechanisms described above. One method is to disperse salt dust of appropriate particle size in the rising air currents just beneath a growing cloud, so that they are carried upward and dispersed through the cloud. In this way the number of particles capable of becoming rudimentary raindrops within the lifetime of a small or moderate-sized cloud is greatly increased, resulting in an increase in the likelihood that the cloud will yield rain, and generally increasing the amount of rain falling from a cloud that would have rained anyway. Although dispersal of salt dust from the ground has been partially successful, it is much more effective to seed each cloud individually with an airplane. To be effective, the seeding should be done before or during the phase of most active cloud growth.

The second method of artificial cloud seeding is to disperse into the growing cloud particles capable of acting as the seeds on which ice crystals can form. The concentration of natural ice-forming dust particles varies greatly; under the conditions prevailing in Suriname, it is almost always less than one particle per liter active at $-15^{o}C$. Artificial cloud seeding is most commonly done with silver iodide dispersed in the form of a smoke, by techniques that permit placing several tens of nuclei per liter active at $-5^{o}C$ in the cloud.

These nuclei act on the cloud first by becoming fast-growing ice crystals that soon become large enough to play the role of coalescence elements, rudimentary snow pellets that melt to rain as they fall through the warmer air below; at the same time, the conversion of the water to ice releases latent heat that adds to the buoyancy of the cloud and to its further growth.

B. <u>The scientific basis - theory and experimentation</u>

1. Seeding of warm clouds

Following widespread acceptance of the thesis advanced by Bergeron (1933) that most precipitation occurs through particle growth in the ice phase in a mixed cloud of water droplets and ice crystals, the case of tropical clouds was recognized as a special one in which rain might occur from clouds not cooled below the freezing temperature. In a review article on precipitation processes, Houghton (1938) suggested that giant condensation nuclei, though relatively few in number, might play a critical role in formation of rain in warm clouds. His suggestion lay largely dormant, however, until the upsurge of interest in cloud modification that stemmed from discoveries of new methods for seeding clouds (Schaefer, 1946). In 1948, water was dispersed in the tops of clouds (Langmuir, 1948) in an effort to multiply the numbers of raindrops within a cloud by repeated cycles of growth and break-up to start a chain reaction. In the same year, a similar effect was reported by dispersing dry ice into warm cumulus clouds (Webber, 1948; Leopold and Halstead, 1948) the stimulation presumably resulting from ice particles shed from the dry ice melting and acting as coalescence elements.

Meanwhile, Dessens (1948), at the University of Clermont-Ferrand, had been making a careful study of the presence of salt particles in the atmosphere and their deliquescence into small drops at high humidities, and Bowen (1950), at the Commonwealth Scientific and Industrial Research Organization of Australia, computed the growth of small drops by coalescence in ascending air currents within clouds. Ludlam (1951), at the Imperial College, London, combined these factors and made a further study of the growth of cloud droplets into raindrops through coalescence, concluding that the attainment of certain critical drop sizes near the top of the cloud was necessary if a shower was to form, adding the suggestion that seeding near the cloud base with droplets approximately 50 microns in diameter would result in inducement of rain from clouds that might not otherwise precipitate.

Further contributions to the computation of growth of precipitation elements were made by Mason (1952), East (1957), and many others, while the work of Howell (1949), Squires (1952), Wexler (1954), Keith and Arons (1954), and others helped to clarify the part played by the spectrum of natural condensation nuclei of which the giant salt particles are a part. The results were used by MacCready and others (1957) to develop graphical methods which they used successfully in Project Seabreeze to predict the time of onset of rain from cumulus clouds and to distinguish between coalescence and ice-crystal rain. Braham et al (1957) of the University of Chicago reported an extensive "census" of the tropical cloud population near Puerto Rico in relation to size, influence of land, and occurrence of showers, from which he was able to determine the range of cloud size in which the probability of rain formation increases from very low to near certainty. In recent years, detailed radar observations of rain formation in warm clouds have been contributed by Moore et al (1964) of A. D. Little and Company, Saunders (1965) of Massachusetts Institute of Technology, and others, which fill in and largely confirm the picture presented by earlier workers. The water content of the cloud, the speed and duration of the updraft, the spectrum of condensation nuclei, and the integrity of the updraft as an organized unit were recognized as the important conditions.

Another line of investigation was being pursued built on the work of Stommel (1947) at the Woods Hole Oceanographic Institute that related the entrainment of environmental air into cumulus clouds to the buoyancy of the cloud and its size. Application of these principles to the modeling and eventually to the prediction of ascent rates and maximum heights of cumulus clouds has been pursued notably by Malkus (1953, 1960, 1963, 1964), which has made it possible to design cloud-modification experiments based on the divergence of seeded and unseeded cumulus respectively from the rates and extents of growth thus predicted (Malkus, 1964). This line of investigation has furnished a powerful complement to the investigations relating initiation of precipitation to these same properties of cumulus clouds, which opens the door to a more penetrating analysis of rain production in terms of the state of the atmosphere immediately prior to cloud formation and to construction of a new hierarchy of experimental designs in this line.

Experimental seedings following the techniques suggested by Ludlam were made by Bowen (1952), Mordy (1954), Davies (1954),* Howell (1954), Fournier d'Albe (1955), DuChaxel (1955), and others, who reported varying degrees of success summarized by Howell (1960) as follows:

"Because of the wide variety of climates under which the several experiments were conducted, direct comparison between them is of doubtful meaning. However, the majority of experimenters agree on many points; that seeding of clouds of about 3,000 ft to 4,000 ft thickness was followed by light to moderate showers falling from them much more frequently than from comparable unseeded clouds; that nearly all clouds thicker than about 4,000 ft yielded rain subsequent to seeding that was often moderate to heavy, with noticeably greater frequency and heavier amount than for comparable unseeded clouds; and that where comparisons of rainfall amount were made, these indicated an increase due to seeding that probably exceeded 50% of the natural rainfall."

Considering the apparent success of experiments for inducing rain from warm clouds undertaken in the 1950's, the early 1960's saw a surprising dearth in this line of endeavor. Although a large number of cloud studies such as those of Battan (1958) at the University of Arizona and Braham (1964) in the University of Chicago's Project Whitetop served to emphasize the role of coalescence in the formation of rain in shower clouds, it was not until 1966 that the National Science Foundation jointly with Fairleigh Dickinson University undertook sponsorship of a program of combined practical application and scientific evaluation being conducted by the Howell Associates at St. Croix in the Virgin Islands.

*Davies is now Secretary-General of the World Meteorological Organization

2. Seeding of supercooled clouds

The Bergeron (1932) theory that most precipitation occurs by the growth of ice crystals in clouds of supercooled water droplets led to a widespread search for means of artificially seeding supercooled clouds with ice-forming nuclei. This search was unsuccessful until the discovery by Schaefer (1946) that any very cold object passing through a supercooled cloud left behind it a trail of chilled air containing very large numbers of tiny ice crystals formed by cooling of the air below the self-nucleating temperature of water, minus $40^{\circ}C$. The importance of this experiment for weather modification was quickly appreciated by Langmuir (1946), who also pointed out that the seeding of updrafts in supercooled clouds would release latent heat as the water turned to ice and thus increase the buoyancy of the updraft and the growth of the cloud. The effect of seeding on the dynamics of the cloud through the latent heat release is of fundamental importance to the situation in Suriname and therefore forms the theme of the presentation that follows.

The first experimental confirmation of heat release in stimulating the growth of cumulus cloud as well as in initiating precipitation from it came from Kraus and Squires (1947) of the Commonwealth Scientific and Industrial Research Organization, Australia, the result of which is shown in Figure 1. These authors noted that the weather condition prevailing during their experiment, one of high humidity aloft as well as near the ground, is an unusual one for that location; it is, on the other hand, quite the usual situation over the Brokopondo watershed, as shown by the airplane ascents made during the course of the present survey. During the following two years of experimentation by the General Electric Research Laboratory group, Vonnegut (1947) discovered the effectiveness of silver iodide as an ice-forming nucleus that has the advantage over dry ice that it does not lose its effectiveness if the local temperature rises above freezing, but remains in the air ready to go to work whenever it reaches a part of the cloud where the temperature is below about $-5^{\circ}C$. Also, a series of experiments by Langmuir and Schaefer (Schaefer, 1953) gave additional evidence of the influence of seeding on the growth of cumulus clouds, reaching a climax in an experiment with periodic seeding intended to influence the weather over a large area through the cumulus-latent-heat mechanism which was followed by an extraordinary series of storms following a precise weekly period in phase with the seeding and culminating in serious floods in the Ohio Valley, causing termination of the experiment and giving rise to controversy over its interpretation that still persists (Langmuir, 1955).

Figure 1. Cumulus cloud, originally similar to the surrounding ones, thirteen minutes after seeding with Dry Ice (after Kraus and Squires).

In parallel with the General Electric experiments, a program of experimental seeding in cumulus clouds was undertaken in 1948 by the Weather Bureau (Coons et al, 1949) and later pursued for a number of years under contract with the University of Chicago (Braham et al, 1957). These experiments were confined to airborne seeding, and the experimental designs specifically omitted the concept of release of latent heat in the cloud as an element of the experiment, a consideration that will be referred to again in a later paragraph. The conflicting results of these experiments were interpreted by the authors as unfavorable to artificial modification, and tended to divert attention from further investigation of cumulus clouds.

The growing interest in weather modification led to the appointment in 1953 by President Eisenhower of the Advisory Committee on Weather Control. The evaluations performed by the Advisory Committee were based on the expectation of Bergeron (1949) that winter orographic conditions would provide the best critical test of weather modification, and were therefore confined to non-summer months and mostly to wintertime programs in the western United States. Late in the life of the Advisory Committee a comparison of actual summertime (hence mainly cumulus) cloud seeding in the Midwest with "dummy" unseeded cases was made in an effort to broaden the studies, but this work was left incomplete and did not figure in the final report published at the end of 1957. The report of the group making this study, however, did reach the conclusion that "all real generator composite maps showed consistent isohyetal (rainfall) patterns entirely compatible with the meteorological conditions which would attend a positive precipitation anomaly emanating from the generator areas." (Visscher et al, 1957). Thus the work of the Advisory Committee was almost entirely unrelated to the problem of seeding in cumulus clouds as it is in Suriname and its final report did not apply to it at all. It did, however, further discourage scientific attention to cumulus cloud seeding.

Gradually, however, the ground was prepared for a new and quite different series of experiments. Cumulus clouds and the formation of rain within them became the subject of intensive research, and rapid advances were made in conceptual modeling of clouds and application of electronic computers to the calculation of such models, leading to the capability of making comparisons between the actual behavior of a real cloud and the performance of the corresponding mathematical model. These calculations emphasized anew the role of the dynamic state of the cloud in its development and in the production of precipitation, and to experimental designs specifically incorporating the release of latent heat as a key element. In particular, a mathematical model computed by Murray and Anderson (1965) shows how it became possible to show that there are certain regions in the cloud where additional latent heat liberated by cloud seeding would stimulate the growth of the cloud and other regions where seeding would suppress its growth, according as the heat is released in rising or descending branches of the circulation. In retrospect, this model goes far toward explaining the conflicting and generally disappointing results of the early airborne seeding experiments in which dry ice was dropped into the top of the cloud, for most of the seeds so produced would be swept into the descending currents around the rim of the cloud's crown.

One of the most important of the new group of experiments was conducted as part of the joint Navy - Weather Bureau Project Stormfury. In the summer of 1963, over the ocean near Puerto Rico, large cumulus clouds tall enough to surpass the freezing level were seeded with massive doses of silver iodide to bring about sudden release of latent heat. These experiments gave startling evidence of almost explosive growth of the clouds (Malkus and Simpson, 1964) and led to repetition of the experiment with a far more extensive observational team and tighter statistical control in 1965. Figure 2, prepared from the report of these trials (Simpson et al, 1966) shows the verification that the growth of the clouds was greatly stimulated by seeding.

A program of cumulus seeding was also carried on by the Australian research team, in which real and dummy seeding missions, alternated at random, were followed by measurements of rain coming from the cloud. Figure 3 is a diagram of the results, prepared from the report of Bethwaite et al (1966), showing the distinctly greater production of rain from the seeded clouds. The heat release in individual seeded clouds has been measured in detail by MacCready (1964) in connection with the Flagstaff Project of the National Science Foundation, and Davis (1966) at the University of Pennsylvania has demonstrated similar effects in summer thunderstorms in Pennsylvania.

C. Practical Experiences

Practical experiences with seeding have been treated separately from the scientific experiments referred to in the previous section because these experiences have not in general been designed and conducted for the purpose of scientific evaluation. They are nevertheless significant because it was through the accumulation of practical experiences indicating repeatedly that something

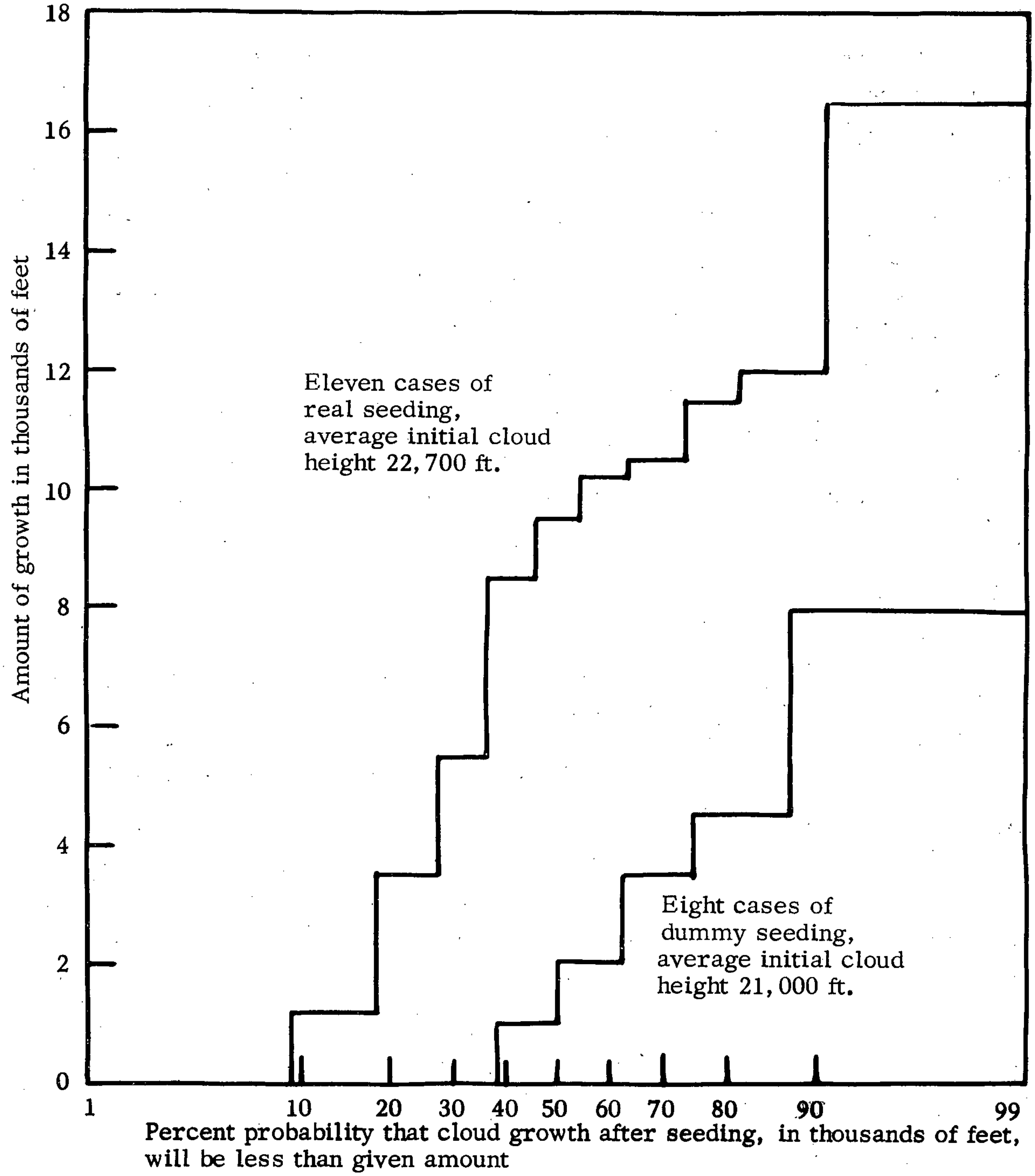

Fig. 2. Growth of Project Stormfury cumulus clouds after real and dummy seeding in 1965 experiments. After Simpson and Simpson.

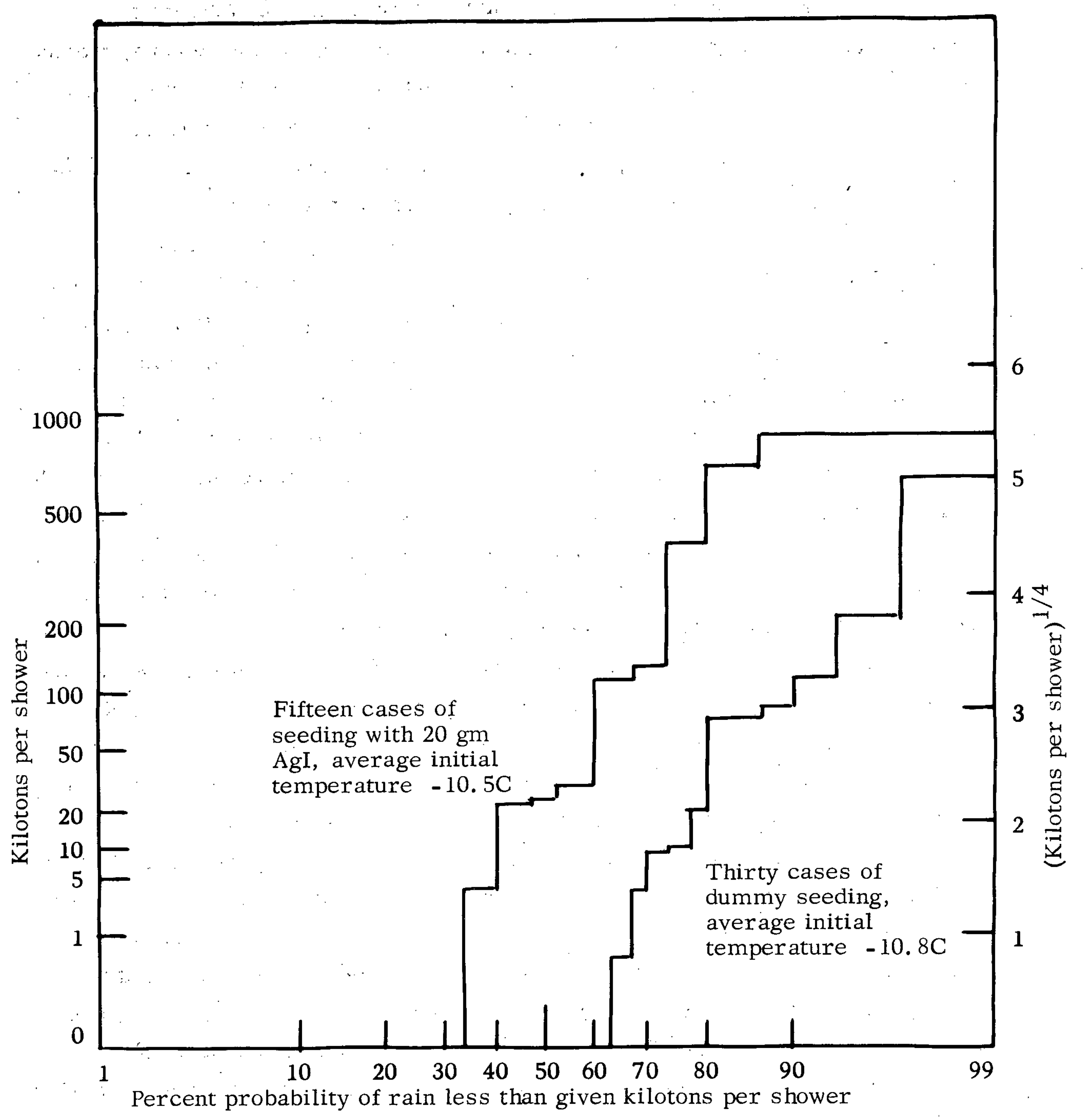

Fig. 3. Rainfall after real and dummy seeding trials in Australia, after Bethwaite et al (1966) for all data-complete cases tabulated

not adequately explained by the then accepted scientific theories was happening that attention was finally directed to more adequate theoretical and experimental approaches.

Cloud seeding for practical ends under tropical weather conditions has been conducted since 1947 in Cuba, Hispaniola, Puerto Rico, Guadeloupe, Mexico, Panama, Colombia, Venezuela, Peru, and Argentina. Outstanding among them is the program conducted since 1949 by the Cia Mexicana de Luz y Fuerza over the watershed of its Necaxa hydroelectric plant, which since 1950 has been conducted according to a randomized scheme in order to provide for adequate evaluation. At latest report (Perez, 1966) it was showing an over-all precipitation increase of 13 percent. Next in seniority is a program in central Peru now in its 17th consecutive season of operation (Howell, 1965). Its purpose is irrigation of sugar lands on the Pacific coast. The results of some thirty commercial operations mostly in Cuba, Hispaniola, and Puerto Rico, were summarized by Howell (1960) as indicating an average 23 percent rainfall increase over more than 22 project-years of experience. Since that time, reports of the results of other rain stimulation operations in Puerto Rico and Colombia have appeared in the literature (Howell and López, 1966; López, 1966; López and Howell, 1961; López and Howell 1965) indicating increases of similar magnitude, as well as operations for mitigation of blow-down damage to bananas (Howell and López, 1961) that indicated a 39 percent decrease in the number of blow-downs per storm. In a hail-suppression program in the wine-producing district of Argentina, Grandoso and Iribarne, (1963) reported apparent beneficial effects in frontal storms but not in air-mass storms. Crow and Cobb (1962) reporting on a wind-suppression program in Panama found little evidence of effectiveness except in the case of small storms.

Evaluations of these practical experiences were until recently confined to those made by persons having a direct interest in the outcome, and they were largely disregarded by the scientific community until, as the consequence of a harsh characterization of them as unscientific in the preliminary report of the Panel on Weather and Climate Modification of the National Academy of Sciences (National Academy of Sciences, 1964) was persuaded to have the Panel investigate the results of commercial cloud seeding. The result of its independent re-working of the evaluations of 14 commercial programs of the Howell Associates and four programs of another commercial operator resulted in substantially complete confirmation of the results previously derived by the operators themselves and were described in the Panel's final report (NAS Publication 1350) (National Academy of Sciences, 1966) as "a new indication of positive effects". Before issuing its final report, the Panel asked for follow-up studies from the Weather Bureau (Brier et al, 1965) and the RAND Corporation, both of which confirmed the validity of the commercial work.

Summary

The release of latent heat within rising air currents inside a cumulus cloud through seeding with silver iodide furnishes a mechanism by which the growth of the cloud and its production of rain can be stimulated. The effectiveness of this mechanism is confirmed by both theoretical and experimental studies conducted at leading universities and research institutions and tends to confirm the experience derived from practical applications of cloud seeding in the tropics over a period of eighteen years.

D. Rainfall climate of the Brokopondo watershed

The rainfall on the Brokopondo watershed comes almost entirely from showers, usually brief downpours or, much less frequently, gentle rains of a few hours duration from the degenerating remains of larger showers. The rainfall climate is the cumulative result of these showers. Furthermore, artificial influence makes itself felt largely on a shower-by-shower basis, and a projection of the expected effect on the climate of the different techniques of weather modification can be obtained only by considering the individual showers as components of the climate.

1. Size and intensity of showers

As a first step, it is desirable to obtain an idea of the number of individual showers that supply water to Brokopondo, the area covered by an individual shower, and the intensity of the shower at its center. Since showers come in all sizes, it is convenient to represent the distribution of sizes in the form of a cumulative curve. Three years of autographic rainfall records at Affobakka were obtained, 1964-1966, and the rainfall amount of each individual shower was tabulated by month and by time of day. In all, 1884 showers fell at Affobakka in the three-year period, an average of 628 per year. From this tabulation, the showers were classified into groups according to rainfall amounts and, following established procedures, the resulting distribution was fitted to an incomplete gamma distribution by the method of maximum likelihood. The fit was found good to within 4 percent, as compared with a Kolmogirov-Smirnoff criterion of 12 percent for a "good" fit. This fitting was done in order to put the distribution into the form of an analytic function suitable for manipulation by computer in the analysis to follow. By multiplying the frequency of showers of each size by their size, the contribution of each shower size to the total three-year rainfall was obtained.

TABLE 1a.
Affobakka cumulative frequency of occurrence (%) of showers of intensity P (mm)

Percent	0	5	10	20	30	40	50	60	70	80	90	95	99	100
Rain P(mm)	0	.008	.03	.11	.33	.63	1.1	1.8	2.9	4.6	7.7	11.2	19.8	<20

TABLE 1b.
Affobakka cumulative percentage of total rainfall in showers of intensity P (mm)

Percent	0	5	10	20	30	40	50	60	70	80	90	95	99	100
Total P(mm)	0	1.0	1.7	2.9	4.2	6.3	8.1	9.9	11.1	14.1	19.2	24.2	40.9	<41

Table 1 shows the cumulative rainfall frequency and rainfall amount for Affobakka thus obtained, indicating that, for instance, nearly half of all showers bring less than one millimeter of rain, which contributes only 5 percent of the total local accumulation; while only about 10 percent of the showers bring about 8 mm or more, but they contribute half of the total accumulation.

These curves are the cumulative result of showers of various sizes and intensities some of which passed directly over the Affobakka raingauge but most of which passed to one side or the other so that the gauge received less than the maximum intensity of the shower. If it is assumed that there is a definite relationship between the diameter of a shower and the rainfall intensity at its center, and if the distribution of intensity between the center of the shower and its edge is regular, then the parameters of the showers that produced the particular distribution of rainfall at Affobakka can be deduced. Data on the relation of shower size to intensity and distribution of rain within the shower was obtained by the Illinois State Water Survey for showers passing over a micrometeorological network in that state. Based on these data, a mathematical model of the shower was constructed and applied to the Affobakka data, resulting in the cumulative distribution of Table 2,

TABLE 2
Theoretical distribution of cumulative watershed runoff for different categories of central shower intensity if no losses occurred

Cum run %	0	5	10	20	30	40	50	60	70	80	90	95	100
Rain P(mm)	0	6.6	7.2	8.3	9.4	10.8	12.2	13.9	16.1	19.0	23.8	28.5	<29

where the arguments are the rain amount at the center of the shower and the percent of total watershed accumulation contributed by showers of up to this intensity. The indication is that even with no losses assumed, showers of less than 6 mm peak rainfall would contribute negligibly to the total rainfall; more than half the total would be contributed by showers with peak rainfall greater than 12 mm. The details of the analysis are set forth in Appendix I.

Showers of different sizes are subject to different losses before the water finally appears in stream channels. Interception in the jungle canopy and evapotranspiration are the principal losses; they affect the small showers to a much greater extent than the larger ones, to the extent that the entire rainfall from a light shower may be totally intercepted by the jungle canopy and none reach the ground. In the absence of exact data from which to construct a loss function, a loss function was constructed that accounts for the known total losses (the difference between total rainfall and total discharge) and is consistent with the available information on forest canopy losses.

TABLE 3
Runoff loss function for given rainfall peak intensity

Rain P (mm)	0 - 5	10	15	20	30	50	75	100	200
Loss function	0	.110	.165	.209	.296	.443	.584	.690	.904

TABLE 4
Theoretical distribution of cumulative watershed runoff for different central shower intensity categories, assuming a canopy interception of 5 mm and a general runoff loss coefficient

Cum run %	0	1	5	10	20	30	40	50	60	70	80	90	95	100
Rain P (mm)	0	10.6	12.8	14.6	17.0	19.2	21.0	23.0	25.2	27.4	30.1	34.0	37.0	<37

This function, shown in Table 3 was applied to the theoretical volumes in Table 2, generating the quantities in Table 4, which shows the cumulative total water reaching the stream channels as a function of shower intensity. It is interesting to note that showers of central intensity of 23 mm or more account now for fully 50 percent of the watershed runoff. The reason for this is that these showers are in reality much more frequent than what the point sampling of one station indicates.

Since temperature and humidity aloft over the Brokopondo watershed vary but little from one rainy day to another it is possible to establish a relationship between the intensity of a shower and the depth of cloud necessary to bring about the corresponding amount of condensation, and hence to infer the temperature at the top of the cloud. Table 5 is derived from the convective cloud model of Davis by making the transformation from shower intensity to cloud-top temperature. It shows that more than 90 percent of the water reaching the

TABLE 5

Theoretical Cloud-top Temperature and Cloud Depth Needed to Produce a Purely Convective Shower of Intensity P, According to Davis Model

Shower Intensity P(MM)	0	5	10	15	20	25	30
Cloud-top Temp (^{o}C)	+4	-3	-10	-17	-25	-33	-41
Cloud Thickness (KM)	3.5	5.0	6.5	8.0	9.5	11.0	12.5

stream channels and 65 percent of the total number of showers should come from clouds having a top temperature below -5^{o}C. These are the clouds that can be glaciated by artificial cloud seeding and stimulated by the resultant release of latent heat.

It would be possible to go on, on the basis of computational models of cumulus clouds, to predict the cloud growth from the latent heat and hence the amount of additional rain produced by seeding. However, the applicability of such models to real situations has not yet been demonstrated in more than a qualitative manner, and the exercise would therefore be of no practical value. Nevertheless, from the relationships so far deduced, it is possible to affirm that the necessary conditions for stimulation by silver iodide seeding are met in a large number of shower clouds over Brokopondo and to deduce something about the relative effectiveness of warm-cloud relative to supercooled-cloud rain processes.

If an increase of 20 percent in rainfall is achieved by silver iodide seeding, in keeping with past experience under comparable weather conditions, and if this increase is achieved by increasing the intensity of rain in existing shower situations rather than by increasing the number of showers, a corresponding adjustment of the cumulative probability of shower intensity and application of the loss function result in an increase of run-off of about 30 percent.

It is of some interest, especially in anticipating the manner of operation of a cloud-seeding program, to obtain an estimate of the number of showers occurring over the watershed in a year corresponding to the Affobakka 1964-1966 data. The total number of showers turns out to be of the order of 2500. About one shower out of every four, then, passed close enough to Affobakka to give some rain there.

2. Seasonal variations in rainfall

The seasonal distribution of rain throughout the year is the basis for determining what portion of the year is judged suitable for rain stimulation activities.

The seasonal character of the rain is shown in Table 6, based on the Brownsweg record from 1911 to 1956. It shows a May-June season that is nearly always rainy, a September-October season that is nearly always dry, and a middle season of wide variability between wet and dry conditions within which there is a far-from-reliable tendency toward a December-January "little wet season" and February-March "little dry season". This information is substantially the same as that compiled for the planning stage of the Brokopondo project.

TABLE 6. Parameters of the Brownsweg monthly rainfall, 1911-1956 (MM)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Upper extreme	540	430	569	543	673	668	466	416	299	194	243	429
Upper quartile	278	246	282	324	411	405	312	217	96	88	164	276
Median	193	157	172	223	376	310	250	151	73	50	94	225
Lower quartile	158	97	132	158	808	255	200	98	48	25	40	152
Lower extreme	13	10	14	65	154	135	73	37	14	5	16	59

The seasonal distribution of the river discharge resulting from this rain is illustrated by Table 7 for Pokeigron. Comparison with Table 6 clearly shows

TABLE 7. Parameters of the Pokeigron monthly discharge, 1952-66, (1953 omitted) (CFS)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Upper extreme	745	1790	1727	1819	3326	2646	2165	1314	770	406	367	742
Upper quartile	693	855	747	1395	2008	2305	1667	1075	520	206	191	329
Median	483	502	545	725	1578	1670	1328	944	398	156	118	148
Lower quartile	266	379	389	324	1183	1327	1063	576	261	116	82	102
Lower extreme	122	176	213	146	252	654	445	298	123	84	39	28

the lag between the time of maximum (minimum) rainfall and maximum (minimum) streamflow due to storage and replenishment effects, displacing the maximum streamflow into June and the minimum into December and greatly delaying the recovery of streamflow after the dry season. From the delay in recovery and from the relationship between rainfall and streamflow in months with respectively favorable and unfavorable antecedent conditions, it is estimated that field capacity in the Brokopondo watershed is approximately 10 cm ; that is, at the end of a dry season, the soil will absorb about 100 mm of rainfall before any appreciable water reaches the stream channels. In a median year the November rainfall is insufficient to maintain field moisture; a major portion of the December rainfall is consumed in field replenishment, leading to recovery of productive streamflow in January. Recovery from the dry season pattern of flow seldom occurs sooner, though it is not infrequently delayed by subnormal December-January rainfall. In about three years out of four, December rainfall is sufficient to saturate the field and bring about a January streamflow recovery; on the other hand, streamflow recovery based on November rainfall is relatively rare. At the other end of the season, streamflow holds up relatively well until rainfall slopes off to the mid-September onset of the full dry season.

3. Diurnal variations in rainfall

The most favorable time of day for cloud seeding depends on the diurnal variations of shower formation. In order to study the diurnal distribution of rainfall, the Affobakka data were tabulated by shower intensities for each hour and month. Table 8 shows the distribution of intensity by hours of the day and Table 9 shows the quantity of Rainfall by hour and month.

Table 8. Numbers of showers at Affobakka, 1964-1966, by intensity classes and hours of the day

Intensity(MM)	< 1	1-2	2-3	3-5	5-7	7-9	9-12	12-15	15-18	18-22	22-26	26-30	30-35	35-40	Σ
Hour															
1st	29	10	8	3	1	2									53
2nd	28	7	0	1	3	2	0	0	0	1					42
3rd	21	1	10	0	1	0	0	1	0	0	1				35
4th	18	6	2	1	0	0	0	1	0	0	0	1			29
5th	15	8	1	5	1	1									31
6th	19	8	2	0	0	0	1	0	1						31
7th	25	6	0	1											32
8th	17	12	2	1	1										33
9th	13	7	3												23
10th	17	6	3	0	0	2									28
11th	16	7	2	1	2	1									29
12th	33	18	5	4	2										62
13th	43	18	8	13	7	0	4	2							95
14th	49	26	23	24	8	9	6	2	1	0	1				149
15th	60	32	21	17	12	10	2	2	4	3					163
16th	47	30	18	22	10	8	7	6	3	1	2	1	0	1	156
17th	51	35	8	21	12	12	8	6	2						155
18th	70	32	11	17	11	5	7	1	3	2	0				167
19th	72	39	20	16	9	2	5	6	1	1					171
20th	62	33	16	16	9	2	5	6	1	1					151
21st	44	23	11	12	5	3	2	1	1	0	0	0	0		102
22nd	40	14	6	3	6	2	3	1	0	1	1	0	1		78
23rd	41	7	4	3	6	0	0	1	0	3	0	0			65
24th	26	11	1	8	4	0	0	1	0	1	0	1			53

There is a marked onset of diurnal rain beginning mostly in the 13th hour, somewhat later in April and October, somewhat earlier in May. The amount of rain increases rapidly in the 14th hour and reaches a maximum in the 16th hour, then falls off irregularly, lasting until the 1st hour in June-July-August but ending mostly by the 21st or 22nd hour in February-March-April and September-October-November. The period of heaviest rainfall appears at the 16th hour in March, spreading over the 14th to 19th hours by May and to the 22nd hour by June, narrowing down to the 16th to 20th hours in July and early August, then reappearing at the earlier time, the 15th to 17th hours, during the little rain season of November-December-January. The smallest showers have a tendency to peak in the 15th hour, with another peak accompanying the peak

Table IX. Rainfall amounts at Affobakka, 1964-66, by hour and month (MM)

Month Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1st	4.4	5.1	1.0	0	5.3	13.6	13.7	9.9	9.5	1.3	8.5	8.7	81.0
2nd	1.5	0.3	0	0	4.9	5.0	1.4	25.6	18.3	7.4	10.4	5.5	77.7
3rd	1.7	0.1	15.5	0	4.7	5.8	0.8	12.9	0	0.4	2.1	28.3	72.3
4th	7.2	0.5	3.6	0.4	3.2	12.2	3.1	6.0	0	0	3.5	29.4	69.1
5th	7.3	9.9	2.2	4.3	6.2	6.5	1.5	9.5	0	3.2	0.2	4.3	54.9
6th	7.0	3.4	1.7	0	11.3	3.8	2.5	0.8	0	1.7	0	1.7	33.9
7th	3.5	2.8	6.9	0	1.8	2.1	0.1	1.2	0	0	0	2.0	19.4
8th	5.9	2.0	6.0	0	5.8	12.1	1.0	1.7	0.5	0	0	2.6	37.6
9th	5.2	5.4	4.2	0.4	2.6	2.7	4.6	0	0	0	0	1.2	26.3
10th	4.5	0.5	11.6	0.4	9.7	5.8	2.1	0	0	0.1	0.1	0.7	35.5
11th	10.4	2.1	12.0	0	12.5	3.2	0.1	0.5	0	0	0	2.1	42.9
12th	6.6	5.5	7.3	4.1	22.6	7.4	1.5	22.6	0.7	0	5.9	6.5	90.7
13th	14.9	31.5	19.1	8.8	16.1	17.1	15.3	1.0	15.0	0.7	13.9	26.0	179.4
14th	45.5	22.5	33.3	9.2	117.0	43.3	23.6	38.6	25.3	13.0	18.5	38.8	325.3
15th	42.0	32.6	38.7	21.6	72.1	47.4	26.8	49.1	7.1	4.7	55.2	62.4	461.6
16th	48.2	30.1	56.7	11.7	156.0	92.9	45.8	30.6	20.4	41.4	9.0	63.3	465.7
17th	36.4	25.5	30.7	51.9	127.4	65.3	74.1	14.1	21.9	48.3	50.5	37.6	583.7
18th	36.4	9.2	19.3	25.7	77.6	34.7	76.5	46.8	40.5	10.7	31.6	46.5	455.5
19th	31.0	22.2	37.1	26.8	69.3	76.6	28.7	45.4	34.8	4.9	36.3	66.7	479.8
20th	29.9	20.3	9.3	29.9	27.1	60.1	53.1	48.6	24.0	20.6	12.0	51.5	386.4
21st	17.6	8.1	6.6	14.8	36.1	67.0	24.5	19.8	3.5	5.3	8.8	9.1	221.2
22nd	15.2	1.0	2.0	11.6	59.0	47.6	61.6	10.6	1.5	3.3	3.6	11.6	228.6
23rd	20.4	12.3	0.9	0	12.6	28.7	37.2	24.2	0.6	23.5	0.5	10.0	170.9
24th	3.9	3.5	2.4	3.2	13.0	72.1	21.4	12.5	5.0	3.9	6.6	3.7	141.2

frequency of heavier showers. The delay of the larger showers to later hours in July and August is reflected in the maximum of thunderstorm activity at Zanderij, which peaks in August at the 19th hour.

There is a general absence of rain centered around the 8th hour from July to December, and having its maximum duration from the 3rd to the 13th hour in October. A second minimum appears in April from the 23rd to the 12th hour. A weak secondary maximum appears in the 4th hour in December and advances to the 8th hour before disappearing in March, reappearing briefly at about the 5th hour in May-June.

Compared with Paramaribo (Braak, 1934), the principal difference is the persistency of the mid-afternoon maximum throughout the year at Affobakka, without the January-February interruption that occurs at Paramaribo and with only a slight reflection (only about one-fifth the strength) of the maximum that occurs in the 5th and 6th hours at Paramaribo during these months. Since the mean wind at this season is from the northeast, it seems clear that the nocturnal showers originate near the seacoast and move inland, nearly disappearing by the time they reach Affobakka.

4. Local effects of terrain

Up to this point in the analysis it has been tacitly assumed that the showers are more or less uniformly distributed over the watershed and that the Affobakka observations are representative of the whole. There are in fact, however, marked local effects of terrain on the distribution of cloud-forming activity and the consequent rainfall.

A series of survey flights were made over the watershed and its surroundings early in February 1967 for the purpose of observing the effects of terrain. It was found that, at that season of the year, there are definite sites of preferred cloud development and other areas where cloud development is inhibited. These areas are indicated on the map, Fig. 4.. In general, the preferred sites are associated with upslope flow over hilly regions and the inhibited areas are regions of downslope flow and local cooling of the surface air over the reservoir.

The effect of the terrain appeared to be most pronounced between the hours of 10 A.M. and 3 P.M.; that is to say, at the time when the sunshine was most effective in warming the air near the ground. Clouds over the preferred sites appeared to be from 1 to 2 km thicker and to cover about 4 times as much

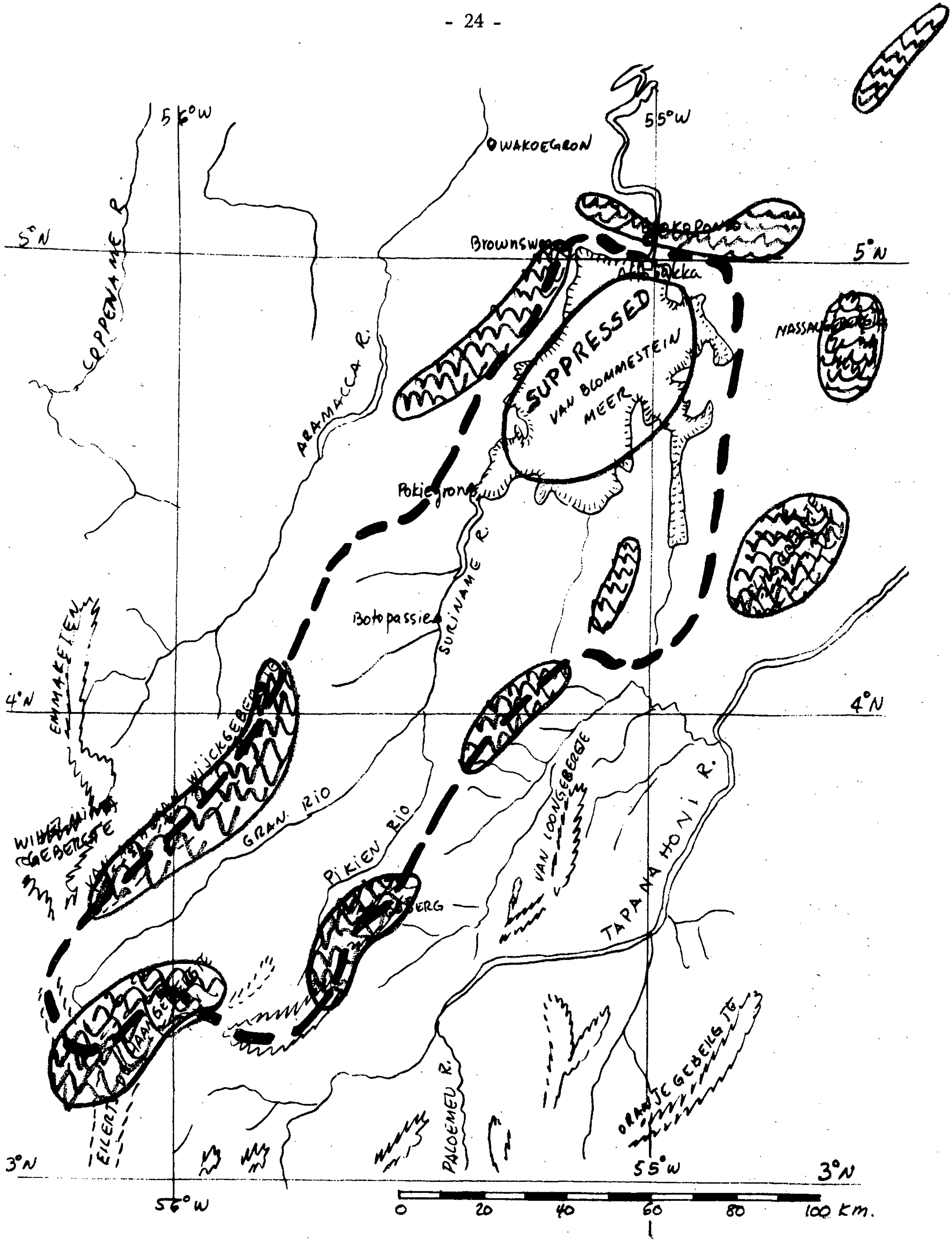

Fig. 4. Areas of preferred cloud formation affecting the Brokopondo watershed.

area as over the inhibited sites, and the earliest showers were always observed to begin there. These showers moved away from the preferred sites, drifting with the wind, and by late afternoon were more or less widely distributed. The more energetic showers continued to grow after moving away from their points of origin, so that the preferred site for initial cloud growth was not always the place that received the most rain from the shower it generated.

In order to investigate further the effect of terrain on rainfall distribution, a comparison was made among the four "main-line" stations, Dam, Sikicamp, Kabel, and Brownsweg for a typical month (April). These stations lie along a line from the eastern side of the reservoir basin to the hills southwest of it; Dam is about 40 km downwind from the preferred cloud-growth site over the Nassaugebergte, Kabel is in the center of the inhibited zone, and Brownsweg is in the preferred growth site associated with the chain of hills that forms the dam site. It was found that the differences in average annual rainfall among these sites are in the same sense as the differences in cloud-development preference but are much smaller in magnitude. The distributive effect of the more or less random drift of the showers after they leave the places where they begin overcomes a large part of the advantage that the former have in the initial stages of shower formation.

In summary, it is apparent that certain hilly areas are important as preferred sites for the growth of clouds to shower size and for the occurrence of the major updrafts that serve to transport silver iodide into the active zone of the clouds. These sites should therefore be the major targets for cloud seeding. Continued growth and development of the more active showers as they move away from their point of origin distribute the effects of the seeding more or less broadly over the target area.

Since the role of the early-morning coastal showers is so much weaker at Affobakka than at Paramaribo, it is safe to assume that the effect of them over the watershed as a whole is quite negligible. On the other hand, it is possible that the frequency and importance of nocturnal and early-morning showers during the months of July and August may be greater for the watershed as a whole than for Affobakka, since at that time of the year the wind is southeasterly and the showers reaching Affobakka are probably the remnants of greater activity over the highland area to the southeast.

Taking the probable effect of these conditions into account, and combining the data on diurnal distribution with the cumulative average distribution, a cumulative distribution of frequency of seedable showers as a function of the hour of the day was obtained and is shown as Table 10. It indicates that the period from 2 to 9 P.M. contains 90 percent of all seedable showers, and that the hours from 1 A.M. to 2 P.M. contribute less than 4 percent of the seedable showers.

TABLE 10
Cumulative distribution of seedable showers

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Cum %	0	1	1	1	1	1	1	1	1	1	1	1	3	11	28	43	63	75	85	93	95	98	99	100

5. Large-scale controls

The picture of tropical weather got from a casual survey of general literature is one of monotony. It rains, so they say, as regularly as clockwork, every afternoon. The falsity of this notion is apparent, however, to anyone who has to deal with tropical weather on a daily basis. True, the diurnal period of rainfall is far more marked than in the temperate latitudes, but the regular afternoon shower to set the clock by is a myth. Some days will be good and rainy, with three or four heavy showers; sometimes, even in the rainy season, there will be several days without rain, even though some small showers may be seen in the distance. Obviously there are varying circumstances that make some days more favorable for rain than others, and these circumstances sometimes prevail over large areas and for considerable periods of time.

Over most of the tropics, the lower part of the atmosphere, where weather takes place, is divided into two distinct layers. Near the ground is a layer of relatively moist air and a steady warm temperature, the temperature and moisture content being governed to a large extent by the extensive ocean surfaces. Above this layer, which is often referred to as the maritime layer, is a layer of very much drier air with more variable temperature characteristics. The degree to which cumulus clouds and showers develop is governed largely by the behavior of the maritime layer and the ability of convection from it to penetrate the drier air aloft.

North of the equator, the northeast trades push the maritime layer southward; south of the equator, the southeast trades push it northward. In the zone between, the maritime layer therefore tends to become thicker and to undergo a general rising motion. Both the great depth of moist air and the general upward motion favor the formation of large cumulus clouds and heavy showers. This phenomenon has been given the name of the intertropical convergence (ITC) and is identical with the doldrums of the mariner.

Within the zone of the convergence, giant cumulus clouds tend to form in long windrows, sometimes thousands of miles in length, within which the piled-up maritime air is rapidly drawn off and delivered to very high altitudes, above the dry layer, until the maritime layer is drained of its excess air to the point where it can no longer support the cloud growth. The windrow of clouds then breaks up and dissipates, only to reform somewhere nearby as the trades continue to supply more maritime air. Figure 5 shows such a windrow of clouds as photographed from a weather satellite, in which the upper parts of the clouds can be clearly seen spreading out toward the north and south. Thus the ITC represents a relatively broad, poorly-defined band within which conditions are especially favorable for convective rainfall, where activity likely to be patterned in the form of long lines periodically breaks out and subsides in an erratic manner.

Where the ITC lies over land, major terrain features such as mountain ranges further complicate the patterns, causing them to mold themselves, as it were, to the terrain. The activity within the ITC is sensitive also to disturbances of the trade-wind zones that produce deeper or shallower regions in the maritime layer or fluctuations in the convergent wind pattern. On a still broader scale, the trade winds themselves respond to worldwide fluctuations in the general circulation, so that the location and degree of activity of the ITC may vary markedly from year to year. It is these large-scale fluctuations that are mainly responsible for the great departures of monthly rainfall from the long-term averages and for the great variations in the development of the seasons from year to year.

The annual variations of the mean circulation establish a mean pattern of behavior of the ITC; it reaches its farthest south position in central Brazil in February-March, follows the sun north and crosses Suriname in May-June, remains over the Atlantic Ocean north of South America from then until November, becoming rather poorly developed, and again following the sun, crosses Suriname southward in December-January. Both the elevation of the sun and the temperature of the Atlantic water favor greater activity during the May-June crossing than during that of December-January, producing the difference between the principal rainy season and the "little rainy season".

Fig. 5. Satellite photographs of the north coast of South America and adjacent Atlantic Ocean showing "spinal column" of cloud associated with the inter-tropical convergence (ITC).

It is the large-scale fluctuations in the ITC that cause the greater part of the variation in the weather over Suriname. These fluctuations affect regions generally many times the area of the Brokopondo watershed, with the result that these fluctuations are on the whole very similar over other nearby watersheds, thus accounting for the high correlation found between the Affobakka and Tapatosso discharges.

II. ASSESSMENT OF EVALUATION PROBLEM

In practical application of cloud seeding, three kinds of questions must be answered sooner or later. 1) Is the application scientifically and technologically sound? 2) Can the skill with which it is being conducted be improved? and 3) Is the cost of continuing it justified by the apparent economic return?

Let us consider the situation of the man with a headache, faced with a decision as to taking aspirin. The scientific evidence is that on the average, aspirin tends to alleviate pain; but there are some headaches recalcitrant to it and there are some individuals who are allergic to it. Our protagonist therefore cannot be 100 percent certain that the aspirin will help his headache. The first time he takes it, he should be alert for a possible allergic reaction.

Then, too, there is the economic aspect. Recognizing that the headache may be recalcitrant to aspirin and that the treatment costs a certain amount of money, is he willing to pay for the aspirin in return for the likelihood that it will shorten his headache? If he takes the aspirin, and the headache goes away, how does he weigh this result against the likelihood that the headache would have gone away anyway, even without the aspirin?

Finally, he might ask whether the aspirin is more effective if taken with one swallow of water or with two glassfulls; or he may ask if it would be more effective with a shot of whiskey, before meals, or after meals. The answers to these questions may be highly individual, dependent upon his own nervous reactions to various circumstances, and unpredictable on the basis of clinical tests on other people.

Obviously, different standards of judgement are brought into play in answering these different sorts of questions. The research investigator studying the analgesic properties of the aspirin will feel he must be quite sure of his ground before he makes a positive statement on the subject, and may be very guarded in his endorsement if he feels there is anyone for whom it may not work. The man with the headache, on the other hand, faced with the alternative of spending half a penny on an aspirin tablet or possibly suffering for hours from a splitting headache may feel he can well afford the trivial cost even though the headache might go away by itself or might prove to be recalcitrant to aspirin. If he has headaches repeatedly, he may wish to experiment with the most effective means for him personally to use the aspirin. On the other hand, the individual patient is not generally in a position to repeat the careful clinical tests that the researcher has carried out, and so must depend upon the advice of his physician.

A. Evaluation of operational techniques

The purpose of operational evaluation is to enable the operator to make program changes and perceive whether the effect of them is beneficial or otherwise. The more quickly and directly he can perceive the effects, the more rapidly he can optimize the program.

Effective cloud seeding increases the size, intensity, and lifetime of individual showers, and to a lesser extent the number of them. For operational evaluation, these are the things to be observed, both in the seeded area and in the unseeded regions surrounding it.

For this type of observation, radar has unique advantages and has almost entirely supplanted the conventional raingauge. Raindrops give a radar echo, but clouds do not. On the radar screen, therefore, the location, size, and intensity of every shower within range is shown at any instant. By time-lapse photography the activity over a longer period can be summarized and summarization of the radar picture by time-lapse photography shows the preferred regions of shower formation and dissipation, speed and direction of motion, lifetimes, etc. This film, besides providing a wealth of reference material for operational evaluation, provides a documentary record in case questions are raised regarding supposed inadvertent effects of cloud seeding.

In its simplest form, the weather radar depicts in plan-position (i.e. map-like) form the areas where rainfall is exceeding some threshold intensity. In a slightly more elaborate form, as it is now used on all airliners and many private airplanes, two or three different critical levels of intensity are distinguished in the form of something like a crude contour map. These basic capabilities have been enormously expanded for particular research applications in which the output of the radar sensors are directly coupled to electronic computers.

Situated at Affobakka, a radar with 100 km range would depict precipitation over the course of the Suriname River from its mouth to Botopassie; to the east it would cover the Marowijne River from a point about 50 km from its mouth up to its junction with the Tapanahony, and cover the lower 50 km of the Tapanahony; on the west it would take in the middle course of the Saramacca River and the eastern tributaries of the Coppename. A set of 200 km range at the same site would cover essentially the entire basins of the Suriname, Saramacca Coppename Rivers, well into the Wilhelminagebergte, and the lower two-thirds of the Tapanahony basin. Eastward, it would reach into the main highlands of western French Guiana.

With the 100-km range, it would be possible to record the behavior of showers originating in the nearby hills immediately east of the watershed, from the Lelygebergte north to the region of Vient Hill, and to compare this in detail with the behavior of showers over the unseeded zone between Affobakka and Paramaribo. The 200-km range would make it possible to track showers originating in French Guiana and drifting into the target area, and also to compare unseeded conditions over the ridges forming the eastern boundary of the Tapanahony watershed with seeded conditions over the very similar terrain along the divide separating the Tapanahony and the Suriname Rivers.

The 200-km-range radar will be capable of keeping all the air routes and airport approach patterns within the area under continuous surveillance to give warning of heavy showers and permit aircraft to be directed around them. These airports include Zanderij, Sorg en Hoop, Oemekondre, Affobakka, Stoelmanseiland, and Botopassie. There is the possibility, therefore, of direct cooperation with the aviation radio service in order to make the radar observations available for this use. It will also be feasible to provide rainfall warnings for outdoor activities such as the proposed dam construction at Saramacca, strip mining, etc.

B. Evaluation of strategy and economics

The purpose of the strategic and economic evaluation is to furnish objective information bearing on future decisions to continue or expand the weather-modification operation or to terminate it. The prospective benefit depends on the volume of water available to the turbines and the head at which it is delivered. Change in reservoir storage (adjusted for outflow) summarizes the cumulative effect of rainfall and evapotranspiration, of which rainfall is by far the most important component. Change in reservoir storage is therefore the most direct link between the intended modification -- increased rainfall -- and the desired effect -- increased power generation.

The benefit is measured as the excess of reservoir storage over what it would have been without rain stimulation; the problem is to make the best estimate of the latter quantity. Past river flows or changes of storage are poor estimators of the probable future values on a monthly or even an annual basis because of their great natural variability.

The usual means of improving the estimate is to use a predictor uninfluenced by the seeding but closely related to the quantity to be predicted. The discharge of the Tapanahony River at Tapatosso is a natural choice to test for this use; the watershed is adjacent to that of the Suriname River above Pokeigron and lies on the upwind side where it will be relatively free of influence by seeding; the basins are of comparable size, slope in the same direction, and are enclosed by mountain ridges of similar heights and orientations.

Data available for the comparison are monthly discharges at Tapatosso and Pokeigron tabulated by the Ministry of Public Works of Suriname and monthly discharges at Pokeigron tabulated by Alcoa that included procedures for cross-checking of the original data. Shown below are month-by-month correlations between these three sets of data for the period 1952 through 1964 after normalization of the data by a cube-root transformation (1965 is omitted because of a discontinuity in the tabulation and obvious gross errors).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P'gron (Alcoa) vs. Tapatosso	.94	.98	.86*	.97	.98	.96	.95	.96	.95	.90	.82	.90
P'gron (Gov't) vs. Tapatosso	.91	.97	.78	.96	.95	.91	.79	.71	.61	.36	.39	.61
P'gron (Alcoa) vs. P'on(Gov't)	.85	.93	.93	.96	.97	.81	.89	.76	.73	.50	.69	.81

Taking these in reverse order, the lack of nearly perfect correlation between the Alcoa and Government series of Pokeigron discharges raises the question whether one or the other, or both, is affected by errors; they are

*The poor March correlation is the consequence of a single figure for Tapatosso in March 1958 that appears questionable and is being checked. If it is found to be grossly in error, the correlation coefficient for March will be in line with the others.

supposed to be two readings of exactly the same thing. The other two lines give the answer. Departures of the correlation coefficients from unity are caused partly by errors in the observations, partly by real differences in watershed run-off. The very high coefficients in the first line thus give positive and comforting assurance that the Tapatosso and Pokeigron (Alcoa) series are both relatively free from observational errors; the relatively poor showing of the second line shows that errors play a much bigger part here, and that they must be contributed by the Government's Pokeigron tabulation. For further work, therefore, the latter tabulation was discarded.

The data were next grouped by wet-season (May-June), middle-season (July-September, December-March) and dry-season (October-November) periods, and for the whole year together. The results are:

Group	Wet-season	Middle-season	Dry-season	Whole-year
P'grn/Tapa correl	0.97	0.96	0.85	0.97

Recent studies of rainfall in other tropical locations have shown that there is a close relationship between the rainfall of a given month and the number of rainy days in the month. The prospect exists, therefore, that the precision of the estimate of natural river flow -- that which would have occurred without seeding -- can be further improved by utilizing historical data on the number of rainy days at Affobakka or Brownsweg in the form of a multiple correlation.

On the basis of these figures, it can be said that estimation of the natural reservoir inflow on the basis of independent variables -- the Tapatosso discharge and the number of rainy days -- will remove all but, at most, six percent of the variance of the inflow on a year-to-year basis, and all but, at most, six to nine percent of the variance on a season-by-season basis outside of the dry season. The remaining variance results in a standard error of estimate amounting to an average of about 20 percent of the mean discharge. This is the ruler with which we will seek to measure the anticipated 30 percent increase due to seeding.

On the basis of this estimate, if a 30 percent streamflow increase is superimposed on the random variations of the estimate of the natural streamflow, the evaluation will indicate an increase in about 70 to 80 percent of the months, decreases will be indicated purely because of the uncertainty of the estimation. For this reason, the month-by-month indications will have little significance taken singly, but may be expected to accumulate results in the course of one year that will approach or surpass the usual statistical criteria for significance.

C. Evaluation of scientific validity

The purpose of evaluation of scientific validity is to supplement the limited experience from a particular application by the appropriate use of verifiable factual information derived from the atmospheric sciences in general. Its task is to establish the relevance of the physical principles and technologies described in the first section of this report to the situation in Suriname.

The basic information that enters into the scientific evaluation is the same as that for the operational and strategic-economic evaluations; only its objectives and principles are different. Its objective is to accumulate a body of reliable knowledge and its master principle is constructive doubt. The pragmatic experience that an electric motor works was not enough for the scientist; he had to understand why as well as how. By doubting the preliminary assumptions as to how and why cloud seeding increases rain, better understanding has been gained and a better technology developed.

The program of the scientific evaluation should be to test the validity of the indications obtained from the operational and strategic evaluations against established principles by means of a continuing critical review and comparison with the results of scientific experimentation.

This is not a program of research in the usual sense. Rather it is a matter of keeping on the lookout for opportunities to match observations furnished by the other evaluations against expectations derived from a broader range of experience. These opportunities will include but not be limited to the following:

1. Comparisons of areas, maximum elevations, and lifetimes of seeded showers with unseeded showers over similar terrain.

2. Comparison of the number of days with significant rainfall in the seeded target with the number in nearby unseeded areas.

3. Comparison of the rate of growth of showers with the rate predicted on the basis of mathematical models based on the moisture content and degree of instability of the atmosphere and on addition or non-addition of latent

heat of fusion.

4. Comparison of rainfall and streamflow in the area with that on control areas.

It is to be expected that the outcome of these comparisons will frequently be inconclusive in the sense that validity of the observation as an indication of seeding effect will often not be either absolutely confirmed or absolutely contradicted by the limited evidence at hand. It will nevertheless serve to indicate what parts of the question are amenable to reasonably certain proof in the physical sense and what parts are the proper realm of pragmatic judgement on the basis of benefit-cost comparisons.

III. RECOMMENDED OPERATIONAL PLAN

The field survey and analysis of weather conditions indicate that important rainfall increases are to be expected from weather modification associated with the seeding of the larger showers with ice-forming nuclei. Opportunities for stimulation of smaller showers by seeding with hygroscopic materials such as pulverized salt are also frequent, but the opportunity they represent is less attractive because they contribute a relatively small part of the total water in the streams and the cost of seeding them is appreciably higher than for the silver iodide seeding.

A program of silver-iodide seeding is therefore recommended, during the operation of which it is anticipated that observations and a modest amount of experimentation will serve to clarify the advisability of expanding the program at a later date to include salt seeding of smaller warm clouds.

A. Seeding agent and method of delivery

Silver iodide is recommended as the seeding agent. Release of it from smoke generators placed at selected sites on the ground is recommended over airborne seeding. These recommendations are based on the following considerations.

1. Of the available ice nucleants, silver iodide is the best proven in practice and the only one for which standards of generator performance have been established. It offers the advantage over dry ice and metaldehyde that the nuclei are persistent and not affected by exposure to temperatures above

freezing. The cost in effective nuclei per dollar is among the most advantageous available.

2. Delivery from fixed sites on the ground is capable of blanketing the cloud-breeding regions important for rainfall over the watershed for extended periods of time, making it possible to maintain ice-nucleus concentrations at effective levels over extensive areas continuously during the periods of shower formation and growth, whereas aircraft seeding would be incapable of doing so unless several aircraft were used simultaneously at relatively great expense.

3. Delivery of the smoke from the ground places the greatest quantity of it in the warmest, moistest air, air that must be involved in the updrafts that feed any major cloud development. The most rapidly growing cloud thereby receives the greatest dose of seeding without the necessity for the meteorologist to make a choice that might be wrong.

B. Base of operations

It is recommended that a base of operations should be established at Affobakka with the facilities and functions detailed below.

1. Staff.

The staff should comprise three to four technical personnel and approximately four field maintenance personnel as follows:

a. Field Meteorologist. The field meteorologist should be a qualified professional meteorologist with previous experience in weather modification. He should have primary responsibility for direction of all phases of the program.

b. Meteorological assistant. This person may be of junior professional grade or a graduate student in completing his professional training. His duties will be to assist the Field Meteorologist in making observations and analyses, preparing mission plans, and maintaining records of the operation.

c. Radar observer. The radar observer should be qualified in the specialty of meteorological radar observation and should also be qualified for first-echelon maintenance of the radar equipment. His duties will be to operate the radar equipment, keep the field meteorologist advised of significant phenomena under observation, and make and analyse the time-lapse photographs of the radar scope.

d. Communicator. The communicator need not be a meteorological specialist but it is desirable that he should be regarded as a meteorologist in training. His principal duty will be to maintain radio communications with personnel in the field, transmit operating instructions from them and relay their observations to the field meteorologist, and carry on whatever program of cooperative communication is established with aviation. When not so occupied, he would assist the other personnel in their duties, especially with respect to routines such as maintenance of field supply records.

e. Field engineer (2). The field engineers should be local personnel well known and well traveled in the area who will be trained to install, supply, and maintain the smoke generator sites in the field. One of these should operate along the Suriname River and the other along the Marowijne-Tapanahony Rivers. Their duties will be to visit all generator sites at frequent intervals to check on their status and condition and to carry out maintenance and supply missions.

f. Field assistants (2). These should be local personnel who will accompany and assist the field engineers.

2. Permanent equipment for the station should include suitable working quarters for the staff, and special instrumentation, among which the following are recommended:

a. A trailer with two rooms, one furnished as a meteorological office and the other as a radar observing room and communication center. This trailer should be air conditioned, with sufficient reserve cooling capacity to handle the heat output of electrical equipment in it and maintain humidity conditions at the point where equipment and instrumentation will not deteriorate.

b. A weather radar set. A radar recommended for this use is the type used by long-range commercial aircraft for storm avoidance such as the Bendix RDR-1 E. This set operates on a wavelength of 3.2 cm with a peak power of 75 kw and a pulse duration of 2.5 microseconds. This set should be modified for omnidirectional plan-position indication and fitted with an antenna reflector of about 5 ft diameter giving a one-degree beam width. In this configuration the set has a range of more than 250 km and will be able to detect showers over the entire extent of the watershed. The antenna and associated parts should be placed on a tower of approximately 40 m height on "Meteo Hill" at Affobakka in order to avoid local ground-clutter problems and allow observation over the hills about 500 m high that lie about 25 km east of Affobakka. The radar should be equipped with a scope camera suitable for making time-lapse photographs of the shower echoes. The recommended radar is of modular construction and is designed for quick replacement of faulty modules in case of breakdown. It should be procured with a sufficient supply of spare modules so that reliable operation can be maintained on the basis of return of faulty modules to the factory for repair.

c. Communications equipment for radio contact with generator sites and field maintenance units. It is recommended that provision be made for future addition of several other communications channels, such as meteorological radioteletype and radiofacsimile, automatic picture taking equipment for use with the meteorological satellite (capable of taking on a real-time basis pictures such as Figure 3 when the weather satellite passes over Suriname), and ground-to-air radio channels for utilization of the weather radar in connection with air traffic control.

d. A pilot balloon set for making observations of winds aloft at times when such observations are not available otherwise. There are a number of suitable instruments available; one recommendation would be the Zeiss automatic-plotting balloon theodolite. Consideration should also be given to obtaining and using balloons equipped with corner reflectors or other radar reflective material that can be tracked by the weather radar set to obtain winds aloft without interference from clouds.

e. Anemograph. The wind sensors should be situated at the top of the radar tower, despite the fact that this location does not conform to international meteorological standards, because the application in this case is to the best approximation to air motions affecting the silver iodide smoke plumes rather than to conditions affecting activities at the ground. The anemograph should be of a design that yields an integration of air motion over a period of time rather than a few instantaneous samples of wind speed and direction.

f. Hygrothermograph. The sensor for this instrument should also be at the top of the tower, for the same reason as for the anemograph; the best approximation to free-air conditions is desirable.

g. Freezing-nucleus counter. This is an instrument that makes a continuous record of the concentration of ice-forming nuclei in the atmosphere. It will serve to establish the background concentration of nuclei present during periods when seeding is not being conducted and to verify the presence and indicate the concentrations of nuclei during seeding events.

h. Transport. The station should be furnished with one vehicle for the use of the meteorological staff. A heavy pick-up truck of 1 1/2 to 2 tons capacity with four-wheel drive is recommended, as it may be called upon to transport supplies and equipment under adverse road conditions. Two boats should also be provided, one on the Suriname River and one on the Marowijne-Tapanahony under control of the base station. It is recommended that these boats be of the sort used by the Department of the Interior for operation on the Colorado River, namely sturdy 19-foot fibreglass boats with planing hulls driven by jet propulsion. These boats are much faster than the dugout canoes traditionally in use on these rivers and are capable of negotiating rapids with as much as 25 mph current and shallows of six to eight inches that necessitate portaging with dugout canoes. The jet propulsion avoids exposure of propellers to rocks and snags. Experience may show the necessity of a third boat on the upper Tapanahony to operate from a base such as the airstrip at Paloemeu that would be supplied by air. The boats should be furnished with two-way radio equipment for communication with the base station.

A possible alternative to boats for the supply function is a STOL airplane on floats or a helicopter on floats. The airplane is far more economical to operate and is therefore probably to be preferred if a survey of the river shows sufficient reaches where it could alight. This system might also be combined with local transport, within reaches of the river bounded by rapids, by native dugout canoes.

C. Generator sites and equipment

Recommendation of generator sites is based on the desirability of placing them in such a manner that all cloud-breeding spots may be reached by smoke blowing from one or another of them. In selecting them, it is also necessary to consider other factors, such as availability of personnel to serve as operators, accessibility for supply and maintenance, and facilities for communicating daily instructions to the operators. The map, Figure 6, represents a preliminary selection of sites based on these considerations. The final selection of sites should be left to coordination between the field meteorologist and the leader of the team actually establishing the sites.

In the selection of equipment, ruggedness and reliability are the

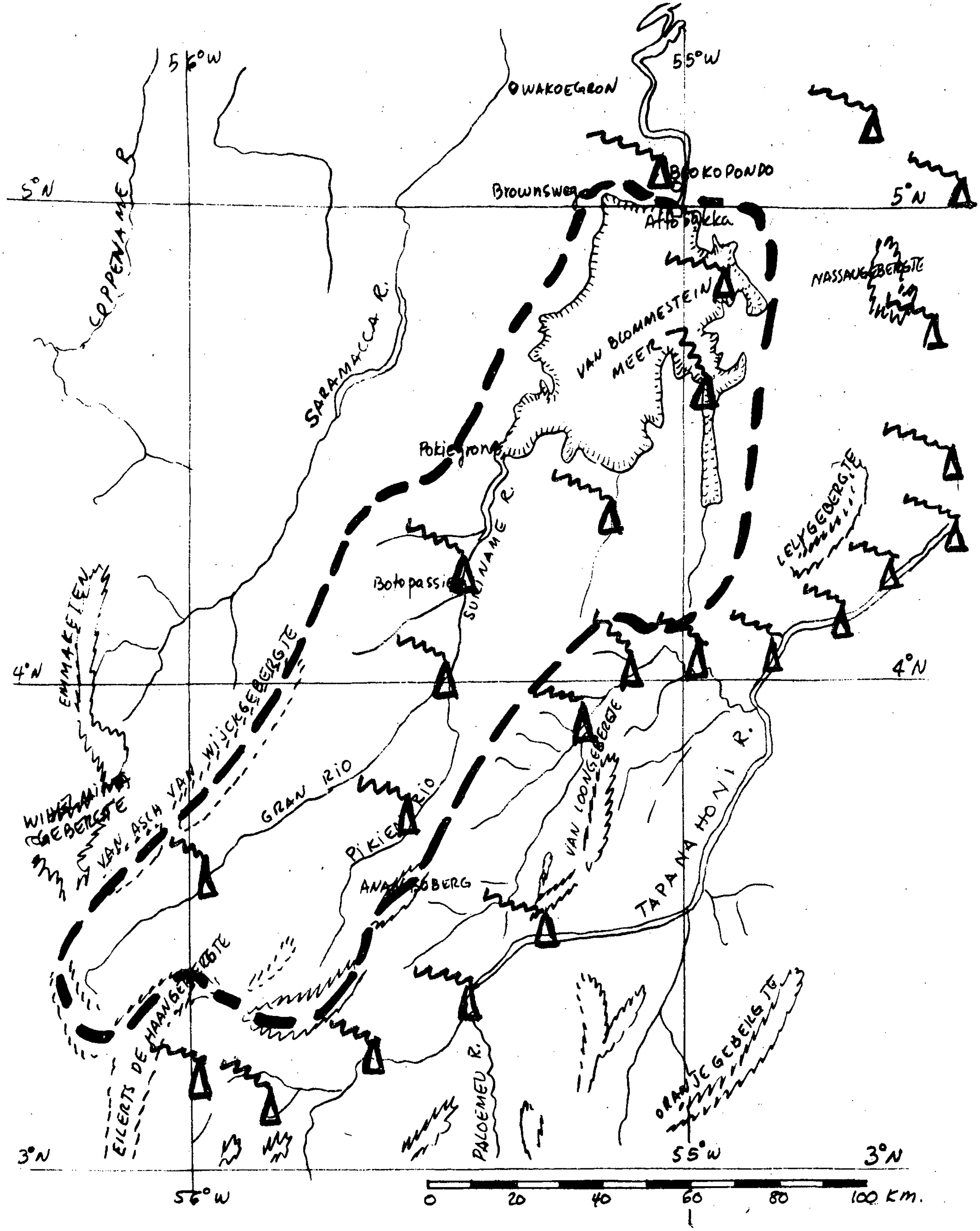

Fig. 6. Proposed smoke generator locations for cloud seeding.

most important considerations because of the repair or replacement in the field would be slow and costly. The following items of equipment are recommended.

1. Smoke generators should be of the propane-fueled type, burning either an impregnated cord or ketone solution of silver/sodium iodide. Each site should be furnished with a spare generator. The generators should be equipped with simple event recorders that make a record of when the generator was operated. At some locations, if suitable operator personnel cannot be obtained, it may be necessary to provide for automatic programming of the generator to operate at predetermined times whenever certain governing conditions such as wind direction are met.

2. Supplies should be stocked for a minimum of one month of operation. At some sites where access by boat may be possible only during the wet season, it may be necessary to stock supplies for a longer period, even for an entire year. Suitable packaging and storage of supplies are then important.

3. Except for sites equipped for automatically programmed operation, each site, in so far as possible, should be furnished with two-way radio communications with the operating base. The type of equipment will depend upon the location; where line-of-site communication is possible, VHF equipment on the 150-170 mc band is recommended; beyond line-of-sight, the 7 mc band is probably the best choice. Where two-way equipment is not feasible for one reason or another, the operator should be furnished with a receiver only. Even an ordinary broadcast receiver is adequate if arrangements are made to broadcast instructions over a locally receivable broadcast station at regularly scheduled times.

4. At selected sites, it may be desirable to install raingauges, depending on the needs for hydrologic as well as meteorological analysis.

D. Selection, training, and supervision of smoke-generator operators

Operating in undeveloped areas, it is the universal experience that the performance of a generator operator is in direct ratio to the conspicuousness to him of the importance of his position. The recommended approach to the selection and compensation of generator operators is therefore to stress the power and responsibility attached to the position.

There is adequate historical precedent for such importance. In all ancient cultures, of Africa as well as other continents, the observances and rites associated with the weather were regarded as being of critical importance and were the prerogative of the most important personages. In keeping with this tradition, it is recommended that recruitment of generator operators aim at enlisting the services of the most important personage in each locality as the operator and that the position should carry with it the most attractive compensations possible, not only in terms of pay but also in terms of prestige and privileges. It is obvious that the recruiter should be a person himself well known and well regarded in the area, thoroughly familiar with the local customs and able to approach prospective operators in the context of their own culture and perception of values.

Operation and routine care of the equipment is very simple, and training of the operators can be carried out by the recruiter after he himself is suitably trained. It is recommended that supervision be exercised through daily radio contact where possible, by periodic visits on the part of the field engineer, and by reference to the event recorder attached to each smoke generator showing when and for how long it was operated.

E. Routine of operation

The steps in the daily routine of operation will be geared to the strong diurnal pattern of cloud and rain development.

Between 7 and 9 A.M., a meteorological analysis and evaluation will be made for prediction of the direction and speed of travel of smoke plumes into the target area, the probable time and degree of development of shower activity, and the pattern of development as influenced by local terrain features under the prevailing conditions. This analysis will include exchange of information and discussion of large-scale weather conditions with the synoptic forecasting staff at Zanderij Airport.

Based on the analysis, a mission plan for the current day will be prepared, specifying the generators to be operated and their hours of operation, and including any special orders for operations or observations. These will be transmitted to the generator operators at a regularly scheduled time at or before 10 A.M. An outlook for the following day's operations will also be prepared and transmitted at the same time. Certain other hours, perhaps 1 P.M. and 5 P.M., should be designated as alternate radio schedule hours when as many stations as possible will stand by for amended operating orders based on observed development of the weather during the day.

Generator operating hours will usually fall between 10 A.M. and 5 P.M. with variations depending on the individual sites, speed and direction of the wind, and expected timing of shower developments. Only those generators will be operated that have a reasonable chance of influencing the weather pattern of the particular day.

During the balance of the day the progress of shower development will be followed by radar and other observation and compared in detail with anticipated conditions. Any necessary changes in the mission plan will be made and transmitted to the field as occasion arises.

F. Operational safeguards

Operation of the cloud seeding program should be suspended under certain conditions when its continued operation might contribute no benefit or when it might produce a disbenefit. These conditions are:

1. Operation should be suspended whenever the current status of the reservoir and the projection of normal inflow and outflow results in expectation of overflow within one week. The suspension should continue in effect until overflow ceases and projection of normal inflow and outflow results in expectation of voids capable of storing additional run-off.

2. Operations should be suspended whenever streamflow in adjacent rivers to the west exceed their mean annual maximum flows. The suspension should remain in effect as long as flows remain above this level.

3. Operations should be suspended whenever in the opinion of the field meteorologist there is reason to believe that artificial stimulation of rainfall would result in or aggravate a hazard to life or property.

As a further safeguard against possible attribution of weather-connected damages, justified or unjustified, to the weather modification program, time-lapse photographs of the radar scope should be taken during all cloud seeding operations and should be maintained as documentary evidence. These photographs should be periodically reviewed and searched for unintended or unexpected effects.

VI. WEATHER MODIFICATION AND PUBLIC POLICY

Among those nations where weather-modification experiments and applications have taken place, some, especially the United States, have begun the development of a national policy with respect to it; in others, the subject lies dormant. Appendix II gives a synopsis of the situation in all Western Hemisphere nations where weather modification has taken place and in selected nations elsewhere whose experience is pertinent, together with examples of legislation relating to weather modification.

Without exception, where national policy has been expressed, weather is recognized as a natural resource of the greatest importance the control of which, even to a limited extent, is of immense significance. The present status is well presented in a comprehensive plan developed by the U. S. Department of the Interior(Dept. of the Interior, 1966), which states:

"A wealth of scientific opinion now holds that it is in the national interest to pursue a greatly expanded program of research directed toward the development of practical precipitation modification techniques. The need to plan and build these developments on a nation-wide scale under an integrated program has been confirmed by experience and is firmly embodied into public policy.

"Developments in precipitation modification and water resources planning have now reached a juncture that changes the nature of both. Water resources management can no longer regard precipitation as an entirely uncontrollable input to its physical and economic systems. In the words of one scientist, 'Weather modification can never again be approached only as a scientific problem. It is now, and will be in the future, an element in the resource planning of the nation and the world' "

The plan to which this publication relates is already in the first stages of execution, and authorization for its full realization is embodied in legislation now before the U.S. Senate with committee recommendation for passage. (Senate Bill S. 373 and House Bill HR 5734).

It is inconceivable that such an immensely valuable power as weather modification will be left indefinitely unexercised. Despite the novelty of the questions that its use raises, the choice is not whether but how the questions will be suitably answered.

A. Elements of National Policy for Suriname

The Government of Suriname has for a long time recognized water power and the industrial complex related to it as an outstanding national natural and economic resource and the development of this resource in close collaboration with free enterprise is firmly established in the national policy. No novel principle is involved in the extension of this policy to weather modification as it relates to the development of water power through atmospheric water resources. Such an extension does, however, require attention to recognizing both the possible benefits and the possible disbenefits and establishing lines of policy that will maximize the former and minimize the latter.

1. Benefits

The direct economic benefits have been extensively considered elsewhere in this report. To what extent secondary benefits will accrue through the consequent economic activity is beyond the scope of the present study.

Direct scientific benefits will also accrue from the weather modification program through strengthening of basic scientific services. The role of a national scientific service in Suriname is perhaps most clearly seen in the case of the hydrologic service, the accomplishments of which form the base on which the expansion of water-power resources is established, which in turn returns income directly to the government as well as to the national economy. An analogous value may be placed on improved national meteorological services through their contribution to commerce and industry; agriculture and especially land reclamation and irrigation; transportation by land, sea, and air; and domestic and industrial water supply. The basic meteorological services supporting a program of weather modification will be equally applicable to these other benefits.

2. Disbenefits

a. Flooding of the Suriname River

Since the purpose of the proposed program is to increase precipitation, it is natural to raise the question whether it may introduce or increase the danger of floods.

With respect to the Brokopondo development, the question is answered as follows. The Brokopondo dam completely regulates the normal flow of the Suriname River up to the point determined by the "design flood", the most severe flood condition that the works are designed to handle.

The Brokopondo "design flood" is based on the all-time extreme rainfall observed anywhere in the region and the supposition that an equivalent weather condition, amplified by the effect of terrain but limited by the ultimate capacity of the atmosphere to transport moisture, might recur directly over the Brokopondo watershed. This weather occurrence comprises a succession of 18 days of excessive rain beginning at a time when the reservoir is full to overflowing and streamflow is at its normal annual maximum.

Under the proposed plan of operation, cloud seeding will be suspended whenever normal inflow is expected to fill the reservoir within one week; therefore, suspension would be in effect before the beginning of any weather event equalling or exceeding the stress of the "design flood" and would not contribute to any consequent flood damage.

b. Flooding of adjacent river basins

It is to be expected that the increase of precipitation over the Suriname River watershed will extend for a distance downwind related to the lifetimes and the speeds of motion of the stimulated showers, and that this effect will therefore be felt to some extent in the adjacent downwind watersheds, particularly in the Saramacca River.

The study of the "design flood" condition for Brokopondo has shown that flood danger arises not from the rainfall of one day or even of a few days; excessive rainfall must accumulate over a period of more than a week, and generally even a long period, before excessive flood conditions result. It is therefore possible by establishing criteria that anticipate the development of major flood situations to suspend rainfall-stimulation operations before the danger point is reached. The proposed plan of operation accordingly provides for suspension of the seeding whenever these rivers exceed their mean annual maximum flows and whenever in the opinion of the field meteorologist stimulation of the precipitation might cause or aggravate a hazard to life or property.

c. Deprivation of adjacent river basins.

There is evidence, as yet inconclusive, that under certain circumstances the stimulation of precipitation in one area may lead to diminution of the rainfall in another area somewhat farther downwind. The indications of this occurrence have been limited to two situations where a relatively shallow layer of moisture-bearing wind flows across a succession of mountain ranges, it drops some moisture on each and becoming successively drier thereby; stimulation of precipitation over one range may then diminish the capacity of the airstream to supply precipitation to the ranges farther downstream. Where additional convective activity is simulated over level country within a relatively shallow moist layer, there is some indication that the region of stimulated activity may act something like a low mountain range, forming billows downstream where the moist layer becomes successively deeper and shallower and inhibiting the formation of showers in the regions of shallow moist layer.

Neither of these conditions is anticipated in Suriname because of the great depth of the moist layer there during the periods suitable for rain stimulation.

There is evidence (Brier, Kline, and Carpenter, 1965) that the more characteristic effect of cloud seeding is an extension of the region of increased rainfall to a distance, in the eastern United States, of up to 200 km. This increase is related, apparently, to dynamic effects not only on individual clouds but also on cyclonic storm systems. The absence of cyclonic storm systems in Suriname should limit this downstream effect, as indicated earlier, to the range of a single shower during its lifetime.

d. Public anxieties

Unusual weather always calls forth unusual explanations, sometimes logical but often irrational and based on natural anxieties rather than on facts. For instance, droughts and floods have within the past two centuries been successively blamed on cannonading, the evil of slavery, the stringing of telegraph wires, the operation of radio stations, invasion of the air by airplanes, the explosion of atomic bombs, and irresponsible weather modification. It has never proven possible completely to eliminate the mistaken attribution of disasters to such causes, but it has been possible to assuage the anxieties from which they spring and prevent them from interfering with progress.

Basic to the control of public anxieties is adequate discharge of the responsibility for determining the real effects of the weather modification. This responsibility will be discharged under the recommended program by documentation of the actual distribution of rainfall in the form of time-lapse photographs of the weather radar observations at all times when cloud seeding is done, covering not only the intended target but a wide area around, including the populated zone along the coastal plain and the principal cities.

Study of attitudes toward weather modification in an agricultural community in the United States (Di Santis, 1967) has shown that these are closely related to attitudes toward the forces of nature in general and to attitudes regarding the relative importance of the past, the present, and the future. In the community studied the tradition of personal independence and self-reliance is exceptionally strong. This community lives perpetually on the brink of drought, so weather is often a source of distress and always a source of anxiety. People who regarded nature from a fatalistic point of view were on the whole opposed to weather modification; they were also the most poorly informed about it and the least willing to inform themselves. Those who regarded nature as subject to human control -- those, for example, who sought to improve their agricultural practices -- were on the whole favorably inclined to weather modification; they were also the best informed about it and the most willing to inform themselves further.

The Di Santis study also concerned itself with the factors tending to influence these attitudes. It was found that the people more readily accepted new ideas if they came from the better-educated and better-informed members of their own community and they tended to distrust and resent the intrusion of outside experts. Information, to be effective, had to be offered to the individual within a familiarly accepted pattern, such as the opinion of a well-regarded neighbor or an article in a publication to which he regularly subscribed.

Fortunately, in Suriname, the amount of distress and consequent anxiety connected with abnormalities of the weather is exceptionally low, and exceptional steps to counteract misinformed public opinion are therefore very unlikely to be needed. Nevertheless, it is recommended that such established channels as do exist for the dissemination of new ideas within the existing pattern of the culture should be utilized to make known the nature and purpose of the weather modification program.

B. Institutional instrumentalities

If it is granted that the successful application of rain stimulation in Suriname offers benefits for both the nation and the Suriname Aluminum Company that greatly outweigh the possible disbenefits, the question becomes: Who should carry it out?

In most countries where it has been used, applied weather modification started out under the principles of the common law, with no special legal guidelines or official policy or legislation. In many countries it has continued on this basis without government interference or legal complications of any sort; in other countries, either governmental regulation in the public interest or government participation has developed.

There are persuasive reasons for recommending that in Suriname a carefully considered determination should be reached as to the policy best fitting its circumstances; the proposed operation is on a large enough scale and closely enough identified with economic considerations of great importance to the nation so that it cannot be considered as a trivial matter. Such an attitude recognizes the actuality that the weather is an indivisible whole, and a part of it cannot be sequestered for the exclusive use of any particular interest, public or private.

The choice appears to be among three alternative instrumentalities: 1) the Suriname Aluminum Company; 2) the Suriname Government; or 3) a non-profit corporation governed by an independent board acting in the public interest.

1. The Suriname Aluminum Company may operate the program in its own name. It may hope to receive credit for an action that benefits the prosperity of the country as a whole and tends greatly to strengthening of the basic scientific services of the country in meteorology, to the advantage of agriculture, air transportation, etc. On the minus side there may be a few individuals suffering the vagaries of the weather who will, mistakenly or otherwise, blame the Company for their misfortunes, and others who may be inclined to sympathize with them and to resent and mistrust what they perceive as intrusion into the affairs of nature. The disadvantage is not so much possible damage claims -- these would be almost impossible to prove and are offset by insurance -- as unpopularity for the Company if weather modification were perceived as a kind of arrogant disregard for the rights of plain people.

This last disadvantage would be minimized if the Suriname Government were to establish an administrative procedure for the issuance of weather modification licenses in situations that it found to be in the public interest and that provided proper safeguards against hazard to life or property. Precedent for this course is to be found in the laws of many states in the U.S. regulating the conduct of cloud seeding for private ends.

2. The Government of Suriname may decide that a program of weather modification, as an extension of its present program for development of natural resources, is in the national interest, and that after due consideration it finds that the program as proposed offers adequate safeguards against possible hazards to life and property. It would be justified in authorizing the program as an activity of the appropriate agency of Government, if necessary accepting financial assistance from the Suriname Aluminum Company in defraying the expenses, and extending the umbrella of national sovereignty over the liability aspect of actual operations. Precedent for this course is to be found in the action of states such as Connecticut and New Hampshire on conduction weather modification programs financed with the assistance of agricultural and hydroelectric interests, and in the National Science Foundation of the U.S., which is likewise authorized to accept private contributions labeled for use in specific places for specific applications.

3. A third alternative is offered by the formation of non-profit institution governed by a board of directors or trustees appointed to act in the public interest and financed by contributions from private and/or public sources, or by the authorization of an existing quasi-official public institution such as a national university, to carry out a specific program of weather modification in the public interest. Precedent for this course is to be found in the incorporation in Puerto Rico of a non-profit corporation, Lluvia Artificial, Inc., with a board of directors representing the Puerto Rican Department of Agriculture, the Land Authority, and the Experimental Farm of the University of Puerto Rico. Similar precedent exists in the weather-modification activities carried on in Colombia by the Corporacion Autonoma Regional del Valle del Cauca, in Mexico by the Compania Mexican de Luz y Fuerza (a government-owned enterprise), and in the United States by the Bonneville Power Administration on the Columbia River.

Appendix I

DETERMINATION OF WATERSHED SHOWER POPULATION

The shower population over the watershed is derived from the observed distribution of shower amounts at Affobakka on the assumption that each shower is circular in shape and has a diameter related to the amount of rain falling at the center of the shower, which we will call its intensity P. The problem is to specify a realistic areal distribution of rain coming from a shower of intensity P, and then to specify the distribution of such showers that generates the rainfall amounts observed at Affobakka. In doing so, it is assumed that Affobakka is representative of the watershed as a whole; that is, that as a first approximation, local influences of terrain may be neglected.

Following Thom (1958) we assume that the frequency f(p) rainfall amounts (p) at a point such as Affobakka are given by a distribution function of the form

$$f(p) = \frac{p^{(\gamma-1)} e^{p/\gamma}}{\beta^{\gamma}\Gamma(\gamma)} \qquad (1)$$

where β and γ are the parameters of the distribution and $\Gamma(\gamma)$ is the complete gamma function. The parameters for the point distribution can be easily obtained by fitting (4) to the actual frequencies observed at Affobakka. If the fitting is done by the method of maximum likelihood, one obtains the most efficient estimators which turn out to be:

$$\beta = 6.296$$
$$\gamma = 0.44 \qquad (2).$$

The cumulative frequency of point rainfall is then given by

$$F(p) = \frac{\int_0^P f(p)\,dp}{\int_0^\infty f(p)\,dp} = I(\gamma, P/\beta) \qquad (3)$$

where $I(\gamma, P/\beta)$ is the incomplete gamma function, which is tabulated by Pearson (1951).

The cumulative frequency of actual rainfall amounts is

$$R(p) = \frac{\int_0^P f(p)\, p\, dp}{\int_0^\infty f(p)\, p\, dp} = I\left(\gamma+1, P/\beta\right) \qquad (4).$$

Table 1 has been computed by using formulas (3) and (4).

To specify the areal distribution of rain in a shower of intensity P, we use a mathematical model derived by Huff (1966) for showers falling on the micrometeorological raingauge network of the Illinois State Water Survey and apply to it proportionality factors from the theoretical model of a convective cumulus cloud derived by Davis (1966). These yield the radius R as

$$R = 0{,}8\, P^{1/2} \qquad (5)$$

where R is in kilometers and P in millimeters of rain. Assuming that rain intensity diminishes linearly from the center of the shower to its edge, the rainfall amount p at any distance r from the shower center is

$$p = P - 1{,}25\, r P^{1/2} \qquad (6).$$

The volume of water V falling from N such showers in the watershed can then be obtained by a double integration of the product of the point rainfall by the storm local frequency, or

$$V = 2\pi 10^3 \int_0^\infty \int_0^r \left(rP - 1.25\, r^2 P^{1/2} \right) P^{\gamma-1} e^{-P/\beta}\, dr\, dP\, N \qquad (7),$$

which can be integrated to yield the volume in cubic meters of water:

$$V = 6.702 \cdot 10^{2} \beta^{(\gamma+2)} \Gamma(\gamma+2) N \qquad (8).$$

The reason for the simplified model is apparent now, since it makes possible the formal integration of (7).

Equation (8) shows that the shape parameter γ of the number of showers has been augmented by 2 over that of the point frequency; this conforms to the logical expectation that the central peak intensity will be larger than that sampled by a point. The median rainfall intensity in the case of a point sample was about 2 mm (for $\gamma = 0.44$, $\beta = 6.296$) while for the watershed as a whole under the present assumptions, the median would be near 20 mm, and the scale parameter accordingly increases also to about 9.65.

Equating (8) to the average Pokeigron flow to obtain a rough estimate of the number of showers needed to equal it, yields $N \simeq 2500$. This is only a rough preliminary estimate, since no corrections have been made for runoff losses etc., but it points out that four times as many showers should occur over the watershed as over any given interior point, and that the central intensity of such showers will repeatedly exceed 20 mm. The average cloud depth and cloud top temperature needed in Davis' (ibid) model to produce such showers are 9.5 km and -25°C respectively.

<u>Estimate of cumulative runoff volumes.</u>

To obtain a more accurate assessment of the cumulative volumes to be expected from this many showers, we now resort to the complete model of Huff (ibid) in which the rainfall at a point distant r km from the center of the storm has a rainfall of p millimeters where

$$r = P - C r^{1/3} e^{DP^{1/2}} \qquad (9)$$

where for the units used

$$C \simeq 1.111 \qquad (10).$$
$$D \simeq 0.233$$

If Huff's shower gradient relations are assumed, the elemental volume in cubic meters of rain generated at a distance r from the shower center is

$$dV = 2\pi r \left(P - C r^{1/3} e^{DP^{1/2}}\right) dr \cdot 10^3 \qquad (11)$$

and the total catch for a circular watershed of radius W would be

$$\Delta V = 2\pi \cdot 10^3 \int_0^W \left(P - C r^{1/3} e^{DP^{1/2}}\right) dr \qquad (12).$$

if the rain extended to the edge of the watershed. Formula (9), however, points out that there is a critical value of the radius r_{crit} beyond which there is no rain.

Solving (9) for this particular case where $p = 0$, we find the critical radius

$$r_{crit} = P^3 e^{-3DP^{1/2}} / C^3 \qquad (13),$$

Since rain cannot assume negative values, (12) should be integrated between this critical radius r_{crit} and either W or zero depending whether the critical radius does or does not exceed the watershed radius W.

Conversely, we can solve for P in (13) and obtain the critical value of the central precipitation intensity P_{crit} which permits the rain to extend to the edge of the watershed. In the case of the Suriname river watershed above Pokeigron, the equivalent watershed radius is

$$\bar{R} \simeq 49.5 \text{ km} \qquad (14).$$

Introducing (14) into (13) and solving for P, we obtain the critical rainfall intensity

$$P_{crit} = 7.83 \text{ mm} \qquad (15).$$

The total volume for all showers would be obtained by a double integration of (12) over all the possible values of the radius r and the central intensities P , and multiplying this result by the total number of storms, i.e.,

$$V = N \int_{\bar{R}}^{r_{crit}} \int_{0}^{\infty} f(P)\, dV\, dP \tag{16}$$

and the cumulative volume would be

$$Cum.\ Vol. = \frac{\int_{\bar{R}}^{r_{crit}} \int_{0}^{\infty} f(P)\, dV\, dP}{\int_{0}^{\infty} \int_{0}^{\infty} f(P)\, dV\, dP} \tag{17}$$

which would be independent of the number of storms assumed.

The resulting integrals are not analytically integrable, but can be computed numerically to yield either volumes per unit period, total volumes (if the number of storms is known or assumed) or cumulative volumes, which would be independent of the number of storms.

So far we have assumed no losses and this is unrealistic. Local measurements made by hydrologists at Suriname have shown that tree canopies intercept nearly 5 mm of rain, and that percolation, evapotranspirations and other losses can run as high as 50 percent of the average total rainfall. The problem of accounting for all these losses analytically is of great complexity, so for this simulation we decided to parameterize the losses by postulating a runoff loss coefficient K such that

$$K = 1 - e^{-AP} \tag{18}$$

which tends to zero as the rainfall diminishes and to unity as the storm intensity increases, and to calibrate the parameter A so as to obtain the average median flow when a reasonable number of storms is postulated, such as the previously made estimate, or viceversa, the coefficient could be computed when the number of storms were independently known, say, if estimated by radar.

Budyko (1948) quotes Schreiber (1904) in proposing a similar coefficient to account for evapotranspiration losses. The use of a runoff-loss coefficient is particularly attractive in the tropics (Solomon 1967) as the net radiation inflow varies little throughout the year.

A tentative calibration, assuming the conservative number of four times the point storm frequency gave a value

$$A = 0.0117 \tag{19}$$

and the resulting equations were

$$V = 93.94 \int_0^P (P-5)^7 e^{-1.398 P^{1/2} - P/\beta} P^{\gamma-1} K \, dP \qquad \text{if } P \leq 7.83$$

$$V = V - 3036000 \int_0^P \left(P - 5 - 3.782 e^{0.233 P^{1/2}}\right) e^{-P/\beta} P^{\gamma-1} \, dP \qquad \text{if } P > 7.83 \tag{20}$$

Tables 2 and 4 show the results of running (20) in a computer simulation for the cases of no losses or all losses including a runoff-loss coefficient. These tables were especially needed because we must have some estimation of the relative importance of shower sizes in the contribution to effective runoff, if we are to infer the effects of seeding which depends on a certain minimum size for the showers.

The effect of seeding on runoff has been adapted from the numerical simulation work of Crawford (1966) which in essence shows that the effect on runoff for a basin which is relatively wet, like Suriname's, is generally of the order of 50 percent greater than the effect on rainfall, and from the pragmatic results of hundreds of practical seeding experiences in similar areas of the wet tropics, (López 1966) which point out to an average of 20 percent increase in rainfall when showers whose cloud tops exceed the $-5^{\circ}C$ are the main runoff contributors.

APPENDIX II

WEATHER MODIFICATION APPLICATIONS AND PUBLIC POLICY IN THE WESTERN HEMISPHERE NATIONS AND SELECTED OTHER NATIONS

Listed below is a synopsis of weather modification applications in each of the Western Hemisphere nations where such programs have operated on more than a casual basis, and of the relation of these operations to public policy in these nations. Also listed are experiences in other nations that have made significant contributions to development of public policy in the field of weather modification.

Canada

Commercial weather modification operations have been carried on in most years since 1951. The principal applications have been for hydroelectric power generation in British Colombia, Ontario, and Quebec, for forest fire control and protection in Ontario and Quebec, and for rainfall stimulation and hail mitigation for agricultural interests in Alberta, Saskatchewan, and Manitoba.

The National Research Council of Canada has carried on a modest program of basic research and evaluation, and the Ontario Department of Natural Resources has carried on a program of applied weather modification.

There is no national regulation governing weather modification. However, in 1964 the Ontario Department of Natural Resources suspended its cloud seeding program in the face of complaints that it was causing damage to hay crops in the Lake St. John regions.

Mexico

Commercial rain stimulation was begun in 1951 under the sponsorship of the Cía Mexicana de Luz y Fuerza for hydroelectric power generation at its Necaxa plant. Design of the program included randomized suspension of operations on one-third of seedable days for purposes of evaluation. The program was continued when the power company was nationalized, and it is now in effect conducted by an agency of the Mexican Government. No legal complications have arisen, and the program has recently been extended to a watershed near Monterrey. (See Pérez 1966)

There is no national legislation on weather modification. A program of basic research was conducted briefly at the National University during the residency of a World Meteorological Organization expert, but is now terminated.

Cuba

Commercial rain stimulation was conducted on an expanding scale from 1951 to 1959, initially by U.S.-controlled sugar companies and later by most of the major Cuban-owned interests as well, with a total of 51 sugar mills engaged in it during 1958. There were no legal complications. These programs ended with the ascendency of Fidel Castro to power.

In 1959, under the Castro government, the Instituto Nacional de Reforma Agraria planned a program of operational adaptation of weather modification which was subsequently deferred. In 1965 the Cuban government was reported to have entered into a program of experimentation in collaboration with the Universite de Clermont-Ferrand, France.

Haiti

Commercial rain stimulation was carried out in 1954 for the benefit of a major sisal plantation. No legal complications were experienced. There is no national legislation concerning or regulation of weather modification.

Dominican Republic

Commercial rain stimulation was carried on for a period of three years for sugar plantations on the south coast of the island. No legal complications were encountered.

There was no legislation concerning and no regulation of weather modification, although the government did maintain extremely close surveillance over aircraft used on the program.

Virgin Islands

A combined program of practical application and scientific research is currently being conducted on the island of St. Croix under sponsorship of the National Science Foundation and the Fairleigh Dickinson University. In anticipation of this program, the Virgin Islands Government in 1966 passed the following legislative act.

ACT NO. 1748

Act Relative to Weather Modifications by a Cloud Seeding Operation and for Other Purposes

BE IT ENACTED by the Legislature of the Virgin Islands:

SECTION 1. Any department or agency of the Government of the Virgin Islands may, with the approval of the Governor, and within the limits of appropriated funds or by means of gifts, donations, or grants, engage in and undertake experimentation in the techniques and methods for weather modification, and may cooperate therein with the federal government, with authorized agencies of other states, and with interested persons and organizations.

Thus passed by the Legislature of the Virgin Islands on June 8, 1966.

Panama

A program of weather modification for mitigation of blow-down losses in the banana plantations was carried on for three years near Puerto Armuelles. No legal complications were encountered.

There is no legislation or regulation relating to weather modification in Panama.

Venezuela

Commercial weather modification was carried on for one year for a sugar plantation. No legal complications were encountered.

An experimental program for relief of domestic water supply shortage during a drought was carried on in 1953-54 by the Instituto Nacional de Obras Sanitarias.

There is no legislation or regulation relating to weather modification in Venezuela.

Colombia

Weather modification operations have been carried on intermittently since 1955 for quasi-official agencies including the Cooperativa Agrícola de Magdalena, the Corporación Regional Autónoma del Valle del Cauca, and the

Australia

A broadly-based program of basic and applied research in weather modification has been carried on in Australia since 1947 under the auspices of the Commonwealth Scientific and Industrial Research Organization. Operational adaptation for specific applications has been the subject of several programs operated by CSIRO and in cooperation with the Snowy Mountains Hydroelectric Authority.

Empresas Públicas de Medellín. The operation for the Cooperativa Agrícola de Magdalena, the purpose of which was to mitigate blowdown damage to the bananas, was financed by a special tax imposed on banana exports, while the other programs, for hydroelectric power and potable water, were directly financed by the interests concerned. (López and Howell, 1961; López and Howell, 1965; López, 1966). No legal complications have arisen.

The official chiefly responsible for the Cauca Valley program, Dr. Bernardo Garcés, is currently the Minister of Public Works for Colombia.

Japan

Cloud-seeding experiments were begun in the early 1950's by a group of hydroelectric companies in central Japan. A modest program of evaluation and applied research is currently under way by the Japanese meteorological service in support of this development. Details of legislative action are not known.

Russia

A program of basic and applied research on weather modification has been under way in Russia since the early 1950's under the general direction of the Central Meteorological Institute. At the present time there are four major regional institutes carrying on field programs for applied weather modification with emphasis on hail mitigation and rain stimulation. The annual budget for weather modification research and development is estimated to be of the order of $15 millions annually.

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