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Rainfall Prediction-Measurement Systems and Rainfall Design Information for Urban Areas

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For this report it was decided to use the English system of units since the primary audience would be engineers, many of whom still use the English system rather than the International System of Units (SI). The following multiplicative factors may be used to convert from the English to the SI system.

Multiples for Converting from English to SI Units.

English	Length	SI
Inches (in.)	25.4	Millimeters (mm)
Feet (ft.)	0.3048	Meters (M)
Miles (mi.)	1.609	Kilometers (km)
	Area	
Square Miles (mi^2)	2.59	Square Kilometers (km^2)
	Volume	
Cubic feet (ft^3)	0.0283	Cubic Meters (M^3)

SYSTEM FOR REAL-TIME PREDICTION AND MONITORING OF PRECIPITATION OVER URBAN AREAS

Most major American cities have some existing form of precipitation measurements, usually involving some type of recording raingages. In a few cities where the management of storm and/or combined sewer systems is or has become difficult, if not critical, these gages are linked to a central office so that real-time rainfall information is available to controllers. In those metropolitan areas where management requires advance notice of rainfall, particularly moderate to heavy rains, some form of rainfall forecasting is made available. This may include special attention to National Weather Service (NWS) forecasts (routine or special), the use of NWS radar-rainfall maps, and/or the purchase of rainfall forecasts from private industry.

After intensive interaction with the Metropolitan Sanitary District of Greater Chicago (MSDGC) and awareness of the Chicago storm-sewer operational need, we concluded that a new form of rainfall prediction and monitoring system *dedicated* to MSDGC (and to other similar urban interests) water management was a viable and optimal approach. A specialized service was now possible by using modern weather radar and joint computer systems, which offered desirable accuracy, and was likely cost-beneficial. The demonstration project conducted by the Water Survey and MSDGC in 1979 proved the general potential of the radar rainfall system designed and developed by the Water Survey.

INTRODUCTION

This report provides guidelines for installing and operating measurement systems for rainfall prediction, plus rainfall design information. It has been prepared at the conclusion of a 4-year project involving the study of rainfall, including its real-time measurement and prediction over and around the Chicago Metropolitan Area. The report satisfies a major goal of the project, that being to examine various mixes of radar, raingages, and scientific-technical skills for operational rainfall forecasts in urban areas and to develop a set of guidelines for use by urban water management authorities.

The growing size of our nation's metropolitan areas with their large areas of impervious surfaces and many pollutant sources, coupled with the nation's desire to minimize flood-related damage and to improve simultaneously the quality of water in our streams, has produced a new set of problems for the operation and management of major urban water resource systems. As water resource systems have become more complex in water management, both to minimize flooding and to allow for water detention and treatment, it has become apparent that real-time information about a) rainfall over the city, and' b) rainfall about to occur there in the near future, is of ever-increasing value. A systems-analysis approach to the operation of complex systems has been developed in a few cities and is being considered in others where the runoff management system was largely developed in years when only flooding was a problem and the objective of the storm drainage system was the rapid removal of water from the urban area.

Our study was called the Chicago Hydrometeorological Area Project (CHAP). It began in 1976 and concluded with a field demonstration program in 1979. It was based on funding from the RANN Program of the National Science Foundation 070%), and the State of Illinois (~30%).

To address the major questions relating to rainfall measurement requirements for monitoring and prediction, the Water Survey installed an extremely large and dense recording raingage network in 1976, as shown in Fig. 1. In addition, two Water Survey radars, whose locations are also shown on Fig. 1, were installed and operated. The operation of the raingage network during the 1976-1979 period, plus the summer season (May-August) operations of these radars during these four years, have provided the data base for much of the information presented in this report. In particular, the results of a 2 1/2-month project demonstration program in the summer of 1979 have provided much of the information needed to prepare this guideline document.

During this 1979 demonstration program, the HOT radar (Fig. 1) was operated continuously with rainfall information transmitted every 30 minutes to the Chicago operational center of the Metropolitan Sanitary District of Greater Chicago (MSDGC). The transmitted information included 1) the accumulated storm rainfall over the city (values presented for all points on a 4- x 4-mile grid), and 2) forecasts of areal mean rainfall for three areas of the city for the rain expected in the next 30, 60, and 120 minutes. The evaluation of this demonstration program, both as to its rainfall monitoring capability and as to its prediction capability, is presented in a CHAP final report (Changnon *et al*., 1980).

A major aim of the CHAP effort was to provide information and guidance to those concerned with water resources management in Chicago and other metropolitan areas. This document helps to fulfill that goal by providing material concerning 1) real-time rainfall prediction-monitoring systems that can be considered for use in urban areas, and 2) hydrometeorological information relevant to various rainfall design considerations in urban areas.

The first section relates to the possible dimensions of the real-time rainfall prediction and monitoring system. It addresses such topics as recommended type of radar systems and associated hardware, raingage requirements for adjusting continuously generated radar-indicated rainfall field, telemetering systems, and computer programs. Also discussed are problems and advantages related to different kinds of equipment and measurement approaches. A discussion is included concerning raingage densities, procedures for siting and installation of gages and radars, and general cost estimates relating to system components and operations.

The second major part of this report deals with the hydrometeorological properties of convective storms and how they relate to urban hydrologic design and operational issues. This section presents information from our studies that treat point-area relations of rainfall frequencies, antecedent storm rainfall, characteristics of heavy storms, and raingage sampling requirements.

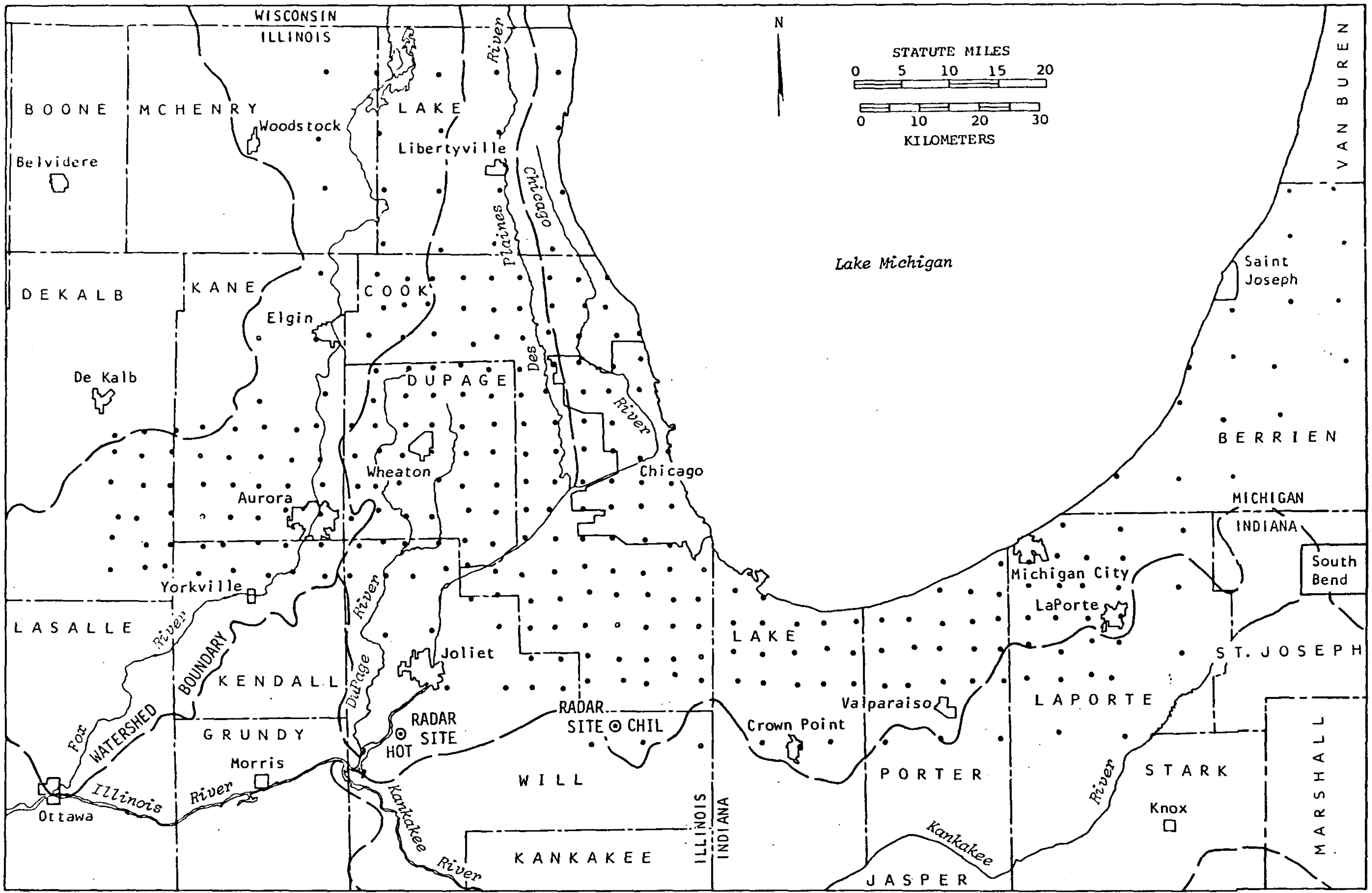


Figure 1. Study area and facilities for Chicago Hydrometeorology Area Project.

The first major section on monitoring and prediction addresses the twin issues of 1) real-time monitoring of the rainfall occurring over a metropolitan area, or 2) the real-time monitoring and predicting of rainfall. Either alternative, the rain monitoring or the monitoring plus prediction, requires recording raingages whose data can be transmitted to a central operational point. However, the weather radar is an essential feature for a city that desires to have a predictive capability.

We believe that there are three "givens" in urban rain prediction systems we recommend and discuss. Thus, there must be some (number and type to be discussed later) recording raingages; a radar system must be available; and, some meteorological skills has to be involved in the prediction and monitoring system (but not in a monitoring-only system).

When there are many variables involved, such as raingages (different types, densities, siting), weather radars of various types, related software and hardware, communication systems, and staffing, the potential matrix or set of recommendations one could consider is very extensive. We recognize that the decisions to designate what types of precipitation measurements systems to employ are also dependent upon many variables including climate, available funds, future operational support funds, and existing facilities (such as computers and raingages).

Basically, we have approached the problem of dimensionalizing potential systems by providing observations, criticisms, and recommendations relating to various types of equipment. How the various equipment are mixed is seen as highly variable and dependent on site, funding, and existing facilities.

The type of a system that could be developed in an urban area also needs to be considered by the user from a multi-agency viewpoint. For example, the operational radar-raingage system that has been developed and demonstrated for MSDGC in the Chicago area also has the potential for serving the Illinois Division of Water Resources and the U. S. Corps of Engineers (monitoring of diversion of water from Lake Michigan) and the City of Chicago (for activities like the measurement of snowfall to assist in the direction of snow removal activities). Thus, other precipitation-impacted groups may exist in other cities in addition to the agency responsible for the drainage and treatment of water from the urban area. These other potential user should be investigated both as a potential financial contributor and in designing a system with the flexibility to address all needs.

In all these instances, it is necessary for a city to do an initial assessment to consider seriously the various possible applications of the information, various funding sources, and the types of system. This then can be followed by a site study investigation involving analysis of historical radar and rainfall climatological records, particularly if implementing the rain forecast system is envisioned.

For those readers who do not find the information they seek in this document, we recommend that they write us concerning their questions and we will attempt to provide answers. A major recommendation to a city which is considering a rain measurement system is to seek professional guidance such that atmospheric scientists are involved and informed of the city's peculiar problems, so as to optimize the choice of system developed. As noted above, an engineering, economic study involving potential users of the information needs to be made, and, in some instances, historical radar data for the area should be studied by experienced radar meteorologists to help provide guidance as to the type of radar, its siting, and what periods of the year operations are advisable.

Components

The system at Chicago integrated

- A 10-cm weather radar incorporating a signal processor;
- A mini-computer system to analyze the echo data, provide rainfall amounts over the city, and forecast rain which was to occur over the city;
- Existing recording raingages (22) of MSDGC with telemetered rainfall data;
- Meteorologists and standard routine weather facilities needed
    a) to monitor and occasionally adjust the radar rainfall estimates, and
    b) to monitor and occasionally revise the rain forecasts;
- Communication system connecting the radar, raingages, and water control headquarters.

These five elements and how they functioned in the Chicago demonstration project are depicted in Fig. 2.

The essential features of the radar are that it provides 1) a much more detailed and, hence, accurate portrayal of storm rainfall than can be obtained with any but the most dense raingage networks; and, 2) data on rain developing and approaching the city needed to make accurate short-term (30 to 180 minutes, depending on area) rain forecasts, particularly those essential for flash flood situations.

The advent and use of mini-computer systems are also critical since these (with complex software) digest the myriad of 3-dimensional rain data generated by a radar in a short period. In essence, this adjunct computer system translates the digital radar data into the rainfall estimates by integrating the raingage-indicated rainfall with the radar signal. It also calculates the motion and rain change fields needed to predict urban rainfall.

Data in real-time from a few recording raingages are needed to "adjust" the radar-indicated rainfall. Experience has shown that radar signals at times can make large errors in estimating rainfall; therefore, it is important to adjust the radar-indicated rainfall over the city with a network of a few raingages.

Meteorologists are a critical link in the prediction-monitoring process. They monitor the above three elements to discern occasional errors and make related adjustments according to current synoptic conditions. Meteorologists

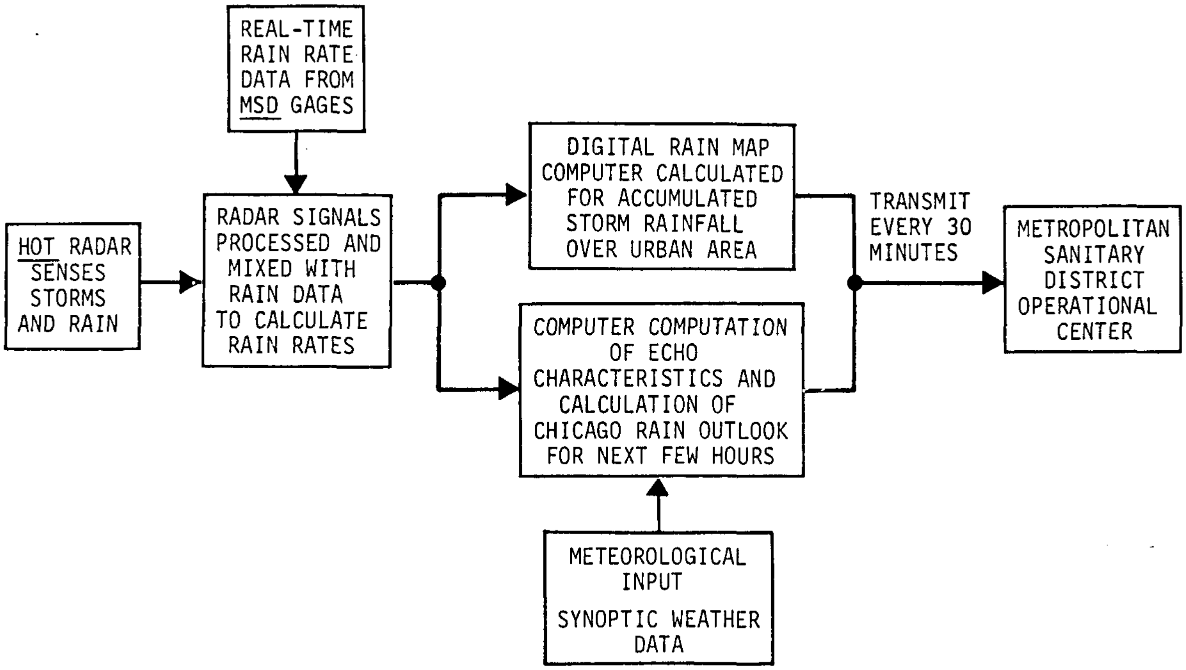


Figure 2. Radar-rainfall monitoring scheme developed in CHAP.

can provide important initial forecasts for rains which develop over the city from current knowledge of the weather pattern. Their involvement with the system insures longer-term forecasts than the radar can derive by interpreting NWS analyses. They can also interpret the predictions for operational users.

Since the radar site needs to be outside of the urban area (radars are largely blind in their immediate area), and since the raingages are scattered over a large area, a communication system (telephone lines, radio system, etc.) is needed to link the raingages, radar, and water control headquarters.

Philosophy

The system illustrated in Fig. 2 can have many different dimensions and costs depending on 1) the criticality of a given city's rain problem (safety of human life versus pollution management), 2) available funding, and 3) existing facilities. One good weather radar may cost $350,000; however, it is subject to power failures and component failures. If flooding and loss of life are critical, a standby power generator and dual system radar could be considered, but obviously at a greater cost. Some cities may have an agency that already has a nearby quality radar that can be modified and operated to satisfy the radar needs of the water control agency.

The message in considering the component problems and recommendations presented in the following sections is that a careful assessment of the rainfall monitoring and forecast needs of a city should be conducted before the system is developed. This functional assessment should also consider a host of local issues including existing skills, relevant facilities (radars, raingages, communication systems, and personnel) and siting studies for new equipment. Background studies of the local hydrometeorological data and past radar data will be of great value in evaluating the prediction-monitoring needs.

RADAR PRECIPITATION MEASUREMENT

The design and placement of instrumentation to measure precipitation in real-time with radar requires a careful engineering study of the requirements for each new radar-rainfall system. Presently, radar relates the back-scattered power from precipitation particles to the rainfall rate. Precipitation particles have two effects on the radar wave; a portion is reflected from the particles and a portion is attenuated by the particles. The attenuation factor is not of great importance at 10-cm wavelength, but is extremely critical at wavelengths below 5-cm. Therefore, for very heavy rainstorms which are of paramount importance to the urban hydrologist, a 10-cm radar should be used because of moderate to severe attenuation at shorter wavelengths can produce large underestimates.

The complexity of the precipitation measurement problem is related to the nonlinear attenuation of rainfall rate and changing drop-size distributions. Radar meteorology, for precipitation quantitizing, has concentrated on S-band

(10-cm, 2700-3300 MHz) wavelengths and uses the Rayleigh scattering theory for particle diameters which are small (1:15) in respect to the wavelength. The Rayleigh relationship is:

$$\eta=\pi^5\lambda^{-4}\ |K|^2\ \sum_1 D^6$$

η is back scattering cross section per unit volume
λ is wavelength
D is droplet diameter
$\sum_1$ summation over unit volume
K is $\left|\frac{m^2 - 1}{m^2 + 2}\right|$
m is complex refractive index

For convenience, the radar meteorologist has defined the term $\sum_1 D^6$ as the reflectivity factor Z. The remainder of the constants are inserted into the radar equation.

The general form of the relationship between the reflectivity factor and the rainfall rate is:

$$Z = AR^b\ (mm^6\ m^{-3})$$

Z is reflectivity factor
R is rainfall rate

Considerable efforts have been expended in determining values of A and b in this relationship (Battan, 1973; Stout and Mueller, 1968) . Most of the investigators have arrived at values by measuring the raindrop size spectra; calculating the expected rainfall rate and radar reflectivity factor from the spectrum; and, finally relating the two calculated values in a logarithmic regression analysis. Results of these investigations usually produce an unacceptably large scatter around the regression line. A summary of measured radar-reflectivity and rainfall-rate relations for several geographical areas is listed in Table 1 (Stout and Mueller, 1968).

The reason for this large scatter has been attributed to a number of causes, but, essentially, it is an indication that in nature, the same rainfall rate can be obtained either with a large number of small raindrops or by a few large raindrops. The amount of radar scattering is vastly different under these two conditions, since the reflectivity factor varies as the sixth power of the drop diameters.

A number of attempts to reduce the scatter in these relationships have been made using meteorological variables such as types of rainfall (thunderstorm, shower, continuous rain), synoptic type (cold front, warm front, air mass showers, etc.), and others (Stout and Mueller, 1968). Though these stratifications frequently reduce the scatter, that which remains is still relatively large. It is mostly due to this scatter that raingages are needed to refine the radar measurements.

Table 1. Radar reflectivity, rainfall rate relationships from drop size spectra.

Investigator	$Z=AR^b$ A	 b	Standard error of estimate of log R	Comments
Marshall *et al.* (1947)	220	1.6		Canada, widely accepted and used
Blanchard (1953)	31	1.71		Orographic Hawaiian rain at cloud base
	16.6	1.55		Orographic Hawaiian rain within the cloud
Fujiwara (1967)	80	1.38		Orographic Hawaiian rain
Hardy (1962)	312	1.36		Arizona and Michigan rain with rates greater than 5 mm hr^{-1}
Imai (1960) [Japan]	700	1.6		One day of probably warm rain
	300	1.6		One day continuous rain
	200	1.5		Air mass showers
	80	1.5		Pre-warm front rain
Diem (1966)	184	1.28		Overall average of different locations
	278	1.30		Entebbe, Uganda (tropical)
	240	1.30		Lwiro, Congo (tropical)
	176	1.18		Palma
	151	1.36		Barza, Italy
	179	1.25		Karlsruhe, Germany, spring
	227	1.31		Karlsruhe, Germany, summer
	178	1.25		Karlsruhe, Germany, fall
	150	1.23		Karlsruhe, Germany, winter
	137	1.36		Axel Heiberg Land
Foote (1966)	520	1.81		Tucson, Arizona
Dumoulin and Gogolombles (1966)	730	1.55		France, highest coefficient
	255	1.45		Lowest coefficient
	426	1.5		Average of all observations, 0.95 correlation coefficient
Mueller and Sims (1966a,b)	286	1.43	0.198	Florida
	221	1.32	0.170	Marshall Islands
	301	1.64	0.136	Oregon
	311	1.44	0.147	Indonesia
	267	1.54	0.142	Alaska
	230	1.40	0.171	North Carolina
	372	1.47	0.153	Illinois
	593	1.61	0.175	Arizona
	256	1.41	0.163	New Jersey

The radar equation which relates Z to the average received power from a radar (Probert-Jones, 1962) is:

$$Pr = \frac{\pi^3}{16 \log_e 2} \frac{Po\ h}{\lambda^2} G^2 \Theta \phi \frac{1}{R^2} \left|\frac{\varepsilon - 1}{\varepsilon + 2}\right|^2 \Sigma r^6$$

Pr - received power
Po - transmitted power
h - pulse length in space
λ - wavelength
G - gain of aerial system
Θ,ϕ - beam widths to the -3 db level for one-way transmission
R - range
ε - dielectric constant
r - drop radius

From this very general overview it is suggestive that the accuracy with which point rainfall may be estimated from radar may have great variability.

With 10-cm radar equipment, the size of raindrops is limited (Magarvey and Taylor, 1956) by breakup as they approach the 15:1 wavelength-to-drop-diameter ratio and the measurement of liquid water precipitation gives directly useable results. However, in the case of hail, larger hydrometeors exist and if the hail is dry, different refractive indices apply. In these cases the Rayleigh scattering theory, without correction, fails and the estimated rainfall amount (Atlas et al., 1960) will be in error.

The complexity of measuring rainfall with radar involves a wide variety of engineering principles whose scope is beyond adequate coverage in this report. General outlines of radar designs and its application to meteorology can be found in Atlas (1964), Battan (1973), Kessler (1980), Nathanson (1969), and Skolnik (1962).

Current investigations indicate the possible future use of differing techniques to alleviate the scatter apparent in reflectivity estimations. Some of these techniques consist of relating rain rate to differential attenuation at two wavelengths (Eccles, 1978), reflectivity and attenuation (Ulbrich and Atlas, 1975), and the differential reflectivity between horizontal and vertical polarized waves (Seliga et al., 1980). Therefore, a project design should include provisions to upgrade equipment when these or other new techniques are able to improve upon present technology.

A minimum design study to implement a radar-rainfall project should consider the following subjects: 1) project duration, 2) acceptable accuracy of data, 3) acceptable reliability of equipment for the project, 4) license and/or legal requirements of project, 5) communication links of project, 6) verification of results, 7) ability to upgrade and modify measuring techniques.

There are several sources of 10-cm radar data for precipitation measurement within the United States. These include the National Weather Service (NWS) radars, research radars, and procured radar systems.

The most attractive source of radar data, in terms of economy for a project co-located with a NWS radar station, is a negotiated agreement to use NWS radar data. At present there are four NWS radar stations which were "upgraded" for the Digitized Radar Experiment (D/RADEX) project, and these would have the precision required for radar rainfall measurements (Greene and Flanders, 1976). They are located near Pittsburgh, PA; Monett, MO: Kansas City, MO; and Oklahoma City, OK. If agreement to operate the antenna in a scan mode that will permit precipitation measurements can be negotiated, the addition of a Digital Video Integrator Processor (DVIP) will permit quantification of radar received power. Currently the NWS is designing and planning to install a network of precision weather radar stations which is expected to provide high quality radar measurements for a major part of the country, as part of the NEXt RADar (NEXRAD) meteorological system for the United States (NSSL Staff, 1979).

A second source of precision 10-cm radar data for any organization operating in the same geographical area as a governmental or institutional weather research group is cooperative sharing of the operational expenditure in return for precipitation data.

A third method of obtaining quality 10-cm radar data is the procurement of a suitable system through a commercial company. Initially, this approach will be more expensive, will require more time to implement, but could be the more versatile long-term solution. With a continuing research and development effort, this offers the long-term probability of a fully automated system.

Radar System

The radar system consists of three major components which logically may stand alone as independent components of the complete system. These components can be obtained separately and integrated into a system or obtained as a complete system. The three components are 1) the antenna, 2) the radar transmitter receiver, and 3) the reflectivity processor. The antenna consists of the beam shaping surface; the wave guide, rotating joints, and antenna feed; and, the azimuth-elevation drive with position-indicating components. The radar will include components required to transmit the high-frequency energy pulses and receive the incoming signals. The incoming signals are amplified and generated into power levels for use in the reflectivity processor. The reflectivity processor will digitally process these signals to obtain the average power and then provide the information for visual displays, data storage, and computers.

Antenna -- The antenna selection is a compromise between a large expensive structure with high resolution and a less expensive structure with power resolution. Considerations for choosing an antenna include requirements for areal resolution, temporal resolution, beam filling, and multiple uses. Thus if a project requires rainfall data with resolution of 1 mile at a range of 60 miles, an antenna with beam widths of $\leq 1°$ is necessary. This can only be met by large antennas. For example, for a 10-cm radar this would require an antenna with a 28 foot diameter. On the other hand, if data requirements permit poorer resolution a smaller antenna can be utilized. It should be noted that as one moves towards smaller antennas, the range at which the beam filling assumption fails is reduced. For example, to keep the high reflectivity region near the freezing level (referred to as bright band) from affecting the estimate of rain rate, the range must be less than the distance required for the upper half of the beam to enter the freezing level. A 2° beam width centered at 0° elevation intersects the 10,000 foot level at 67 miles while a 4° beamwidth intersects the 10,000 foot level at 42 miles (Fig. 3).

The pedestal upon which the antenna is mounted must be capable of moving the antenna in both azimuth and elevation. It is necessary that this drive system allow no longer than 3 minutes to elapse before a scan sequence is repeated.

Additionally multiple use considerations may impact on antenna size. For instance, it is possible that severe storm warnings could be issued from this radar. Such useage might well increase the size of antenna required.

A partial list of other parameters which are normally specified for an antenna are given in Appendix A. A complete discussion of tradeoffs and relative merits that are possible is beyond the scope of this report.

Transmitter Receiver -- The radar transmitter's most stringent requirement is one of stability. In order to relate the return power to the reflectivity factor or to rain rate, the transmitted power level must be known accurately. A procedure which permits automatic monitoring of the power level is highly desirable. For example, if a coherent cancellor to eliminate ground clutter is implemented, the transmitter must maintain a phase coherency from transmitter pulse to transmitter pulse. Such requirements may be most significant with respect to the amount of money needed to implement such cancellor techniques. Other parameters are listed in Appendix A.

The radar receiver is one of the more sensitive areas in a modern radar. In meteorological applications, the expected range of return power spans at least 7 orders of magnitude. A dynamic range of the entire receiver must therefore be at least 70 db. Logarithmic receivers of 80 db are presently available.

Again the stability of the receiver is very important to a quantitative system. In some radar systems an Automatic Frequency Control (AFC) is required to maintain the receiver frequency tuned to the transmitter frequency. Since any drift in this circuit is disastrous to the signal level, a very stable and working AFC is necessary. Other related parameters are listed in Appendix A.

Reflectivity Processor -- The radar produces a return signal which is proportional to the power reflected from targets along the beam. This signal is a composite of the signals received from each raindrop in the beam. Since the raindrops are a random group of scatterers at random ranges from the radar, the phase of the return from each drop varies between 0 and 2π.

Thus, a signal whose intensity fluctuation is quite large is observed. As the raindrops are reshuffled, by turbulence and fall velocity, the signal strength will fluctuate. Repeated measurements at a fixed time are found to be distributed exponentially with an average which has been determined to be a measure of the rain rate in the pulse volume. It is necessary to average the reflected power from a number of transmitter pulses covering a period of at least 60 milliseconds to obtain a representative estimate of the intensity

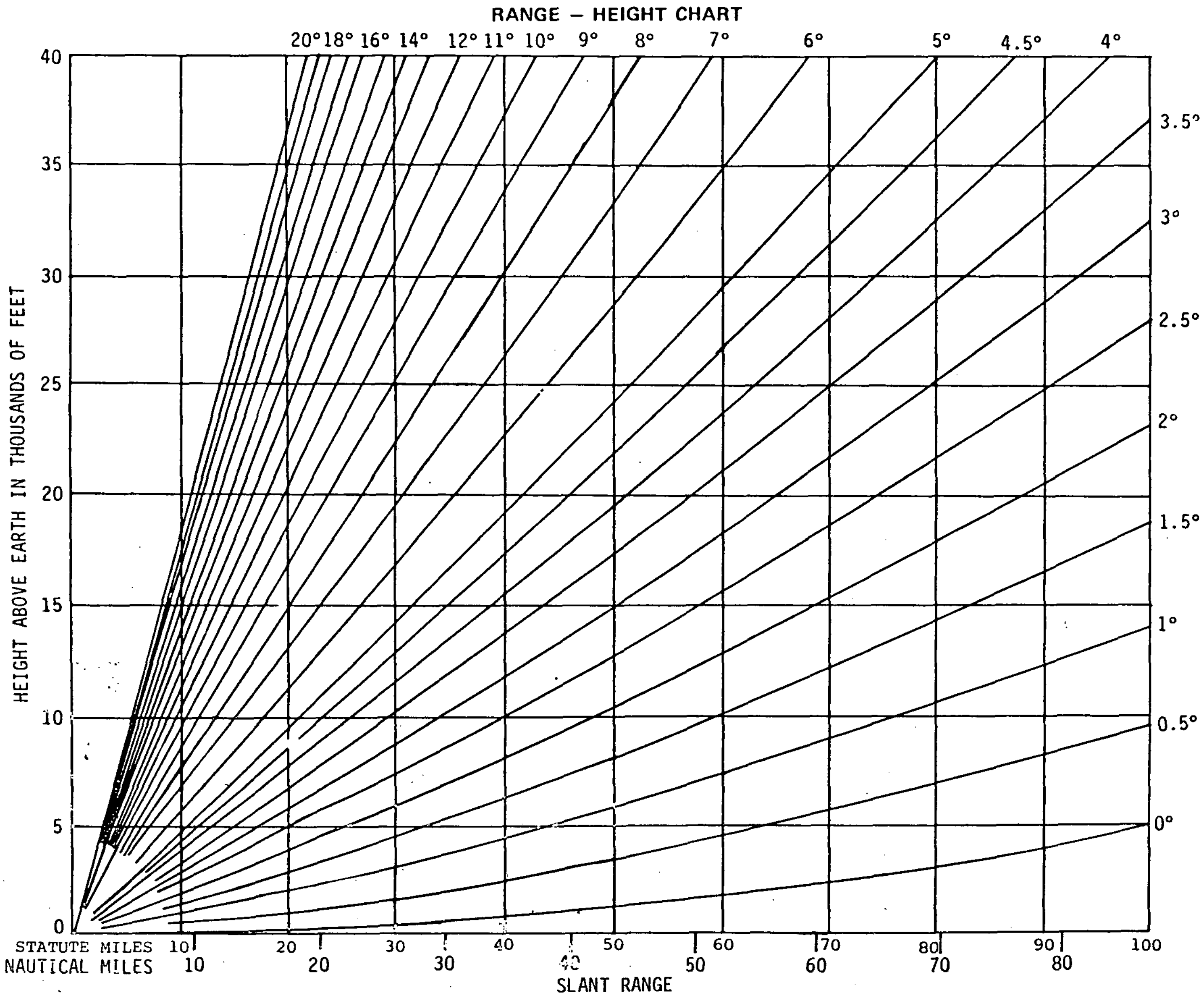


Figure 3. Radar range height.

of the rainfall. Video processors which perform this averaging function at 200 to 500 locations (bins) along the radial are commercially available from several manufacturers. These processors are generally non-programmable digital devices that produce a number for each range bin which may be related through a calibration procedure to the radar received power and/or the reflectivity of a small volume in space. The location of the small volume in space is identified by the range bin number (i.e., 1-500) and the azimuth and elevation angles of the antenna. A typical processor will produce a burst of 200-500 numbers at a rate of 200-500 KHz every 60 ms.

The radar preprocessor (DVIP) requires extensive specification and only the highlights can be considered here. Many of the parameters of the DVIP should be matched to the characteristics of the radar, antenna, and system requirements. For example, the number and spacing of the range intervals (range bins) is related to the pulse width and receiver bandwidths (Sirmans and Doviak, 1973), and should be approximately equal to the azimuthal resolution at the nearest range.

The preprocessor must provide the averaged data to the display scopes, to any attached computer or communication lines, and provide for a permanent record for post-storm evaluation and analysis. The desirable mix of the other parameters of the preprocessor are difficult to assess in any detail. In many respects there exists a tradeoff between the preprocessor and the computer as to where individual tasks are performed. In this category are range square correction, contouring or gray scaling for display, range averaging, replay capability, and automatic system performance monitoring.

Range square correction has been largely accomplished in recent years in the computer. This term arises in the radar equation and in the past was frequently corrected by analog methods in the receiver (this reduces dynamic range requirements). As better receivers have become available it is now usually performed at a much later stage.

Range averaging in the preprocessor is sometimes used to reduce the data rate to the computer. Provided that high resolution is not required this is an acceptable practice and easily performed in the preprocessor.

Real-time displays at the radar serve two major purposes: 1) they communicate the present weather to an observer so that objective interpretations can be made, and 2) they permit evaluation of system operation to this point in the chain. The more modern systems use the computer to generate displays for observer interpretation. These displays are frequently a color scope and have proven to be much superior to the monochromatic displays. Observers, even highly trained observers, find the polychromatic displays significantly easier to interpret. Also, composite displays are obtainable from the computer. For example, a display might use the 3° elevation angle scan for near ranges (say to 15 miles), 1.5° elevation angle scan for intermediate range (15-30 miles) and finally the 0° elevation scan for all ranges greater than 30 miles. Such a composite display effectively removes a large portion of the ground echoes in the vicinity of the radar, and provides the operator with a truer depiction of the radar echoes, especially echoes within 30 miles of the radar. This and other types of composite displays can aid in the interpretation of weather-related echoes.

Site Selection

Selection of the radar site location is a very critical task that may be an important factor in the future success of a project. Uncompromising qualities that must be available at the selected location are: 1) unobstructed horizon, 2) minimum of ground targets in areas of interest, 3) surveillance of all areas of precipitation measurement, and 4) utilities and access.

A study of U. S. Geological Survey topographic maps*, aeronautical flight charts**, and telecommunications SHADO digitized topographic data*** will usually permit the selection of an adequate radar location. If this procedure indicates sites of marginal quality, it is recommended that substantial test operations using portable radar equipment be conducted at the possible site locations. More sophisticated and costly techniques are available and can be obtained from competent telecommunications engineering firms.

Horizon -- For radar-rainfall measurements it is necessary to obtain an unobstructed view of the horizon near 0° tilt to permit the view of near and distant precipitation below cloud base level and near the earth's surface. This will minimize the accretion, evaporation, and displacement errors that occur when precipitation measurements aloft are used to represent the ground level precipitation. Using Fig. 3 in conjunction with the applicable physics of precipitation it is possible to specify the maximum range of precipitation measurement for a project which may be used for reliable measurements (usually less than 80 miles). Some long-range radar-rainfall measurements can be obtained to serve as a guide or a first-estimate of precipitation quantities. These radar-indicated rainfall amounts could then be refined as the precipitation moves closer and adjustments can be made to yield more reliable precipitation measurements.

If the measurement area is located in mountainous areas it may be necessary to use more than one radar system to monitor the reflectivity values. Mountainous areas require special consideration of the refractive index which can cause beam deflections into outer space or severe reflectivity signals from ground targets.

Ground Targets -- Ground targets are the result of echoes from nonmeteorological targets 1) in the vicinity of the radar, or 2) occasionally at great range due to abnormal lapse rate of refractive index with height. These latter conditions produce bending of the propagation path and permit echoes from distant objects on the earths surface (Battan, 1973). This case is frequently referred to as Anomalous Propagation (AP).

*Available from the U. S. Geological Survey, Washington, D.C. 20242

**Available from U. S. Department of Commerce NOAA Distribution Division C-44 National Ocean Survey, Riverdale, MD 20840

***Available from U. S. Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunications Sciences, Spectrum Utilization Division, 325 Broadway, Boulder, CO 80303, Attention: Administration Officer Spectrum Utilization Division.

The contribution of non-precipitation targets to the reflectivity total often causes a substantial error in the precipitation measurement. Corrective methods to compensate for these errors are to remove the ground targets by site selection, software, coherent cancellors, absorbent screens, and antenna tilt. If the targets are all from nearby objects and the radar is not being used for other types of data, a simple solution is to run additional scans above 0° tilt and measure the reflectivity for near ranges from angles of tilt that do not contain ground targets. The removal of AP is more difficult to achieve. Coherent cancellors are becoming available (Aoyagi, 1978) which aid in AP elimination but, at present, an operator using associated meteorological data is indispensable.

Surveillance Area -- For predictive purposes the radar should be positioned so that the maximum length of measuring time for each rain area can be achieved. A climatological study of the average rain motion should be made before siting the radar, and the radar should be located upstorm of the most frequent direction of motion. For example, in many areas of the Midwest storms move from the southwest to west to west-northwest, and the radar should be situated southwest to west of the urban area. Ideally, the area to be measured should be at a range of 20-60 miles from the radar with the best possible pre-measurement surveillance selected as a secondary condition.

Access and Utilities -- Given the choice of several locations which will yield satisfactory measurements, the consideration of roads, power-distribution systems, telephone lines, and water systems are considerations which, may decrease the installation and annual operating costs by thousands of dollars.

Federal Communications Commission License -- Radio regulations, which are the result of international agreements and Federal Communications Commission actions, allocate frequencies 2700 to 3300 MHz for use of meteorological radar equipment.

The frequencies of 2700 to 2900 MHz are available for use by United States Governmental entities and subject to coordination with other users in the area. This is a desirable band to license meteorological radar for use by United States Government departments.

The frequencies of 2900 to 3300 MHz are available for use by both United States Governmental and non-Governmental users with non-government use restricted to the condition of no harmful interference to the United States Government users. Table 2 is a reproduction of the applicable parts of the FCC Table of Frequency Allocations including definitions and footnotes.

On September 24, 1979 delegates from 154 countries gathered in Geneva, Switzerland to discuss and reallocate the radio spectrum. This conference was called the World Administrative Radio Conference (WARC) and was sponsored by the International Telecommunications Union (ITU), a United Nations organization.

The desires of the Third World nations to reserve parts of the radio spectrum, which will not be used in the immediate future, is in conflict with the industrialized nations' desires to allocate the spectrum for specific uses and assign it on a first come basis. Decisions made at WARC have treaty status and will be reviewed by the U. S. Senate before they receive United States

Table 2. FCC table of frequency allocations, definitions, and footnotes.

Table of Frequency Allocations—Conditioned

Worldwide		Region 2		United States		Federal Communication Commissions				
Band (MHz) 1	Service 2	Band (MHz) 3	Service 4	Band (MHz) 5	Allocation 6	Band (MHz) 7	Service 8	Class of station 9	Frequency (MHz) 10	Nature of services of stations 11
2700-2900 (366)	AERONAUTICAL RADIONAVIGATION. (346). Radiolocation.			2700-2900	G. (316) (366) (US42) (US43)					
2900-3100	RADIONAVIGATION. (367) (367A) (367B). Radiolocation.			2900-3100	G, NG.	2900-3100	MARITIME RADIONAVIGATION. Radiolocation. (US44)			
3100-3300 (354) (365) (369)	RADIOLOCATION.			3100-3300	G, NG. (369) (US 110)	3100-3300	Radiolocation.	Radiolocation land. Radiolocation mobile.		RADIOLOCATION.

Definitions.

The following definitions are issued:

Aeronautical radionavigation service. A radionavigation service intended for the benefit of aircraft.

Hertz. A unit of frequency equivalent to one cycle per second. The terms hertz (Hz) and cycle(s) per second (c/s) are synonymous and may be used interchangeably.

kHz (kilohertz). A unit of frequency equivalent to one thousand hertz.

Maritime radionavigation service. A radionavigation service intended for the benefit of ships.

MHz (megahertz). A unit of frequency equivalent to one thousand kilohertz.

Radiolocation. Radiodetermination used for purposes other than those of radionavigation.

Radiolocation land station. A station in the radiolocation service not intended to be used while in motion.

Radiolocation mobile station. A station in the radiolocation service intended to be used while in motion or during halts at unspecified points.

Radiolocation service. A radiodetermination service involving the use of radiolocation.

Radionavigation. Radiodetermination used for the purposes of navigation, including obstruction warning.

FOOTNOTES

(346) The use of the bands 1300–1350 MHz, 2700–2900 MHz and 9000–9200 MHz by the aeronautical radionavigation service is restricted to ground-based radars and, in the future, to associated airborne transponders which transmit only on frequencies in these bands and only when actuated by radars operating in the same band.

(366) In the band 2700–2900 MHz ground-based radars used for meteorological purposes are authorized to operate on the basis of equality with stations of the aeronautical radionavigation service.

(367) The use of the band 2900–3100 MHz by the aeronautical radionavigation service is limited to ground-based radars.

(369) In the band 3100–3300 MHz, existing racons and shipborne radars in merchant ships may operate within the band 3100–3266 MHz.

US42 Temporarily, and until certain operations of the radiolocation service in the band 2700–2900 MHz can be transferred to other appropriate frequency bands, the aeronautical radionavigation and meteorological aids services may, in certain geographical areas, be subject to receiving some degree of interference from the radiolocation service.

US43 Non-Government land based radars in the aeronautical radionavigation service may be authorized in the band 2700–2900 MHz, subject to the conclusion of appropriate arrangements between the Commission and the Government agencies concerned, and upon special showing of need for service which the Government is not yet prepared to render.

US44 *The non-Government radiolocation service may be authorized in the band 2900–3100 MHz on the condition that no harmful interference is caused to Government services.*

US110 In the frequency bands 3100–3300 MHz, 3500–3700 MHz, 5250–5350 MHz, 8500–9000 MHz, 9200–9300 MHz, 9500–10,000 MHz, 13.4–14.0 GHz, 15.7–17.7 GHz, 24.05–24.25 GHz and 33.4–36 GHz, the non-Government radiolocation service shall be secondary to the Government radiolocation service and to airborne doppler radars at 8800 MHz, and shall provide protection to airborne surface detection equipment (ASDE) operating between 15.7–16.2 GHz.

endorsement. Until the WARC agreements are finally adopted it will not be known if the 2700-3300 MHz frequency band will remain available for the meteorological service organizations.

Computers and Programming

Small computers can be used to process and present the information from the video processor without significantly increasing the overall system cost. The exact function of the on-site computer will vary depending on the specific application. However, there are several functions which would likely be included in any system of this type.

The computer might control the motion of the radar antenna, at least to the extent of signalling the antenna when to start a scan sequence. In addition, the computer could ensure that the antenna scans the atmosphere at low elevation angles to measure the rainfall as close to the ground as possible, and that the area of interest was scanned once every three to five minutes. As the antenna scans the area of interest, the computer could convert the power reflectivity numbers generated by the video processor to estimated rainfall rates. To make this transformation, the assumption that the radar beam is filled with drops whose pulse volume is of an average drop-size distribution is made. This drop-size-distribution is not generally known, and may vary in time and space, and is a source of errors in radar rainfall measurements. The computer would then transform the coordinate system of the data from the spherical system of the radar to a cartesian grid.

The cartesian grid is more convenient to use in subsequent analysis. Grids consisting of 4096 points may be accommodated by most small computers. The computer must operate fast enough to keep up with the incoming data from the video processor. Computers with 16 bit word length, 32k words of memory, and capable of 250,000 to 500,000 integer arithmetic operations per second have proven adequate for this task (Brunkow, 1980; Changnon *et al*., 1980).

The grid spacing on the cartesian grid should be no less than the spatial resolution of the radar at the range of interest. Generally, grid spacing in the range of 1 to 3 miles will be used. If the spatial resolution of the radar is better than that of the grid, a simple average of all the range bins adjacent to the grid point will provide a reasonable value at that grid point. If, however, the resolution of the radar is comparable or less than that of the grid, some type of interpolation will be required to evaluate grid points at distant ranges where radar data is relatively sparse. The cartesian grid values may be thought of as the amount of rainfall which fell during the scan period at each grid location. The computer can maintain a running-total grid to which it adds the grid values generated from each scan. This total grid would be equivalent to having a network of raingages spaced every 1, 2, or 3 miles depending on the grid length.

The radar estimated rainfall will differ from the rainfall measured by raingages, in most cases. These differences can be corrected using real-time telemetered raingage data. One method of doing this is to calculate the gage/radar ratio at each gage location (Hildebrand *et al*., 1979). The radar estimate at each grid point is then scaled by the weighted average of nearby gage/radar ratios. One weighting factor that could be used is e-EP/R; where R is the distance from the grid point to the raingage, and EP is a constant which is determined by the typical raingage spacing. This is one of several approaches which have been applied to the problem of measuring rainfall with radar. A summary of these techniques is given by Wilson and Brandes (1979).

The possibilities for analysis of the cartesian grids by the computer are very extensive, and certainly need to be tailored to each application. One approach used by the McGill Stormy Weather Group (Bellon, 1973; Bellon and Austin, 1978) employs a pattern recognition technique to determine the average velocity of the whole system of storms within the range of the radar. This velocity is than used to extrapolate the motion of the storm system and sum up the expected accumulation at each grid point. This system is particularly well suited to regions where large storm systems are prevalent.

Another approach to forecasting has been used by the Illinois State Water Survey (Changnon et al., 1980). This technique divides the grid into individual cells. The area, intensity, and location of each cell is extrapolated separately. During this extrapolation, the cell is allowed to change in areal extent and intensity. The final forecast is calculated by summing the expected accumulation from each cell.

RAINGAGE NETWORK

A key element of any system designed to monitor and/or predict rainfall over an urban area in real-time is a raingage network. This network must be designed to provide real-time rainfall information, usually to some central location, over the region of interest. If only a raingage network is employed the density requirements might be more stringent than if a radar is also to be employed. A raingage network provides the "ground truth" necessary for the adjustment of the radar-indicated rainfall and can provide a climatological base for other studies within the urban area.

Siting

Two factors determine the accuracy with which precipitation may be measured. They are equally important. The first is the engineering of the instrument by the manufacturer. The second factor is the proper siting of the instrument - its exposure. The function of the gage is to record the amount of precipitation which falls on a horizontal area at the earth's surface. On flat land and under no-wind conditions this measurement is easily realized. But when a wind is blowing, "The disturbance of the air flow by the instrument results in wind eddies around the gauge. Up currents over the orifice reduce the catch whilst down currents increase it. The overall effect of such eddies is generally to reduce the catch" (WMO, 1971). Studies to eliminate the effect of the wind have resulted in the adaptation of several criteria for instrument siting. "An ideal exposure would eliminate all turbulence and eddy currents near the gage. . . . As a general rule, an isolated obstruction should not be closer to the gage than twice (preferably four times) its height above the gage. . . . The best exposures often are found in openings in a grove of trees or bushes....." (U. S. Department of Agriculture, 1979). Although installation of the gage within a clearing among trees or bushes is considered excellent, it must be remembered that trees and bushes grow and that they should not exceed the height-distance criteria during the period of the operation of the gage.

In general, it is not possible to site a precipitation gage in a forest clearing, so that it is, and it will be necessary to place it in an available open site with the strong possibility of catch-reducing eddies. A wind shield should be used around the gage when installed at these open sites. The Nipher shield is more effective in all tests than any other shield in blowing rain. However, the Nipher shield will trap snow and cause erroneous readings if some means is not found to clear it of snow. The Alter shields approximate the shape of the Nipher shield when the wind is blowing as well as swinging to loosen the snow falling upon them. Intuitively, the Shasta shield should be more effective than the Alter shield since the Shasta is fabricated with aluminum vanes rather than the galvanized steel of the Alter. The lighter vanes of the Shasta shield should swing to the Nipher shape in a lighter wind.

Keeping in mind the above discussion, it is strongly recommended that the precipitation gage be installed at the surface in an open area. Equipment storage yards, sewage treatment plants, water treatment plants, and, possibly, supervised nature-study areas in public parks are suggested. If surface areas with reasonably open exposures are not available, roofs of public buildings will have to be used. The precipitation gage should be installed near the center of a large flat roof away from any obstructions on the roof. A wind shield should surround the gage. Extreme care should be taken to follow the instructions for installing the shield to the correct height with respect to the rim of the gage orifice. An incorrectly installed shield will reduce the catch of the gage.

Types of Precipitation Gages

This discussion of precipitation recording gages will be limited to those which are suitable for telemetry. Telemetered gages may require operation in precipitation at below freezing temperatures. The gages discussed can operate with or without heating. The World Meteorological Organization has set up guide lines for the performance of precipitation gages in international use. These are: ability to record ±0.02 mm h^{-1} with rain rates below 2 mm h^{-1}, ±0.2 mm h^{-1} at rain rates between 2 and 10 mm h^{-1}, and ±2% with rain rates above 10 mm h^{-1} (1 inch is 25.4 mm).

The tipping bucket gage as fabricated by many manufacturers is the most commonly telemetered gage because the tipping of the bucket results in a pulse. "The tipping of the bucket takes a finite time, of the order of 0.2 sec. While the bucket is going through the first half of its motion, water is still running into the full side; therefore the amount of water collected for each tip of the bucket will be a linear function of the rate of rainfall....The error is not serious except for rates in excess of 2 inches an hour,...." (Middleton, 1943). "Since no record is made until 0.01 inch of rain has fallen, however, they are not recommended for use in maritime climates where very light drizzle is the rule" (Middleton, 1943). In the light of the finite length of time required in the tipping of the bucket, it seems reasonable that the bucket material should be as light as possible, although the water which tips the bucket is a large portion of the total mass of the bucket. Some manufacturers are fabricating buckets of plastic material. The traditional bucket pair is fabricated of brass or brass with chromium plating.

The commerical tipping-bucket gages which are heated in order to be useful in measuring precipitation at below freezing temperatures usually have two electric heaters which are thermostatically controlled. One heater is usually placed below the tipping bucket and the other warms the receiving collector - surfaces. They should be insulated to reduce heat loss. Unfortunately, a surface which is elevated above ambient temperature enhances evaporation of melted precipitation from that surface and sets up a column of convection above the gage orifice which will influence the path of precipitation particles about the orifice. The tipping-bucket gages may be operated so that the liquid precipitation drains out the bottom of the instrument after measurement is completed.

The weighing-bucket gage, sometimes called the universal rain and snow gage, may be used for telemetry also. Telemetry is accomplished by the movement of a precision linear potentiometer in response to the weight of the accumulated precipitation as balanced by an isoelastic spring or counterbalance. Output varies from 0 to 5 v dc and the gage may include a chart recorder for analog recording. Because the gage weighs the collected precipitation in solid or liquid form, heating is not necessary and is undesirable. The only consideration is to insure that the precipitation moves from the collector to the receiving bucket in as short a time as possible. A disadvantage of the weighing-bucket gage is found in the necessity of emptying the bucket when the accumulated precipitation or total bucket contents approaches 12 inches. The telemetry form of the gage includes a bucket over-flow, but this does not empty the bucket. In addition, it is desirable to melt the frozen precipitation, particularly snow, in order to reduce its bulk. An antifreeze solution is added to the bucket to melt the precipitation, but this reduces the effective volume of the bucket for the measurement of precipitation. This amounts to a loss of approximately 2 inches out of the 12 available.

Both the inconvenience and the cost of the available gages are reduced if there is no concern with frozen precipitation. A listing of some of the various manufacturers and the characteristics of telemetered raingages is given in Table 3.

Installation Procedures

The gage should be installed with its orifice level and the base firmly attached to the underlying surface. It should be mounted with the orifice as low as possible, but above any possibility of splash from the underlying surface and any blowing snow or resultant snow surface. Any gage installation likely to remain for a period of more than 2 years should be considered for mounting on a concrete base with studs protruding from the concrete to match the base or extension base of the gage. Any windshield should be mounted independent of the base of the gage to reduce the probability of the shield transmitting shocks to the gage. If the gage is to remain at the site temporarily, it may be mounted on a base that is bolted to stakes driven into the ground sufficiently to keep the gage level and stable.

Table 3. Listing of telemetered gages and their characteristics.

Tipping-Bucket Gages

WEATHERtronics, Inc., 2777 Del Monte St., West Sacramento, CA 95691

Model 6020, thermostatically-controlled electrical heaters of nichrome wire imbedded in insulated double case. Buckets are metal.

Model 6010, unheated.

Robert E. White Instruments, Inc., 33 Commercial Wharf, Boston, MA 02110

Model 8-578, unheated, metal buckets.

Model 8-501, unheated, polyethylene buckets.

Model 8-511, thermostatically-controlled electrically-heated with insulated case. Buckets are polyethylene.

Sierra Weather Instrument Corporation, P. 0. Box 771, Nevada City, CA 95959

No. 2500, unheated, stainless steel buckets.

No. 2500 E, thermostatically-controlled electrically-heated. Stainless steel buckets.

Belfort Instrument Company, 1600 So. Clinton St., Baltimore, MD 21224

No. 5-405A, unheated, metal buckets, 12" diameter orifice.

No. 5-405HA, thermostatically-controlled, electrically-heated in insulated case. Metal buckets. 12" diameter orifice.

Weighing-Bucket Gages

Belfort Instrument Company, 1600 So. Clinton St., Baltimore, MD 21224

No. 6089-12, without recorder.

No. 6089R-12, with recorder.

Rate-of-Rainfall Transmitter

Belfort Instrument Company, 1600 So. Clinton St., Baltimore, MD 21224

No. 6069A, unheated.

Prices have not been given since they are subject to change without notice.

There is an instrument available for measuring the instantaneous precipitation rate if this is desired. It measures only liquid precipitation with the electrical output as a variable voltage.

Density Requirements for Radar-Rainfall System

The CHAP results have led to conclusions and recommendations for raingage sampling required in conjunction with the real-time, prediction-monitoring system. The sampling criteria apply specifically to convective rainfall in the Midwest, but can be applied to other areas having similar precipitation climate, in which urban flash-flood rainfalls are primarily a product of convective storms in the warm season.

For prediction purposes, it is essential to have quantitative estimates of rainfall intensity in storms before they reach the urban area. For prediction, our studies indicate one should have telemetered recording gages spaced approximately 10 mi apart. These gages should be situated 20 to 40 mi beyond the urban network in the directions from which most storms move to allow for adjustment of the radar indicated rainfall 1 to 2 hours prior to moving across the monitored area. In the Midwest, this would be from the south through west to northwest.

Within the urban area, greater accuracy in the measurement of rainfall would be needed than in the periphery region where the measurements would be primarily for prediction purposes. For radar quantitative measurements of rainfall over an urban storm-sanitary system (storm monitoring) the telemetered raingage density should be increased to one gage every 5-7 mi if possible, so as to keep the average measurement error of short-interval intensities (30 minutes or less) 520%. However, even a lesser density, such as recommended for the surrounding rural area, would be quite helpful in interpreting the rainfall intensity distribution within the urban area.

Cold season rainstorms seldom produce heavy amounts that pose an urban flooding problem in the Midwest and other areas of similar precipitation climate. Much of the precipitation is steady rain that tends to be quite uniform spatially. If a need exists to measure this rainfall with radar, the associated raingage density could be considerably less than in the warm season when highly variable convective rains prevail. Based on earlier studies at the Water Survey (Huff and Shipp, 1969; Huff, 1970a), a raingage spacing of 20 mi should be adequate for adjusting the radar-indicated intensities in winter rainstorms approaching an urban area. Within the urban area, a spacing of 10 mi is considered sufficient for monitoring purposes. However, in most instances the primary interest will center around the potential of urban flooding during summer or during convective rain periods. Thus, except when raingage servicing or maintenance is a problem, the summer network should be used in all seasons.

There is little information upon which to evaluate the density of measurements needed to adjust the radar return for accurate quantitative measurements in snow storms. These storms are occasionally a major urban problem, but more from the standpoint of transportation rather than flooding.

Since most heavy snowfalls result from steady-type precipitation, it seems reasonable to expect that the adjustment densities would be approximately equivalent to those for steady rains discussed above. However, most snowfall measurements are notoriously poor because of measurement problems, and more research is needed before the utility of radar for achieving accurate quantitative measurements of snowfall can be determined.

Density Requirements for Hydrologic Design Data

For accumulating rainfall data for point frequency analysis in an area of uniform precipitation climate, a network of recording raingages is not required. The NWS climatic network, which averages one recording gage per 600 mi^2 in Illinois, will usually satisfy needs in the absence of significant localized effects. However, in a large urban area, such as Chicago, the urban effect has been found to substantially alter the time and space distribution of heavy storm rainfalls (Changnon *et al.*, 1977). For evaluation of intraurban differences in point rainfall frequency distributions, a recording gage density of one per 5-7 mi is recommended.

For most urban hydrological applications, mean rainfall frequencies over areas of various sizes are needed. Mean rainfall frequencies can be obtained by developing relationships between point and areal mean rainfall in a raingage network operated for several years, preferably 5 years or longer, and then applying the point-areal mean relationships to point rainfall frequency relations developed from long-term point records. A recording raingage network is needed for this purpose. A gage spacing of approximately 3 mi is recommended, and the spacing should not exceed 5 mi. The 3-mi spacing is also recommended for isohyetal analysis and derivation of area-depth relations in heavy rainstorms. A 5-mi spacing is of questionable reliability in the time-space analysis of short-duration storms (less than 3 hours) and in analyzing isolated air mass storms in which great spatial variability exists.

The following discussion has been abstracted from a report by Huff (1970b), and provides quantitative estimates on the magnitude of the measurement errors when using the gage densities recommended for urban hydrometeorological uses in the foregoing paragraphs. Table 4 summarizes the rainfall sampling needs for the real-time operation of forecasting-monitoring systems and for the collection of rain data for urban design information.

Mean Precipitation. From considerations of measurement accuracy, equipment costs, operational requirements, and data processing, a gage spacing of 3 mi is recommended for the measurement of areal mean rainfall in small basins. Also, this gage density is considered very satisfactory for deriving storm area-depth relations and adequate for estimating storm maximum precipitation. If this density can not be achieved for any reason, the gage spacing should never be greater than 5 mi. These recommendations are based upon results of various hydrometeorological studies made in the past (Huff and Neill, 1957; Huff, 1970b).

With a 3-mi spacing, the average sampling error in a large sample including all types of storms should not exceed 2-3%, even in short-duration storms of light to moderate intensity which normally exhibit the highest spatial relative variability. In fact, the above percentage error is based upon calculations for an average 1-hour storm with mean rainfall of 0.10 inch occurring in the warm season. One must understand, however, that the sampling error may exceed 5% in approximately 5% of the storms and, occasionally, increase to 10% or more.

The above error estimates are for all storms combined. The sampling error will maximize, on the average, for air mass storms. If only this storm type is involved in a seeding experiment, the average sampling error rises to 5-6% for a gage spacing of 3 mi. Similarly, the error can be expected to exceed 10% in 5% of the storms and reach 15-20% occasionally.

If the maximum gage spacing of 5 mi is used, the average sampling error increases from 2-3% with the recommended density to approximately 5-6% for all storms combined, based on the 1-hour, 0.1 in, warm season storm. Similarly, the average error in air mass storms increases from 5-6% to 9-10%.

From the standpoint of raingage sampling requirements, the use of very short-interval measurements of mean rainfall, such as 1-minute or 5-minute amounts, is not considered practical. In a study of 1-minute rainfall amounts on a 50-gage network, it has been shown that the average sampling error with a gage spacing of 3 mi ranges from 18 to 26% at rates of 0.1 in/hr (Huff, Shipp, and Schickedanz, 1969). In the same study it was found that the correlation between gages showed no significant increase with 5-minute and 10-minute amounts.

Pattern Analysis. Correlation decay with distance provides one means of estimating sampling requirements for establishing isohyetal patterns. From the study by Huff and Shipp (1969), it has been determined that the spacing of one gage every 3 mi recommended for areal mean precipitation measurements is generally satisfactory for pattern analysis. With this spacing, the variance explained on the average is approximately 90% for all warm season storms combined. It decreases to 75% for storms with durations less than 3 hours; otherwise, it is greater than 80% for all other storm durations, synoptic weather types, and precipitation types. The 5-mi spacing in the minimum acceptable network is of questionable reliability in short-duration storms (less than 3 hours) and in air mass storms since the variance explained decreases to 60% and 70%, respectively. Again, 1-minute to 10-minute stratifications of rainfall amounts are considered impractical, since variance explained is less than 60% with a gage spacing of only 1 mi for such short time-integrated amounts.

Detection and Areal Extent. Reference to a paper on precipitation detection (Huff, 1969b) shows that the gage spacing of 3 mi in the recommended experimental network is satisfactory for detection of all storms with significant precipitation and to measure accurately their areal extent. The spacing of 5 mi in the minimum network is also generally satisfactory for detection and areal extent measurements.

Rain Cell Analysis. A network with gage spacing of 3 mi is adequate for the detection and measurement of the areal extent of individual surface rainfall cells 90 to 95% of the time. The 5 mi spacing would be adequate for this purpose approximately 75% of the time.

Table 4. Rainfall sampling requirements for design and operation of urban hydrologic systems.

Application	Raingage Spacing, mi^2/gage Recommended	 Maximum Acceptable
Real-Time Operation of Systems		
a. Storms Approaching Urban Area	10	15
b. Storms Within Urban Area	5- 7	10
Urban Data Collection for System Design		
a. Point Rainfall Frequency	5- 7	10
b. Mean Rainfall Frequency	3	5
c. Individual Storm Analyses	3	5

Operational Use

The real-time acquisition of rainfall data from a dense network of telemetered raingages at a central point can provide information about the onset of rain, point rainfall amounts, areal average rainfall, and a measure of the storm movement. The accuracy of this information decreases as the gages are spaced farther apart. For example, if accurate measurements of the areal rainfall are required a raingage density of at least 1 gage/10 mi^2 would be required (Huff, 1970a). Also, unless the raingages are extended well beyond the area for which monitoring is required, the raingages can only provide reactive information. The operator of the water system can only react to the rainfall amounts that are telemetered to a central location after the rains have fallen. He cannot react to the future evolution of the storm.

Radar can provide information about the future evolution of storms. It can provide the speed and direction of a storm, the relative intensity of the storm, and can be used to make predictions about the onset and ending time of a storm. The radar signal provides a measure of the rainfall intensity using a relation between the reflectivity factor (Z) and the rainfall rate (R), which is sensitive to the drop size spectrum of the rain within the storm. The drop size distribution in storms, especially convective rainfall, varies from storm to storm and within storms (Jones, 1956; Atlas, 1964; Brades and Sirman, 1976). Thus, the most effective information which can be provided to the operator of a water system is a combination in real-time of the data from the telemetered raingage and the radar. The telemetered raingage data can be used to adjust the radar-indicated rainfall amounts. Then, the radar can be utilized to predict the future intensity of the storms over the area and can supply detailed information about the location of maximums and minimums of storm rainfall within the monitored area. Thus, the effective combination of radar and rainfall data can optimize the real-time storm information for an operator, so that rational decisions about the storage and deployment of storm runoff can be made.

COMMUNICATION SYSTEMS

Several types of communication links may well be required. Information from raingages should be made available to the computer; or the radar data must be available to the computer; and computer output data must be made available to the user. Again there are many options available in designing a system. The data rates vary considerably, and to a large extent depend upon the amount of preprocessing performed at the transmitting site. The availability of low cost digital electronic devices has decreased the cost of preprocessing and made it much more attractive than in the past. The inclusion of preprocessing lowers the amount of data that must be transmitted. In the case of the radar to computer data link, the processing must be performed ultimately. Therefore, it will be a matter of convenience and/or existing computer capabilities as to which stage of processing the data is supplied to the computer.

Radar-Raingage Communications

Dedicated Land-Line--Raingage data could be transmitted using a dedicated phone line which could provide a simple switch closure (or opening) indicating a measurement of an increment of rainfall. The timing and accumulation of the closures could be recorded at the radar station or the computer center by either mechanical counters or by directly interface with the computer. Such a system would provide lower cost transmitting stations, but moderate to high monthly land-line cost.

Dial Land-Line--The raingage could be interrogated by the computer which initiates a call to the station only when data is required. Thus, providing a means of reducing the monthly land-line costs. A dial-as-needed system requires a more complex sensor station to communicate with the computer. The essentials of an interrogated sensor station include an accurate time base, data buffering, call answering, data access arrangement, and electrical power. With proper engineering, a dial land-line provides high reliability and economical land-line cost.

A combination of these systems is also possible. In this scheme a number of raingages might be connected to a central station by dedicated land-lines. At the central station a processor would collate data, format it, and on command transmit the data to the central computer. Thus, the complexity of the stations at the individual raingages can be kept low and still maintain a relatively low land-line cost.

Telemetered Data Link--A telemetered communications system requires the additional capital investment of radio equipment at both the sensor stations and the computation station. However, the cost of radio equipment maintenance will be less than the cost of a dial type land-line system for long-term communication links in favorable climates. This system is capable of extremely high data rates and may be multiplexed to serve other functions.

Interrogated-Beacon Data Link--An interrogation-beacon scheme of providing remotely sensed data to the surveillance radar involves placement of a radar frequency receiver-transmitter at the sensor station. As the radar looks at the remote station azimuth the remote station receiver, after an appropriate delay to prevent interference with the reflectivity data, or on differing frequency, directs the transmission of a pulse coded message to the radar which decodes into the desired data. Conceptually, this technique seems very attractive and has been proposed by researchers for many years with very little field implementation. The technique was used in a weather service project in 1959 (Soltow and Tarble, 1959).

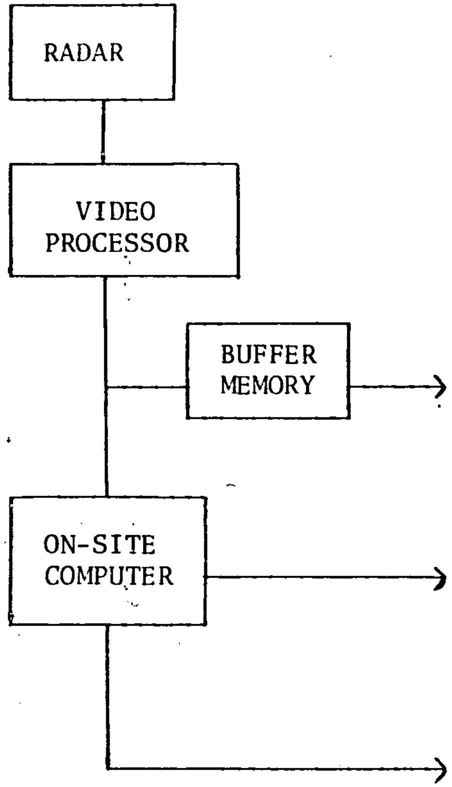
Radar System to User Communication

The communication of the radar information from the radar site to the user presents three options (Table 5) which differ primarily in the amount of processing done at the radar site. The first option calls for the transmission of the radar reflectivity directly from the video processor to a remote site where all of the computer analysis would be done. The advantage of this approach is that it requires a minimum hardware configuration at the radar site, and makes it the best candidate for an unattended radar operation. Another advantage is that all computation is done at the users site which will likely be more convenient for program development and modification. The primary disadvantage is that the required data rate demands a dedicated conditioned phone link which is more expensive than that required for the other options. An alternate communication system, a microwave data link to the remote computer, may be more economical than a dedicated phone line and would permit more rapid scanning of the storms. The high data rate would probably require a dedicated minicomputer at the computer site, which would either do all of the processing, or generate cartesian grids for transmission to a larger computer for cell tracking and forecasting.

The second option would be to install a small computer at the radar site. The function of the computer would be to generate the cartesian rainfall amount grids. This reduces the data transmission rate requirement considerably. For example, a grid of 4096 points could be transmitted in 35 seconds over conventional switched telephone network. This would need to be done every 3 to 5 minutes. This option is also a good candidate for unattended radar operation. The on-site computer could operate without disks or other mechanical devices which require occasional operator assistance. The on-site computer program would be relatively simple. The complex programs would be performed by the remote computer which would presumably be a larger and more conveniently located computer. It could be either a dedicated minicomputer, or a larger computer which is used for other tasks as well.

The third option is to have a computer at the radar site do all the computation needed to monitor and forecast rainfall. The results of these computations could be transmitted and displayed on a simple terminal at the user's location.. The main advantage of this approach is to minimize the data rate and the equipment at the user's end of the data link. The disadvantage of this approach is that it puts the complex computer programs at the radar site which is likely to be in a remote and inconvenient location. If the monitoring and forecasting scheme requires human input, the meteorologist must also be located at the radar site.

Table 5. Three communications options.



DATA LINK	DATA SENT	DATA SPEED	DUTY CYCLE
Conditioned phone line or microwave link to remote computer	Radar reflectivity in polar coordinates	16,000 bits/ second	Continuous
Switched or leased telephone line to remote computer	Rainfall cartesian grids	1200/bits second	35 seconds every 5 minutes
Switched or leased telephone line to remote terminal	Final forecast rainfall amounts	300-1200 bits/ second	30 seconds to 2 minutes every 15-30 minutes

In summary, there are many communications options within the realm of the existing technology. There should be no difficulty in meeting the communication requirements of any specified system of this type.

DATA ANALYSIS AND INTERPRETATION

The final component within a radar-precipitation system is the synthesis of all data through analysis and interpretation. This results in a product for the user in a format that is commensurate with its application. For example, an elaborate grid of radar-rainfall values would be only partially useful if all that is needed is an average value for a basin or an area. The final product produced by a radar-rainfall system may be of immediate use, such as a warning, or it may provide data for other calculations or models to predict runoff, to assess water quality, or to determine other water-related needs.

The final product may be totally objective; it may be a combination of objective analysis and people, who either make adjustments throughout the process or only interpret the objective output; or it can be produced totally by an operator. As experience is gained with radar-rainfall systems more of the product can be made objective, but in the developmental stages people must play a major role in the analysis and interpretation of any monitored or forecasted rainfall values.

Depending on the requirements of the user, the analysis and interpretation procedure can range from a simple set of tools and/or operators to highly complex radar-computer systems which are accompanied by a wide range of additional meteorological information and calculations. In this section, an attempt will be made to describe the possible range of data analysis and interpretation needs that are available and applicable today. Also discussed are some possible future capabilities, which conceivably could be added to the system array to aid in the monitoring and forecasting of quantitative rainfall amounts. In addition, an attempt will be made to define 1) the time constraints of objective forecasting techniques using radar observational data, and 2) the role people and objective techniques can play in forecasting precipitation for time frames longer than 3 hours.

System Analysis and Interpretation

The needs of the user help determine the form of the final product, and subsequently the analysis and interpretation needs. For example, if the user only needs to know if it is going to rain in the next several hours, or if the rains are going to move away or dissipate, this question can often be answered by a radar with no digital equipment and a person capable of some very simple analysis techniques. Such a problem can be answered by a series of overlays or an operator with a grease pencil who can make the analysis directly on the scope and provide adequate information. In addition, facsimile equipment is available which can obtain radar information from NWS radars and similar analysis techniques can be employed using this equipment. However, only qualitative estimates of the rain amounts can be made with the above equipment.

Slightly more detailed estimates of rain amounts (none, light, heavy) can be made using radars equipped with iso-echo presentations of radar returns, which differentiate radar-indicated rainfall intensities using various tones of black and white or colors. Many TV weather shows give similar presentations of radar-rainfall return. However, such equipment does require that the analog signal be transmitted in a digital format, and the data display gives a range of rainfall rate. Therefore, the final presentation actually loses some of the available information. The equipment is available commercially. Each tone or color represents a range of radar-rainfall intensities, not adjusted by any ground-truth rainfall measurements, and only qualitative rainfall estimates can be made. However, if for a particular use such qualitative estimates are adequate, then this type of system would be considered effective. For example, the Urban Drainage and Flood Control District located in Denver, Colorado, is utilizing remote color radar displays, along with current meteorological and hydrologic information, to aid in the prediction of flash flood potentials for a six-county region (Henz, 1980; Pearl, 1980; DeGroot, 1980).

With the advent of digital radar processing and some type of on-line computer capabilities many new data analysis techniques became available for real-time use, and many of the qualitative parameters which had previously been done by hand can now be done objectively. Not only can objective techniques be applied, but much more detailed analyses of precipitation systems can be done in real-time. Previously, such detailed data analyses were only possible by research groups after the event, who would try to analyze the fine-scale detail of the evolution of convective systems or follow intensity maximums within general precipitation systems. The digital capabilities provide more exacting presentations of radar-indicated intensities than are possible from the qualitative presentations described above.

The digital capability allows radar-indicated rainfall amounts to be collected at many points within a region of interest. The separation or grid spacing of these points is limited or defined by the computer storage, the radar characteristics, and the user's needs. Applications of this type have been made by Wilson and Pollack (1979), Brandes (1975), Brunkow (1980), Bellon and Austin (1978) and Harrold *et al*. (1974). Such an arrangement is similar to placing an extensive raingage network over a large area, which would be cost prohibitive for the real-time or even climatic collection of precipitation amounts. During the summer of 1979 a demonstration of a radar-precipitation system over northeast Illinois used a grid spacing of 2 miles (Brunkow, 1980; Vogel, 1980) to collect real-time, radar-indicated precipitation data. Conceptually, this was equivalent to having 4096 raingages over 16,384 mi^2, or a raingage every two miles. Thus, a detailed presentation of cumulative storm or instantaneous radar-indicated rainfall was available in real-time for a large area. Wilson and Pollack (1977) used a similar technique to provide a precipitation climatology which occurred during the International Field Year of the Great Lakes.

The real-time calculations of storm motion (Bellon and Austin, 1978; Browning, 1979) or of convective entities within the storm (Brunkow, 1980; Crane, 1979) can be readily performed by on-line computers with adequate facilities. The objective analysis techniques can make detailed computations of elements embedded within a general precipitation system. The details of such computation are dictated by the radar capability and the requirements of the user. For example, Crane (1979) made detailed computations of echo elements which have a diameter of about 3 miles. Such elements have average life spans of 20 minutes or less. Nevertheless, these convective elements are the ones that could be responsible for extreme wind shears or surface gustiness at or near the surface at airports and can have dramatic impacts upon aircraft which are landing or taking off (Fujita, 1979). On the other hand, Bellon and Austin (1978) determined the speed and motion of general precipitation systems for use in a forecasting system developed for the Montreal area. Thus, the computation scheme which is developed is defined by the capabilities of the overall system and by the user.

Radar-indicated rainfall within a precipitation system can vary dramatically from the rain occurring at the surface. To compensate for this inherent error, it is necessary to adjust the radar-indicated rainfall with telemetered raingages. A variety of methods have been proposed (Brandes, 1975; Cain and Smith, 1976 and 1977; Brunkow, 1980; Woodley et al., 1975; Eddy, 1979; Huff, 1967), but the actual system which is used is dictated by available computation capability and the user's needs. Some methods such as the Brandes (1975), can be applied climatically as was done by Wilson and Pollack (1977), because no adjustment is required to the radar-indicated rainfall amounts until after the storm. However, the real-time adjustment of storms requires that the Brandes technique be altered. Brunkow (1980) adapted the Brandes technique to update the Z-R equation using accumulated radar-indicated rainfall amounts and accumulated surface rainfall amounts from telemetered raingages every 30 minutes. If the real-time needs of the user does not require updating or adjustment of the radar-indicated precipitation as often, the Cain-Smith (1977) method could be applicable. This method does not require updating of the radar-indicated precipitation amounts until the error between the raingage-measured precipitation and the radar-indicated precipitation is greater or less than some predetermined value. These are some methods which have been devised to adjust radar-indicated rainfall, and new methods, depending on the needs of the users, will be devised in the future.

Objective methods using the computer to forecast quantitative rainfall amounts can be developed. The radar-indicated rainfall system can be advected forward in time after determining the speed and direction of movement of the system (Bellon and Austin, 1978), or the forecast of the radar-indicated rainfall can include the potential increase or decrease of precipitation intensity and/or areal size (Changnon et al., 1980). At the present time most of these forecast techniques, whether they are forecasting the movement of general precipitation systems or the growth and decay of convective entities, are based upon extrapolation; i.e., the rain quantity forecasted is based upon the past performance of the precipitation system, and it is assumed that the system will continue to perform in the same manner. An exception to this is Crane (1979), who also allows the generation of new convective elements based upon a predetermined formula, developed from a climatic sample, albeit limited. At the present time the objective techniques take into account data available from the radar. Some plans are presently being made to incorporate satellite data into the forecasting of general precipitation systems (Browning, 1979; Lovejoy and Austin, 1979).

With experience and once adequate controls have been devised, the system can be totally objective or the system can be designed to be an interactive graphics system in which the operator is constantly called upon to make decisions about the validity of any calculations or data acquisitions. The operator's role will be formidable, especially in the early stages, of any radar-precipitation system in operation. Many decisions must be made and it is not possible to preprogram a computer system to answer all the possible permutations. Also, the role of the operator depends on the capacity and complexity of the system. For example, if the area of a convective cell has increased some 400% in the past 10 minutes, which is not unusual during the early stages of a thunderstorm, an objective forecast analysis, based upon the performance of convective activity during the past 10 minutes, can allow this cell to continue to grow at a rate of 400% every 10 minutes, if left unchecked. If the original cell size was 2 mi , the cell would have grown to 128 mi^2 after 30 minutes, and after 60 minutes it would cover an area of over 8000 mi . Such growth of a single convective element is unreasonable. In addition, intensity and areal changes can vary considerably from one convective system to another, even if they are moving across an area within 1 to 2 hours of each other. Some objective controls can be developed, but an operator must be available to alter any unreasonable estimates. As new data analysis techniques are added or changed within a system, an operator must closely monitor these systems. With time it is anticipated that more and more of the calculations can become objective.

Long-Range Prediction

The longer range prediction of quantitative precipitation amounts and of precipitation system movement (greater than 3 hours) is primarily dependent on man aided by objective analyses and forecasts provided by computer systems or objective aids. Precipitation predictions of 3 to 6 hours are usually accomplished by a combination of the present location of precipitation systems and careful mesoscale analysis (Mogil and Groper, 1976). Forecasts of precipitation system movement and potential amounts for more than 6 hours in advance are usually the product of man and his interpretation of computer-derived objective analyses and forecasts.

Many numerical and statistical forecast models have been developed since the 1940's and there has been much advancement in the capabilities of the models to more closely approximate the physics of the atmosphere (Haltiner, 1971; Shuman, 1978). However, most of the advancements have resulted in better depictions of the surface pressure and upper-air height fields, rather than quantitative precipitation forecasts (Stackpole *et al*., 1978). The interpretation of the resulting dynamic forcing and vertical motion fields from the numerical models and the forecasting of precipitation has been the job of man. Refinements of these models to forecast individual parameters (maximum temperature, probability of precipitation and others) at specific stations or for small regions have been made using statistical relations of the present weather and parameters from the numerical models. The placement of large-scale precipitation systems, such as exist during the winter, are often predicted well by the models and man, but the placement of precipitation systems during the summer, which is dominated by convective precipitation processes, is not good. These precipitation processes often act on a scale less than the grid spacing of the numerical model, and the temporal and spatial resolution of the data is often inadequate for detailing the location of the convective precipitation system (Perkey, 1976). Thus, the forecasting of quantitative precipitation amounts and the placement of precipitation systems for longer periods is primarily the result of the interaction between man, objective analysis, and forecasting techniques.

Some advancements in mesoscale modeling and forecasting techniques are envisioned in the future. However, unless a major breakthrough is made, it is anticipated that the objective forecasting of precipitation placement and amounts, especially during the summer, are at least 10 to 20 years in the future. Even then the model interpretation will require coupling the experience of man with the model before a forecast of precipitation amounts can be made.

Future Expansion of the System

The increased capability of computers and of remote sensing devices will further enhance the abilities of radar-rainfall systems to monitor and forecast quantitative precipitation amounts. For example, satellite observations are available today in near real-time. Such observations provide the operator with more detailed updates of the position of dynamic features within the atmosphere than conventional meteorological observations, which are limited temporally and spatially. From this same data base, mesoscale cloud features, not detectable by radar, can aid the operator in determining whether the system may dissipate or be enhanced (Purdom, 1979).

Several researchers (Scofield and Oliver, 1977; Lovejoy and Austin, 1979; Sickler and Thompson, 1979) have developed techniques using satellite data to provide estimates of the amount of rain falling from various rain systems. These techniques do not have the detail or accuracy possible from a radar-rainfall system. However, as these techniques are refined and as new remote sensing devices on satellites become available, it is anticipated that these new tools can be incorporated with the radar-rainfall system to increase the warning time, and to provide auxiliary information for use either objectively by the computer or subjectively by the operator.

Many urban regions have installed real-time weather networks to provide information about air pollutants. It is possible that these networks could serve a dual role. Ulanski and Garstang (1978a and b) have noted a relation between the surface wind convergence and the initiation and rainfall rate in convective storms. Thus, these relations or similar relations could be used to provide weather information to the radar-rainfall systems which could aid in the monitoring and forecasting of convective rainfall. It is such rainfall which is responsible for many of the locally heavy rainstorms within the Midwest.

Climatological relations could be used to aid in the forecasting of precipitation for urban or flood-prone regions. For example, the distribution of precipitation over and downwind from an urban region can be affected by the urban area itself (Huff and Vogel, 1978). It is possible that these man-induced changes of precipitation could be made part of the monitoring and forecasting scheme for a local area. In addition, natural features such as hills, mountains, lakes and oceans can also affect the distribution of precipitation in a local area. Statistical or physical relations could be established for these phenomena and could be incorporated as part of the radar-rainfall scheme.

Advances in the mesoscale modeling of convective storms and systems have been made in recent years (Achtemeier, 1978; Klemp and Wilhelmson, 1978). As more advances are made, it may be possible to update the meteorological forecasts with real-time modeling capabilities to aid in determining whether a rainstorm is increasing or decreasing in areal coverage and/or intensity. This type of information could either be fed directly into the radar-rainfall system or be made available for use by the operator. These are but a few of the possible advances that can be anticipated in meteorology over the next several years, and which could improve the operation of a real-time, radar-rainfall system.

HYDROMETEOROLOGICAL PROPERTIES OF CONVECTIVE STORMS

Introduction

Our rainfall studies in the Illinois area have focused on the *principal* rainfall problem for storm-sewer system, that is, heavy convective rainfall. Many of the findings on precipitation are considered directly transferable to all cities in the eastern half of the United States, and the principles are generally applicable to any areas which must deal with convective rainfall.

Our studies thus provide directly useful data and information. They also point to the *issues and type* of information one should seek in any areas where similar or drastically different convective rainfall regimes exist. Much of this analysis is aimed at application of the rational method of basin analysis. These local issues include:

1. The relation between basin point and area mean rainfall frequencies;
2. Antecedent rainfall (that before heavy rains or storms) distributions;
3. Duration of periods between heavy storms;
4. Orientation and movement of heavy storms;
5. Synoptic weather conditions associated with heavy rains;
6. Heavy raincell characteristics;
7. Temporal rainfall distribution within storms; and
8. Spatial distributions of storm rainfall.

Relation Between Point and Areal Mean Rainfall Frequencies

An important parameter to urban hydrologists and urban planners is the frequency distribution of heavy rainstorms of various intensity and duration. The frequency distributions of point rainfall is readily available in published reports (Huff and Vogel, 1976; Hershfield, 1961). Of even greater importance is the frequency distribution of areal mean rainfall in heavy storms. However, raingage networks of sufficient density to derive this information have seldom been available in the past. This problem can best be solved by relating point and areal mean rainfall relations through use of data for relatively short periods of time collected on the very few dense networks adequate for this purpose. Then, this relationship can be used in conjunction with long-term point rainfall data to provide estimates of areal mean rainfall frequencies. Earlier studies (Huff, 1956; Hershfield, 1961) had shown the applicability of this approach. Data collected on the CHAP network were used to examine point-areal mean rainfall relations in the large urban area of Chicago and to determine whether the relationship varied significantly from the rural relations derived in the earlier study. Considering natural sampling variability, the Chicago results were in close agreement with those previously obtained in studies by the National Weather Service and by the Illinois State Water Survey. There was no evidence found in the CHAP or earlier METROMEX studies at St. Louis that the point-areal mean relationship varies significantly between rural and urban areas.

Table 6 shows the relationship between the frequency distributions of point and areal mean rainfall for areas ranging from 10 to 400 mi^2 and storm durations of 1 to 24 hours. The ratios are averages determined from use of all available information on the subject. The table was extracted from curves derived for each storm duration. Table 6 is applicable to the Midwest and other areas where the heavy storm rainfalls are usually associated with convective storms.

The use of Table 6 is illustrated by the following example. Assume one wishes to determine the 3-hour mean rainfall which will occur on the average of once in 25 years on an area of 75 mi^2 in the vicinity of Chicago. According to Ackermann (1970), the 3-hour, 25-year point rainfall for the Chicago area is 3.4 inches. Table 6 shows the conversion factor is 0.88 for 3-hour rainfalls on 75 mi^2. Multiplying 3.4 in. x 0.88 gives an areal mean rainfall of 3 inches.

Antecedent Rainfall Distributions

The amount of rainfall preceding heavy storms is of major importance in both flood prediction on a real-time basis and in the design of hydrologic structures. For design purposes, the probability distribution of rainfall amounts for several days preceding a heavy storm event is of prime concern. As part of the CHAP research, data for dense networks that have been operated by the Water Survey in Illinois in the past 25 years were studied to provide an answer to this problem (Huff *et al.*, 1978). Analyses were confined to the warm season from mid-April to mid-October when convective rainfall predominates and most of the flash-flood storms occur in Illinois and the Midwest. Probability distributions were derived for 1 to 10 days preceding all storms in which the network mean rainfall equalled or exceeded 1 inch. Distributions have been computed for areas ranging in size from 10-400 mi^2. These are areas which are of major interest in urban and small watershed hydrology.

Table 6. Ratio of areal mean to point rainfall frequencies in heavy storms.

Storm Period (hours)	Ratios for Given Area (mi^2)					
	10	20	50	75	200	400
1	0.93	0.89	0.83	0.77	0.68	0.63
2	0.95	0.93	0.89	0.83	0.75	0.71
3	0.97	0.95	0.92	0.88	0.81	0.78
6	0.97	0.96	0.94	0.90	0.86	0.83
12	0.98	0.97	0.95	0.93	0.90	0.87
24	0.99	0.98	0.96	0.94	0.92	0.91

Results are shown in Table 7 which presents probabilities for selected areas of 10, 100, and 400 mi^2 during antecedent periods of 1 to 10 days. Amounts in the table were abstracted from probability curves derived for each specified situation. Table 7 can be used as a design guide in Illinois in particular and in the Midwest in general.

Table 7 shows that the antecedent rainfall tends to be greater as the sampling area increases. This is related to a strong trend for heavy convective storms on the larger areas to be associated with organized convective activity of a macroscale nature and to occur during periods of relatively heavy rainfall in the general region. Whereas, a single air mass shower of strong intensity could produce a 1-in mean on 10 mi , it would require a storm system of considerable areal extent to produce a mean of this magnitude over 400 mi^2. Intense, isolated air mass showers frequently develop in summer during periods when rainfall is not widespread.

Time Between Successive Heavy Storms

The frequency with which one heavy storm may follow another is a matter of concern in hydrologic design and operations. Huff (1980) has investigated this problem in conjunction with hydrometeorological studies of Illinois basins. Figure 4 taken from this study has been included in this report for guidance to hydrologists who may have need for such information in designing urban hydraulic structures in the Midwest.

Figure 4 shows the frequency distribution of elapsed time between storms having average recurrence intervals of 2 to 5 years. The elapsed time in months is plotted against probability in percent.

Table 7. Probability distributions of antecedent rainfall for 1 to 10 days on selected areas in storms producing rainfall of 1 inch or more.

Average rainfall (in) exceeded for given antecedent period (days) and area (mi)

Probability (Percent)	1 Day			2 Days			3 Days			5 Days			10 Days		
	10	100	400	10	100	400	10	100	400	10	100	400	10	100	400
5	1.04	1.40	1.80	1.48	1.68	2.00	1.64	1.88	2.16	2.00	2.28	2.48	3.08	3.40	3.56
10	0.60	0.84	1.16	0.96	1.20	1.40	1.08	1.36	1.60	1.48	1.68	2.00	2.40	2.64	2.84
20	0.24	0.36	0.56	0.40	0.68	0.84	0.56	0.80	1.00	0.96	1.16	1.44	1.68	1.88	2.20
30	0.08	0.12	0.28	0.16	0.36	0.52	0.28	0.48	0.64	0.68	0.80	1.00	1.28	1.44	1.72
40			0.12		0.16	0.28	0.12	0.24	0.40	0.40	0.56	0.72	1.00	1.12	1.36
50						0.16		0.12	0.24	0.24	0.36	0.48	0.76	0.84	1.08

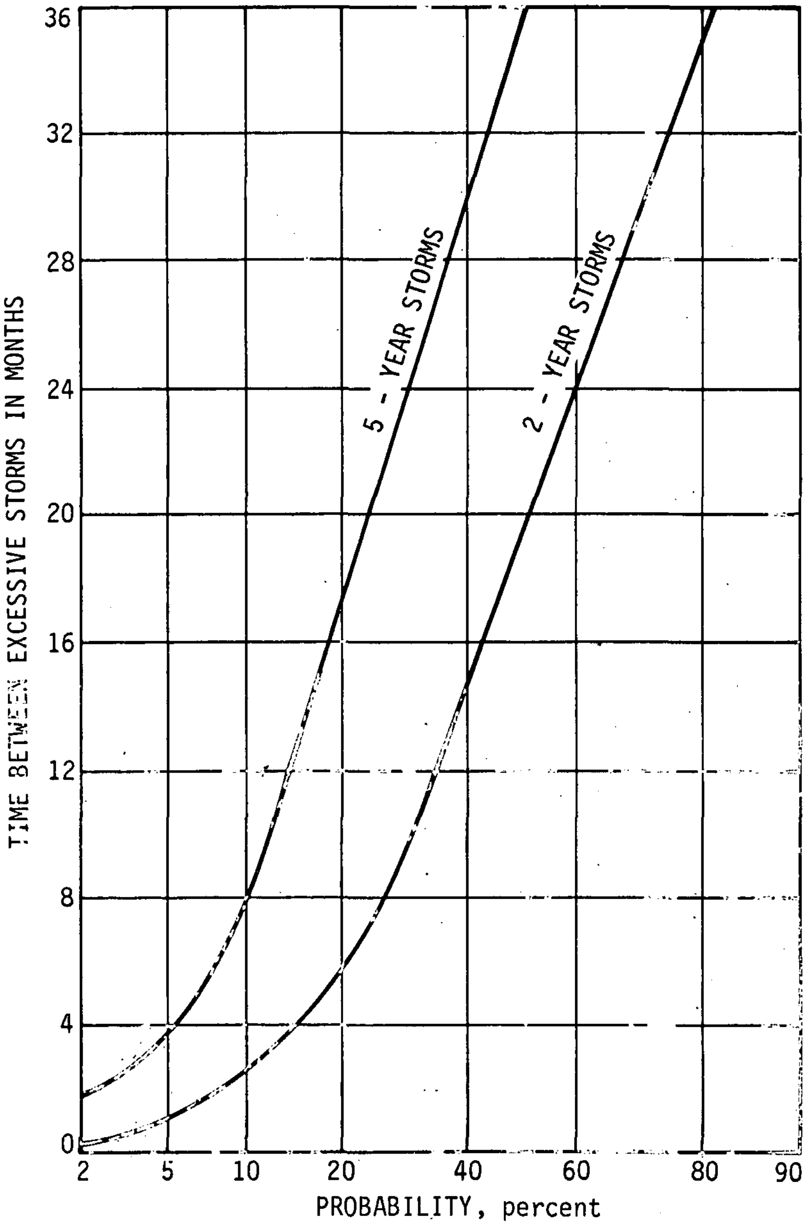


Figure 4. Time between successive rainstorms. i

Use of Fig. 4 is illustrated by the following example. Assume one wishes to determine the probability of two storms with mean rainfall equalling or exceeding the average 2-year recurrence value following each other within a period of 1 month, 6 months, 12 months, and 24 months. Moving horizontally from the 1, 6, 12, and 24-month points on the y-axis to the 2-year curve gives the desired probabilities. The probability of two such storms following each other within 1 month is 4 percent, or one chance in 25 that the next 2-year or greater storm will occur within one month. Similarly, the probability is approximately 22 percent that the next storm will come within 6 months, 36 percent that it will occur within 12 months, and 60 percent that it will take place within 24 months.

Orientation and Movement of Heavy Storms

Several studies of the orientation of heavy storms have been made in Illinois utilizing historical data (Huff and Semonin, 1960), field surveys of severe rainstorms (Huff, 1979), dense raingage network data (Huff, 1967), and radar storm tracking (Changnon and Huff, 1961). Results have shown that the major axis of heavy storms is most frequently oriented from SW-NE, WSW-ENE, W-E, or WNW-ESE. As the intensity and areal extent of flood-producing storms increases, their most frequent movement and, consequently, the orientation of the storm core veers from SW-NE toward WSW-ENE and W-E. The Huff and Semonin study (1960) was concerned with large-scale storms in which the mean rainfall over 10,000 mi^2 averaged 1 inch or more. The most common orientation in these storms in which storm center amounts equalled or exceeded 5 inches was WSW ENE, followed by W E and WNW-ESE. Field surveys of severe storms in Illinois also showed that there storms were most frequently oriented WSW-ENE. Huff and Vogel (1976) obtained similar results for heavy storms crossing the Chicago metropolitan area. Huff (1967) in a study of 260 network storms in which the mean rainfall exceeded 0.50 inch over 400 mi^{2}showed most frequent orientation from WSW-ENE, followed closely by SW-NE. The increase in SW-NE storms is related to the incorporation of less intense storms in this sample than in those discussed above. The study of radar-depicted precipitation lines also showed a WSW-ENE orientation most frequently (Changnon and Huff, 1961). Studies of the orientations of the CHAP storms (Changnon *et al*., 1978) show general agreement with the earlier findings reviewed above.

Information from the several studies was used to develop the frequency distributions of storm orientation summarized in Table 8. The first frequency distribution is applicable to very heavy storms in which rainfall amounts at the storm center equals or exceeds 3 inches in 2 hours or less. These storms usually encompass areas of several hundred to several thousand square miles with amounts of 1 inch or more. The frequency distribution for moderate storms includes those in which central amounts are 1-3 inches. These occur much mors frequently than the heavy storms, encompass less area than very heavy storms, and typically last 3 to 6 hours. Table 8 is considered applicable to the Midwest and other areas of similar precipitation climate, and is recommended for use where an estimate of storm orientations is needed.

When viewed in their entirety, heavy rainstorms most frequently exhibit an elliptical shape. This shape tends to become more elongated (increasing ratio of major to minor axis) as the area encompassed by the storm increases.

When only partial storms are analyzed, such as in a raingage network of limited areal extent, the network storm patterns tend to become less distinct in shape. Huff (1967) has shown that on a densely-gaged area of 400 mi^2 in Illinois, the network storm shapes tended to cluster into the four types shown in Fig. 5. Recent analyses of storms on the much larger CHAP Network (approximately 4000 mi^2) indicate a predominance of the same four types, although their frequency distribution is different.

However, for design purposes it is likely that the hydrologist will prefer to use a single, typical shape for modeling purposes. The elliptical shape is recommended for this use. Figure 6 provides an average shape curve for elliptical storms that was derived from heavy storm studies in Illinois (Stout and Huff, 1962). This figure can be used for guidance by urban hydrologists in Illinois and the Midwest.

Figure 6 shows the ratio of major to minor rainfall axis as a function of the elliptical area encompassed by the enveloping isohyet of the rainstorm system. The shape did not vary significantly with increasing rainfall in the heavy storms studied. For example, assume one is interested in the average dimensions of the rainfall pattern within an area of 200 mi^2 enveloped by a 2-in elliptical isohyet. Reference to Fig. 6 shows the average ratio of the major to minor axis of the enveloping ellipse would be 2.55 in this situation. Average storm patterns over areas of various sizes can be constructed from Fig. 6.

Table 8. Frequency distribution of heavy rainstorm orientations.

Storm Orientations		Storm Intensity	
General Direction	Azimuth (deg.)	Heavy*	Moderate*
		Percent of Storms	
SW-NE	220-239 to 040-059	9	25
WSW-ENE	240-259 to 060-079	31	27
W-E	260-279 to 080-099	21	18
WNW-ESE	280-299 to 100-119	18	10
NW-SE	300-319 to 120-139	11	10
Others		10	10

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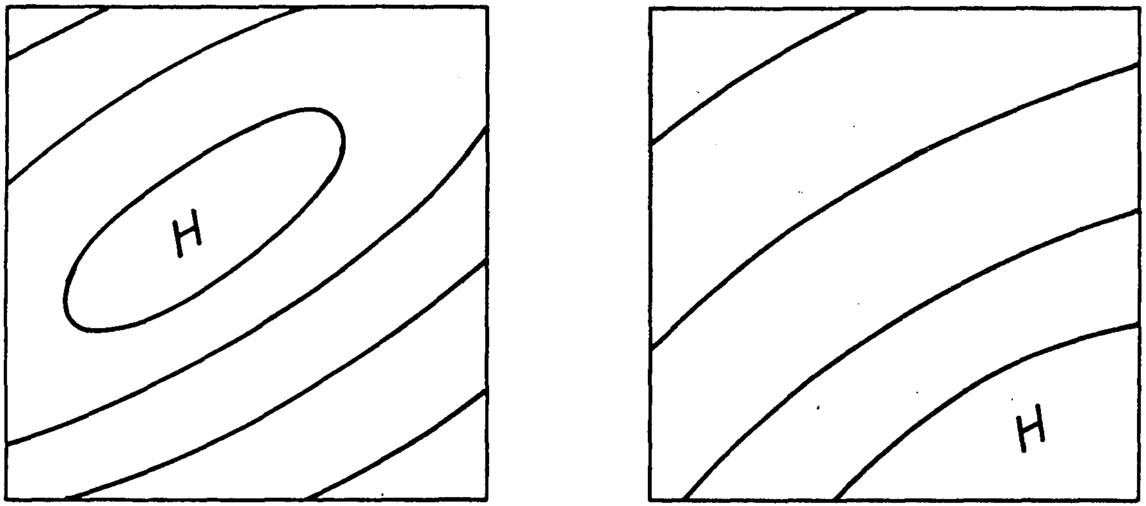
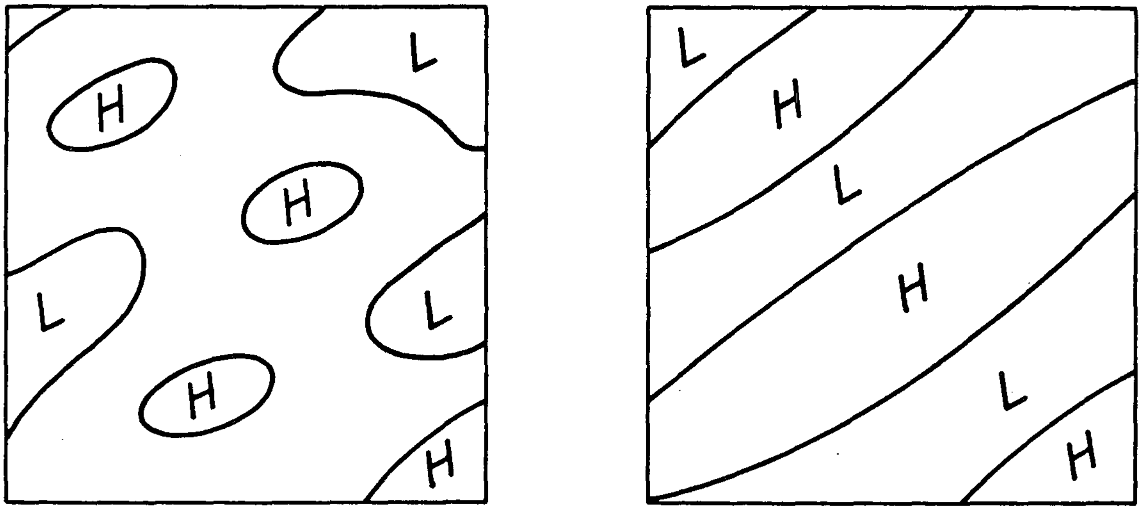
*Heavy: Storm center amounts > 3 in.
*Moderate: Storm center amounts = 1-3 in.



a. CLOSED ELLIPTICAL

b. OPEN ELLIPTICAL



c. MULTICELLULAR

d. BANDED

Figure 5. Major types of storm patterns.

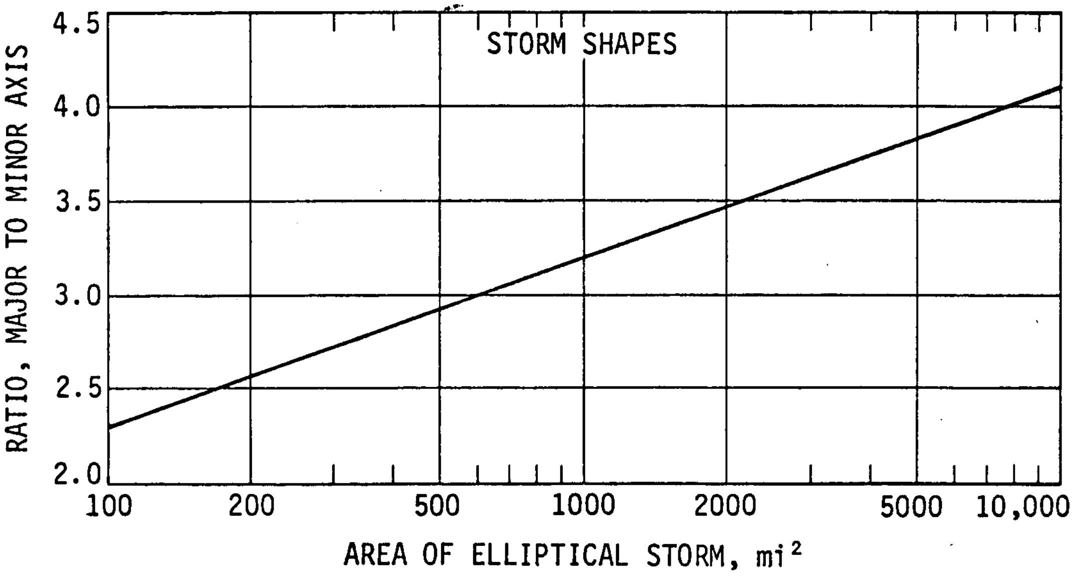


Figure 6. Mean shape factor.

Synoptic Weather Conditions Associated with Heavy Rainstorms

In Illinois and the Midwest, heavy rainstorms are usually associated with organized convective activity, which, in turn, is most frequently associated with cold fronts, quasi-stationary fronts, and squall lines or squall areas that develop in conjunction with the fronts. Except over very small areas, flash-flood storms are seldom associated with unorganized air mass activity. In our urban studies (METROMEX and CHAP), no evidence has been found that significant differences exist between urban and rural areas with respect to synoptic weather systems that produce heavy storms.

Several studies have been carried out at the Illinois State Water Survey to define better the relationship between synoptic weather conditions and heavy rainstorms. For example, Huff and Semonin (1960) studied the synoptic weather conditions associated with relatively large-scale heavy rainstorms in Illinois having durations of 24 to 48 hours and found them to be most frequently associated with cold and warm front activity. Huff and Vogel (1976) made a study of heavy 1-day storms in Chicago and northeastern Illinois, and found that cold fronts and squall lines (usually pre-frontal) were most frequently associated with these heavy storms. In a study of 8 urban areas, Huff and Changnon (1972) found that cold fronts were the most common type of storm system associated with rainstorms in the eastern part of the country. In METROMEX, the 5-year urban study at St. Louis, Changnon *et al*. (1977) made a much more detailed study of synoptic weather conditions associated with rainstorms. Approximately 75% of the total rainfall occurred with squall lines or squall areas, most of which were associated with fronts, particularly cold fronts. Huff *et al*. (1978) made a study of synoptic weather conditions associated with storms in which rainfall exceeded 1 inch at one or more gages on the CHAP Network of 317 recording raingages in approximately 4000 mi^2 in and around Chicago. Results verified those from METROMEX. In the CHAP study, squall lines and squall areas accounted for 61% of the heavy storms, and along with cold fronts, which are the most common breeding place for squall activity, were identified with 83% of the heavy rainstorms.

The various Water Survey studies have shown that the urban flash-flood storms, in which our primary interest is centered in this report, usually occur in the warm season from mid-spring to mid-fall, with a majority occurring during the summer (June-August) in Illinois and the Midwest. These storms usually have durations of less than 24 hours with a major portion of the rain occurring in 3 to 6 hours. Table 9 shows a typical distribution of *urban* heavy storms, defined as those producing rainfall exceeding that to be expected once in two years, on the average. This table may be used as a guide by urban hydrologists in the Midwest concerned with the flash floods of the convective season. The distribution in Table 9 is not applicable to large-scale heavy storms having durations in excess of 24 hours. Although urban areas may suffer the consequences of such storms occasionally, they are not the most frequent producer of the urban flash floods of the convective season. The synoptic types are defined below.

Squall Line Storms. A nonfrontal group of thunderstorms accompanied by a trigger mechanism, usually a short wave trough. The convective activity associated with the storm systems is intense, well-organized, and often arrayed in a narrow band or line of active thunderstorms.

Squall Zone Storms. A mesoscale system of thunderstorms organized into an area or cluster and independent of a frontal zone. These storms, like squall lines, tend to move across large regions of the Midwest, and an upper-air impulse is usually discernible.

Frontal Storms. Precipitation formed within 75 mi of a surface front (cold, static, or warm). There is no synoptic evidence that this precipitation is associated with a squall line or squall zone which, on occasion, moves 25 mi or more ahead of the fronts.

Air Mass Storms. A shower or thunderstorm generated within an unstable air mass. No large scale or mesoscale synoptic causes are evident. The resulting convective activity is usually widely scattered to scattered and weak.

Low Pressure Storms. A cyclonic storm situated so close to the area of interest that it is not possible to associate the precipitation with a frontal or mesoscale weather structure. These systems are rare during the summer months.

Table 9. Typical distribution of synoptic storm types associated with urban flash floods in the Midwest.

Synoptic Type	Percent of Storms
Cold Front	20
Warm Front	4
Stationary Front	10
Squall Line	36
Squall Area	26
Low Center	2
Air Mass Storm	2

Heavy Raincell Characteristics

The heavy convective storms of the warm season in the Midwest are usually produced by squall lines or squall areas. During a storm, a given area will normally be exposed to several individual thunderstorms. The thunderstorms are usually multicellular and these cells are responsible for the burst characteristics observed in convective storms. As used here, a raincell is defined as a closed isohyetal entity within the enveloping isohyet of the parent storm system. They are the basic convective entity from which heavy, short-duration rates develop during thunderstorm activity.

Because raincells are responsible for the short-duration heavy rates that occur over relatively small areas during convective storms, they are of concern to hydrologists in various problems relating to urban sewer design and engineering. A comprehensive study of raincells was conducted in conjunction with the 5-year METROMEX research at St. Louis. Huff (1977) made a study of heavy raincells, defined as those producing cell mean rainfall of 0.25 inch or more. These results are briefly summarized here because of potential applicability in urban hydrology.

Of special significance to the urban hydrologist was the finding that cells exposed to the urban environment have a median water yield that is 70% greater than cells exposed only to the rural environment. Table 10 shows a comparison of the frequency distribution of water yield (rainfall volume) between urban-effect and rural or no-effect cells in 659 heavy cells sampled during 1971-1975. Table 11 shows median values of various raincell parameters. The movements of the raincells should be of special interest, since they control the motion of heavy rainfall bursts within an urban area or other region of interest. Table 12 shows the frequency distribution of the heavy cell motions. The azimuth denotes the direction from which the cells move. Note that nearly one-half of the cells studied remained quasi-stationary after formation; that is, they exhibited little or no motion and rained themselves out where they developed. This lack of motion in the heavy cells is a major contributor to the production of flash-flood conditions. Among the 51% of the cells showing significant motion, the most frequent movements were from the WSW, W, and WNW (240°-300°). All but a very small percentage of all cells moved out of the SW and NW quadrants.

Table 10. Comparison of water yield between urban-effect (U) and no-effect (C) raincells among the heaviest cells during 1971-1975 at St. Louis.

Cumulative percent of raincells	Urban-effect volume (m^3)	U - C (m^3)	Percent difference
5	3.70×10^6	1.55×10^6	72
10	2.74×10^6	1.15×10^6	72
20	1.89×10^6	7.90×10^5	72
30	1.46×10^6	6.10×10^5	72
40	1.15×10^6	4.70×10^5	69
50	9.31×10^5	3.82×10^5	70
60	7.52×10^5	3.02×10^5	67
70	6.04×10^5	2.46×10^5	69
80	4.62×10^5	1.85×10^5	67
90	3.21×10^5	1.30×10^5	68
95	2.34×10^5	9.20×10^4	65

Table 11. Medians in cells having mean rainfall of 6 mm (0.25 in.) or more.

Raincell parameter	Medians for given parameter Urban effect	Topographic effect	No effect
Mean rainfall (mm)	10	9	9
Area (km^2)	99	91	60
Volume (m^3)	9.31×10^5	7.25×10^5	5.49×10^5
Duration (min)	35	34	24
Path length (km)	8.0	6.5	3.6
Rainfall gradient (mm/mi)	2.38	2.21	2.21

Table 12. Frequency of heavy raincell movements in the St. Louis region.

Azimuth (degrees)	Percent of cells
181-209	3
210-239	8
240-269	11
270-299	10
300-329	7
330-359	4
1- 29	2
30- 59	1
60- 89	1
91-119	1
120-149	1
150-179	2
Quasi-stationary	49

Temporal Rainfall Distribution Within Storms

Knowledge of the time distribution of rainfall in heavy storms is essential to optimize applications of rainfall data in urban hydrologic problems, such as the design of storm sewer systems. Utilization of time distribution characteristics has become increasingly important in hydrologic models used in storm drainage design. For example, the ILLUDAS model provides an objective method for the design of urban storm drainage systems and for the evaluation of existing systems (Terstriep and Stall, 1974). This technique, which is utilized widely in Illinois and the Midwest, employs a time distribution model devised by Huff (1967) in its computations.

An extensive study of the rainfall distribution within heavy storms (areal mean >0.5 in.) was performed by Huff (1967) through use of dense raingage network data collected by the Illinois State Water Survey. Results from this study were expanded later using data from a Chicago urban network (Huff and Vogel, 1976). In general, there was excellent agreement between the time distribution characteristics of the rural and urban network storms. This was verified further from later analyses performed with data from the METROMEX Network of 225 recording gages in 2000 mi^2 operated for 5 years in the St. Louis region, and the CHAP Network of 317 recording gages in approximately 4000 mi^2 operated during 1976-1978.

Time distribution models for convective storms, applicable to the Midwest and other areas of similar precipitation climate, are shown in Figs. 7 and 8. The first set of curves apply to point rainfall and the second set to areal mean rainfall over areas of 50-400 mi^2. The method derived by Huff (1967) was used in determining the curves, and the reader is referred to this paper for a complete description of the methodology.

In the Huff method, the data is initially stratified into four groups, depending upon whether the heaviest rainfall occurred in the first, second, third, or fourth quarter of the storm period. The time distributions are then expressed as cumulative percentages of storm rainfall and storm duration to enable valid comparisons between storms and to simplify analyses and presentation of the data. Areal grouping has shown only small changes in the time distribution with increasing size of sampling area. Therefore, the range of areas shown in Fig. 8 could be combined with only small losses in accuracy, as illustrated in Table 13. Furthermore, when the non-dimensional analyses were performed, it was found that the effects of areal mean rainfall and storm duration (up to 24 hours) was minor and exhibited no distinct trend. This permitted establishment of a single set of curves to encompass various mean rainfalls, storm durations, and areas such as used in Fig. 8.

The curves in Figs. 7 and 8 were determined from median values for all storms combined. The point rainfall curves were derived from a combination of rural and urban network data. The areal curves are those presented earlier by Huff (1967), which were based upon a large storm sample from dense raingage networks operated over a 12-year period in Illinois. The reader is referred to the Huff paper (1967) for a more detailed presentation of time distribution curves. In that paper, a family of curves is provided for each quartile. These show the more extreme percentage changes that may occur within a storm,

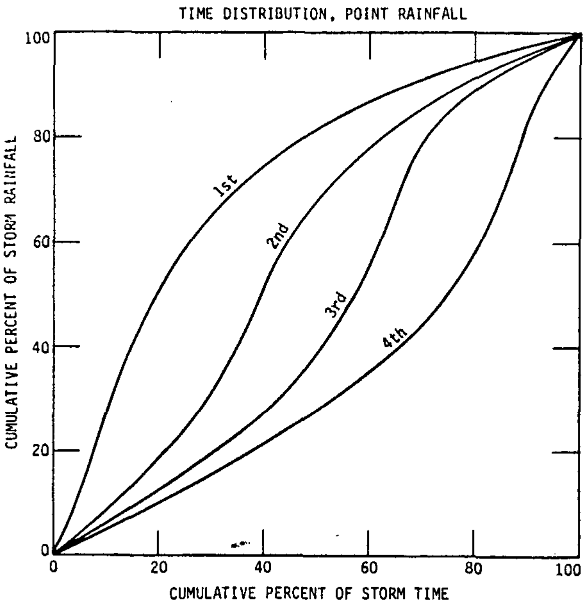


Figure 7. Time distribution of point rainfall.

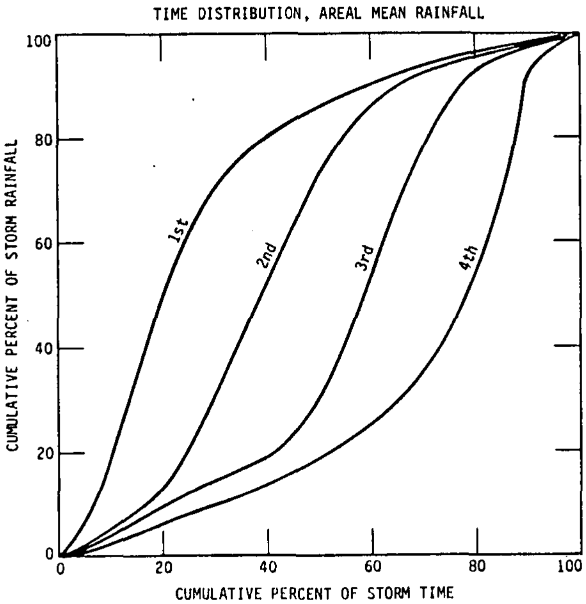


Figure 8. Time distribution of area rainfall.

along with a probability estimate for each curve in the family. Only median curves are shown here, since we have found these are the distributions normally desired by the present-day design engineer.

Table 13. Differences between Figure 8 and specific area curves.

Area (mi^2)	Difference (%) for Given Cumulative Percent of Storm Duration 10	20	30	40	50	60	70	80	90
50	-2	+3	+3	+2	+2	+2	+1	0	0
100	-2	-3	0	0	0	0	0	0	0
200	-2	-3	-2	-1	-1	0	0	0	0
400	+6	+4	-1	-2	-2	-1	-1	0	-1

Interpretation of Figs. 7 and 8 is illustrated by the following example. Assume one wishes to incorporate a typical time distribution model into his storm sewer design for an urban area of 75 mi^2, and he wishes to consider a 6-hour, 3-inch storm in which the rainfall is heaviest 1) early in the storm period, and 2) late in the storm period. Reference to the first-quartile distribution in Fig. 8 shows that in a typical distribution approximately 63% (1.89 in.) of the total storm rainfall will occur in the first quarter of the storm period, 86% (2.58 in.) in the first half of the storm, and 95% (2.85 in.) when three-fourths of the storm has passed. Similarly, in a fourth-quartile storm, only 9% (0.27 in.) would fall in the first quarter of the storm, 19% (0.57 in.) at the halfway point, and 41% (1.23 in.) when three-fourths of the storm period had passed. Then, 59% (1.77 in.) would fall in the last quarter (1.5 hours) of the 6-hour storm.

Spatial Distribution of Storm Rainfall

Knowledge of the spatial distribution of rainfall in heavy storms is pertinent in solving certain hydrologic problems, such as the design of urban storm sewer systems and evaluating the flood potential of various types of storms.

Area-depth curves are frequently used to portray the spatial distribution properties of heavy storms, since they provide a simple mathematical expression of the rainfall areal distribution. These curves are derived from planimetering isohyetal maps of storm rainfall, and summarizing the areal mean rainfall from the storm center outward (high to low values). The y-intercept of the curve represents the maximum point rainfall, and the last point on the curve is the areal mean rainfall. The slope of the curve provides a measure of the gradient of mean rainfall in the storm.

Considerable effort has been directed toward defining the spatial distribution characteristics of heavy storms in the applied research program of the Illinois State Water Survey. Using data from a dense network of raingages on 100 mi2, Huff and Stout (1952) found that an area-depth equation relating rainfall depth to the square root of the area frequently described the spatial distribution in thunderstorm rainfall on small areas. Later research on larger raingage networks in Illinois showed that the Huff-Stout general equation provides the best overall mathematical fit, but also revealed that the spatial distribution varies with several storm factors, such as basin size, mean rainfall, rain duration, precipitation type, and synoptic storm type (Huff, 1968).

Several studies of area-depth relations have been made in urban areas in recent years. Huff and Vogel (1976) studied relations in the Chicago urban area, and this work was continued later with operation of the large CHAP Network (Huff et al., 1978). Similar studies were performed in the St. Louis area using data from the 2000 mi^2 METROMEX Network. The urban studies, in general, supported the earlier findings of Huff (1968) who employed a much larger sample of 260 storms obtained from a 12-year operation of a dense raingage network in central Illinois. Also, the urban studies revealed no evidence of significant differences in the spatial distribution characteristics of urban and rural storms.

Knowledge obtained from the various network area-depth studies has been used to construct Table 14 which can be used for guidance by design hydrologists needing information on the spatial distribution characteristics of heavy rainstorms in Illinois and the Midwest. Table 14 is based primarily on the 260-storm sample from the central Illinois network, since other studies were less comprehensive and provided no major disagreements with the 1968 findings.

Derivation of Area-Depth Relations. Because of the relatively great interstorm variability, area-depth relations were developed in terms of probability distributions for given sets of conditions with respect to rainfall volume, duration, and area. Although various other factors, such as rainfall type and synoptic weather type, influence the characteristics of the area-depth curve, these factors cannot be expressed mathematically or adequately integrated into hydrologic design formulas. Furthermore, derivation of area-depth relations after grouping according to all known influential factors would require a sample several times larger than available in this study. The method used provides both average area-depth curves and curves applicable to more extreme patterns of storm rainfall under specified conditions of mean rainfall, rainfall duration, and basin area. The effects of other storm factors are integrated in the probability relations.

In deriving the probability relations, the ratio of maximum point rainfall (P_m) to areal mean rainfall (P_a) was obtained from the best-fit equation in each storm. This ratio (P_m/P_a) was then related to area (A), duration of rainfall period (T), and basin mean rainfall (P_a).

Table 14 shows P_m/P_a ratios for the 5%, 50%, and 95% probability limits for an area of 400 mi2. Values for 200, 100, and 50 mi^2 can be obtained by multiplying the 400 mi2 values in Table 14 by 0.96, 0.93, and 0.90, respectively. The ratios in Table 14 were derived largely from mean rainfalls of 0.5 to 3 in,

Table 14. Ratio of maximum to mean rainfall on 400 mi^2.

Rainfall Period, hrs	Mean Rainfall, Inch							
	0.5	1	1.5	2	2.5	3	4	5
		5% Probability Level Ratios						
0.5	5.20	3.00	2.18	1.70	1.41	1.30	1.26	1.22
1	5.50	3.21	2.29	1.80	1.48	1.35	1.30	1.25
2	5.80	3.38	2.44	1.90	1.55	1.41	1.33	1.28
3	6.05	3.54	2.53	1.99	1.61	1.46	1.36	1.30
6		3.77	2.69	2.12	1.72	1.52	1.43	1.35
12		4.01	2.86	2.25	1.83	1.60	1.50	1.40
18		4.14	2.96	2.33	1.90	1.65	1.54	1.43
24		4.27	3.05	2.40	1.96	1.69	1.57	1.45
48		4.55	3.25	2.55	2.08	1.77	1.63	1.50
		50% Probability Level Ratios						
0.5	2.66	2.02	1.57	1.32	1.22	1.16	1.14	1.12
1	3.03	2.15	1.65	1.39	1.27	1.20	1.18	1.16
2	3.46	2.29	1.75	1.46	1.32	1.24	1.21	1.19
3	3.77	2.42	1.85	1.52	1.38	1.28	1.23	1.22
6		2.59	1.98	1.63	1.43	1.33	1.28	1.26
12		2.78	2.12	1.75	1.50	1.39	1.32	1.30
18		2.89	2.20	1.81	1.57	1.43	1.35	1.32
24		3.00	2.28	1.87	1.60	1.47	1.38	1.33
48		3.17	2.44	1.99	1.68	1.53	1.46	1.38
		95% Probability Level Ratios						
0.5	2.38	1.53	1.28	1.18	1.16	1.13	1.11	1.10
1	2.75	1.72	1.38	1.23	1.20	1.17	1.15	1.14
2	3.15	1.90	1.47	1.28	1.24	1.20	1.18	1.16
3	3.46	2.02	1.53	1.33	1.27	1.22	1.20	1.18
6		2.24	1.67	1.43	1.31	1.27	1.24	1.21
12		2.50	1.78	1.50	1.38	1.31	1.28	1.25
18		2.67	1.89	1.53	1.41	1.33	1.30	1.27
24		2.77	1.92	1.58	1.43	1.35	1.32	1.29
48		3.07	2.07	1.64	1.47	1.40	1.36	1.33

values above this are essentially extrapolations of the basic curves constructed in deriving the relations. In deriving Table 14, all storms were used in which the areal mean rainfall equalled or exceeded 0.5 inch and one or more gages recorded point amounts exceeding the 2-year recurrence interval value for the given rain period (hours).

The 50% ratios in Table 14 can be used to approximate average conditions of spatial variability. For applications involving rainfall patterns approaching uniformity, the 95% ratios are recommended. Similarly, for the user confronted with extreme conditions of spatial variability, the 5% ratios are recommended as close approximations in the Midwest and other areas of similar precipitation climate.

The 5% values in Table 14 result from storms with exceptionally steep rainfall gradients on the sampling area. For given values of area, mean rainfall, and rain duration, these extreme values are most likely to occur with air mass storms and with storms in which the rainfall core is located at or near the basin border. The 50% ratios are more representative of storms centered on the basin. The 95% ratios result from storms with weak rainfall gradients and are most likely to result from steady-type rains as opposed to rainshowers and thunderstorms, and with large-scale synoptic weather systems, such as the passage of a low pressure center through the sampling region.

The ratios presented in Table 14 are to be interpreted as representative values for rainfall patterns of various degrees of uniformity. They do not represent a historical frequency distribution of all storms that have occurred. Only those storms in which excessive rainfall amounts were recorded were incorporated into the analyses. However, these storms appear to be the type of major interest to most hydrologists, although not necessarily to climatologists and all other possible users. As a result of the selection criteria, a minimum value of P_m (2-year frequency) dictated the selection of samples from the 0.50-inch or greater mean rainfalls for each rainfall duration. This limiting value, which increases from 1 inch for 0.5 hour to 2.75 inches for 48 hours, results in the Pm/P_a ratios' increasing with duration in Table 14 for any given mean rainfall.

Application of Results. The ratios of P_m/P_a developed in this study can be used to construct area-depth curves for average or extreme storm conditions through the use of known or assumed values of area, mean rainfall, and rainfall time period. In constructing area-depth curves from Table 14, an equation relating logarithm P to $A^{0.5}$ is recommended for storm periods of 3 hours or less. For longer rain periods, use the Huff-Stout equation which relates P to $A^{0.5}$.

The use of Table 14 is illustrated by the following example. Assume the user wishes to construct an area-depth curve representative of average conditions in Chicago on an urban area of 400 mi^2 in which a 3-hour storm producing an areal mean rainfall of 2.4 inches occurs. Reference to Table 14 shows a P_m/P_a ratio of 1.41 (interpolating between 2.0 and 2.5 inches for a 3-hour rain period at the 50% probability level. Multiplying 2.4 inches (P_a) by 1.41 gives a maximum point rainfall of 3.38 inches. Plotting these two values on the proper scales (log P vs. $A^{0.5}$) for a 3-hour storm results in the area-depth curve shown in Fig. 9.

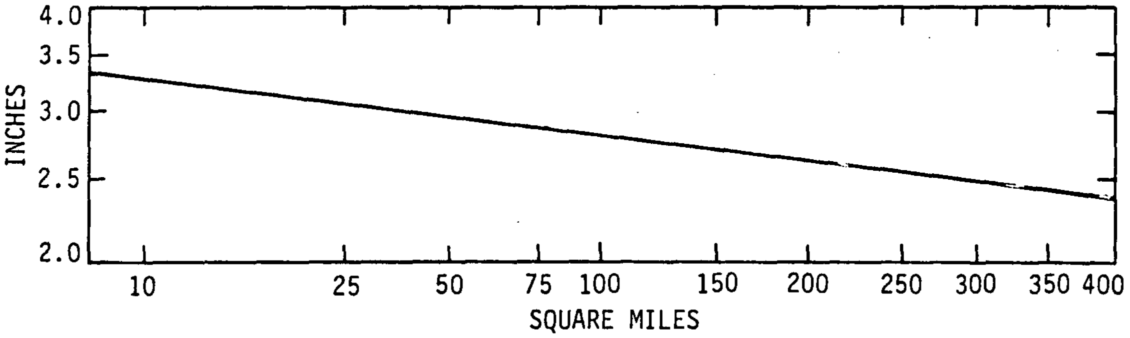


Figure 9. Average area-depth relation for 3-hour, 10-year storm at Chicago.

The reader is referred to the several references listed above, particularly Huff (1968), for more details on area-depth relations resulting from studies by the Illinois State Water Survey.

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APPENDIX A

Radar parameters which should be specified when procuring a radar system for quantitative precipitation measurements.

TRANSMITTER

Transmitter frequency
Frequency tuning range
Peak power
Pulse recurrence frequency
Pulse length
VSWR (voltage standing wave ratio)
Duplexer

RECEIVER

Pre-amplifier

Signal dynamic range
Frequency band pass
Stability

IF-amplifier

Frequency
Frequency bandwidth
Noise figure
Gain (dynamic range)
Stability
AFC precision
Rise time $\}$ bandwidth
Decay time
Minimum Detectable Signal recovery time after saturation
DC coupling of circuits after video detector

DVIP

Range resolution
Number of range increments
Analog stability
Long term stability
Number of samples in average
Ability to average range intervals
Range delay
Iso contour
R^2 characteristics
Block integration
Calibration procedure
Outputs for real time scopes
Tape recorder
Parity checks
Tape editing
Replay capability

DISPLAYS

PPI scope
RHI scope
A scope
Range markers
Ranges
Date and time
Azimuth indicator
Elevation indicator

ANTENNA

Mechanical drive type, rotational speed, and acceleration
Reflector size, shape, and surface accuracy
Beam polarization type, switchable
Antenna gain
Beam shape
Half power beam width
Side lobe specifications
Antenna feed, type VSWR
Position indicators, type, number, accuracy
Leveling devices
Radome, type, size
Antenna controller
Scan type
Scan speeds
Automatic sequences
Manual controls

ENVIRONMENTAL

Temperature range
Relative humidity range
Pressure range (elevation feet)
Wind speed: operational and survival