COLORADO STATE UNIVERSITY

EXPERIMENTAL RAINFALL-RUNOFF FACILITY

Design and Testing of Rainfall System

by

M. E. Holland

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ACKNOWLEDGEMENTS

CONSTRUCTION OF AN EXPERIMENTAL RAINFALL-RUNOFF FACILITY

Chapter 1

INTRODUCTION

The advantages of controlled experimentation into the problems of flood runoff, as distinct from the use of actual storm and flood data on natural catchments, are sufficiently great that many attempts have been made to utilize laboratory experiments in the study of runoff processes (1,2,3). Rainfall simulators have been used in the past mainly for studies of infiltration, detention storage, and overland flow. Hydrologists have long felt the desire to use rainfall in such a way that results obtained from a rainfall-runoff simulator could readily be applied to natural catchments. However, the size, complexity and cost of a structure suitable for study of the whole runoff cycle, and the inherent difficulties of extrapolating results from a "model" catchment to a natural catchment have discouraged the use of rainfall-runoff simulators for these purposes.

The rainfall-runoff experimental facility described in this paper makes possible the study of a number of processes that cannot be studied by small-scale laboratory models because of the problems of achieving dynamic similarity of hydrologic events. The philosophy and the general classes of problems that can be studied on the experimental facility have been presented previously (4) and will not be discussed in detail here. However, a brief review of the history of the development of this facility will be presented before the facility itself is described.

Development and use of the experimental facility is one phase of a three-phase research program into floods on small catchments. The other two phases are:

(i) The collection and processing of rainfall, streamflow, and catchment data for a large number of flood events that have been recorded

on small catchments throughout the world, and the storing of these data
on punched cards and magnetic tape for ready use and distribution, and,

(ii) Theoretical studies of the relation between flood hydrographs
and the factors that affect them, as well as the study of statistical and
other techniques that can be used for the analysis of data from experimental
investigations as well as from natural catchments. The three phases of the
research program operate in a complementary fashion to permit the application
of data and analysis techniques from a spectrum of sources to the study of
the rainfall-runoff relationships in natural watersheds.

OBJECTIVES AND CRITERIA

The rainfall-runoff experimental facility was established in the early
1960's as a part of the three-phase approach to the study of floods from
small watersheds. Although the rainfall-runoff simulator was originally con-
ceived as a tool in the study of floods, it soon became clear that such a
device could be useful in studying other hydrologic problems not related,
or only indirectly related to flood estimation. These include such things
as erosion studies and studies of the travel and dissipation of pollutants
(chemical, biological and radioactive) in the watershed environment. The
potential uses in these areas are discussed in more detail in the previous
report (4). The aspects of interest for this report are the advantages in
using the experimental facility and requirements that such uses place on
the facility.

All the advantages in studying simulated rainfall-runoff events on an
artificial catchment rather than naturally-occurring events on natural
catchments derive from the fact that the simulated event can be controlled,
whereas the natural event cannot. Briefly, the advantages are: (a) the
potential homogeneity of any factor; (b) the controlled variability of any

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factor; (c) the time factor in obtaining results; and (d) the convenience in experimentation. These will be explained more fully below.

Homogeneity. Whereas in nature all variables in general are variable in either space or time or both, in a rainfall-runoff simulator, any one or all variables can be made homogeneous over the whole area of the simulator and throughout the period of a test. This capability should be helpful in isolating the effect of a variable, since it will avoid the necessity of developing and using "average" or "index" measures of variables, or sampling variables across the area or in time. For example, if main stream slope is made uniform for a particular test, there will be no doubt about the appropriate measure of this variable as there is in the case of natural streams. This doubt has led to the development and use of at least four different measures of main stream slope, two being purely geometrical, and the others allowing for the effects of slope changes on velocity of flow. No one method is widely accepted, so the avoidance of this confusion will be an advantage for the artificial stream. The advantage applies to all characteristics of both the rainfall and the catchment.

This capacity for homogeneity of variables will also be useful in providing standard conditions against which results for non-homogeneous conditions can be compared. For instance, it seems logical to run tests in which rainfall intensity is approximately uniform with respect to time and area (although this never occurs in nature) to provide a yardstick against which the results of rainfalls of varying degree of non-uniformity can be compared.

Variability. An obvious advantage of the artificial event over the natural is the ability to change any particular variable between tests, while keeping all other variables unchanged. This variability between tests is not to be confused with the homogeneity or otherwise of a variable within a

test, which was discussed in the preceding paragraphs. Any particular variable can be either homogeneous or non-homogeneous over the area of the simulator or throughout the duration of a test, but it is important to be able to vary its value or average value over a wide range in a series of tests (without varying any other independent variable) to isolate its effect on whatever dependent variable (such as flood peak) is being studied. This is impossible to do on natural catchments and so it has been impossible to isolate the effect of any one variable with confidence.

In nature, it is necessary to use data from many catchments in order to get a range of values of any one variable, but use of many catchments also results in a range of all other independent variables. Thus, extracting the effect of any one variable becomes an inaccurate process, especially if, as is usual, the number of catchments and runoff events used is small.

Time Factor. A major disadvantage and inconvenience in most hydrologic studies is the relative paucity of data that arises from the relative shortness of most hydrologic records. Since, with an artifical rainfall simulator, it is not necessary to wait for natural storms to occur, a large body of data can be obtained in a short time. This is an important advantage of the use of simulated events.

Convenience. The location of the experimental facility at the Engineering Research Center makes workshop, laboratory, storage, office and data digitizing facilities readily available. The faculty members can supervise and monitor the progress of experiments during each day. Continual contact can be had with the experimental effort.

REQUIREMENTS FOR FACILITY

The requirements for the experimental facility may be presented in three general classes: (1) control of rainfall, (2) measurement of variables and (3) modification of basin characteristics.

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1. Control of Rainfall

Uniformity and reproducibility. The controlled application of rain-
fall is the most important feature of the rainfall-runoff simulator. This
is the characteristic that distinguishes the facility from experimental water-
sheds. The basic requirements of the artificial rainfall are areal uniformity
and reproducibility. The facility should be capable of producing an approxi-
mately uniform spatial distribution of rainfall over the basin to minimize the
masking of the basin response by rainfall variations. A perfectly uniform
distribution will not be achieved, but a close approximation should be
possible. Natural rainfall is never completely uniform, but the more nearly
uniform the rainfall is over the entire basin, the more easily the effects
of the watershed response may be evaluated from the experimental data.

The reproducibility of rainfall conditions is more important than
uniformity. A repetition of an experiment under identical conditions is
frequently useful to confirm results for the observed trial or to fill in
measurements that may have been missed when an instrument did not operate
properly. It is not necessary that a specified distribution be achieved
without a trial-and-error approach, but once the control settings for a given
pattern of rainfall have been determined, it should be possible to reproduce
the conditions with a high degree of reliability at any later time by
making the appropriate control settings.

For many studies it will be convenient to have the ability to vary
the input in time and space. The experimental facility does include some
provision for this.

For erosion studies, the artifical rainfall should approximate the
spectrum of impact energies of natural raindrops. This will be difficult
to achieve over the full range of input intensities.

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2. Measurement of Variables

General requirements. The distribution of parameters and variables in both space and time are needed to interpret the response of the watershed system. If control of the input and state parameters of the system were perfect, their measurement would be of only minor significance because the values could be determined from the control specifications. Since the control is imperfect and the uniformity of rainfall can only be estimated before the facility is operated, the measurements will be quite important.

The instrument readings from all instruments should be transmitted to one location for observation and as much of the data as possible should be recorded automatically. This is needed because the changes in the variables may frequently occur faster than a person can take down values. Also, when the data are recorded automatically, there is less chance of error in recording values. Since most of the data will be analyzed with a computer, direct digital recording should be utilized as much as possible to speed the assembly of the basic data into form for computer input.

3. Controlled Parameter Variations

The third requirement of the rainfall-runoff experimental facility is the ability to vary the basin parameters in a controlled manner. The shape of the basin and the stream configuration represent large scale parameters that can be varied, and the surface roughness and detention characteristics represent more readily variable parameters. The large scale parameters will be modified by using earth-moving equipment to reshape the basin, so they will be varied less frequently than the other variables.

The major points that should be recognized in scheduling parameter variations are (a) that the research plan should be designed so the more easily varied parameters are modified as much as possible

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before the major features such as shape and stream network are changed; (b) that the ranges and step sizes of parameter variations should be adjusted as experimental data clarifies the relative significance of various factors; and (c) the processes may be more readily evaluated if they can be physically isolated in the basin.

PRELIMINARY STUDIES OF FEASIBILITY

The initial investigations of the concept of the experimental facility were supported by the Colorado Agricultural Experiment Station, now called the Colorado State University Experiment Station. These efforts included the selection of the location for the facility, the review of literature concerned with the use of rainfall simulators in erosion, infiltration and overland flow studies and the determination of how the slopes and overall shape of the catchment would be changed.

The location of the experimental facility was determined on the basis of water supply, shop, office and automatic analog-to-digital data conversion facilities. All of these facilities are readily available at the CSU Engineering Research Center, Foothills Campus. A site that could contain the one-acre facility was available adjacent to the Research Center and was selected. The water supply for the hydrologic and hydraulic facilities comes from Horsetooth Reservoir, beside which the Engineering Research Center is located. A 36-inch supply line brings an ample supply to the facilities.

The literature review on rainfall simulators revealed that simulators have been used for a number years for erosion and infiltration studies and for small-scale laboratory experiments in overland flow. No system was found in the preliminary reviews that could be

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efficiently adapted to the proposed facility. A tentative design based on large fog nozzles mounted on towers was formulated during this period, but a continuing review was made of other potential systems. The existing system was adapted from one found later in the study.

The final decision in the feasibility phase of the research concerned the method of changing the slopes and shape of the catchment. Small-scale laboratory models can utilize platforms that are tilted to provide the desired slopes. The 3-foot diameter, 800-foot long pipe at the Engineering Research Center facilities, had also been provided with slope adjustment. However, because of the large area involved in the proposed facility, the platform would be very costly. It was decided, instead, to use earthmoving equipment to mold the large-scale features of the facility. A number of experiments can be run with small-scale features varied before a major change is required.

OWRR GRANT-PHASE I

In 1966 the Department of the Interior, Office of Water Resources Research, provided a matching grant for Phase 1 of the design, construction and use of the experimental facility. The work during this two-year period consisted of making a concise formulation of the philosophy of use

and objectives of the experimental facility, conducting preliminary design studies and installing the major facilities, such as the water supply lines from the 36-inch main to the experimental facility. The results of this work are reported in a previous report (4) and only a few points will be touched here.

The first design project was the main supply line for the facility. A 26-inch diameter main ran past the site of the facility carrying water

from the 36-inch main to the Hydromachinery Laboratory. A 10-inch line was connected to the 26-inch main and was laid around the site of the facility. The 10-inch line lies outside the experimental runoff area except at the upper end where it had to cross the area. Thus, whatever rainfall system was later installed could be supplied from both sides of the facility. The main control valves were installed in the 10-inch line and a drain line was located between the 10-inch line and a creek draining the site. The drain line can be used to empty the 10-inch line or to control the pressures in the line by diverting part of the flow at times.

Although no attempt was made to model a specific watershed, it was necessary to decide on a shape and slope for the Facility representative of typical small watersheds. Rather than make a capricious decision, it was decided to study the shapes and slopes of actual watersheds for which data were available.

Sixty-one small watershed were studied to determine a representative shape. For the initial geometric shape of the Facility it was decided to compromise between the results obtained in the survey of the small watersheds in nature and the natural shape of the selected Facility site. Furthermore, it was decided to simplify the initial shape and drainage characteristics as much as possible. The less complex the geometrical shape of the basin, the less difficulty will occur in data analysis. The shape selected is composed of two intersecting planes and an upper conic section. Each of the sections can be readily described by a simple mathematical function.

The preliminary shaping of the facility was performed after the 10-inch supply line had been installed. The slopes were brought approximately to their design values so that settling could take place before the final adjustments were made.

The tests of rainfall systems during Phase 1 were related mainly to nozzles that could be used in the tower system. A number of tests were performed on individual nozzles under varying wind conditions to determine the distributions of intensities. The testing program will be discussed more in Chapter 2. A rotating head was designed to provide a more uniform spatial distribution with the nozzles. The intensities of rainfall that would occur with several of the towers operating were rather high, so alternative systems were still being considered.

The necessary prerequisites in the operation of the facility are the simulation of natural precipitation, and the subsequent measurement of the precipitation and runoff. Precipitation measurement should be as accurate as possible and should be continuous during any given simulated storm. To accomplish the objective of both accuracy and sensitivity, the capacitance gage system for measuring and recording very small surface waves was adapted to a standard precipitation gage. The capacitance gage senses the depth of water at a given instant of time. The depth is transmitted as an electric signal either to a magnetic tape recorder or directly to the analog-to-digital converter. The latter records the data on punch cards for analysis by computer.

In addition to precipitation, it will be necessary to measure the runoff amount produced by a given rate of precipitation. The H-flume developed by the Agriculture Research Service was chosen for the purpose. The principal reasons for selecting the H-flume were: (a) simplicity in design and construction, (b) freedom of passage of debris through the measuring section, and (c) below surface construction of the head box minimizing the formation of backwater at the measuring structure.

OWRR GRANT-PHASE 2

The second phase of the construction of the experimental facility was funded under a two-year matching grant by OWRR in 1968. The level of funding was less than had originally been planned for, and therefore only the upper conic section could be developed to demonstrate the use of the facility.

The primary emphasis during the first year of Phase 2 was on the selection of the final rainfall system. Two alternatives to the tower system were examined. One was the use of large irrigation guns located outside the catchment area. These guns left the area free of obstructions, but had significant disadvantages that led to the rejection of this approach. The second alternative was based on small-diameter aluminum irrigation pipe with small sprinklers, such as are used in lawn sprinkler systems. A number of sprinklers were investigated, and one was found that performed acceptably. The individual nozzles were tested in the laboratory to determine the distribution of intensities. A computer program was then used to simulate the operation of a number of nozzles with overlapping patterns. A coefficient of variation of about 10% was found to be possible for a range of intensities from 0.5 to 4 inches per hour.

A pilot system was field tested and found to be satisfactory. The full system for the upper conic section was installed during the second summer of Phase 2, and an initial set of experiments were run during the fall.

During Phase 2, a cooperative effort by the Department of Agriculture, Agricultural Research Service, became a part of the experimental research. This cooperation included professional

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and graduate research assistant work on the development of the facility and provision of equipment such as chart-recording gages for rainfall and streamflow. The chart-recording gages provide immediate graphical presentation of data to supplement the digitized records.

The treatment of the surface of the facility to make it impermeable was changed in Phase 2. Originally, the covering of the facility with butyl material had been rejected on the basis of cost. However, the availability of a quantity of butyl on surplus made it economically feasible to use. The upper conic area was, therefore, covered with butyl after the final shaping was performed.

The capacitance raingages, which had performed satisfactorily in the laboratory, were found to have instabilities when installed in the field. A number of tests by project personnel resulted in the use of larger probes with heat-shrink plastic coatings instead of enamel. Several gages have been modified and appear to be operating satisfactorily in the field.

The upper conic section is essentially complete and has been used for a series of tests in the cooperative effort of CSU and the ARS. The tests varied the area of the catchment contributing runoff by (a) separating off a 30^0 sector, giving data from 30^0, 90^0 and 120^0 sectors, and (b) by using shorter radii than the 110-foot radius of the basic sector. In addition, a series of tests was run with small-size gravel providing roughness and surface detention effects.

The following chapters of this report describe the development of the major components of the experimental facility in more detail. Chapter 2 discusses the rainfall system, Chapter 3 presents the instru-

mentation for measuring rainfall and runoff and Chapter 4 discusses the shapes and surface treatment of the facility.

POTENTIAL APPLICATIONS

The experimental facility has potential, not only in studies of watershed response as reported in Chapter 5, but also in other investigations. Two such uses are included in research that has already been funded this year. One study concerns the quality of water running off from waste piles of oil shale in Colorado. Part of the research will use the facility to provide artificial rainfall on oil shale material and collect the runoff for chemical analysis. The other project is a study of the geomorphological development of river basins. An erodable material will be used and several drainage systems will be developed. This project is funded through the Geology Department at CSU, but is of interest in Hydrology as well.

The potential of the rainfall-runoff facility is indicated by the nature of the research that has already begun to develop around it. The results from these initial studies will stimulate additional research efforts. The facility will be of very great value in the study of many processes of watershed response in runoff, water quality and geomorphology that are now either obscure or neglected.

Chapter 2

ARTIFICIAL RAINFALL SYSTEM

Preliminary Studies

The artificial rainfall system is such an important part of the experimental facility that considerable research and test studies were performed before the final design was achieved. A review was made of literature concerning the use of rainfall simulators in laboratory studies of overland flow and field studies of erosion and infiltration. Based on this review the following factors were considered to be important in the design of the system: (1) distribution of intensities in time and space, (2) distribution of drop sizes compared to the drop size distribution of natural rainfall, (3) cost of constructing the system, (4) convenience and flexibility of the system in providing a variety of inputs under a range of field conditions and (5) the degree of interference with access to the catchment and with operation of other hydraulic facilities at the Engineering Research Center.

The intensities and drop sizes are related because large nozzles tend to produce larger drop sizes and higher intensities, while smaller nozzles can generally provide more uniformity and greater flexibility in the choice of intensities. A number of indices of the uniformity of rainfall have been described in the literature. For the purpose of comparing different systems, the coefficient of variation of the spatial distribution of intensities was used. The criterion for acceptance of the uniformity of an input was set as a coefficient of variation less than 0.10 over the range of intensities to be used for the rainfall tests. The criterion for drop sizes is more difficult to specify. The point of interest is the distribution of impact energies for erosion. The effect

of rainfall is modified by the protective influences of natural vegeta-
tion and the overland flow water depth in natural watersheds. Another
factor to be considered in selecting the rainfall system is the sensi-
tivity of the input to wind. The facility will be subject to a certain
amount of wind at all times. If the system is highly sensitive to wind,
there will be more times that the facility must be shut down and there
will be more difficulty in reproducinginput patterns.

Combining the criteria for the rainfall system with the study of
simulators that had been used previously led to the selection of three
types of rainfall systems for further study. A system of fog nozzles
on towers about 30 to 50 feet high was the first system investigated in
detail. The second type of simulator was the large-diameter irrigation
gun system that has been used for irrigating large fields. The third
system was based on the concept of a grid of small nozzles over the
catchment. This type was originally rejected because of the cost of the
supporting structure, but a modification of this type was found to be
feasible and was given further testing.

Fog Nozzle, Tower System

The system utilizing fog nozzles of the type used in fire fighting
seemed to offer the most potential for adaptation to the needs of the
facility. The first studies were therefore conducted with these nozzles.
A number of nozzles were obtained from government surplus and laboratory
studies were performed to determine the flow characteristics of the nozzles
under various line pressures. The head loss through the nozzle and the flow rate
at each pressure and at each position of the nozzle, from the smallest
opening to the full open position, were determined. It was found that

the discharge was the same for all openings at a given pressure and the loss characteristics were similar for all pressures. Thus, the nozzles could be modeled by the standard hydraulic principles to extend experimental results with computer analyses.

The fog nozzles have too long a trajectory for the jet to be tested in the laboratory to determine the distribution of intensities that will be generated. Therefore, an outdoor testing rig was constructed as shown in Figure 1. A framework on the right side of the figure provides support for the nozzle at a height of about 8 to 10 feet above ground. Water was supplied to the test site by the large supply line from Horsetooth Reservoir. The water was pumped through a fire hose to the nozzles. For some of the tests an elevation greater than 10 feet was required. A 2-inch diameter steel pipe was temporarily supported by a crane for this series of tests, and heights up to 50 feet were tested. A grid of cans was set up to collect the precipitation from the nozzle during a measured length of time. The nozzle was oriented at various positions from horizontal to vertical to provide varying trajectories.

Examples of the test results from three of these runs are shown in Figures 2, 3 and 4. The isohyets of the depths of water collected in the cans are drawn on these figures. In the first example the nozzle is located in the lower righthand corner and is oriented in a horizontal direction. It is seen that the larger drop sizes provide a concentration of input in the area where the main jet is directed, and a decreasing amount is carried beyond and to the sides of the main jet. The degree of spreading that occurs depends on the opening of the nozzle.
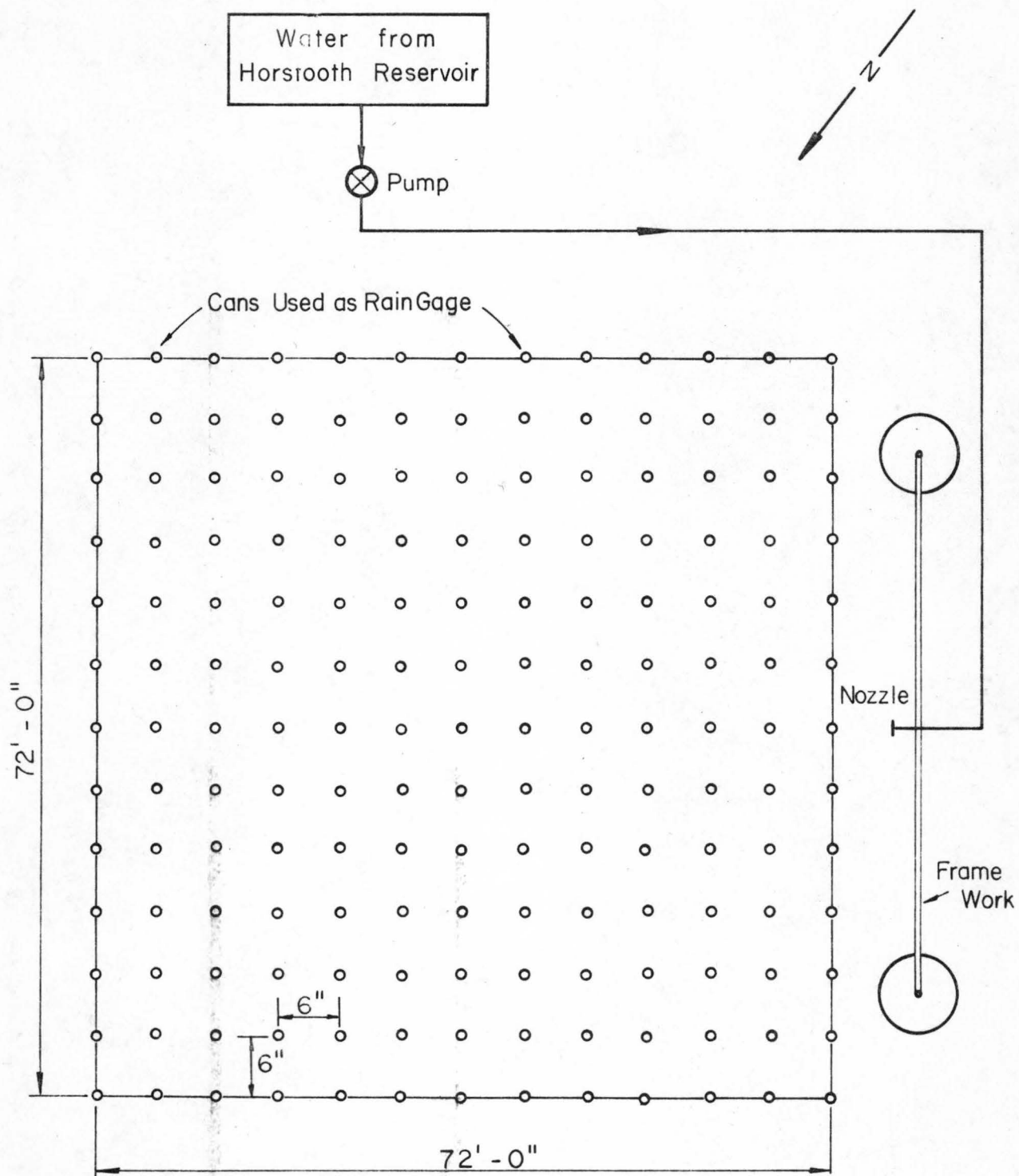
Figure 1   Testing Rig and Measurement Grid for Testing Fog Nozzles
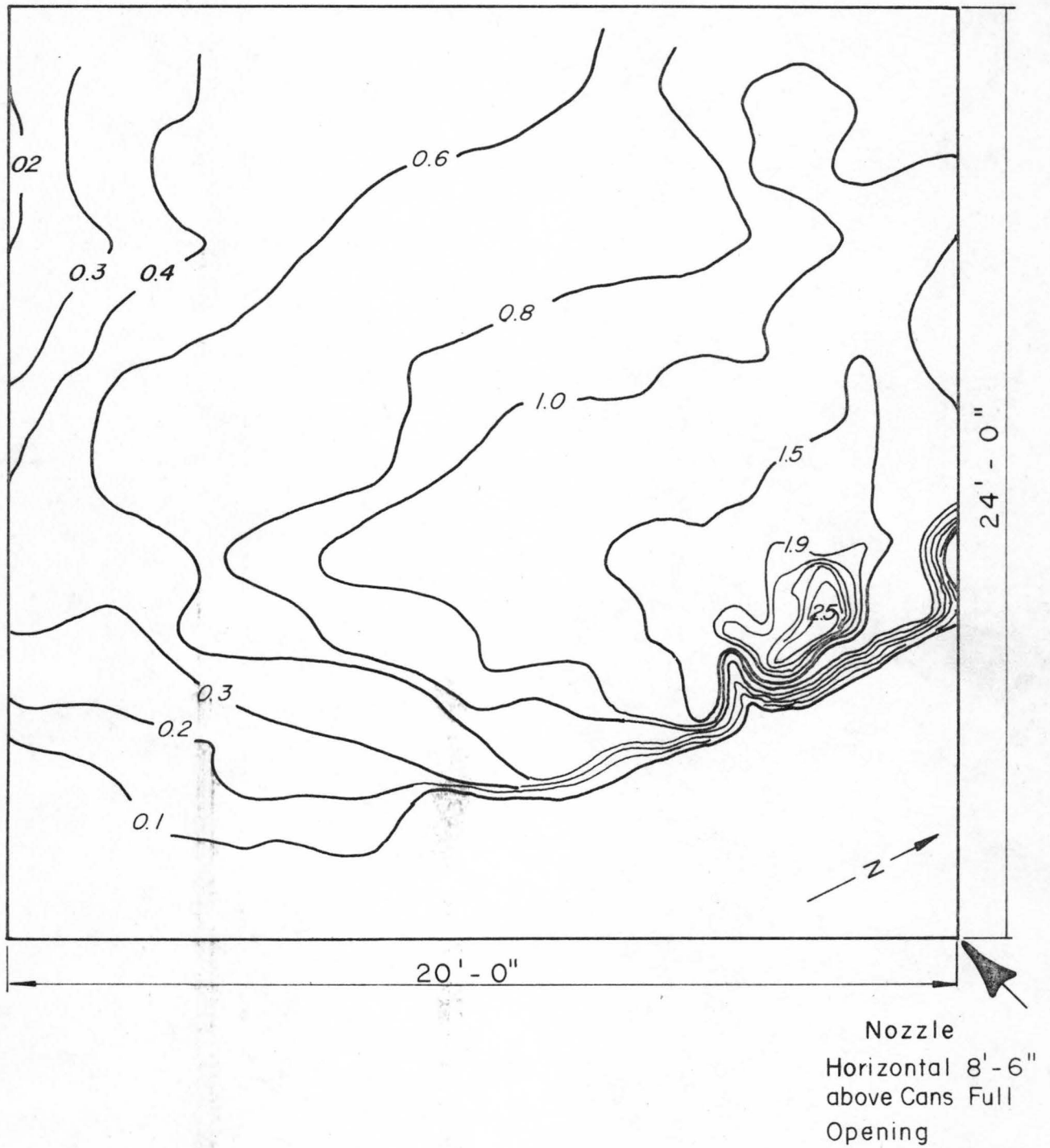
Date: Oct. 4, 1966   Run No. 1

Figure 2 Distribution of Precipitation from a Nozzle Directed Horizontally
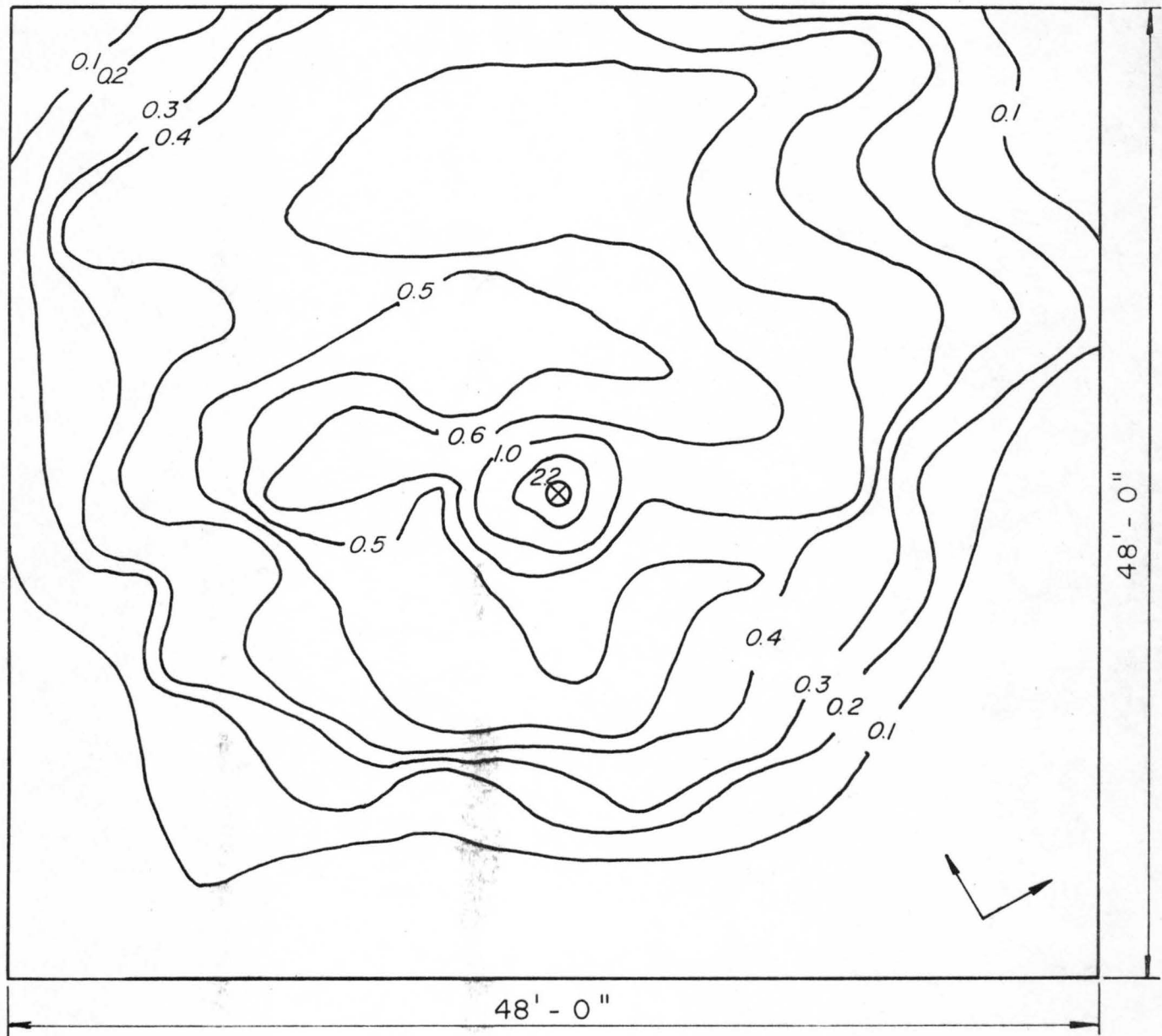
Date: Oct. 6, 1966   Run No. 2

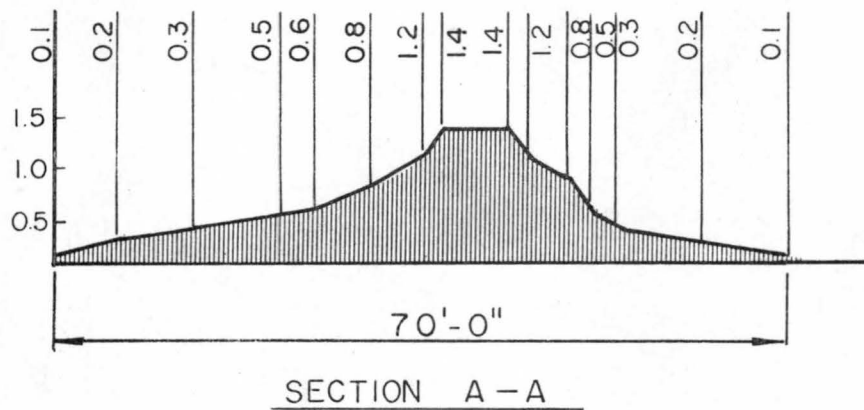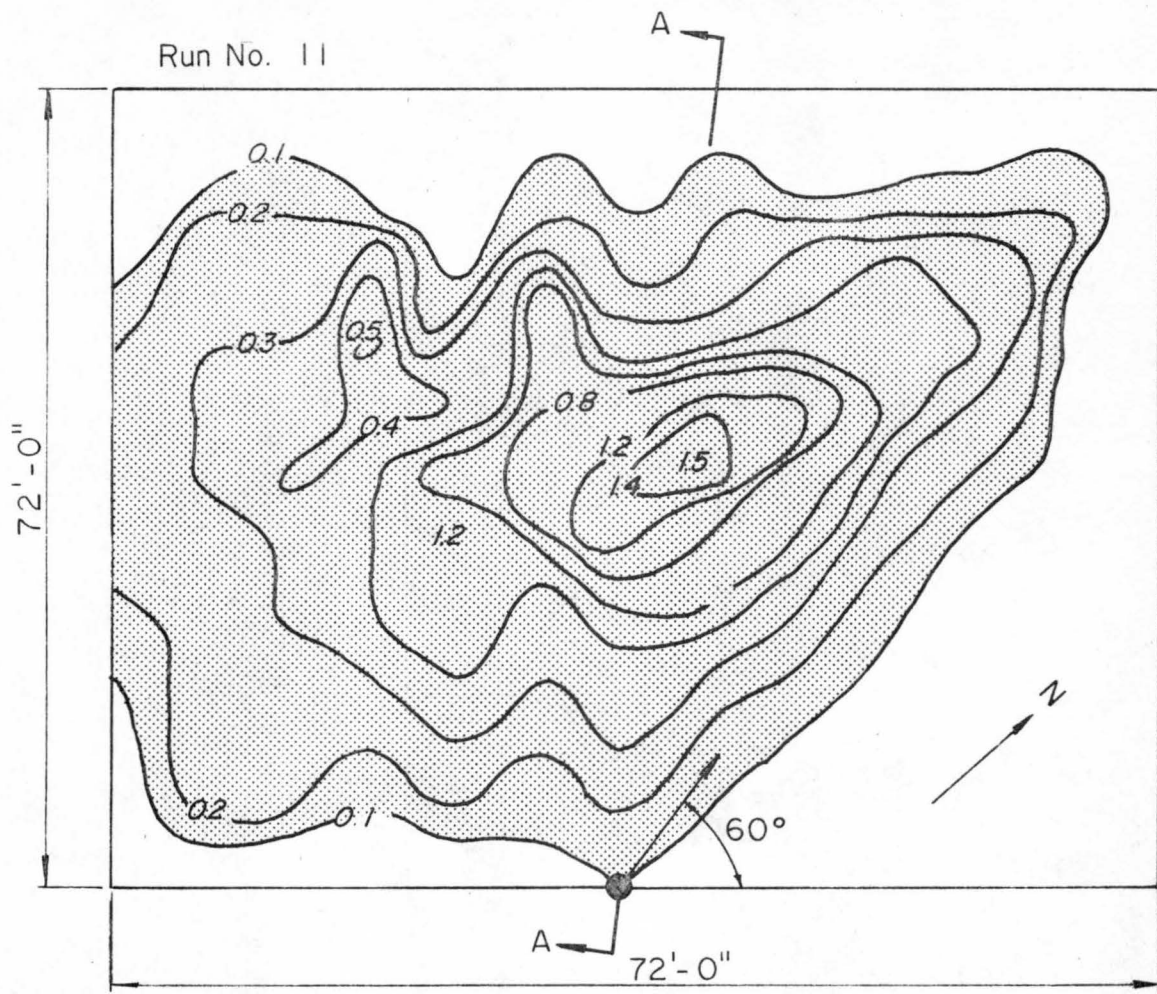Figure 3 Distribution of Precipitation from a Nozzle Directed Vertically

Figure 4   Distribution of Precipitation from a   Nozzle at 45° from Horizontal

The second example shows a nozzle in the center of the measurement grid and oriented vertically. The isohyets show the general radial character of this distribution, grading from a high intensity at the nozzle to zero as you move away from the nozzle. A slight wind effect is noticeable in this test. There is a shift of the isohyets toward the top of the figure from the radial symmetry that would be expected in the absence of wind. Note that the higher intensities are less affected than the lower intensities. This supports the hypothesis that the higher intensities are in areas that have larger drop sizes. The smaller drops are affected more strongly by the wind.

The 45-degree orientation is shown in the third example. A large concentration still occurs in the immediate vicinity of the nozzle. However, the distribution is more uniform a short distance away from the nozzle and the highest concentrations occur slightly removed from the nozzle. The center of the pattern shows greater uniformity than in the case of the vertical orientation.

The effect of the wind was investigated more fully in a set of tests is which the wind speed and direction were measured several times during each run. Figures 5 and 6 show the isohyets from a few of these tests. The runs illustrated are made with the nozzle at different elevations. This shows that the effect of the wind is greater at the higher elevations. Part of this is due to the greater degree of breaking up of the large drops into smaller drops as the fall is increased. A second factor is the higher velocities of wind that occur at greater heights above the ground. The velocity measurements were all made at about the same height, so the wind speeds actually acting on the nozzle is greater at the higher heights than the measured wind speed indicates.

Run No. 11

SECTION A — A

Nozzle Position and Direction
Nozzle Opening : half
Nozzle Height : 30'-0"
Wind Speed : 3 - 6 - 2 - 3 - 3 - 2 - 2 - 1 - 0 - 1 mph
Wind Direction: SE
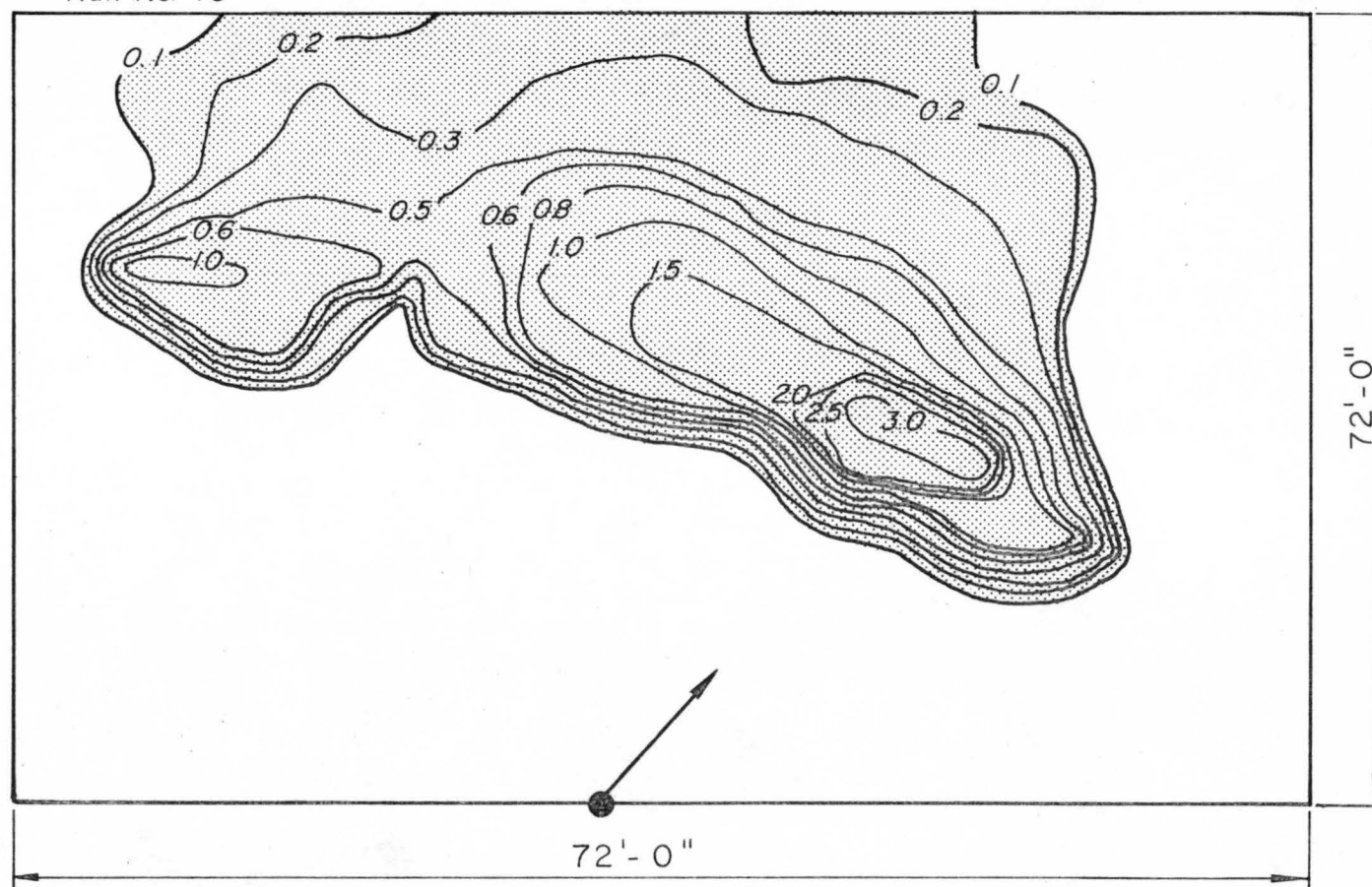Time : 10 minutes

Figure 5 Effect of Light Wind on Precipitation Distribution of Nozzle 30 feet High

Run No. 10

72'-0"

72'-0"

Nozzle Position and Direction:

Nozzle Opening :   half

Nozzle Height :   20'- 0"

Wind Speed :   8-10- 5½ -8½ -5 - 6 - 10 - 6½ - 5½ mph

Wind Direction : SE

Time :   10 minutes

Figure 6   Effect of Stronger Wind on Precipitation of Nozzle 20 feet High

The greater influence of the wind on the areas of lower intensity is still shown in these results.

Another effect of increasing the height of the nozzles is to increase the area of coverage. Part of this is due to the influence of the wind on the smaller drop sizes. The effect is to cover more area with relatively low intensities, so the average intensity over the original area of coverage is not changed much. The increased area covered tends to counter some of the disadvantages of increased height, but is not a dominating influence by itself.

The testing program also provided data for comparing the effectiveness of the different nozzle openings. The smallest opening gives the concentrated jet that has a long, narrow distribution. This pattern is not satisfactory for a nozzle that is held stationary over the facility because of the small area covered. The full open position gives the extreme fog effect, which has small drops and a small area of coverage. This causes high intensities and high sensitivity to the wind. An intermediate opening gives a greater area of coverage and a more uniform pattern of input. The major disadvantages of both extremes are absent, giving the most satisfactory stationary distribution.

The distributions of rainfall provided by the nozzles were superimposed to determine the pattern of input that would result from a set of nozzles located on a single tower and directed in different directions. Several patterns were tried, with the superposition being done manually. It was clear that there is considerable non-uniformity in the distribution over relatively small distances and the pattern is not very satisfactory. In the real system there would be a certain amount of randomizing due to the wind and the interaction of drops from different nozzles,

so the actual distribution should be more uniform than is indicated by these tests. However, the basic characteristics of the pattern will persist in the actual system, giving high intensities with considerable local variation. In addition, the best orientation for the nozzles change as the wind pattern changes.

Because of the unsatisfactory nature of the distribution that was expected from the stationary placement of the nozzles, a rotating head was designed to be mounted on the top of a tower or pipe. Four or five nozzles can be mounted on the head, and, as the assembly rotates, each of the nozzles sprays over the entire 360-degrees of the compass. The result provides radial symmetry in the absence of wind effects. The rotating head is driven by the reaction of the jets issuing from the nozzles. The directions of the jet can be adjusted, so the amount of reaction can be controlled and the spray can be directed at some angle between horizontal and vertical. The rotating head has been described in the previous report and will not be presented in more detail here. A pilot system was constructed and operated satisfactorily, under moderate wind conditions, but the high intensities and the sensitivity to wind led to further study of alternative systems.

Irrigation Gun System

The tower system described above also had the disadvantage that it required the installation of permanent towers on the interior of the facility. This restricts the movement of large machines used to change the shape of the catchment. Therefore, one of the criteria given extra weight in the additional studies was to leave the catchment as free from obstruction as possible. The system based on large irrigation guns was particularly attractive from this standpoint. These guns have been used

in irrigation systems to give a very uniform input over large areas. The catchment could be left entirely free of towers. Four of the guns were obtained and a pilot system was tested on the facility.

The testing indicated several problems that had not been anticipated in the preliminary study of the system. The first problem was the intermittent nature of the jet because of the reaction arm used to drive the sprinklers. Part of this was anticipated, so a motor drive was designed for the system. However, the reaction arms were left on the nozzles to give a more uniform distribution of input. It was found that the reaction arms caused a definite jump in the position of the nozzle as can be seen in Figure 7, where the jet on the far side has two jets, or parts of jets, separated by a discrete increment. The near jet shows a related problem, namely, the intermittent input that occurs in the immediate vicinity of the nozzles. There is input only when the reaction arm has just hit the jet, as is the case with the near nozzle. The reaction causes a long delay before the arm again hits the jet. Thus, the areal average may be uniform over long periods of time but there is considerable short-term variation in the distribution. This can be partially overcome by replacing the reaction arm with a stationary deflector in the jet. This causes a more uniform distribution, but it also cuts down the distance to which the jet can reach.

A second problem with the large guns was the interference occurring between jets from different nozzles. The jets reach beyond the center of the facility and collide with those on the other side. This causes localized areas of high intensity. The deflector in the jet could only partially overcome this effect. The nozzles on one side of the facility

were lowered slightly to further reduce the interaction, but the problem was not completely removed.

A more serious problem was found to be the concentration that occurred at the ends of the sweep of the nozzles. There is a certain amount of time required to stop the nozzles and reverse the direction of movement. As the speed of movement increases to provide a more uniform distribution in time, the proportion of time required to reverse the movement becomes greater. Large concentrations develop at the ends of the sweep. This could not be lessened without causing the time distribution to be worsened.

The above problems, coupled with the sensitivity of the jets to the wind, led to the rejection of the rain gun system. The wind effect is partly shown in Figure 7, where the lower part of the facility, at the right edge of the figure, is receiving no rainfall. The break-up of the jet to reduce other problems only intensifies the sensitivity to wind. This sensitivity is greatest for the lower intensities, which would be a frequent part of the testing anticipated on the facility.

Grid System

When the preliminary survey of literature was made, the grid system was rejected because of the cost of the structural support required to hold the nozzles and water supply lines above the facility. During the fall and winter of 1968-69, a modification of the grid system was given further consideration. The system used by Shachori and Seginer (5) used supply lines laid along the ground with the nozzles raised by small pipes to a height of 2 meters. Thus, no additional structural support is required. The design that was considered for the experimental facility
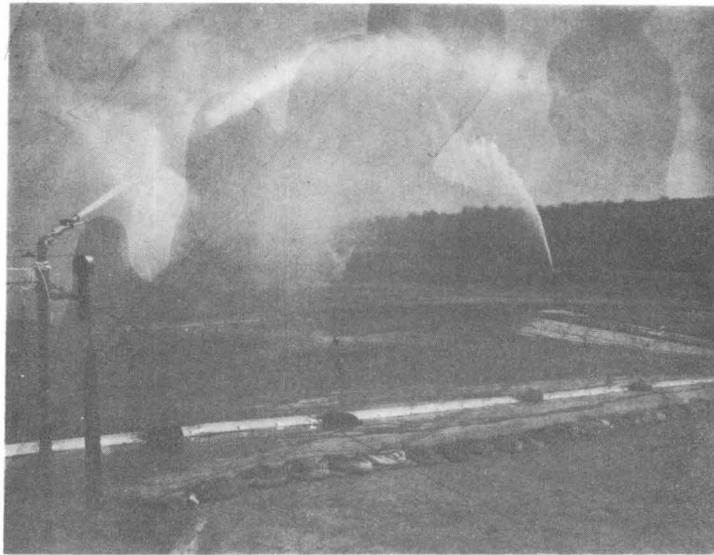
Figure 7   Testing of Irrigation Guns
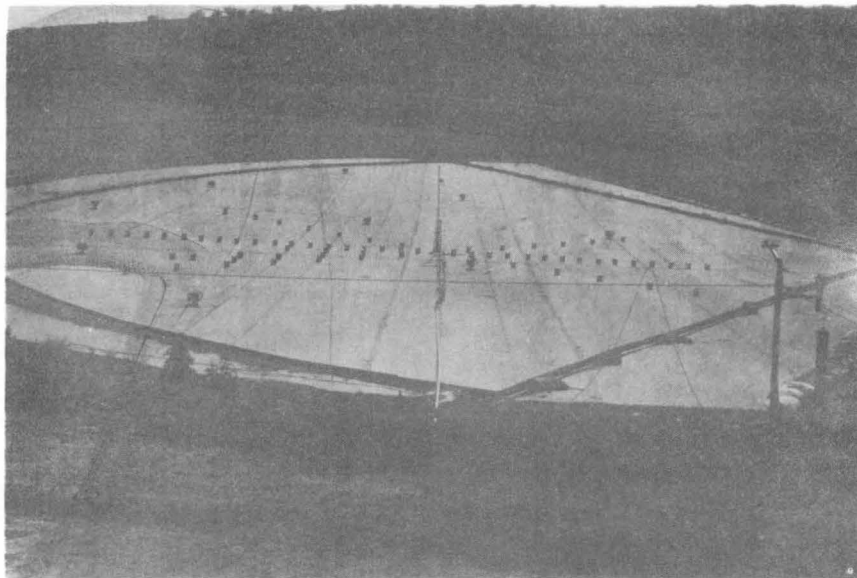
Figure 8   Test for Distribution of Intensities
for a Nozzle with Circular Pattern

T
10
22
31
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24

• 1   • 2
• 26   • 33
• 18   • 18
• 20   • 18
• 25 • 26 • 26

1 13 21 24 28 20 19 18 20 20 20 21 22 23   23 22 24 23 24 24 20 19 22 23 25 28 25 5 0

23
• 22 • 22 • 20
22
• 18 • 20 • 20
20
• 17 • 18 • 17
18
• 25 • 17 • 22
20
• 10 • 19 • 11
23
• 0 • 28
27
15
1

Figure 9   Sprinkler Test–Low Pressure Type 415
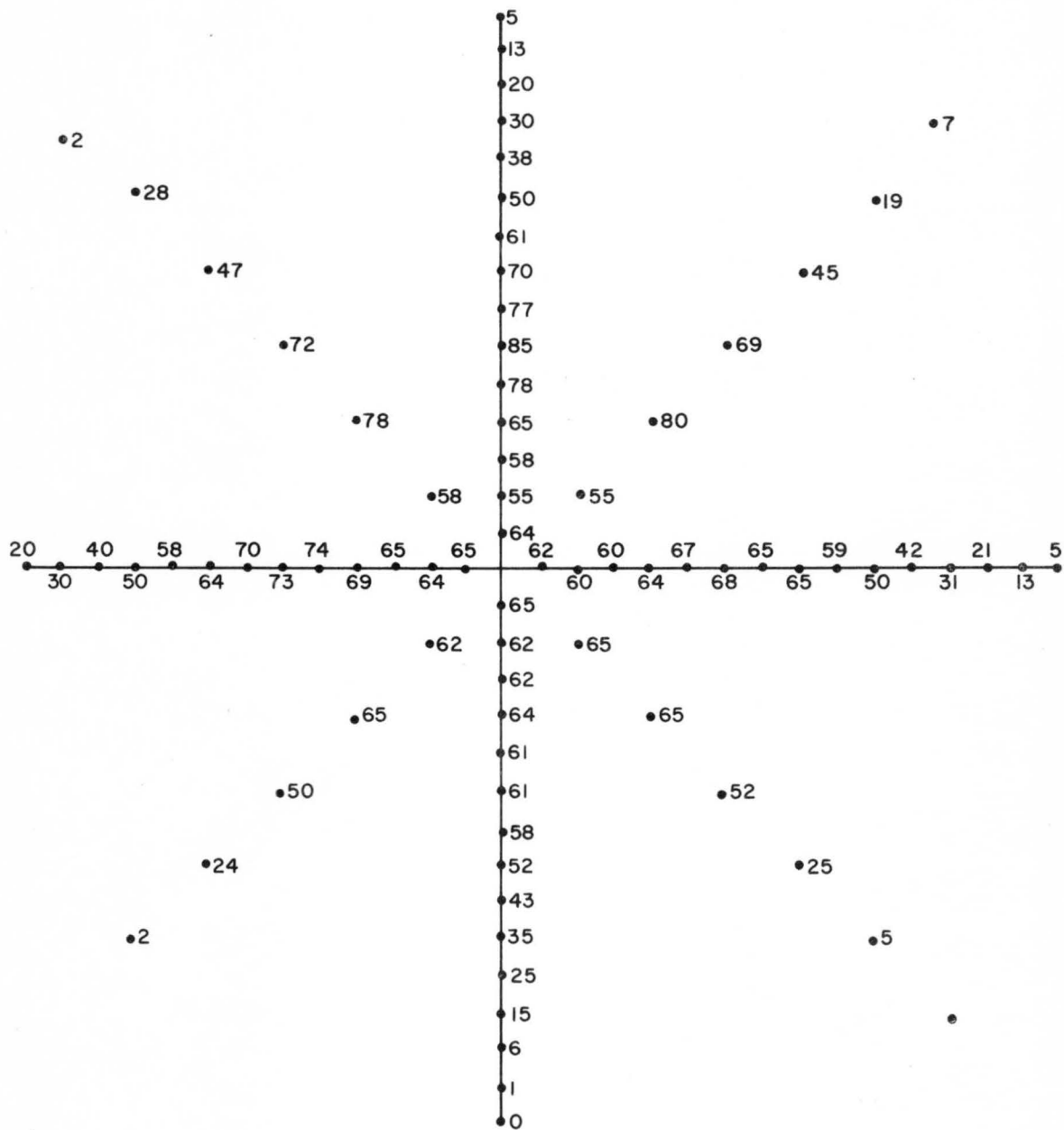
Figure 10   Sprinkler Test-Nozzle No. 78
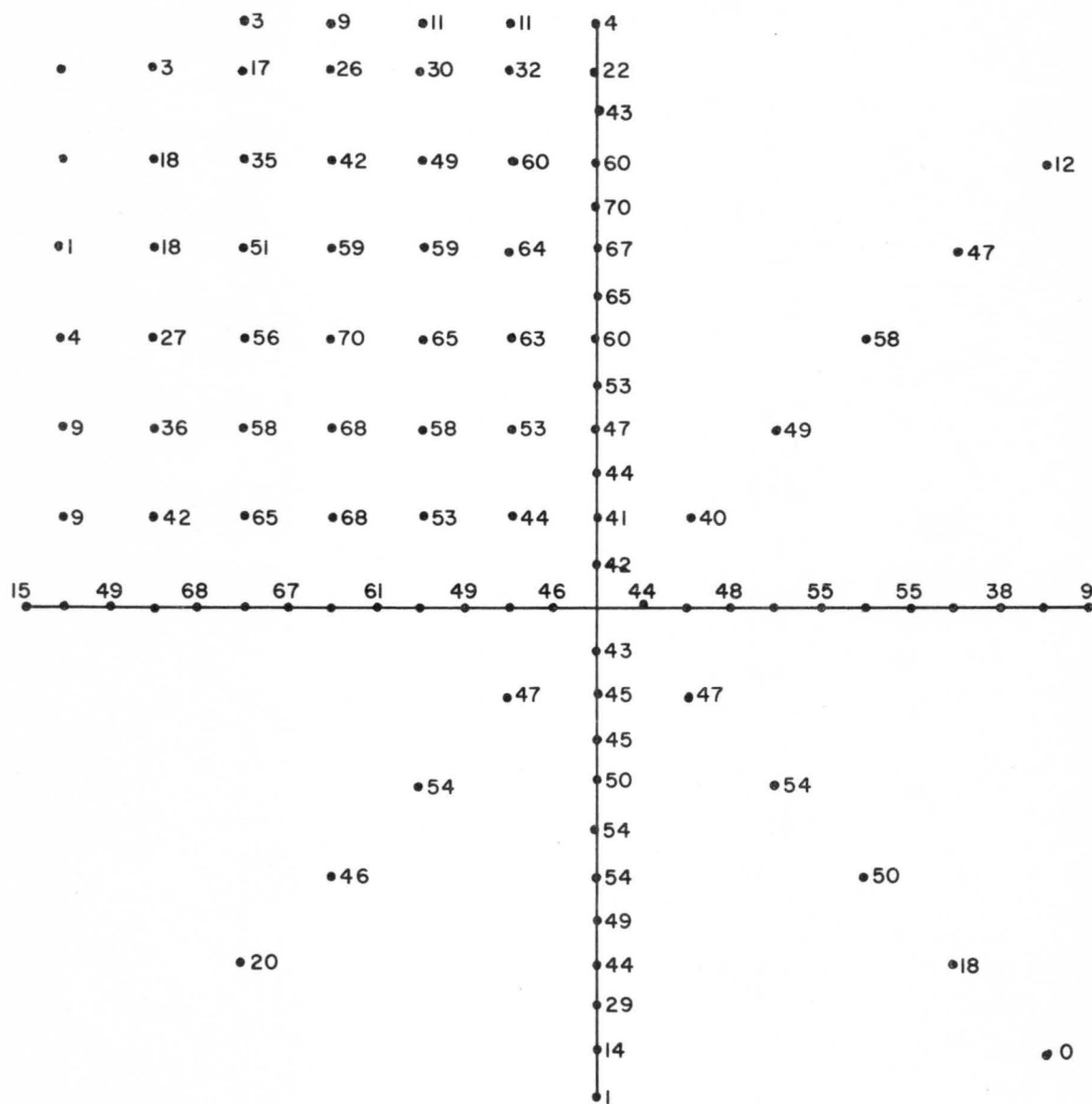
Figure 11   Sprinkler Test-Square Pattern

here at Colorado State University is based on the use of small diameter aluminum irrigation pipe supported slightly above the ground and having the nozzles raised to height of 10 feet by the smaller steel pipes. The aluminum pipe is supported by a small bipod at the riser for the nozzle. Thus, a minimum of structural support is required and the pipe is above ground so it does not influence the surface flow. The details of the system will be presented in a later section of this chapter.

A number of nozzles were given a preliminary screening to find some that could satisfy the needs of the facility. (The nozzles that were used by Shachori and Seginer were no longer available.) Several sprinklers of the type used in lawn sprinkler systems were found to be worthy of further testing. The individual nozzles were first tested in the laboratory to determine the distributions of intensities that are given. Some of the nozzles being tested provided circular patterns and one nozzle gave a square pattern. A series of tests were run at different pressures to determine the intensity patterns. Then the testing was shifted to the outdoors to include the effects of wind. The test facility is shown in Figure 8, set up on the outdoor facility for one of the nozzle tests. The results of three tests are shown in Figures 9, 10 and 11. The nozzle was operated for a measured length of time, usually 15 or 20 minutes, and the volume of water collected in each of the cans was measured.
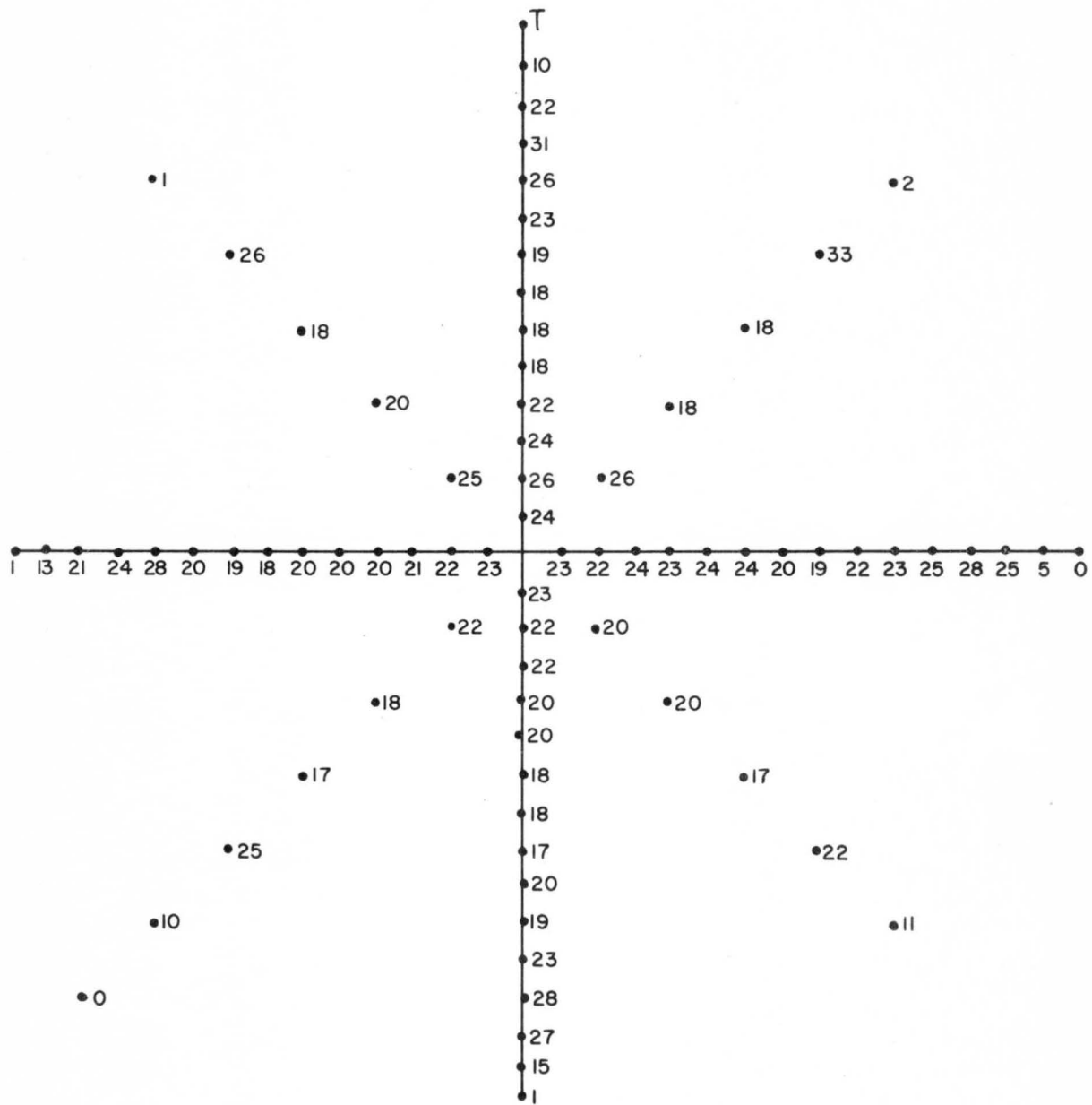
Computer Simulation

A computer program was written to simulate the operation of the system of nozzles over a part of the facility. The program reads in the data from the test run and converts the measured volumes to intensities in inches per hour. The locations of the nozzles are read in terms of

coordinates on a master grid. The distribution of the input is then determined as a function of the relative position with respect to a nozzle. This is handled in one of two ways, depending on whether or not radial symmetry is assumed. If radial symmetry is assumed, then the location of each measurement is computed as a radial distance from the nozzle. The measurements within one grid interval, centered on a grid point along a radius, are then used to determine the average value of the input at that distance from the nozzle. For example, looking at nozzle 415, there are eight measurements that are between 5 feet and 7 feet from the nozzle. The average volume is 23 ml. The corresponding intensity, 0.15 in/hr, would then be assigned to the 6-foot radius if a 2-foot grid increment is being used. The other measurements would be treated in a similar manner. If radially symmetry is not assumed, the observed data are used to fill in the complete grid by a process of inter-polation. One quadrant of the distribution is given more completely. For example, the second quadrant is filled in on 4-foot increments for the square nozzle of figure. The second quadrant would then be filled into 2-foot increments to correspond to the step size on the axes. Then the second quadrant data is used with the observations in the other quadrants to complete the entire grid about the nozzle.

For each nozzle, the positions of the locations of data points on the relative grid about the nozzle are converted to the corresponding location on the master grid, and the intensity contribution for the nozzle is added to the intensity matrix of the master grid. When all nozzles have been thus considered, the effect of the set of nozzles is contained in the master grid intensity matrix. The average intensity over a section in the center of the overlap area is computed and the coefficient of

variation of the intensities in that section is computed. These items
are printed out along with the master grid intensity matrix. A summary
of the averages and coefficients of variation for the last simulations
before the grid system was designed is presented in Table 1.

The criterion for acceptance of a distribution pattern had been set
at a coefficient of variation of 10% for the spatial uniformity. An
examination of the table of simulated patterns indicates that all of the
circular patterns could meet this criterion for all but the lowest inten-
sities. The performance of the nozzles is better at a pressure of about
28 psi than at lower pressures. The square-pattern nozzle, which must
operate at the lower pressure, was found to be unsatisfactory. The
nozzle that was selected for the prototype system is the #78. The
system was installed on the upper conic section of the facility during
the summer of 1969. The distribution that actually resulted on the
facility is shown for one test in Figure 12. The location of the cans
used for the test are shown on the figure and can also be seen in
Figure 13, which shows the facility in operation. In addition to the
grid of cans in the upper part of the facility, a number of cans were
located at random positions elsewhere on the facility. The average
intensity and the coefficient of variation were computed for both sets
of cans. For the grid, the average was 2.76 in/hr and the coefficient
of variation was 0.049. For the randomly spaced cans, the values are
2.76 and 0.053, respectively. The averages and the coefficients of
variation of several tests are listed in Table 2. The results show the
same trends as the computer simulations, except for the run at 1.22
inches per hour, which has an anomalous coefficient of variation. This
run will have to be examined in more detail to determine the cause of

Other Gages Located
at Random Outside
the Grid Pattern

```
      323  345  332                                                                    315  305  310
      325  315  308                                                                     •    •    •
      325  310  304
      340  345  273                                        380  328  295  295  320  325  325
      312  315  302                                         •    •    •    •    •    •    •
      308  324  298
      330  322  338                      330  327  342  338  310  308  302  312  320  312
      330  305  310                       •    •    •    •    •    •    •    •    •    •
      350  312  333
R̄  2.75974 in/hr                   310  318  327  342  330  292  303  313  308  300  315
                                     •    •    •    •    •    •    •    •    •    •    •
C.V. 0.05334
                          310  310  305  312  320  312  315  318  325  320  310  312  312
                           •    •    •    •    •    •    •    •    •    •    •    •    •

                     314  327  340  297  305  333  340  318  318  340  352  318  290
                      •    •    •    •    •    •    •    •    •    •    •    •    •    •

                320  315  312  315  315  310  330  318  308  325  332  320  315  292  310
                 •    •    •    •    •    •    •    •    •    •    •    •    •    •    •

           340  333  312  325  310  305  320  328  320  315  320  320  312  310  295  298
            •    •    •    •    •    •    •    •    •    •    •    •    •    •    •    •

      338  338  343  342  335  325  322  355  360  335  320  325  330  327  325  308  308
       •    •    •    •    •    •    •    •    •    •    •    •    •    •    •    •    •
```
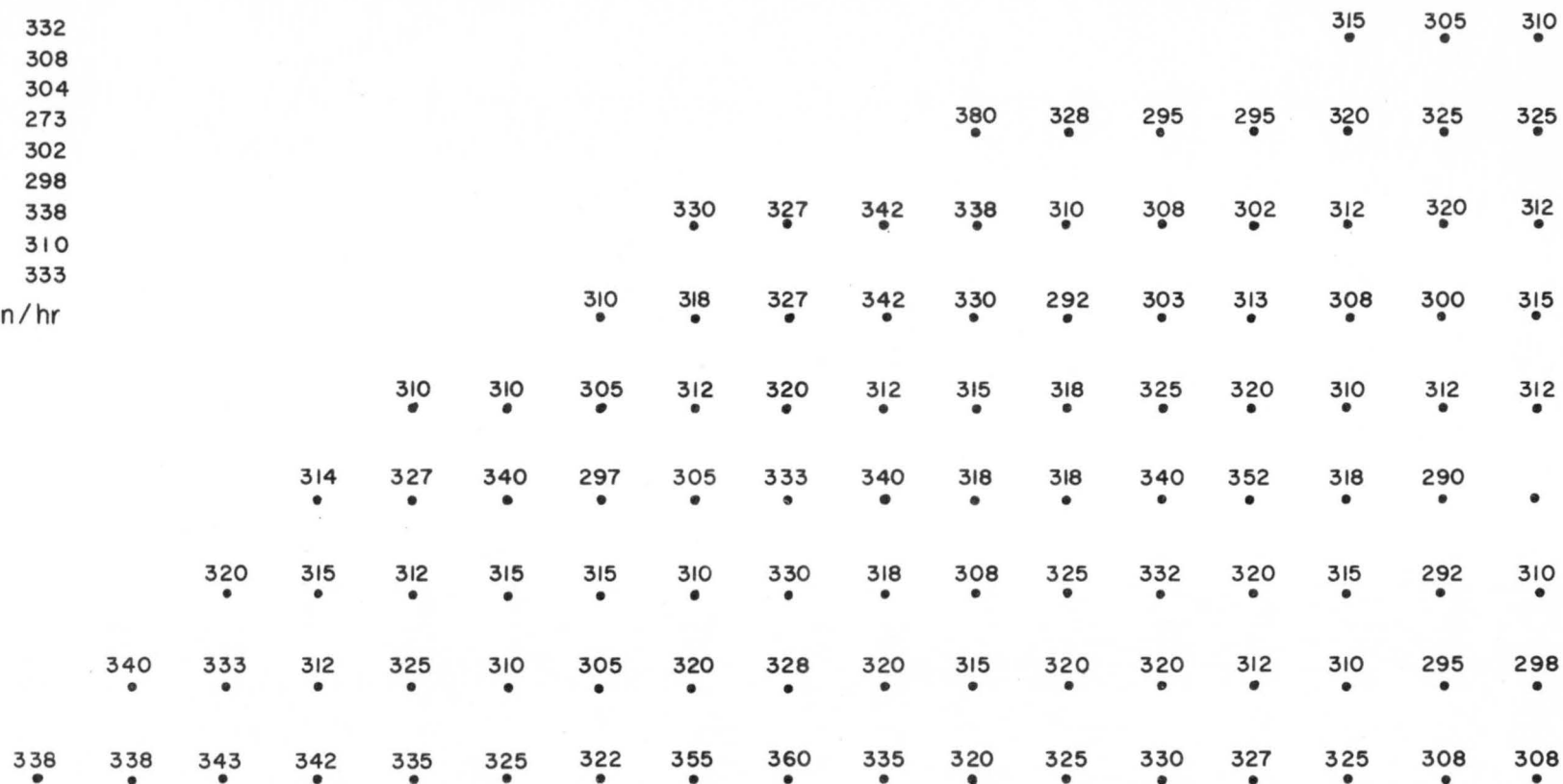
Within the Pattern
C.V. = 0.04924
R̄ = 2.7647 in/hr

Figure 12   Precipitation Distribution of Prototype System in an Actual Run

Table 1   SUMMARY OF COMPUTER SIMULATIONS
OF INTENSITY PATTERNS

Nozzle	Pressure psi	Spacing ft.	No. sets operations	P in/hr.	C. V.
Square Pattern	20	40	1	0.390	0.288
			2	0.783	0.185
			3	1.172	0.175
			4	1.560	0.154
415C	20	48	1	0.160	0.311
			2	0.323	0.195
			3	0.484	0.185
			4	0.647	0.165
415C	24	48	1	0.138	0.260
			2	0.276	0.150
			3	0.415	0.130
			4	0.553	0.103
415C	28	48	1	0.341	0.111
			2	0.672	0.0985
			3	1.013	0.0779
			4	1.343	0.0761
415C	28	40	1	0.473	0.137
			2	0.952	0.0713
			3	1.433	0.0662
			4	1.910	0.0561
			5	2.388	0.0590
			6	2.868	0.0546
			7	3.348	0.0548
			8	3.830	0.0525
415C	28	35	1	0.634	0.104
			2	1.274	0.0504
			3	1.907	0.0439
			4	2.546	0.0294
75	20	40	1	0.368	0.210
			2	0.738	0.127
			3	1.106	0.113
			4	1.476	0.0838
75	24	40	1	0.426	0.199
			2	0.853	0.104
			3	1.279	0.102
			4	1.706	0.0738
75	27	40	1	0.414	0.0909
			2	0.827	0.0618
			3	1.238	0.0466
			4	1.652	0.0366
			5	2.066	0.0365
			6	2.482	0.0333
			7	2.895	0.0304
			8	3.311	0.0276

Table 1 - Continued

Nozzle	Pressure psi	Spacing ft	No. sets Operations	P in/hr	C.V.
75	27	35	1	0.547	0.171
			2	1.102	0.100
			3	1.649	0.0576
			4	2.203	0.0235
78	19-20	40	1	0.412	0.224
			2	0.824	0.147
			3	1.235	0.132
			4	1.648	0.101
78	24	40	1	0.473	0.186
			2	0.944	0.125
			3	1.417	0.112
			4	1.888	0.0868
78	28	40	1	0.442	0.146
			2	0.890	0.0902
			3	1.337	0.0838
			4	1.790	0.0685
			5	2.234	0.0680
			6	2.671	0.0630
			7	3.142	0.0626
			8	3.565	0.0558
78	28	35	1	0.707	0.124
			2	1.419	0.0824
			3	2.132	0.0546
			4	2.852	0.0402
78	28	30	1	0.933	0.149
			2	1.870	o.104
			3	2.841	0.0739
			4	3.818	0.0558

Table 2   PARAMETERS OF RAINFALL DISTRIBUTION
                    OF PROTOTYPE GRID SYSTEM

Average (in./hr.)	Coefficient of Variation
0.64	0.199
1.19	0.089
1.22	0.131
1.26	0.073
2.76	0.049
4.93	0.037

the high values. A large number of runs have been made, but the data
for the other tests have not yet been analysed completely.

Drop Size Study

The distribution of drop sizes provided by the artificial rainfall
system will be of significance in later studies of erosion processes.
Therefore, a study of the drop sizes at various distances from the nozzle
was made for the two nozzles that were considered best from the intensity
distribution study.

The article by J. Otis Laws and Donald A. Parsons (6) was used as a guide in determining the drop-size distribution for the number 75C and 78C nozzles. The procedure used was the flour technique whereby drops of rain are allowed to impinge into sifted flour thus creating pellets. Under the system developed by Laws and Parsons and followed in the analysis under discussion, the flour pellets were left undisturbed for 24 hours before being placed in an oven for an hour for hardening and further dehydration. The particles were then sieved, using a stack of standard U.S. sieves in the appropriate size range. Following sieving, the pellets retained on each were counted and weighed on an analytical balance to the nearest one ten-thousandth of a gram. Using this information and a calibration curve (Figure 2 in Laws and Parsons), the diameter of the drop retained on each of the sieves was obtained for each sample location.

In selecting raindrop samples from the 75C and 78C nozzles, 9-inch pie pans were used. A sample was taken along a radius in 2.5 foot increments starting at the nozzle. The pie pans were filled with sifted flour, covered, hand carried, and placed on top of a gallon can about 6 inches above the ground to avoid splash from raindrops hitting the ground. The covers were taken off for a period of 4 to 10 seconds to allow the drops to impinge into the flour. As stated above, the pie pans were stored for 24 hours before being placed in a drying oven for an hour at 250°F. They were then sieved. On the larger sieves all pellets were counted but on the smaller sieves, where the number of drops was much more numerous, only 50 pellets were counted and weighed. However, the total mass on each sieve was determined so that the percentage of total rainfall falling as a given drop size could be determined.

Following the collection and weighing as described above, the data was initially processed in the manner outlined in Table 2 of Laws and Parsons. The 9100 A.H.P. Computer was used in the data reduction. One program is used to determine $mp = M_{p/n}$ = mass of the average pellet. Using this value a mass ratio "R" is determined from Figure 2 in Laws and Parsons and this value is entered into the program so the mass of all drops $M = RM_p$ may be determined. This program also determines the diameter of the average drop using the formula $d = \sqrt{6/\pi^{(m)}}$. A second program was developed to find the percent of rain that fell as a given drop size at each location.

At this point in the data reduction, the data was processed to get it into a form that would be suitable for input data into the CDC 6400 digital computer programs developed previously for overlapping rainfall intensities from a given nozzle pattern.

The data collected in the above analysis was summarized as shown in Table 3.

After collecting the data in one table, the weighted mean-drop size at each location was determined by multiplying the average drop diameter by the corresponding percent which indicated the fraction of rain that fell as the given drop size. Another program for the 9100 A.H.P. computer was used for this determination.

The mean drop size at 2.5 foot intervals from the nozzle and the intensity at the given points are shown in Table 4. This table indicates the deficiency in the 75C and 78C nozzles in providing a high percentage of large drops. The drop size increases as the distance from the nozzle increases but the intensity decreases with distance from the nozzle. Hence, there is only a small percentage of the total rain that falls as large drops.

Table 3   Nozzle #75.   Drop-size Analysis.   August 8, 1969   C. Brent Cluff

Pos.in ft.from nozzle	Drop Size 5		Drop Size 6		Drop Size 7		Drop Size 8		Drop Size 10		Drop Size 14		Drop Size 20		Drop Size 28		Drop Size 35		Mean Diam.
	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%	
0											1.37	.4	1.00	4.4	.80	34.6	.58	60.6	.68
2.5												0	.97	9.0	.73	34.4	.52	56.6	.63
5.0												0	.99	14.9	.75	58.6	.47	26.5	.71
7.5											.84	.1	1.00	8.0	.81	42.7	.56	48.5	.70
10.0											1.37	5.3	1.07	43.9	.82	47.8	.60	2.9	.95
12.5											1.41	19.7	1.09	74.5	.86	5.1	.60	0.7	1.13
15.0										2.24	4.2	1.64	80.6	1.21	9.9	.80	2.9	.60	2.4	1.57
17.5								2.72	2.7	2.34	29.5	2.00	63.3	1.16	1.5	.78	1.5	.50	1.4	2.07
20.0										2.37	35.5	2.00	55.1	1.14	2.1	.75	3.8	.57	3.5	2.02
22.5								2.87	19.5	2.43	55.3	1.98	18.2	1.14	1.6	.75	3.6	.56	2.7	2.31
25.0			3.60	12.0	3.34	38.0	2.82	28.7	2.51	4.1	1.43	3.0	1.04	5.9	.82	4.1	.56	4.2	2.77
27.5	0		3.94	43.1	3.59	27.9	3.15	3.1	0	0	1.53	10.8	1.05	3.6	.78	6.0	.60	5.3	3.07
30.0	0		4.14	59.1	3.41	20.0	2.91	9.4	2.51	2.0	1.97	3.6	1.03	3.1	.77	3.5	.53	4.1	3.37
WT Meandrop) Size)			4.00		3.43		2.86		2.38		1.79		1.10		.82		.55		

Table 4   MEAN DROP SIZE DISTRIBUTION

Dist. From Nozzle	75C		78C	
	Intensity in/hr.	Mean Drop size-mm	Intensity in/hr.	Mean Drop Size-mm
0	.325	.68	.497	.66
2.5	.325	.63	.497	.66
5.0	.353	.71	.434	.67
7.5	.373	.70	.455	.51
10.0	.378	.95	.468	.90
12.5	.373	1.13	.460	1.16
15.0	.330	1.57	.403	1.09
17.5	.289	2.07	.358	1.45
20.0	.259	2.02	.285	1.62
22.5	.185	2.31	.209	1.83
25.0	.095	2.77	.152	2.18
27.5	.061	3.07	.093	2.42
30.0	.009	3.37	.097	2.78
32.5			.069	2.68

The 9100 A.H.P. Computer was used to determine the weighted drop size retained on each sieve size. The percentage that fell at each location was used a weighting factor to determine the mean drop size at each sieve. The percent of rain that fell as a particular drop size at each location was used to weight the respective diameters in the determination of a weighted mean for each sieve size because it was noted the the accuracy of the diameter determination was a function of the given percent.

The next step in the procedure was to determine the quantity of rain in inches per hour that fell as a particular drop size at each location. In order to do this the intensity at each location determined from a previous test was tabulated in column 2 of Table 6. These intensities were then proportioned into the different drop sizes using the percentages determined in the drop size analysis.

Table 6   Nozzle #75.   Drop-size Analysis.   August 8, 1969   C. Brent Cluff

Pos. in ft.from nozzle	Inten-sity in/hr.	Drop Size (mm)														
		4.00		3.43		2.86		2.38		1.79		1.10		.82		.55	
		%	in/hr.**	%	in/hr.	%	in/hr.	%	in/hr.	%	in/hr.	%	in/hr.	%	in/hr	%	in/hr
0	.325*									.4	.001	4.4	.014	34.6	.112	60.6	.19
2.5	.325									0	0	9.0	.029	34.4	.118	56.6	.18
5.0	.353									0	0	14.9	.053	58.6	.207	26.5	.09
7.5	.373									.1	0	8.0	.029	42.7	.159	48.5	.18
10.0	.378									5.3	.020	43.9	.166	47.8	.181	2.9	.01
12.5	.373									19.7	.074	74.5	.278	5.1	.019	.7	.00
15.0	.330							4.2	.014	80.6	.266	9.9	.033	2.9	.010	2.4	.00
17.5	.289					2.7	.008	29.5	.085	63.3	.183	1.5	.004	1.5	.004	1.4	.00
20.0	.257							35.5	.091	55.1	.251	2.1	.005	3.8	.010	3.5	.00
22.5	.185					19.5	.036	55.3	.1023	18.2	.034	1.6	.003	2.6	.005	2.7	.00
25.0	.095	12.0	.011	39.0	.036	28.7	.027	4.1	.004	3.0	.003	5.9	.006	4.1	.004	4.2	.00
27.5	.061	43.1	.026	27.9	.017	3.1	.002	0	0	10.8	.007	3.6	.002	6.0	.004	5.3	.00
30.0	.009	54.1	.005	20.0	.002	9.4	.001	2.0	0	3.6	0	3.1	0	3.5	0	4.1	(

* Rate in inches/hr. of rain falling in given drop size.

**#75 nozzle May 30 at 27 psi, average using circular overlap program.

The intensities of a given drop size at every sample location were used as input data to determine the effect of overlapping on drop-size distribution for the nozzle patterns found to be best for uniformity in the rainfall intensity analysis. It is to be noted that the nozzle patterns selected may not be the optima for drop-size distribution, but are close to the optima for uniformity of rainfall intensity.

The overlap program printed out the amount of rain falling in inches per hour of each drop size at grid points within a sample area. By combining the results of all drop size overlaps, the drop-size distribution at any point within the sample grid can easily be determined.

As an example of how the overlap output can be used, the drop-size distribution at two different locations was made. The drop-size distributions of 78C nozzle at two arbitrarily selected locations, (13,11) and (23,13), for the basic and maximum intensity nozzle patterns are given in Table 5.

Table 5   EXAMPLES OF POINT DISTRIBUTIONS
OF DROP SIZES

Drop Size (mm)	Location 13, 11				Location 23, 13			
	Basic		Maximum		Basic		Maximum	
	Intensity in/hr	%	Intensity in/hr	%	Intensity in/hr	%	Intensity in/hr	%
.55	0.01	1.9	.31	7.0	.22	44	.50	10.9
.68	.04	7.7	.64	14.5	.20	40	.56	12.2
1.04	.25	48	1.30	29.5	.04	8	1.21	26.4
1.64	.13	25	1.27	28.8	0.0	0	1.54	33.6
2.36	0.0	0	.20	4.5	0.0	0	.17	3.7
2.77	.05	9.6	.39	8.8	0.02	4	.37	8.1
3.29	.04	7.7	.26	5.9	0.02	4	.21	4.6
3.71	0.0	0	.04	0.9	0.0	0	.02	.4
Total	.52	100.0	4.41	100.0	.50		4.58	100.0

For the basic pattern there is a considerable difference in the drop-size distribution although the intensities are the same.

For the maximum intensity pattern both the intensities and drop-size distributions are essentially the same even though the sample points are 25 feet apart. This indicates the value of the multi-nozzle approach for increasing the uniformity of the distribution patterns.

The mean drop-size distributions over the sample area for both the 75C and 78C nozzles, with a comparison with natural rainfall, are given in Table 7.

Table 7   COMPARISON WITH NATURAL RAINFALL (Ref. 5)

Drop Size mm	Natural Rain Intensities 0.5" hr	2.00"/hr	75C Drop Size mm	%	78C Drop Size mm	%
0.0-0.5	0.5	0.2	.47-.66	7.1	.47-.59	8.1
0.5-1.0	5.4	2.3	.73-.83	14.2	.65-.82	15.6
1.0-1.5	14.1	6.4	.97-1.21	18.0	.93-1.17	22.7
1.5-2.0	18.7	10.4	1.37-1.98	35.5	1.32-1.86	37.5
2.0-2.5	21.5	13.9	2.24-2.51	14.6	2.16-2.59	4.6
2.5-3.0	16.3	15.3	2.72-3.15	4.4	2.49-2.87	7.1
3.0-3.5	12.1	14.4	3.34-3.59	3.3	3.17-3.34	3.9
3.5-4.0	7.0	12.4	3.60-4.14	2.9	3.71	.5
4.0-4.5	2.9	9.5				
4.5-5.0	1.5	6.5				
5.0-5.5		4.1				
5.5-6.0		2.4				
6.0-6.5		1.2				
6.5-7.0		1.0				
Total	100.0	100.0		100.0		100

Although the above chart is based on the basic pattern, additional patterns will have essentially the same mean drop size over the sample area because the basic pattern is superimposed. Thus, the mean drop-size distribution over a given area will be essentially the same for all intensities for the simulator. However, for natural storms the drop size increases as the intensity increases. The two nozzles are seen to have a higher percentage of drops smaller than 2 mm than natural rainfall. If larger drops are required for later studies, it will be necessary to seek nozzles with different characteristics or to modify some of the existing nozzles in the higher intensity patterns.

DESCRIPTION OF THE CURRENT SYSTEM

The current rainfall input system is shown in operation for the upper conic section of the facility in Figure 13. It is based on nozzle 78, with each nozzle located on a riser above the aluminum supply main. The riser section is about 10 feet high and is pictured in Figure 14. The entire riser is shown in Figure 14a, where it can be seen that the 3/4-inch riser is guyed to the adjacent risers by a wire. The wire is anchored at the ends of the aluminum supply line. Figure 14b shows the detail at the bottom of the riser. The elements that make up the riser are identified in the schematic of Figure 15. The sprinkler head is mounted at the top of the riser. A 7-foot section of 3/4-inch steel pipe joins the sprinkler to the tire pressure tap. The pressure tap allows a rapid check of pressures at a number of risers in a very short time, using a pressure gage that has been equipped to fit the tire pressure tap. The pressure regulator maintains the pressure for the sprinkler at a constant value, so all sprinklers will have the same pressure. The pressure is currently set at 28 psi. The hydraulic valve below the pressure regulator turns the sprinkler on and off. Each nozzle is fitted with a control valve, and a series of valves
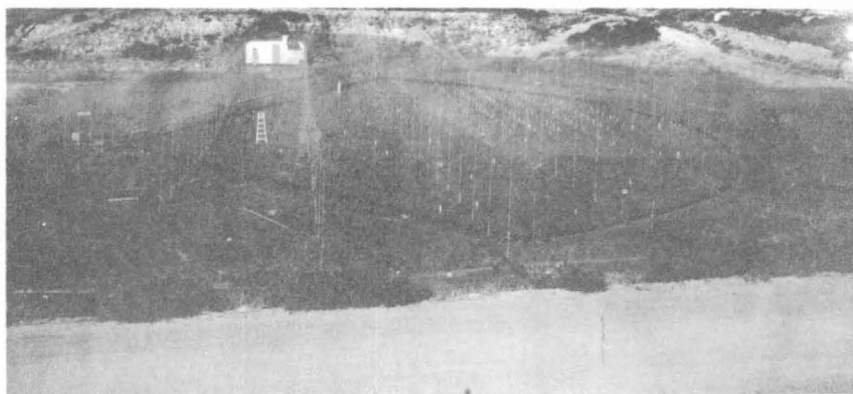
Figure 13 Operation of Grid System on Upper Conic Area

Figure 14(a)   Typical Riser for Sprinkler
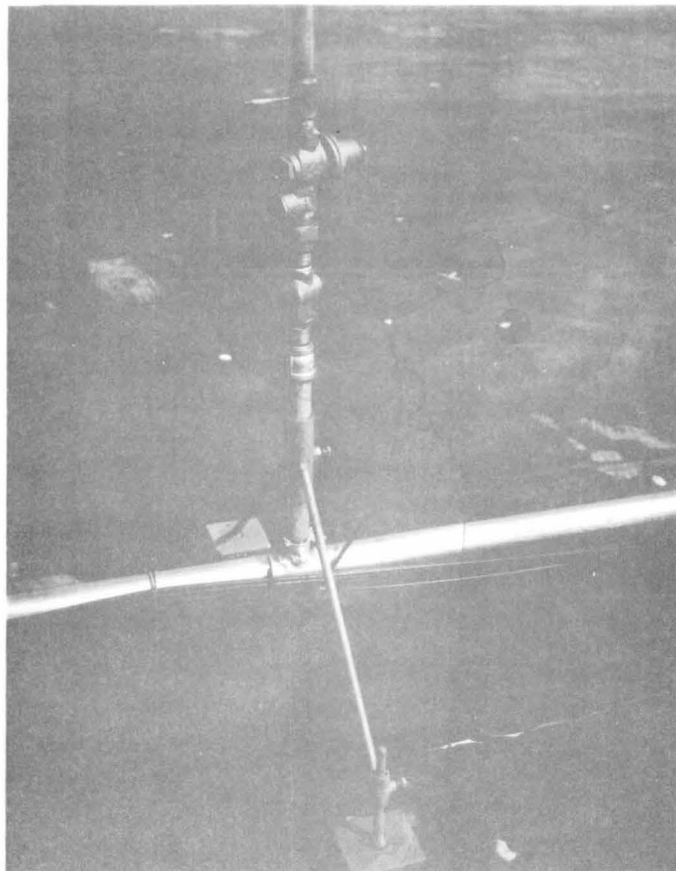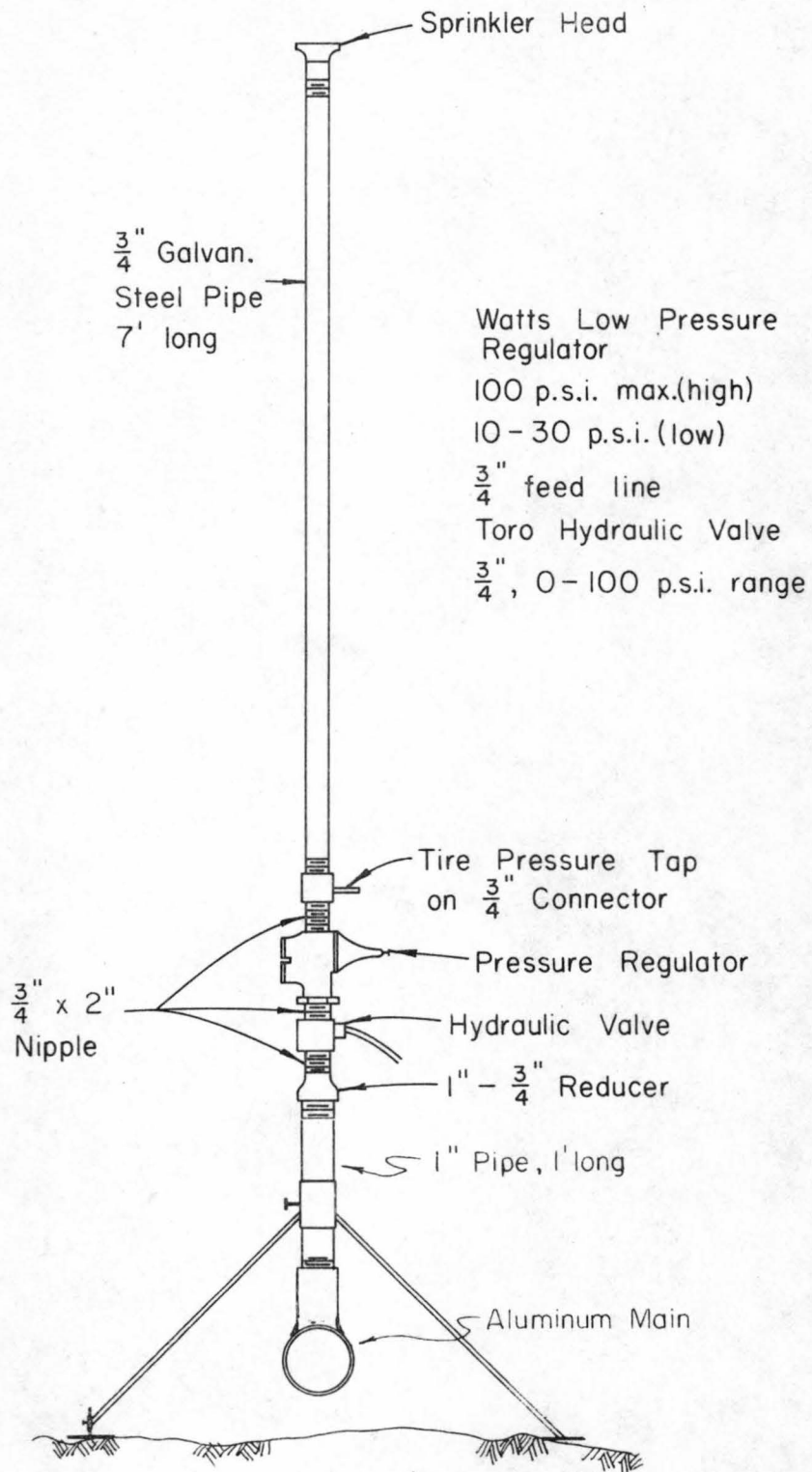

Figure 14(b)   Detail at Base of Riser

Figure 15   Schematic of Sprinkler Riser for Grid System

is connected to one pressure manifold to provide simultaneous operation of a set of sprinklers.

The control system is illustrated in Figure 16, where several risers are shown on a 2-inch aluminum supply line. A small plastic pipe joins a set of risers to the pressure manifold. In this figure only the first and last risers are connected to the pressure manifold that is shown. The other risers are connected to other manifolds. The supply to the pressure manifolds is controlled by electric control valves that are connected to a switching panel in the instrument trailer. There are four different sets of sprinklers in the system at the present time. These are shown in the overlay Figure 17. The colored overlays represent the pressure manifolds for the hydraulic control valves. The arrangement can, of course, be changed by changing the connections of the sprinkler risers to the pressure manifolds, but the system shown in Figure 17 will be used for the current studies. The four intensities available are approximately 0.5 inch/hour (red), 0.5 inch/hour (yellow), 1 inch/hour (green) and 2 inch/hour (blue). By adding the sets as illustrated with the overlay, the four intensities listed on the figure can be obtained. Starting with the red set, there is an intensity of 0.54 inch/hour. By adding the yellow set, it is increased to 1.11 inch/hour, and with the green and blue sets added in turn it becomes 2.31 and 4.24 inches per hour, respectively. By changing the switching patterns it is also possible to obtain the intensities of about 1.5, 2.5, 3, and 3.5 inch/hour. The actual location of the risers on the pipe system is shown by black dots on the solid black lines of the base figure. The black lines represent the 2-inch aluminum supply lines. They are connected to the larger aluminum supply manifolds along the east side of the facility. The slashed lines on these aluminum pipes indicate the locations of the quick coupling joints. Because of these joints, the system can be set up or taken down rapidly. The supply
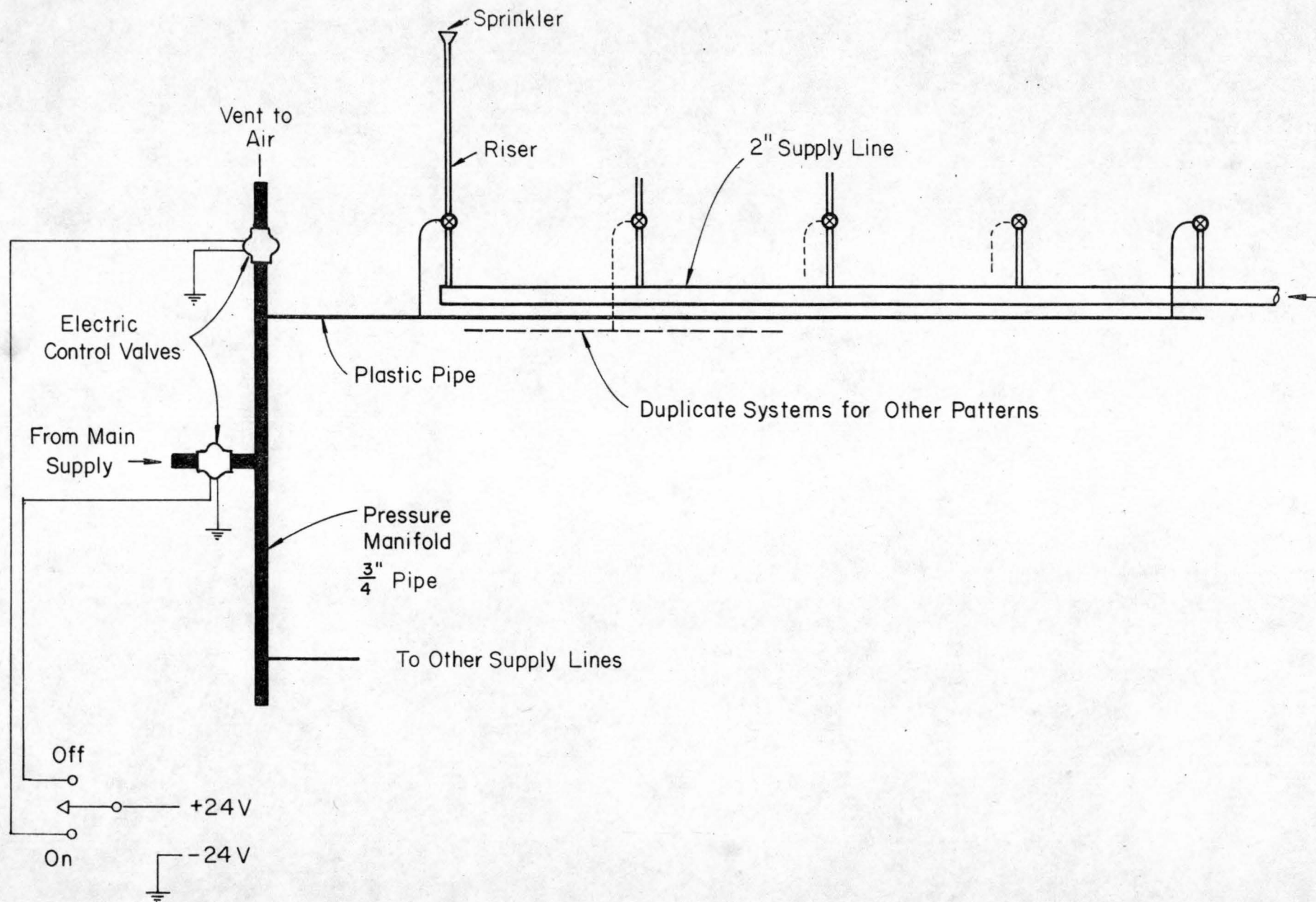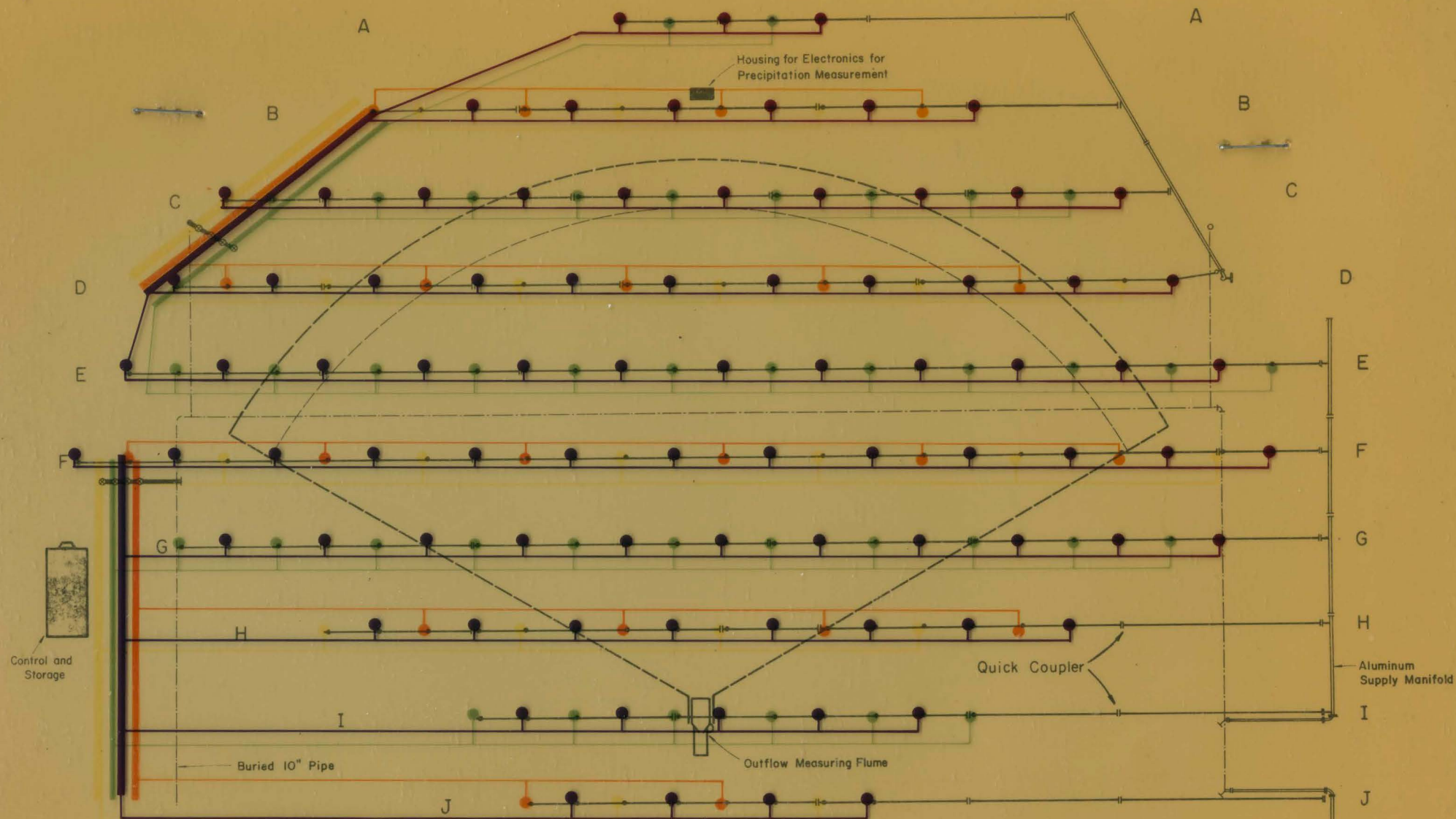
Sprinkler

Vent to
Air

Riser

2" Supply Line

Electric
Control Valves

Plastic Pipe

Duplicate Systems for Other Patterns

From Main
Supply

Pressure
Manifold
$\frac{3}{4}$" Pipe

To Other Supply Lines

Off

+24 V

On

−24 V

Figure 16   Schematic of Hydraulic Control System for Sprinklers

Housing for Electronics for
Precipitation Measurement

Control and
Storage

Quick Coupler

Aluminum
Supply Manifold

Buried 10" Pipe

Outflow Measuring Flume

SCALE
0   10   20   30 feet
S C A L E

COLORADO STATE UNIVERSITY
ENGINEERING RESEARCH CENTER

RAINFALL - RUNOFF EXPERIMENTAL FACILITY

SITE MAP — UPPER PORTION
CONTROL MANIFOLD

RAINFALL RATES

(R)	=	0.54 inches / hr.
(R) + (Y)	=	1.11 inches / hr.
(R) + (Y) + (G)	=	2.31 inches / hr.
(R) + (Y) + (G) + (B)	=	4.24 inches / hr.

(R) --- Red , (Y) ---Yellow , (G) ---Green ,(B)--- Blue

manifolds are connected to the 10-inch supply main the surrounds the facility. Only part of the 10-inch line shows in the figure of the upper section.

This rainfall system has been operated during the fall of 1969. It can be programmed to generate pulses of varying durations for any of the intensities available. By increasing the capacity of the switching circuit it is possible to create varying distributions in space as well. This is, however, not planned at this time. A summary of the runs that have been made on the facility this fall will be given in Chapter 5.

Chapter 3. MEASUREMENT OF RAINFALL AND RUNOFF

REQUIREMENTS OF INSTRUMENTS

In a system with complete control over the input in both time and space variations, there is little need for the measurement of rainfall. This is the condition for the laboratory models which have individual droplet formation by small tubes or other similar systems. The experimental facility, on the other hand, utilizes the measurement of rainfall as the prime means of determining the input over the catchment. There is a reasonable degree of uniformity and reproducibility provided by the artificial rainfall system described in the previous chapter, but there are also variations due to the natural atmospheric conditions that vary in a random fashion over the facility. The wind patterns over the outdoor facility will cause small variations that need to be recorded. Therefore, the selection of a measurement system for the rainfall was a very important part of the design of the instrumentation for the facility. The runoff measurement is the dependent variable in nearly all hydrologic studies and is important in all physical modeling systems, even those inside laboratories.

The objective in both rainfall and runoff measurement is a nearly continuous record of the variation of the respective variable as a function of time. In addition, the rainfall must be determined at a number of locations across the catchment. Because of the large quantity of data that is collected in a relatively short time on the facility, computer analysis is essential. Therefore, automatic recording of the data in a form suitable for input to the computer is also very important.

PRELIMINARY STUDIES

In the preliminary studies of raingage systems, several types of

automatic recording gages were considered.   The need to record data from a number of locations on the catchment using only one analog-to-digital converter placed an additional constraint on the system.   It is impossible to record the data from each location continuously, so it is necessary to arrange for a recording from the various locations in a sequential manner. This makes it more difficult to use gages that record on an intensity basis, because extremely high or low values may occur at the measuring point during the short interval of time data are being recorded.   For gages of the volume type, that is, those that measure the volume of precipitation that has accumulated to a given time, there is an averaging of the extreme points, so the sequential sampling procedure is not a serious problem if the period between readings is small.

The most common recording raingages are the weighing type and the tipping bucket type.   The tipping bucket gage provides a signal that is already in an electrical form when the bucket tips.   However, this is an intensity form of measurement, and it would be necessary to remain at a given gage for a short time to record the number of times the bucket tips during the known time interval.   This increases greatly the time between measurements at each gage.   The weighing type raingage can be modified to generate an electrical signal by replacing the weighing mechanism with a pressure transducer.   But the weighing gage is not very sensitive at low small volumes of input that may occur in tests of short duration at the lower intensities.   Alternatives were sought that would be more sensitive at low volumes.

The Bell Telephone Laboratory (7) has a raingage that records the intensity of rainfall by measuring the depth of water running down an

inclined plane between two plates. The two plates form a capacitor, and the changing depth of water changes the capacitance between the plates. This suffers from the disadvantage of sampling point intensities if it is used for the facility. However, the idea of using a capacitance gage to measure rainfall led to the consideration of a gage that was developed by Dr. Eric Plate for the measurement of waves in a flume. Dr. Plate's gage was developed in the Fluid Mechanics Laboratory to measure the waves generated by wind in the water-and-wind tunnel.

CAPACITANCE RAINGAGE

The capacitance gage can be used to measure the depth of water in the raingage. The greater sensitivity for lower volumes of rainfall is obtained in the same manner as in the standard non-recording gage, by using a smaller tube inside the large can. The depth in the smaller tube is magnified by a factor of 10. The operation of these instruments is outlined as follows. Referring to Figure 19 a _probe_ is installed vertically in a precipitation measuring can, such that the height of water directly causes a change in the capacitance to ground. This probe is essentially an insulated rod, with water as one capacitor "plate", and the rod as the other. This capacitor probe is connected by a shielded cable approximately 100 feet long to a _converter,_ which converts the capacitance to a voltage by means of an electronic circuit and amplifier. There is one converter for each probe in the present system, although a switching device could reduce the number of converters as desired. Voltage from the converters is recorded either on magnetic tape or punched cards as shown in Figure 18. The details of the recording system have been presented in the previous report on the facility (4).
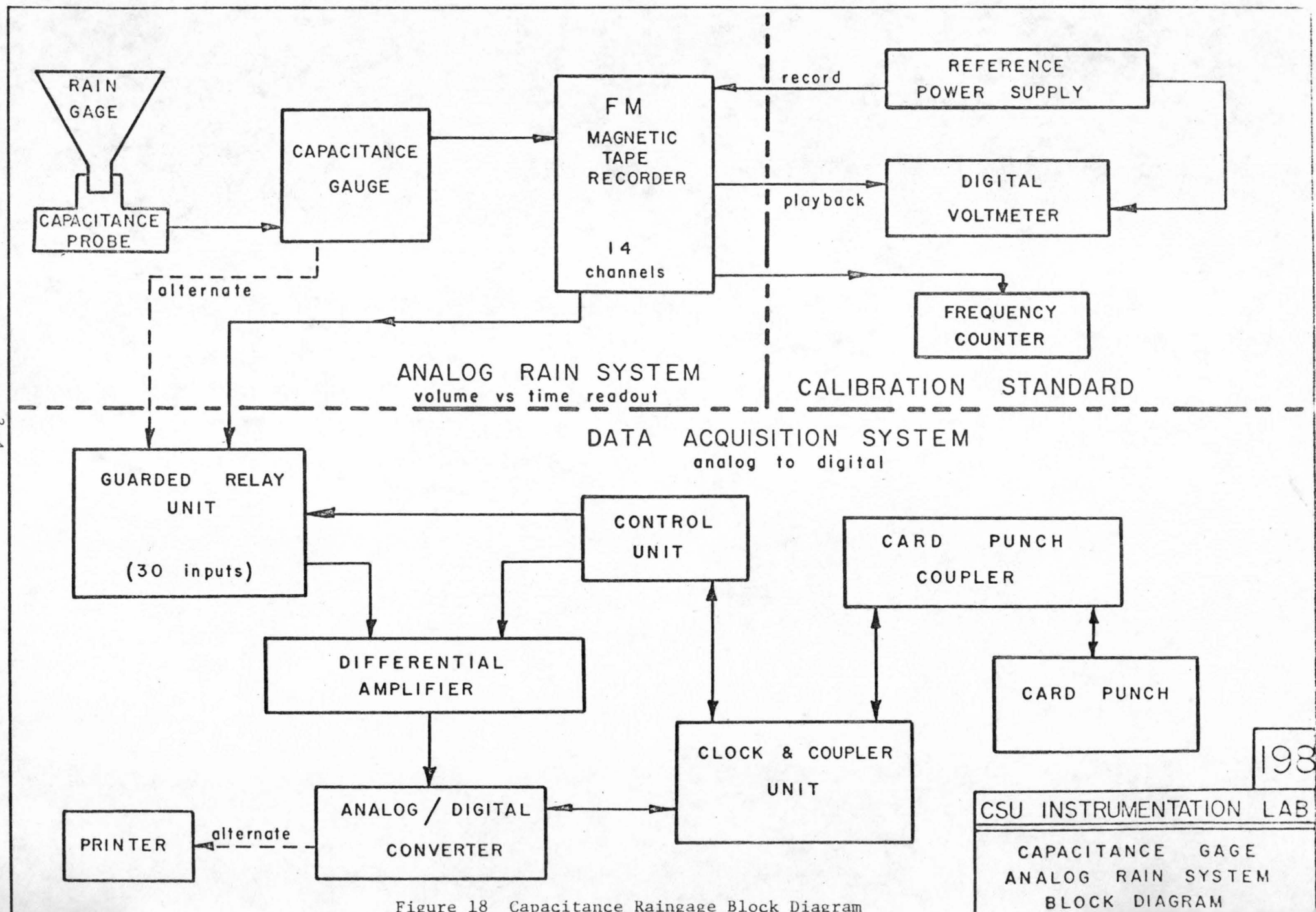
Figure 18   Capacitance Raingage Block Diagram

As shown in Figure 19, the measuring unit consists of an outer aluminum measuring can 7.6 inches inner diameter and 6.5 inches high, and a smaller concentric plastic cylinder 2.5 inches inside diameter. The inner can overflows when full into the outer can. Rain enters the smaller inner can through a funnel-shaped cover. Probes measure water rise in both inner and outer cans. The capacitance probes in the cans originally consisted of a lacquer-coated copper wire running the depth of the can, plus a bare wire to make contact with the water. These probes were copied from the system developed by Dr. Plate.

The raingages were tested in the electronics laboratory and found to work very well. They produced consistent records of high sensitivity and precision. However, when they were installed in the field, the results were not satisfactory. After a series of tests, the electronics laboratory concluded that the cause of the problem must be a temperature sensitivity. The testing program was turned over to a graduate research assistant working for the Agricultural Research Service and assigned to the facility.

TEMPERATURE SENSITIVITY STUDIES

Using 120 feet of cable like that installed in the field setup and a randomly selected can and converter, tests were conducted in the laboratory making measurements at various water and can temperatures. It was quickly noted that for any test, starting from a dry can, a severe initial drift in voltage output occurred for several minutes after water was added. Tests of an empty can at temperatures from less than 40^0 to 75^0,F, however, indicated negligible effect of can temperature. Tests with water temperature varying from 33^0 to 75^0 F showed only a small temperature effect, as presented in Figure 20. These results were taken after allowing the initial drift mentioned above to subside.
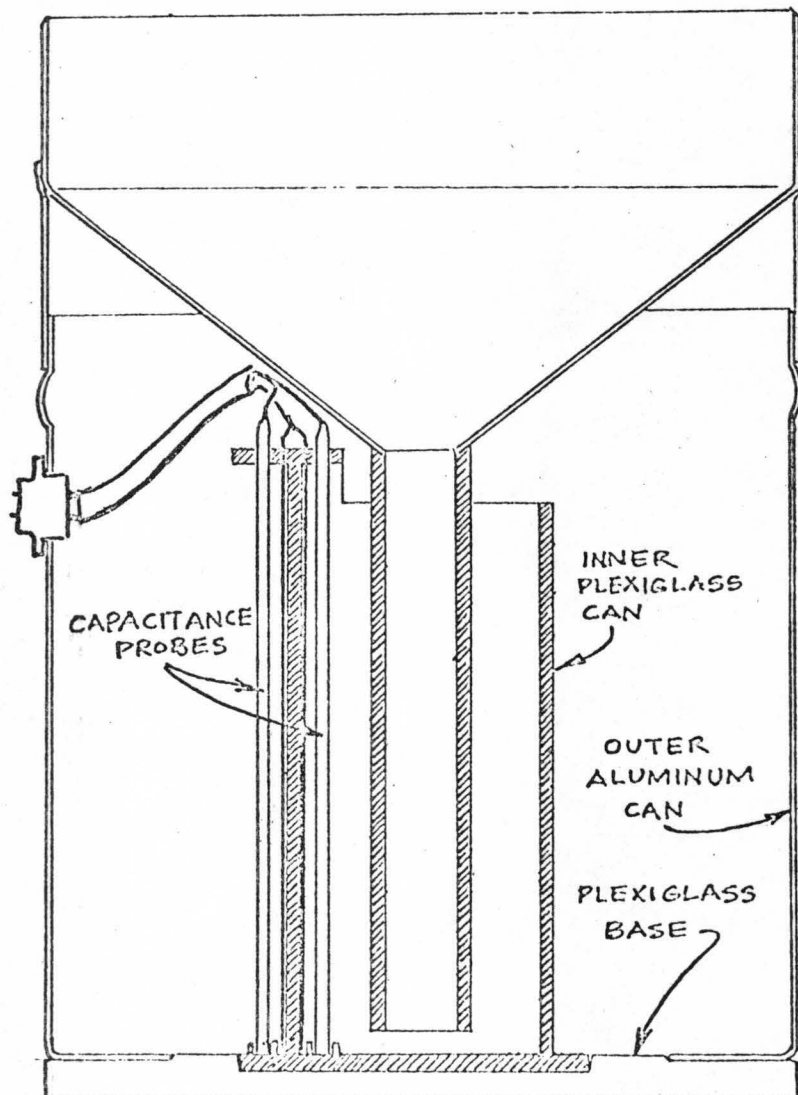
Figure 19   Section Through Electronic Raingage

Further measurement of the nature of this drift indicated it was in some way connected with the initial dryness of the can, and that it continued even when water was temporarily removed from the can. Figure 21 shows the results of one such test.

The conclusion drawn was that the wire coating was affected enough by contact with water to alter its dielectric strength some 20 percent.

IMPROVEMENTS MADE

It was decided that a probe with capacitance comparable to the old probes was required, since the electronics were designed for a certain capacitance range, but that a uniform coating inert to water should be found. Since capacitance is proportional to plate area and inversely proportional to "plate" separation, a larger diameter probe could be used with a somewhat thicker insulation. From suggestions of Dr. Plate, it was decided to try a larger rod or tube. After a trial with thicker materials, a high tolerance 0.009 inch thick KYNAR heat shrink tubing was chosen as quite suitable as a watertight dielectric coating. Brass tubing was used as the probe, the bottom was sealed with epoxy after the shrink-fit tubing was shrunk on, and a lead soldered to the top end. Different sizes of tubing were tried, and each had different sensitivity to water height. A 1/8" O.D. tube was chosen as being most suitable for the inner can, and a 5/32" probe used in the outer can. Allowable sensitivity is limited in this case by the converter, since too high capacitance will "saturate" the amplifier, and dv/dc will approach zero.

Each can and new probe was calibrated by careful titration, and the results analyzed by least squares regression. All gages were slightly nonlinear, but all data fit on the same normalized curve to within 0.9998
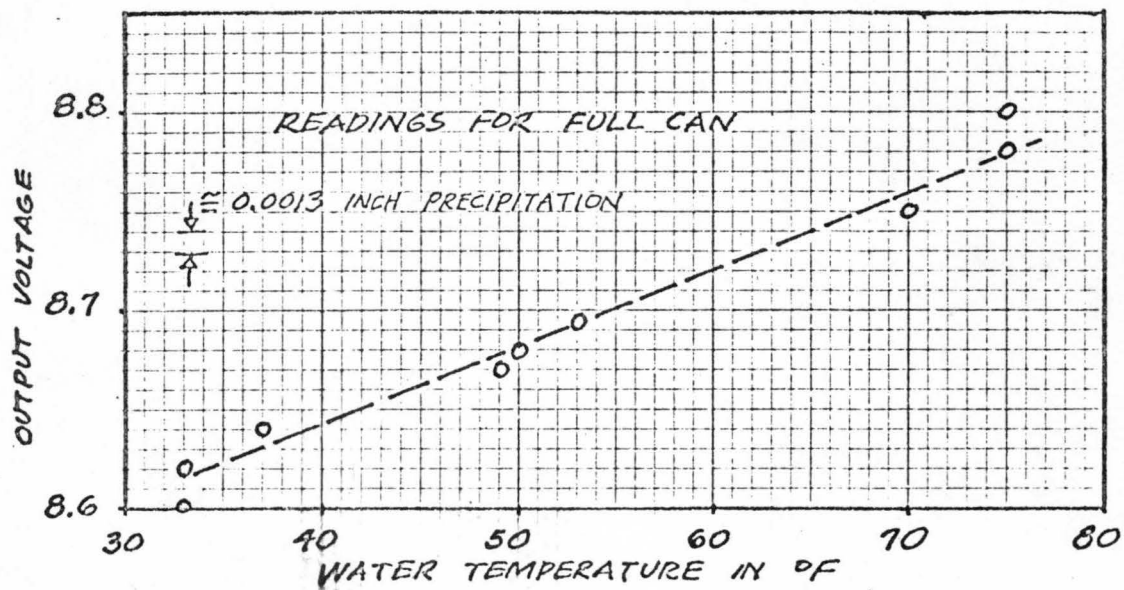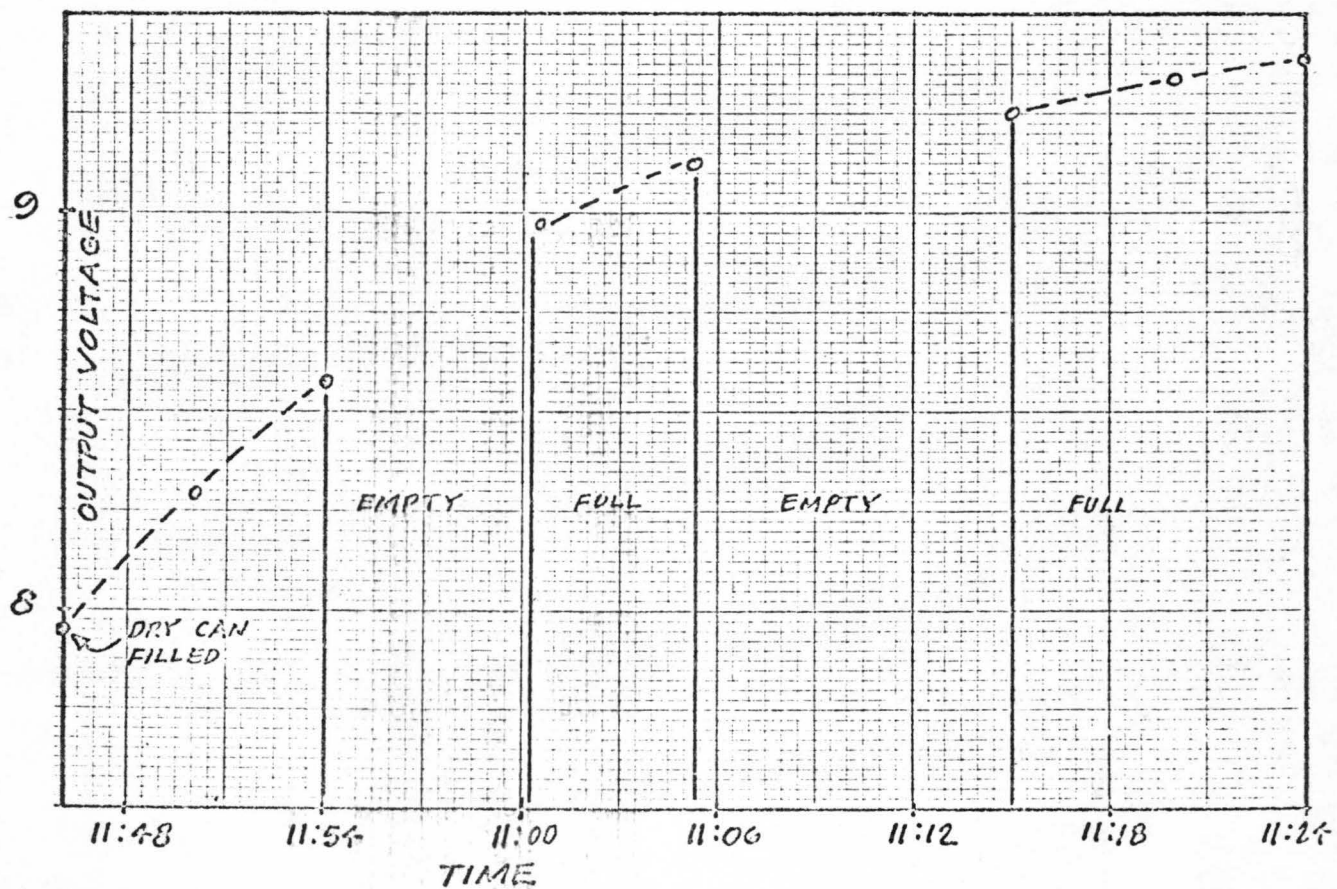
Figure 20   Sensitivity to Water Temperature

Figure 21   Typical Drift of Enameled Wire Probes

multiple correlation coefficient, and a standard error of estimate of 0.0029 inches of precipitation. No drift on wetting was noted.

Six of the modified raingages were operated during the fall series of tests on the facility. The complete data have not been analyzed, but the data collection system appears to be functioning satisfactorily. There is one problem that has occurred in the field tests with the modified gages. The capacitance gage does not always give a reproducible zero. The gages must be warmed up for several hours before a series of tests is run. When the zero depth reading has shifted from that used in a previous set of tests, it is necessary to provide a new calibration. This is not a major problem because the calibration curves all fit the same type curve when they are normalized. This is an inconvenience, but not a major fault. The warm-up problem is also a minor one because the system can be left on for several days at a time without damaging the components.

The raingages sense the depth of water accumulated as a capacitance measurement. The measurement of the capacitance is not made at the gage but is made at one of the bunkers located at the edge of the facility as shown in Figure 22. The length of lead wire from the gage to the bunker is the same for all gages. Since only the upper conic section of the facility is in operation, only bunker A, at the top of the area is being used at this time. The power supply to the bunkers and the readout lines have been installed to all of the bunkers.

ADDITIONAL RAINGAGES

In addition to the capacitance raingages, which transmit readings to the A-D converter for punched card format, there is one weighing bucket raingage on the facility that produces a chart record. This raingage was provided by the Agricultural Research Service and has been modified to use a synchronous motor drive that provides a chart rotation
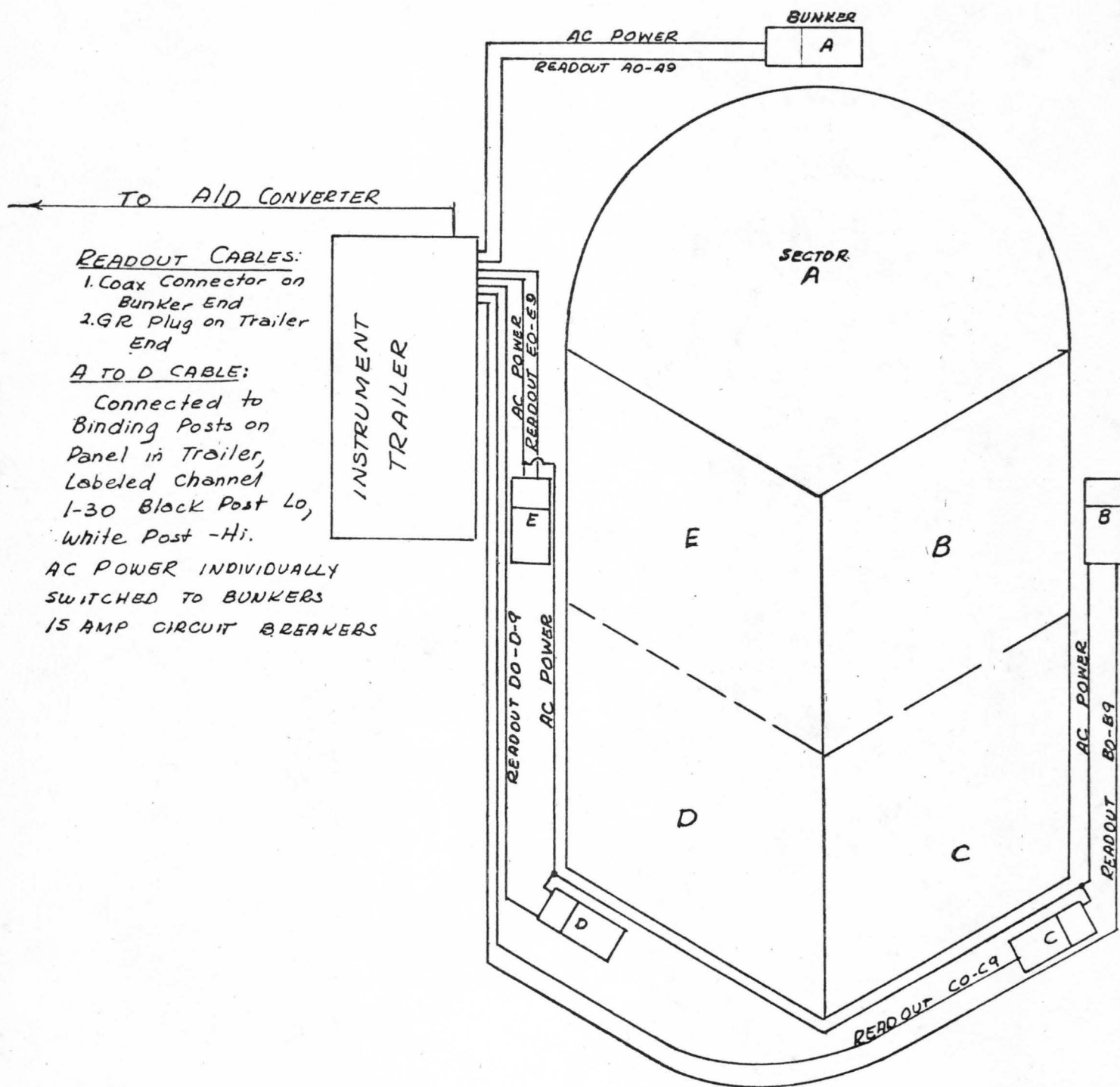
Figure 22   Schematic of Automatic Data Recording System for the Experimental Facility

in 15 minutes, instead of the normal 6 hours. This gage has two uses. First, it serves as a check on the operation of the capacitance gages. It can be moved to locations near the capacitance gages to provide additional calibration data. Second, the chart gives a visual trace of the rainfall pattern that can be checked to see that the performance of the input system was along the lines that were intended.

A large number of cans will also be used in the early tests on the facility to determine in more detail the actual distribution of rainfall in space that is provided by this system. The results of the early tests have already been mentioned in Chapter 2. After the characteristics of the input distribution have been defined, less use will be made of the non-recording cans.

The data for the weighing bucket raingage and for the non-recording cans must be converted to the form used for computer input. The data for the cans must be punched by hand. The chart record from the weighing bucket gage is digitized by using an AutoTrol digitizer. This converts the record to a series of x and y coordinates as a tracer is moved along the pen trace. The data must be adjusted for the curvature of the chart grid lines, but this is a simple matter on the computer.

RUNOFF MEASUREMENTS

The measurement of runoff from the experimental facility uses the H-flume developed by the Agricultural Research Service. The design and construction of the flumes for the facility has been adequately described in the previous report (4). The measurement of stage is now being done by two methods -- a chart recording float gage and a capacitance gage.
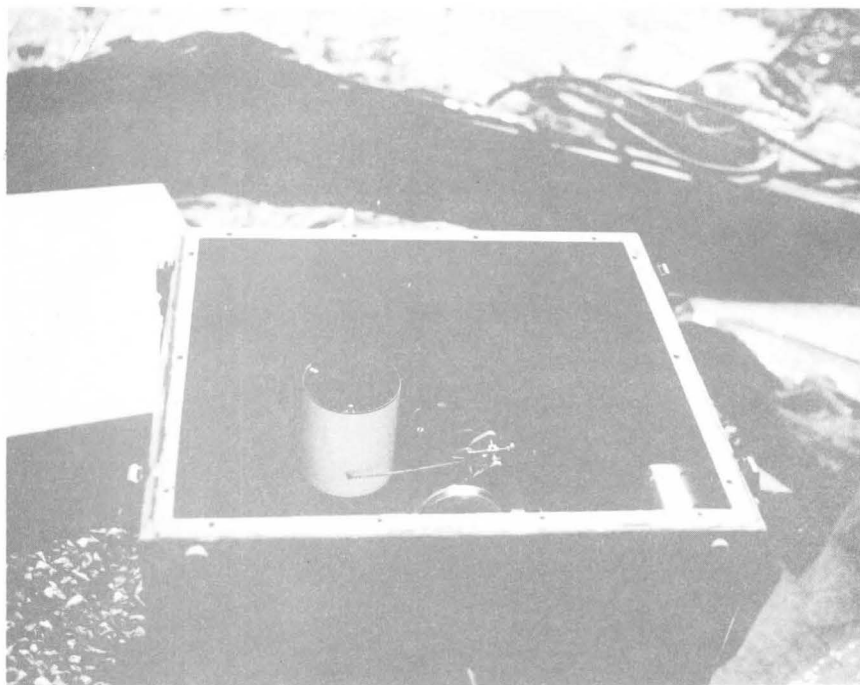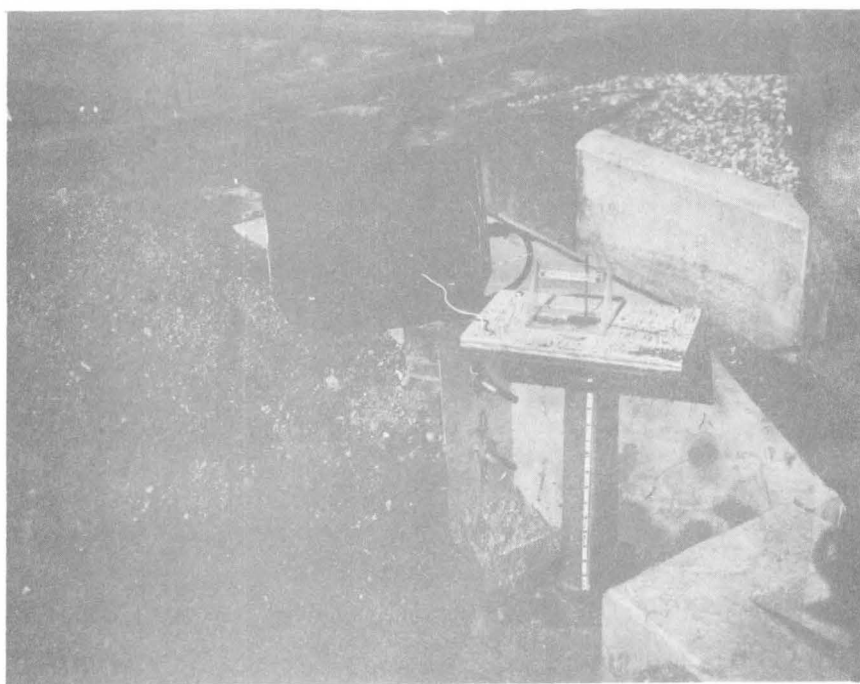
Figure 23(a)   Chart Recorder at H-Flume

Figure 23(b)   Capacitance Gage at H-Flume

When the difficulty with the raingage capacitance probes developed, the use of the capacitance probe in the flume was shelved because the conditions in the flume would be even more variable than in the raingages. The runoff in the flumes will contain a more variable quantity of dissolved and suspended material, especially in later stages of use of the facility. Therefore, the float gage was made the prime recording system. There are only two flumes for the facility, so the conversion of the data to digital format by the AutoTrol is not too difficult. At the present time, of course, only the upper flume is in operation.

The chart recorder at the flume was also supplied by the ARS and was modified to use the synchronous motor drive for a faster revolution. The successful modification of the capacitance probe for the raingages led to the installation of a longer capacitance probe at the flume. The two systems are pictured in Figure 23. The chart recorder in Figure 23a shows a recession occurring. The capacitance probe in Figure 23b requires a smaller stilling well and has a faster response than the chart gage. The two systems will both be operated for some time before a decision is made about which will ultimately be the preferred system. The direct recording of the capacitance gages is an advantage that is offset by the value of the visual record immediately available from the chart.

ANALYSIS OF DATA

The rainfall and runoff data will be analyzed jointly to determine the input to the facility. The recording and non-recording raingages will be used to determine the volume of input. The volume of runoff will also we used as a reference for the total quantity of input to the catchment. The time distribution of rainfall will be well described by the recording raingages. There are

six capacitance raingages and one weighing gage for a total of seven observations over an area of 1/3 acre. Additional data for each run can be added when the data from the non-recording cans is added to the computer input.

Chapter 4.   GEOMETRY AND SURFACE TREATMENT

The selection of the geometry for the experimental facility was described in the earlier report (4). It was based on a study of sixty-one small watersheds drawn from the Research Data Assembly Program for Small Watershed Floods (8). The general shape of the facility was decided as a compromise between the best-fit shape for the natural watersheds in the study and the existing configuration of the area in which the facility was to be located. In addition, it was decided to use simple geometric shapes to make up the facility, so description of the areas would be readily provided to the computer. The result is the shape made up of three segments, each 1/3-acre in size. The two lower segments are planes that intersect to form an arrowhead shape, and the upper area is a sector of a cone. This shape gives the general characteristics of natural watersheds in idealized form.

A decision was made early in the project design to use an impervious surface in the initial operation of the facility. This provides a significant simplification of the watershed processes, and will be more suitable for the first studies. After the system has been in operation for a period of time, the infiltration process will be included.   A variety of methods were considered for making the surface impermeable, including treatment of the soil with soil cement, the use of plastic or rubberized sheeting to cover the ground and the placement of asphalt or concrete surfaces.

SOIL CEMENT STUDIES

A series of tests were run to determine the characteristics of the soil cement treatment. It was found that the soils existing at the facility site were

not suited to soil cement treatment. An example of this is shown in Figure 24. In the upper part of the figure the natural soil is shown before and after water has been run across it. This series of tests was run in a flume in the ERC laboratories. The natural soil shows the effects of erosion, which was being tested at the time, but the soil remains in a continuous mass. At the bottom of the figure the soil has been treated with soil cement. It is clear that the cracking which takes place when the soil is dried causes a permeability that will vary with time when water is added to the system. This is of course completely unsatisfactory.

Both soil cement and lime were tested for use on the facility. The reduction in permeability for these is indicated in Figure 25. The only region in which the soil cement had a significant effect of lessening the saturated permeability of the soil is in the range where cracking is the most serious. The lime treatment also requires a fairly high dosage to provide any reduction in permeability. There is also a marked variation in the soil characteristics at certain points on the facility because of an outcrop of shale. The shale is a problem to work with in all conditions, wet or dry.

The use of soil cement treatments were rejected as an alternative for the development of the impermeable surface on the facility.


OTHER METHODS CONSIDERED

The second method considered for the treatment of the soil was the use of liquids, such as paraffin-base materials. Some samples of the materials were obtained and a few tests were made on small area within the facility. However, these liquids were very expensive, and before the tests were completed, the availability of less expensive alternatives led to the discontinuance of the testing.
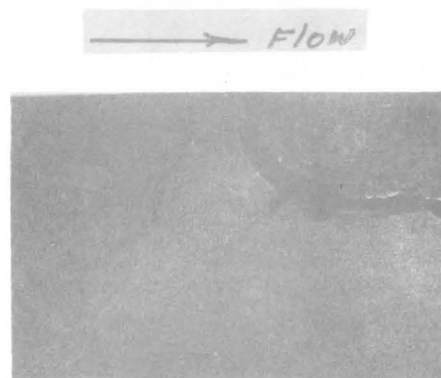
Flow
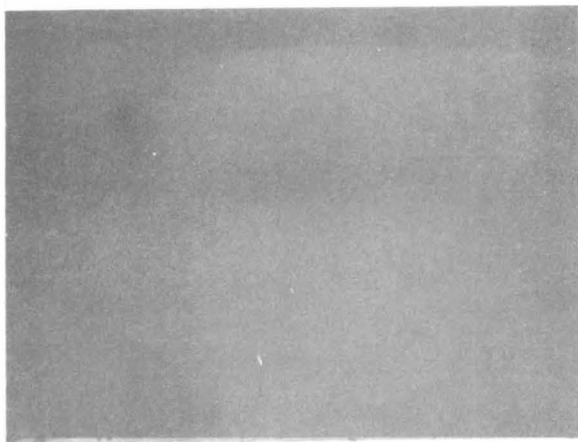
Natural Soil Sample (no admixture)
before Erosion test. Sample is in a
a saturated Condition.
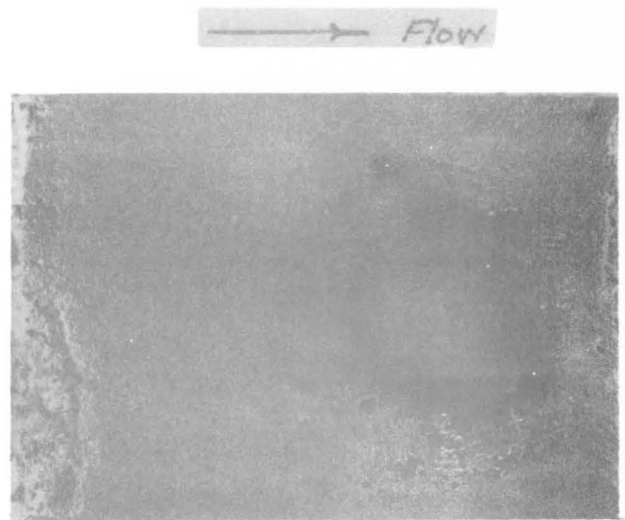
Natural Sample after 20 minutes
of Erosion. Depth of Water Over
Sample was 2 inches.

Flow
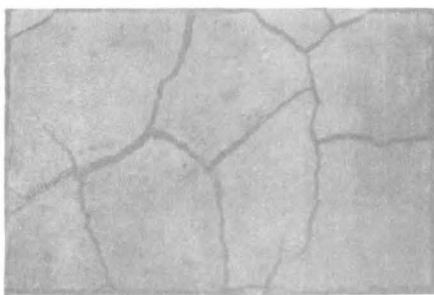
Soil Sample with 6 % Cement before
Erosion Test. Sample is in a dry
Condition

Soil Sample after 50 minutes
of Erosion. Depth of Water over
Sample was 3 inches.
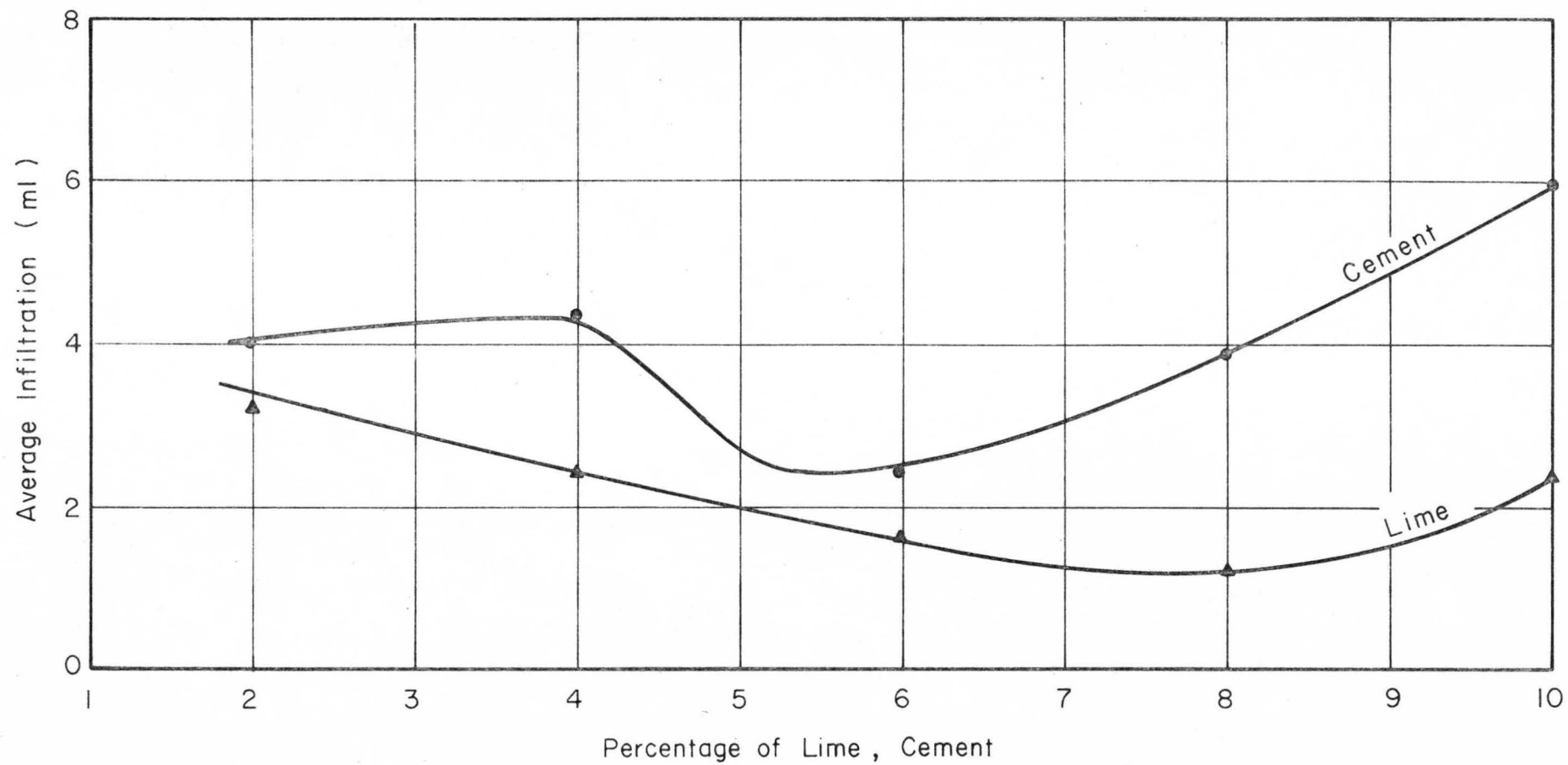
Figure 24   Erodability   Tests

Figure 25 Effect of Lime and Soil Cement on Infiltration Capacity

The use of asphalt or concrete surfaces was considered as a possible last-resort solution. The cost of these approaches would be high and the surfaces are rigid. One of the objectives in the use of the facility is to test the response of the system under a variety of conditions of slope, drainage network, etc., and the use of the rigid surface would preclude this to a great extent. Therefore, these methods were never given detailed study.

Plastic sheeting has been used as a covering material in a variety of ways in outdoor applications. The lining of canals and reservoirs are examples of uses that are somewhat similar to the use on the facility. However, in the previous uses of plastic, the material was covered by a layer of soil or other material to weight is down or the use was such that the effect of wind lifting the plastic would be unimportant. For the experimental facility application there will be times when it is desired to use the facility with no soil cover of any type. The shifting of the surface as wind causes waves on the plastic is also unacceptable. Therefore, plastic sheeting, although a potential material when covered by a thin layer of soil, was rejected for the present.

RUBBERIZED CLOTH SHEETING

Butyl sheet with cloth reinforcing was considered as an alternative for the facility at a early date. The material is very expensive, and was therefore rejected. However, when some of third material was found to be available in government surplus, it became a feasible method. The butyl material is better than the plastic material because it is stronger and wears longer, and also because it is heavier. The material is affected by the wind when it is first installed, but is quickly stabilized by the action of the soil moisture adhering to the underside enough to keep it down. The

weight of the material is sufficient, together with the moisture effect, to provide stability.

The material available in surplus was not sufficient to cover the facility, so more was purchased. However, the upper conic section and most of the lower area could be covered at a reasonable cost. A survey of government surplus material is continually made in case additional material becomes available.

The butyl material is placed in strips extending completely across the catchment, and the ends are buried in a small trench to prevent the wind from getting under the material to lift it from contact with the ground. The material has been in place for over a year and shows some wear in a few locations. When water seeps through the material, it may collect at a joint and form a small ridge that affects the flow on the surface. Therefore, the worn areas are patched by painting with a rubber-based liquid or, if the area is more extensive or more seriously worn, by cutting out the worn area and replacing it. Patches can be made fairly easily, and joints can be covered with a light plastic sheet glued to the rubber to make a watertight joint without overlapping the thicker rubber material.

DEFINITION OF BOUNDARIES

The boundary of the facility is sharply defined by using a wood section covered with a sheet of plastic. The plastic is bonded to the rubber covering the area, and the wood prevents water from overtopping the boundary. This method has also been used to form temporary boundaries for changing the area contributing runoff to the flume. Ponding on the contributing area can also be created in this way.

Chapter 5. USES OF THE FACILITY

INITIAL RUNS

The initial series of tests run on the experimental facility are currently being analyzed. A set of 68 runs were made in the fall to test the facility and to provide data for testing a kinematic model of overland flow on a converging section. This model was developed under the direction of Dr. Woolhiser of the Agricultural Research Service and will be presented by him elsewhere.

The variations that were made in this series of tests illustrates some of the potential of the facility. The first tests were on the bare facility, with the intensity of rainfall as the variable. The intensity was maintained constant until an equilibrium flow was achieved in some cases. In other runs, the duration was less than the time to equilibrium and in some runs the intensity was changed during the course of the run. In later tests the area contributing runoff to the flume was changed by erecting temporary boundaries to separate a 30⁰ sector from the remaining 90⁰ sector and to create shorter radii of 72 feet and 36 feet. The results of these experimental tests are being compared with the computer model output to determine the ability of the model to reproduce the variations that are caused by the res-pective parameters.

In the final series of tests, a very coarse gravel was used to provide roughness and detention effects on the facility. This is illustrated in Figure 26, where a uniform spread is shown in part (a) and a section without gravel spread were used on the facility at different times. Only the 30⁰ sector was used for this series of tests because the spreading was done entirely by hand and a number of test runs were desired before the cold weather set in. A number of different patterns were used in the placement of gravel for the runs. The uniform spread and the lower bare section
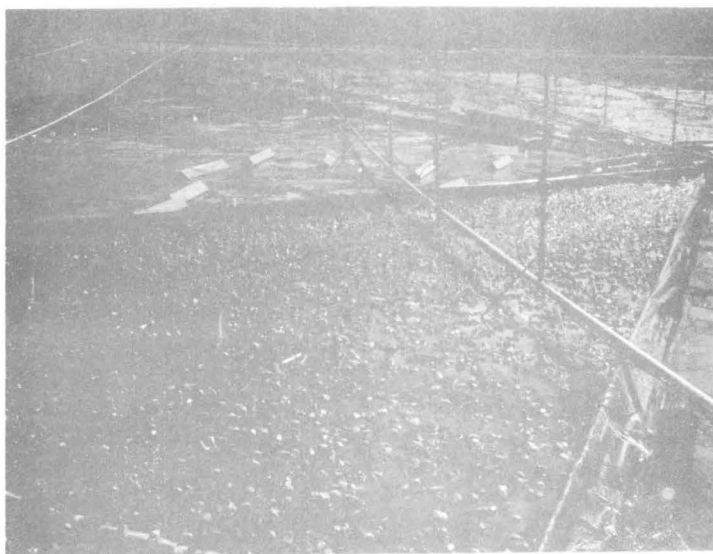
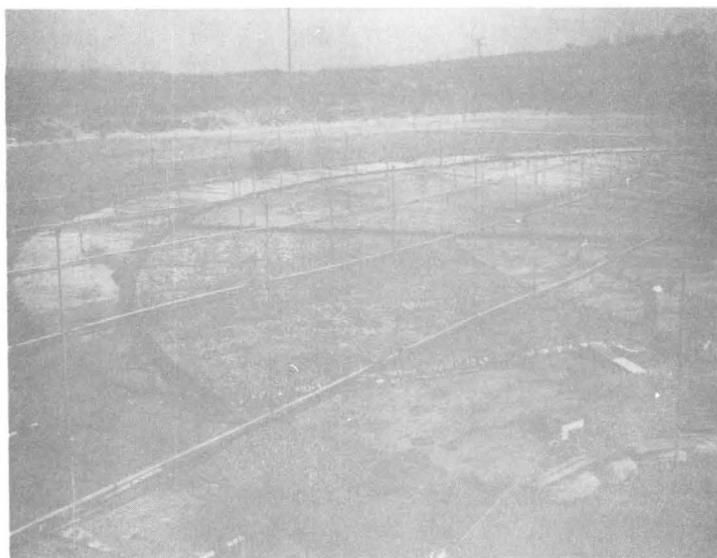Figure 26(a)   Gravel Spread for Uniformly Distributed Roughness

Figure 26(b)   Roughness on Upper Section with Bare Section Below

have been shown. In addition, alternating strips of gravel and bare surface each 10 feet wide were used, a checkerboard pattern of sections with gravel cover was tested and finally a uniform gravel was laid out with a tree arrangement cleared to represent a stream network. The initial results indicate that the total quantity of gravel on the system is the most important parameter and the pattern makes little difference except when the flow can define a route to the flume by-passing the gravel completely. A more detailed analysis will yield more definite conclusion on the effect of the gravel in specific patterns.

FUTURE STUDIES USING THE FACILITY

The experimental facility will be useful in a number of different studies of hydrologic and related phenomena. Two projects have already been funded that will utilize the facility.

The first project is a study of the pollution characteristics of waste piles from oil shale development. As a part of this study, several piles of oil shale wastes will be arranged in the form of lysimeters on the facility. The artificial rainfall will be provided and the runoff, both surface and subsurface, will be collected and chemically analyzed. The effects of varying periods without rain can be determined with the facility. It is not currently known whether drying and weathering effects will increase the pollutant outflow from the system. This project is being conducted by the Sanitary Engineering group of the Civil Engineering Department.

The second project was funded to the Geology Department in cooperation with personnel from the experimental facility project. It is a study of the geomorphic development of stream networks. Under this project several containers about 10 feet by 40 feet in size will be filled with material that can be easily eroded. The development of the stream networks will be

observed and recorded photographically. The process that requires many decades and centuries in nature will be studied in a few weeks.

Both of these projects will be utilizing the experimental facility in the coming spring and summer. The possibility of conflicting needs for the projects using the facility have already become clear. The operation of the facility will have to be carefully managed to allow effective use for a diverse set of projects. This will be even more important as additional projects in the areas of water quality and geomorphology, for example, are funded to use the facility.

Each project that uses the facility is expected to provide some permanent contribution to the development of the facility. Thus, no single project or agency will have to provide the entire funds for developing the facility while little is gained in terms of research results. Now that the value of the facility is being shown, a number of proposals are being made to use it. Each of the projects using the facility and benefiting from the investment that has already been made will be investing in the further development of the area and versatility of the experimental facility.

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